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Experimental and Modeling Study of the Effects of Sealing Structures in Lost Circulation Prevention and Remediation

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Abstract

Drilling fluid lost circulation leads to non-productive time and increases the overall well cost. In general, wellbore strengthening and lost circulation control are achieved by creating effective sealing structures to inhibit fluid flow through loss conduits such as formation fractures. This research aims at improving the understanding of the effects of sealing structures in fluid loss prevention and remediation, and providing useful references to effectively establishing filtercakes on the wellbore and plugs in the fracture.

Recent research on wellbore strengthening disclosed the critical role of filtercake in sealing microfractures during the initial stages of fracture initiation and propagation. The performance of a filtercake to strengthen the wellbore depends on its capability to maintain integrity. In this research, a new parameter –"filtercake rupture resistance" and a new testing method are proposed to simplify the evaluation of the filtercake's potential to withstand pressure over a small fracture. Experiments were conducted to understand the effects of fluid and filtercake properties on filtercake's rupture resistance and the effectiveness of filtercake in reducing fracture sealing time. The effects of filtercake with lost circulation materials (LCMs) in reinforcing fracture sealing were explored and it is recommended to consider the role of filtercake when evaluating the LCMs and designing lost circulation preventive treatment.

In addition to studying filtercakes for lost circulation prevention, this research also investigated LCM fracture plugs for fluid loss remediation. When drilling through naturally fractured reservoirs, the remediation of drill-in fluid loss needs to be designed considering both fracture plugging and formation damage. Statistical methods were used to better design the experiments and optimize the LCM implementation schemes, in order to efficiently create the desired fracture plug with less fluid invasion into fractures. The plug structure was visualized by

SEM and Micro-CT scan to understand the effects of plug soaking process. A mechanistic model for calculating plug permeability with soaking time was developed to optimize hesitation schemes.

This research presents new understandings about lost circulation and wellbore strengthening, and provides improved recommendations for optimal fluid loss solutions.

Chapter 1. Introduction

1.1 Overview of Drilling Fluid Loss and Wellbore Strengthening

Lost circulation or drilling fluid loss is the loss of drilling fluid to the formation in an overbalanced drilling operation. Associated hazards are non-productive time (NDT) in lost circulation remediation, formation damage in a pay zone, loss of hydrostatic pressure and associated well blowout, etc.

Preventing and remediating lost circulation while drilling has been a challenge in the petroleum industry for decades. The economic impact of drilling fluid loss events is approximately $800 million per year. One of the primary tasks in preventing fluid-loss issues is good drilling operational practice, the key factor to take into consideration is the operational mud window. Especially for depleted formations and deep-water drilling, the operational mud window becomes narrower and there are high risks of fracturing the formations and creating fluid loss channels. Fracture-initiation pressure (FIP) and fracture-propagation pressure (FPP) are both important considerations to combat lost circulation. For drilling-induced fractures, a fracture must initiate on an intact wellbore or reopen as a pre-existing fracture, and then propagate into the far-field region by overbalanced pressure (Feng and Gray, 2017).

Wellbore strengthening (WBS) methods are designed to enhance wellbore integrity and provide higher FIP and FPP. It is cost-effective and less complicated compared to other methods such as managed pressure drilling and dual gradient drilling when applied appropriately (van Oort and Razavi, 2014). WBS may not physically “strengthen” the wellbore, instead, it provides possible solutions to increase the pressure at which lost circulation occurs, thus provides a wider operational window (Feng and Gray, 2017). It can be claimed that the wellbore is strengthened if the lost circulation pressure is increased.

Lost circulation materials (LCMs) are commonly applied to mitigate fluid loss into subterranean formations, they also play a major role in WBS. The concept of LCM can be broad, it involves materials that are capable of creating structures to seal the fluid loss conduits. The sealing structures include but are not limited to: (1) filtercakes covering the formation pores to reduce seepage loss; (2) LCM plugs blocking the natural fractures to prevent fluid from flowing through; and (3) filtercakes and plugs sealing induced fractures to inhibit fracture propagation.

1.2 Motivation

Developing solutions for lost circulation prevention and remediation has been an industry research focus for years. Strategies relying on drilling fluid properties and additives such as LCMs are cost-effective and do not require additional equipment like casing while drilling and managed pressure drilling. In general, WBS and lost circulation control are achieved by creating sealing structures around the wellbore (filtercakes) and inside the fractures (LCM plugs). Studies for characterizing the sealing structures, evaluating their performance, and improving the sealing structure creating process can provide more information in assisting WBS and lost circulation mitigation.

1.2.1 Fluid Loss Challenges in Depleted Zones

The issues of fluid losses when drilling through depleted zones, especially the mature areas, have received considerable attention. High risks of fluid loss and wellbore stability problems in these zones can be associated with pre-existing natural fractures and drilling-induced fractures. Incorporating a high concentration of large LCM particles in the fluid as a pill is commonly applied after identifying fluid losses, such delayed remedial methods carry disadvantages such as long non-productive time.

There is a clear need for improved approaches to drilling through sections with high risks of lost circulation. Recent researches have disclosed the importance of filtercake in preventive WBS. The filtercake can provide a barrier to prevent fluid from entering the fracture at the fracture initiation stage. A fluid system with the ability to form an enhanced filtercake has the potential to continuously strengthen the wellbore (Falgout and Stefano, 2017). A better understanding of filtercake mechanical properties and the mechanisms of filtercake in increasing lost circulation pressure can help better design corresponding fluid loss prevention methods.

1.2.2 Filtercake Characterization for Wellbore Strengthening

Field evidence has shown that lost circulation problems in depleted formations can be prevented by adding proper additives to the mud to improve filtercake quality and thus strengthen the wellbore (Feng et al., 2016) (Ziegler and Frederick Jones, 2014). However, there is no well-defined criterion that characterizes the filtercake quality in terms of its capability in WBS. The filtercake quality can be generally represented by filtercake strength, which is currently part of the API low-temperature fluid loss test regarding the filtercake's consistency. However, the descriptions such as hard, soft, tough and rubbery are subjective (Bailey et al., 1998). Different methods for filtercake strength measurement are available in publications, but none of them are specially designed to reflect the filtercake's resistance to rupture. Large-scale experiments such as hydraulic fracturing test could comprehensively simulate the WBS process, but the experimental setup may be complicated, costly, and not efficient enough for filtercake quality evaluation. It may also be difficult to catch the fracture aperture during the hydraulic fracturing tests.

A criterion and an effective method to characterize the filtercake quality regarding its resistance to rupture is needed to provide a reference for better drilling fluid design.

1.2.3 Filtercake and LCM Evaluation

The filtercake's ability to provide a barrier to isolate fluid and pressure between wellbore and formation depends on several factors: the fracture aperture, the filtercake thickness, the filtercake yield strength in shear, the filtercake yield strength in tension, the bonding between filtercake and the formation, etc. How each factor affects the filtercake's quality should be further explored. LCMs designed for lost circulation prevention are sometimes called lost circulation prevention materials (LPMs), they are often added into drilling muds as a preventive treatment for lost circulation. It is generally believed that these materials can bridge/plug the fractures to reduce the risk of lost circulation. A common approach to evaluate the effects of LPM is incorporating them into drilling fluid and directly test the fluid's performance in sealing fractures without considering the effects of filtercake. However, filtercakes can form on the wellbore before fracture initiates, the capability of LPM/LCM in sealing fractures should be evaluated considering the effects of filtercake.

1.2.4 LCM Implementation in Naturally Fractured Reservoirs

The design of drilling fluid lost circulation remediation strategies is complicated in naturally fractured reservoirs. It has been a great challenge for engineers to ensure the effects of fracture plugging and meanwhile to minimize formation damage risk. Implementing acid-soluble LCMs to create a fracture sealing structure is a conventional and cost-effective approach. Hesitation squeeze or soaking the LCMs is a common implementation practice for high-fluid-loss LCM systems. Soaking the LCM plug can strengthen it by increasing its length and decreasing its permeability. When plugging the fractures in pay zones, the less amount of LCMs being used, the easier the fractures can be unchoked for production. And less amount of LCM-laden fluid invading into the fracture leads to less formation damage risk.

The LCM implementation strategies should be carefully designed to effectively utilize the materials to achieve desired fluid loss remediation and formation damage control. However, the LCM pill implementation seems to be empirical-based or a trial and error process. More studies are needed for improving LCM implementation strategy design.

1.3 Research Objectives

The main objective of this research is to investigate the effects of sealing structures in lost circulation prevention and remediation, then provide references to effective creation of sealing structures to promote fracture sealing. The sealing structures investigated were filtercakes on the wellbore wall and LCM plugs inside the fracture.

Special attention has been paid to explore the role of filtercake in strengthening a wellbore with drilling-induced or natural microfractures. A simple and efficient experimental method is proposed to characterize the performance of filtercake in resisting rupture and sealing fractures with different apertures. Filtercake rupture resistance is defined as a representation of the filtercake's capability to hold the differential pressure over the fracture before the filtercake loses its integrity. The performance of LCMs in sealing fractures is evaluated in consideration of the effects of filtercakes. The effects of filtercake properties: filtercake thickness, filtercake yield strength in shear, and the effects of LCM properties: LCM type, concentration and particle size distribution on filtercake performance in filtercake rupture and fracture sealing processes are investigated.

One of the most common sealing structures inside a fracture is the combination of dehydrated mud and LCM plugs for mitigating fluid loss and fracture propagation. Factors involved in LCM implementation schemes are studied using statistical methods for effectively creating the desired plug, reducing the LCM-laden fluid invasion into the fractures, and thus reducing formation damage risks in fractured pay zones. Understanding and predicting the properties of the LCM plug are important for effective fluid loss remediation, a model that predicts the plug length and permeability with the soaking/filtration process is developed to guide the evaluation of LCMs and the design of soaking schemes.

The dissertation covers four related topics, the details about each topic are presented through Chapter 3 to Chapter 6. Each topic has its individual objectives, Topic 1 and Topic 2 focus on filtercakes on the wellbore, Topic 3 and Topic 4 focus on LCM plugs inside the fracture. Topic 1 proposed an efficient method for characterizing filtercake's capacity to maintain its integrity over fracture; Topic 2 explored the capability of LCMs to create filtercakes; Topic 3 tried to optimize LCM implementation for more effective fracture plugging; Topic 4 developed a model to calculate fracture plug permeability change with the filtration process.

1.4 Research Methodology

This research incorporates theoretical study, laboratory experimental study and modeling study. A comprehensive literature review was conducted first to introduce the backgrounds and build-up the research foundation. Experiments were designed after finding the current research gaps and setting the research objectives. The performance of filtercakes and LCM plugs in reducing fluid loss, preventing fluid transmission between wellbore and fractures, and preventing fracture propagation was evaluated. A permeability plugging apparatus with various kinds of slotted discs were mainly used for experimentally investigating the effects of filtercake and operation schemes in fracture sealing. Fluid rheological properties and filtercake yield strength were characterized using an advanced rheometer. Statistical methods such as design of experiments, ANOVA and regression analysis were used to investigate the statistical importance of factors affecting LCM implementation effects. LCM plug structure and property change after soaking were observed using Scanning Electron Microscope (SEM) and Micro-computed Tomography (micro-CT) scan. Mechanistic models for presenting the filtration process were reviewed, and a model for calculating LCM plug length and permeability change during filtration was developed.

Chapter 2. Literature Review

This chapter provides general background about drilling fluid loss mechanisms, fluid loss treatments, and LCM design principles. Critical literature review regarding a specific topic is presented in the introduction section of each chapter.

2.1 Drilling Fluid Loss Mechanisms

Drilling fluid lost circulation is defined as the fluid loss to the formation due to the overbalanced differential pressure from the wellbore to the formation. Overbalanced pressure and fluid loss channels are the two key factors that cause fluid loss. Based on the fluid loss rate or intensity, the fluid loss types are typically classified as seepage loss, partial loss, severe loss and total loss (Nayberg, 1987). Currently, there is no consensus on the fluid loss rate range for each fluid loss type, plus that for oil-based mud, a relatively low rate of fluid loss can be considered server due to the cost and environmental issues. To characterize the fluid loss mechanisms and suggest approaches for fluid loss mitigation, Ghalambor et al.(2014) classified fluid loss mechanisms based on fluid loss mediums/channels, which include fluid loss to pore throats, to natural or induced fractures, to vugs and caverns, and the fluid loss rates are typically seepage, partial or severe, and total, respectively.

Drilling fluid loss into fractures is typically classified concerning the fracture type: natural fractures and drilling-induced fractures. Losses through natural fractures occur in naturally fractured formations. The fracture width is critical to fluid loss remediation as it is an important reference to design LCMs. The effects of solid plugging are critical considerations for stopping fluid loss in natural fractures (Razavi et al., 2017), and fluid loss may eventually stop due to the rheological properties of the fluid (Majidi et al., 2010). The fluid loss models mostly assume that a wellbore perpendicularly intersects a radial horizontal fracture in the center (Sanfillippo et al., 1997) (Lietard et al., 1999)(Majidi et al., 2008). Natural vertical fractures are less considered since it is a rare scenario that a wellbore passes through a fracture along the fracture aperture.

Fluid losses through drilling-induced fractures are more sensitive to the overbalanced pressure between the well and the formation. In field operations, the fracture gradient of the formation is the lower limit of the operational mud window. At a given depth, the fracture gradient is the pressure needed to induce fractures in the formation rocks. Fracture-initiation pressure, formation breakdown pressure and fracture-propagation pressure are important considerations to combat lost circulation in drilling-induced fractures (Feng et al., 2016). When the overbalanced pressure exceeds the fracture initiation pressure of the formation, fractures are created and provide fluid loss channels (Dupriest, 2005). The fractures can easily propagate if they are not sealed effectively, leading to enlarged fluid loss spaces and then more severe fluid losses. Filtercakes can form on the wellbore wall before the initiation of the fractures and can maintain their integrity over the fracture at the initial stages of fracture initiation and propagation. The filtercake prevents the transmission of the fluid and pressure between the wellbore and the fractures. If the fluid contains properly sized particles, it can further prevent fracture propagation by forming a filtercake inside the fracture and isolating the fracture tip. The actual downhole condition is complicated and it involves changes in overbalanced pressure, mud flow rate, and drill string rotation speed, etc. The fluid loss in induced-fractures is a dynamic process that combines the filtercake rupture, fracture propagation, fracture aperture widening, and filtercake self-healing.

2.2 Drilling Fluid-Based Treatments to Lost Circulation

Many solutions have been proposed to prevent and remediate lost circulation. A better drilling practice, especially a more precise prediction and control of downhole pressure is one of the key factors to prevent fracture creation and lost circulation. Approaches like managed pressure drilling, casing while drilling and offshore dual gradient drilling require advanced facilities and operational skills. Drilling fluid-based treatment, for example using LCMs to plug the fracture and strengthen the wellbore, is relatively simple and as effective as other approaches when applied properly.

Lost circulation treatments can be classified as preventive and remedial treatments. In terms of applying LCMs, the preventive treatment incorporates LCMs in drilling fluids to inhibit fracture initiation and fracture growth. The remedial treatment is applied after the detection of considerable fluid loss and aims at bridging/plugging or sealing the fractures using LCM.

2.2.1 Preventive Treatments

One of the key aspects for preventing lost circulation is to increase the ability of the formation to tolerate high mud weights and surge pressures in order to avoid drilling-induced fractures. In the event of fluid loss through induced fractures, a fracture must initiate on the wellbore or a pre-existing fracture must reopen, and an overbalanced pressure should also enable these fractures to propagate into the far-field region (Feng and Gray, 2016).

Lost circulation should be prevented rather than remediated. Preventive treatments are generally more effective than remedial treatments (Guo et al., 2014). The common purpose of preventive treatments is to strengthen the wellbore, or in other words, to increase the pressure thresholds that lead to lost circulation. Salehi and Nygaard (2012) defined wellbore strengthening as a variety of approaches that give room for drilling a wellbore or an interval of interest with an increased fracturing pressure. Feng et al., (2016) classified wellbore strengthening approaches into preventive approach and remedial approach. The preventive WBS approach is applied when the fluid loss zone is known or anticipated and the drilling fluid system is designed for increasing the fracture initiation pressure and sealing the fracture at the initial stage. The remedial WBS approach is applied to weak zones with high risks of fracture initiation and propagation, such zones may already cause hazards in drilling operations. The purpose of the remedial WBS approach is actually to “prevent” further fluid loss issues due to induced-fractures. LCM pills are pumped to bridge and seal the fracture, forming a stress cage, increasing the hoop stress of the formation, isolating the fracture tip, so that the fracture initiation pressure and fracture propagation pressure of the targeted zone are increased.

Currently, field applications of WBS are a trial and error process, implementation of similar operating procedures does not always guarantee satisfactory results. The mechanism of WBS is still not well understood, it is generally believed that WBS could successfully increase the operational window through one or the combination of the following three mechanisms: (1) Propping open induced fractures near the fracture mouth could increase the local compressive hoop stress, which leads to a higher fracture initiation pressure (Wang et al., 2008)(Feng et al., 2015); (2) Creating a bridge inside the fracture to maintain certain fracture width may increase fracture closure pressure (Dupriest, 2005)(Lai and Woodward, 2014); (3) Isolating the fluid and pressure communications from the fracture tip to the wellbore can prevent fracture propagation (van Oort et al., 2011) (van Oort and Razavi, 2014).

Incorporating a relatively low concentration of LCMs into the drilling fluid is commonly applied as a lost circulation preventive approach. The LCMs can help enhance the properties of the filtercake so that it can seal the fracture at the initial stages. However, the LCM design guidelines for such approaches are limited and the effects of filtercake in this process may have been overlooked.

2.2.2 Remedial Treatments

Remedial treatment can be defined as any treatment method that is applied to cure fluid loss after a loss event has occurred. Conventional LCMs are commonly used in this type of treatment. The LCMs are constantly added to the drilling fluid or work as a high concentration LCM pill to seal the fluid loss channels (Morita et al., 1990)(Fidan et al., 2004). Other technics beyond traditional LCMs for remedial treatment are also available, for example, crosslinked additives that can be chemically activated (Fidan et al., 2004), thermally activated smart LCMs (Mansour and Dahi Taleghani, 2018), nanoparticles and gels (Wagle et al., 2019)(Fidan et al., 2004), deformable-viscous-cohesive (DVC) materials (Wang, 2011)(Whitfill, 2008)(Traugott et al., 2007), and functional cement (Mata and Veiga, 2004), etc.

Special attention should be paid to fluid loss in fractured pay zones. The selection of LCMs for non-reservoir zones is broad and does not need to consider the issues of formation damage. However, for a fractured reservoir, the LCM solutions have to be non-damaging to the formation, or at least inflict minimal formation damage. The LCM choices are limited to degradable or acid-soluble materials. In the event of severe losses, acid-soluble calcium-carbonate particles with a larger PSD may be used along with acid-soluble fibers (Savari et al., 2016b)(Savari et al., 2017). Acid-soluble cement can also work as a solution for lost circulation across producing zones (Seymour and Santra, 2013). Solid-free polymer pill or crosslink system are alternative solutions for fluid loss in fractured pay zones (Vasquez and Fowler, 2013)(Himes et al., 1994). Such chemical sealants may require specialized personnel or equipment. Effectively using acid-soluble LCMs is still a commonly used solution and a relatively simple choice. Optimizing the LCM implementation schemes is important to minimize the invasion of LCMs into the formation fractures while ensuring the plugging effects. There is less risk of fracture permeability damage when there is less amount of LCM invading the fractures.

2.3 Lost Circulation Material Properties and Design Principle

Lost circulation materials (LCMs) are common drilling fluid components that are used for blocking, bridging and sealing fluid loss channels in the formation. Fine-particle LCM also plays an important role to enhance the quality of the filtercakes. The materials used for strengthening a wellbore are sometimes called loss prevention materials (LPMs), they can also be categorized into LCMs.

The classification of LCMs is often based on their physical appearance. The most commonly seen LCMs types are granular (for example graphite and calcium carbonate), fibrous (cellulose fiber, sawdust), flaky (flaked calcium carbonate). Other types are classified based on their properties and applications (Alkinani et al., 2018). Usually, the LCMs are a mixture of different types of materials. The physical appearance and properties such as LCM resilience are important in LCM design. Especially for WBS, the materials for plugging and bridging the fractures should be hard enough to withstand the fracture closure pressure without being smashed. The materials should also be resilient and can deformable with the change of compressive force, since the change of downhole conditions may change the fracture aperture, a resilient material can deform with the fracture and keep the fracture plugged (Savari et al., 2012).

Another key factor to consider for LCM design is the particle size distribution (PSD). It can be defined as the spatial distribution of various-sized particles within a mixture system. The PSD is a crucial design aspect of LCMs and it should be designed according to the known or predicted geometry of fluid loss channels (Salehi and Nygaard, 2012)(Zhong et al., 2017) (Ezeakacha and Salehi, 2018). A carefully designed LCM with proper PSD can also enhance the corresponding filtercake properties such as filtercake thickness, tightness, permeability and cohesion (Kiran and Salehi, 2017). Several PSD design principles have been proposed by different authors. Abrams (1977) proposed two-rule for LCM selection and claimed that the median particle size should be no less than one-third of the mean pore size, and the minimum particle volumetric concentration should be 5%. Smith et al (1996) concluded that 90% of the particles should have a diameter larger than the pore size. Vickers et al.(2006) proposed a detailed PSD design method that specified the particle diameter for each portion of the particle mixture, the minimum value for D90, D75, D50, D25 and D10 compared to the pore throat size are stated. These researches provided valuable information for controlling filtration fluid loss through pore throat. However, the mechanisms of fluid loss through fractures are quite different from those through pores. Whitfill (2008) stated that to effectively seal the fracture, more than 50% of the particles should have a diameter larger than the fracture width. Kageson-Loe et al.(2009) showed that the most competent fracture seal is formed at the entrance to the fracture and this process requires that the materials are larger than the fracture aperture. The effectiveness of the seal can be sensitive to the relative concentration of larger particles. Alsaba et al. (2017) claimed that the D50 value of a mixture should be larger than 3/10 of the fracture width and the D90 value should be larger than 6/5 of the fracture width. Razavi et al.(2015) claimed that optimum PSD can be of overriding importance in WBS and it is dependent on the rock properties that govern fracture dimensions. A bi-modal PSD distribution LCM blend is preferred over a unimodal blend for improved WBS effects. Wang et al.(2019) suggested that for granular LCMs, the size ratio of D90 to the fracture opening should be between 0.5 and 0.7, the relative granularity span should be greater than 1.5, and D10 should be between 0.1 and 0.2 mm. Apparently, the design of LCM PSD requires further studies to reach a unified standard.

Moreover, the fluid loss during drilling is a combination of dynamic processes, which makes the design of LCMs more complicated. The design of LCMs needs to consider the degradation of the materials due to the dynamic wellbore condition (Valsecchi, 2014)(Grant et al., 2016). For example, calcium carbonate is “fragile” and can degrade into smaller particles during the fluid mixing stage due to the string of the mixing blade, or during drilling due to the rotation of the drill pipe. And lots of LCMs have their temperature limit beyond which they start to degrade and lose their functionality.

The design of LCMs also needs to consider formation damage issues to the pay zones. The fluid system should be able to form a tight filtercake around the wellbore to seal/isolate the pores. The particles in the fluid that are smaller than the pore throat tend to enter and invade further into the pores, if the fluid system lacks the capability to form a structure like the filtercakes to prevent the fine particles from further invasion, the fine particles will reduce the backflow permeability of the formation, this will greatly impact the formation production capacity. The particle packing mechanism can depend on particle shape, concentration, morphology and PSD (Ezeakacha et al., 2017) (Chellappah and Aston, 2012). And for lost circulation mitigation of fractured pay zones, the reservation of the fracture permeability is of great importance. The LCMs need to be soluble so that the fractures can be unchoked to provide fluid flow channels during the production stage. And the plug needs to be created effectively with carefully designed LCM implementation strategies so that the LCMs are plugging/bridging the fracture instead of “filling” the fracture, the invasion of the LCM particles to the fracture should be minimized.

Chapter 3. Filtercake Performance in Resisting Rupture and Reducing Fracture Sealing Time

3.1 Introduction

The performance of filtercakes in strengthening a wellbore with narrow fractures may depend on the filtercake's capability to provide a strong barrier over the fractures. Such a barrier must be "tough" enough to maintain its integrity to withstand the differential pressure. To the authors' best knowledge, there is no well-defined criterion for evaluating the capability of filtercake to resist rupture over fractures. In this chapter, a simple approach is proposed to characterize the filtercake's ability to resist rupture. Particulates such as sands, drilled cuttings and LCMs may be parts of the filtercake components. These solid particles can play a significant role in sealing the induced fractures and limit fracture propagation. The effect of filtercakes in reducing the time required to achieve fracture sealing is disclosed in this study. Filtercake rupture resistance, together with fracture sealing time were used to evaluate the performance of filtercake in wellbore strengthening. The effects of fracture aperture, as well as filtercake thickness (permeability), yield strength in shear and solids concentration (both bentonite and a fibrous LCM) on filtercake rupture resistance and sealing time were investigated.

3.1.1 The Role of Filtercakes in Lost Circulation and Wellbore Strengthening

Morita et al. (1996a) has firstly claimed the importance of the sealing capacity of drilling fluids in WBS. Drilling fluid acts as a good sealant for narrow cracks and fracture tip. The sealing

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structure prevents pressure from reaching the end of the fracture tip and increases the fracture propagation resistance.

Aadnøy and Belayneh (2004) developed an Elasto-Plastic Fracturing Model that takes the filtercake on the wellbore wall into consideration. This model treats the filtercake as a similar structure to the sand arch formed during sand production through perforations. Fracturing experiments on concrete cores showed a much higher fracturing pressure than predicted by linear elastic theory when using fluids with loss control. The extra pressure can be provided by the barrier formed by the filtercake on the wellbore wall over the fracture. The authors believed that the particle size distribution, the compressive strength of the particles, and the filtrate fluid control are critical parameters to create effective barriers across fractures. Extended experimental research was then conducted based on the elastoplastic barrier model (Aadnoy et al., 2008). The authors tested commercial LCMs to provide an optimal composition of LCM pill that can form a better barrier over the fracture, thus increases the fracture pressure of the formation. They concluded that the mechanical strength of the bridging material and the filtrate loss required to establish a bridge are the two critical parameters to form a good barrier. This model does not adequately take into account the interaction of the formation rock and the filtercake. And there is a lack of evidence that the filtercake and LCMs seal the fracture with a sand-arch-like structure.

It has been recently disclosed that filtercakes on the wellbore wall can play an important role in wellbore strengthening. Under the assumption of an intact wellbore, filtercake thickness and permeability can be key factors in strengthening the wellbore (Liu and Abousleiman, 2018)(Feng et al., 2018). A layer of tight filtercake may effectively prevent the development of tensile stresses in the near-wellbore region by inhibiting the increase of pore pressure. The strength of the filtercake may play a less significant role before the fracture is initiated. However, in real field applications it is likely that the wellbore is already fractured, and the filtercake strength, or in other words, the capacity of the filtercake to sustain pressure over a fracture, cannot be overlooked when taking into consideration the fractures on the wellbore wall. It has been experimentally shown that the fractures can be created behind the filtercake and lost circulation does not necessarily occur upon the initiation of the fracture (Guo et al., 2014). Higher formation break-down pressure than that predicted by conventional continuum-mechanics theories is often observed experimentally or in real applications. Indeed, filtercake may play an important role in this anomalous behavior (Feng et al., 2016). The role of filtercake in WBS has been further explained by Cook et al.(2016) after extensive experimental work. It is claimed that filtercake has the capacity to bridge narrow fractures in the initial stages of fracture formation and prevent fluid flow from the wellbore into the fracture. The fracture propagation can then be inhibited. A synthetic invert emulsion fluid system was designed accordingly for continually strengthening the wellbore while drilling depleted zones (Falgout and Stefano, 2017).

It should be noted that the performance of filtercake in providing pressure and fluid transmission barrier over fractures may highly depend on the width of the fracture aperture. During the initiation of drilling-induced fractures, the aperture width is small and likely comparable to the sizes of pores in the formation. The filtercake is a viscoelastic material that is thought to have the ability to resist rupture over fractures at this stage. Given that the filtercake provides effective isolation, the fracture extension may only be driven by the overbalanced pressure acting on the wellbore wall, rather than the pressure acting on the fracture surface. With the increase of the overbalanced wellbore pressure, the fracture-opening enlarges and tends to tear the filtercake apart, the filtercake is also under shear stress over the fracture opening due to the differential pressure. It will be a combined effect of fracture widening and differential pressure increasing that leads to filtercake rupture. The rupture of the filtercake can be defined as when the filtercake loses its integrity. Once the filtercake completely lost its integrity and there are no fracture plugging materials in the fluid, the fluid will surge into the fracture which leads to a high tendency of fracture propagation. Improving filtercake mechanical properties such as thickness, yield strength in shear, yield strength in tension and the bonding between filtercake cake and formation rocks may potentially enact the increase of the pressure threshold at which severe lost circulation occurs.

As a summary of this section, the effect of filtercake on the wellbore wall in WBS can be classified based on the stages of the fracture initiation. Under the assumption of intact wellbore, in other words, no fracture is initiated and there are no natural fractures, a layer of tight and thick filtercake on the wellbore may change the stress state of near-wellbore regions, the low-permeable filtercake inhibited the increase of formation pore pressure and thus increased the fracture initiation pressure. The strength of filtercake does not contribute significantly to this process. At the fracture initiation stage, the fracture aperture is small and the fracture is able to expand and widen when the filtercake has not been ruptured. The filtercake on the wellbore wall provides an effective barrier to isolate the fluid and pressure between the wellbore and the fracture, the fracture growth is limited and only subject to the overbalanced pressure acting on the wellbore, rather than together with the pressure acting on the fracture surfaces after the barrier breaks and fluid enters the fracture. The capability of the filtercake to maintain its integrity over fractures, or the strength of the filtercake, is significant at this stage. Severe lost circulation does not necessarily occur upon the fracture initiation, improving the filtercake mechanical properties such as thickness, yield strength in shear, yield strength in tension and the bonding between filtercake cake and formation rocks may potentially enact the increase of pressure threshold at which severe lost circulation occurs.

The filtercakes may be made from drilling fluids with or without LCMs. The fracture aperture is a significant factor that determines the effectiveness of filtercake. For fractures with tiny apertures, it may be effectively isolated by filtercakes without large LCM particles, while with the enlargement of fracture aperture, the fracture sealing needs to be achieved by incorporating relatively larger LCM particles. The LCMs may seal the fracture by plugging/bridging the fracture at the mouth or inside the fracture. The evaluation of the LCMs should take into consideration the effect of filtercake.

3.1.2 Filtercake Property Measurements

Several studies have shed considerable light on the property measurements and characterizations of drilling fluid filtercakes. Ba et al.(2013) summarized common techniques for characterizing important filtercake properties including filtercake thickness, porosity, permeability, and filtercake mineralogy. The measurement of filtercake thickness is commonly achieved by a caliper scale or a ruler. More advanced technics such as laser method, penetrometer and CT scan are applied when there is a high requirement for accuracy and/or precision (Zamora et al., 1990)(Amanullah and Tan, 2001) (Elkatatny et al., 2012). In drilling fluid applications, filtercake thickness and filtration fluid loss are both measured after 30 min in the API standard filtration test, and they are usually measured with different formulations to compare the qualities of those drilling fluids. The thicker the filtercake, the more permeable it can be, and the greater is the fluid loss. When filtercake thickness is measured at different times on essentially the same fluid formulation, with increasing filtration time, filtercake thickness goes up but permeability goes down since the filtercake is highly compressible. In this case, filtercake thickness is inversely proportional to a complex function of permeability; whereas in the API test, relative thickness of filtercake produced by different formulations at a fixed time like 30 min will be directly proportional to relative permeability. The filtercake porosity and permeability are closely related, Khatib (1994) provided empirical models correlating filtercake porosity and permeability for various filtercakes. It should be noted that the filtercake is not a homogenous material, filtercake porosity and permeability are a function of the layer distance to the filtration medium surface. With the increase of filtration time, the total filtercake thickness increases and the average filtercake porosity/permeability decreases. While the permeability decreasing rate with filtration time is different for the layer of filtercake closer to the rock surface and the layer closer to drilling fluid (Elkatatny et al., 2013).

Filtercake mechanical properties have been measured using various techniques. “Yield strength” and “yield stress” are used to describe the filtercake’s ability to resist deformation and destruction. Ryan et al.(1995) proposed the mudcake-cleanup test to establish the “lift-off pressure” as a measurement of filtercake mechanical property and the adhesion between filtercake and the rock surface. It evaluates the strength of the filtercake for the filtercake-cleanup process. Bailey et al.(1998) provided a detailed explanation of filtercake strength and summarized previous efforts on filtercake yield stress measurement and the theories underlying the methodologies. Cerasi et al.(2001) presented three different experimental methods of measuring the mechanical properties of filtercakes, especially the yield strength. Rheometer was used to measure the strongly non-linear elasticity of the soil-like filtercake. Also proposed was a method to scrape filtercake off a surface to estimate the force of adhesion of the filtercake to the rock. The scraping test method provides another option to estimate the filtercake yield strength, but the theory behind it is oversimplified, and the estimated results are 50% higher or lower than the results measured by a rheometer. Finally, there is the scratch test, which was used to assess the impact of different fluids on filtercake quality and internal filtercake properties (Cerasi et al., 2006). In addition to such bench-scale tests, large-scale experiments like hydraulic fracturing tests are commonly used for wellbore strengthening investigations and may also be useful for filtercake evaluation (Guo et al., 2014)(Contreras et al., 2014).

In summary, the filtercake property measurement methods introduced above provide general approaches to assess filtercake quality. However, none of them is designed to directly evaluate the filtercake's capability to resist rupture over fractures and to seal fractures. Hydraulic fracturing tests can potentially reveal such details during WBS process, but the experimental setup is complicated, costly, and not efficient enough for filtercake quality evaluation.

3.2 Experimental Methods

3.2.1 Experimental Setup and Procedure (Non-porous Metal Slotted Disc)

The experiments aim at evaluating the filtercakes' capability to resist rupture over an open fracture, and exploring the effects of filtercakes in the fracture sealing process. The experiments simulated a process as illustrated in Figure 3.1: It was assumed that a layer of filtercake has already deposited on a wellbore surface, and there is an increase of the overbalanced pressure that initiated a fracture on the wellbore behind the filtercake. While the filtercake maintained its integrity, it provided pressure and fluid isolation. The overbalanced pressure across the filtercake ramped up until the filtercake ruptured. The pressure ramp is continued, pushing the ruptured filtercake into the fracture.

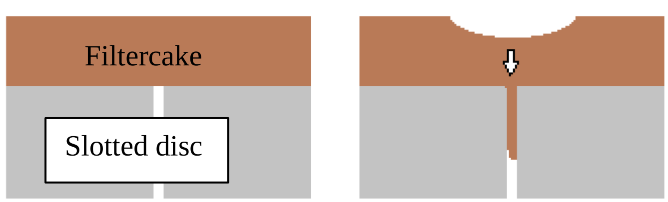


Figure 3.1. Illustration of filtercake rupture in the experiment: filtercake being pushed through a slot and lost its integrity when sustaining high differential pressure, modified after (Cook et al., 2016)

The pressure behavior is recorded for the understanding of the status of the filtercake during the process. Typical plots showing the pressure behavior during the tests are presented in Figure 3.6 in the next section.

Figure 3.2 is a schematic of the experiment setup. A permeability plugging apparatus (PPA) is an effective facility for evaluating LCM performance in sealing fractures (Savari et al., 2014)(Savari et al., 2016b)(Sanders et al., 2010)(A. Mansour et al., 2017). The PPA was modified in this study and applied to assess the quality of filtercakes. The tests were mainly conducted using PPA fluid cylinder. A Teledyne 500D series syringe pump was connected to the inlet of the fluid cylinder to provide pressure input and for precise pressure control and monitoring. Metal discs with different slot opening sizes and number of radial arms (shown in Figure 3.3) were placed at the outlet of the fluid cylinder to simulate various sizes of fracture. However, the capability of filtercake in holding pressure and sealing slots was hardly measurable with the wider slots such as the 0.02 in ones. So the disc with 0.008 in slots was used for the majority of the tests. A few tests were conducted using the disc having 0.02 in slots.

During field operations, at the moment the fracture is induced, the width of the fracture mouth rises from zero to a very small value, potentially comparable to the pore size of the rock. Given the filtercake can form over the porous rock, it should also block the fracture at this stage (Cook et al., 2016). And this is the stage that the filtercake plays the important role in wellbore strengthening. In general, the performance of the filtercake to resist rupture is closely related to the fracture aperture. The rupture resistance of the same filtercake can be much higher over a smaller fracture aperture. The two slotted discs used in this study are commercially available and the 0.008 in slots are the smallest ones accessible at the time of conducting this research. In the following exploratory tests shown in section 4.6 of Chapter 4 and Appendix A, ceramic discs were used for creating narrower slots.

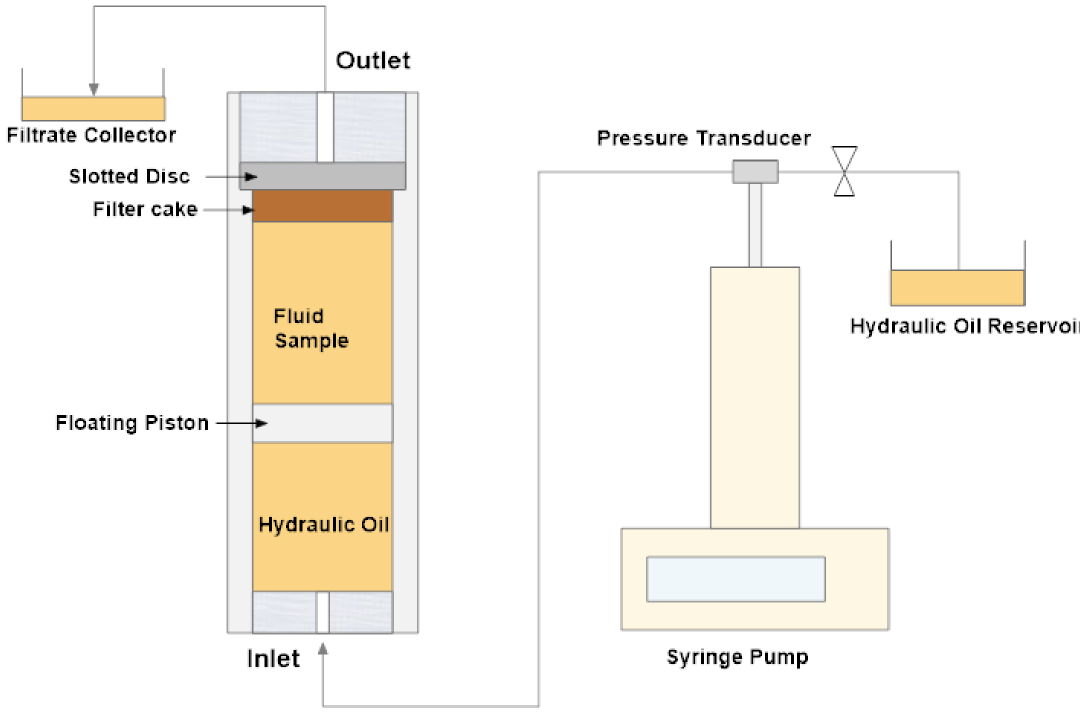


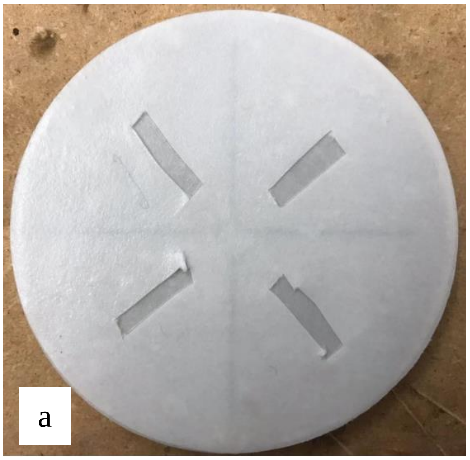
Figure 3.2. Schematic of the modified permeability plugging apparatus.

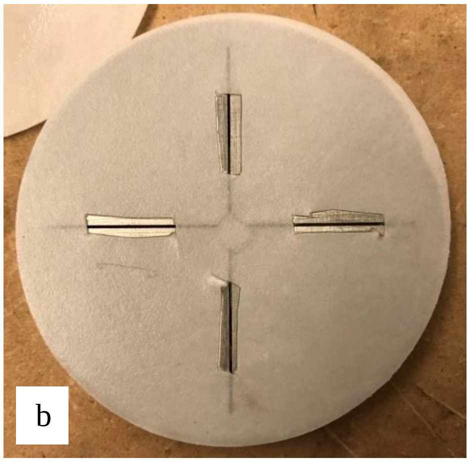
a  b 

Slot Description			
Disk #	Length (Inch)	Width (Inch/Micron)	Type
a	1	0.008 in. 203.2 µ	10 radial arms
b	1	0.02 in. 508 µ	4 radial arms

Figure 3.3. Slotted discs with different opening sizes used for simulating fracture aperture. (Pictures are from Slotted Discs for LCM Evaluation by Fann Instrument Company)

Filtercake deposition was carried out first with the PPA at room temperature and a pressure differential of 100 psi. Filter paper with a diameter of 2.5 in and compatible with HPHT filter presses was used as the filtration medium. The filter paper was pre-cut with small openings along the slots of the metal disc. Another layer of filter paper was placed on top of the pre-cut one during the filtration step to prevent fluid leakage. It was proved that the removal of the top-layer filter paper after filtration test will not cause significant damage to the integrity of the filtercakes being tested in this research. The slotted disc was then placed on top of the pre-cut filter paper and oriented accordingly to ensure the slots were parallel to the pre-cut openings so that the filtercake ruptured over the slots, Figure 3.4 shows the configurations for preparing the filtercakes before rupture tests.





For creating filtercakes: fluids filtrates through the filter papers, filtercake can form over the pre-cuts as another layer of filter paper is placed between the pre-cut filter paper and the slotted disc.

For filtercake rupture tests: after creating the filtercakes, the intact filter paper is removed, the slotted disc is oriented to ensure the filtercakes are exposed to the open slots.

Figure 3.4. Methods to prepare filtercakes before filtercake rupture tests.

Filtercake rupture test begins after creating the desired filtercake, the differential pressure across the filtercake was increased slowly by the Teledyne 500D series syringe pump at a constant flow rate. The pressure would build inside the cylinder until the filtercake ruptured over the slots. A significant pressure drop indicated the rupture of the filtercake. Preliminary tests indicated that the fluid injection rate has limited effects on the filtercake rupture behavior, in other words, the filtercakes with similar properties ruptured at similar pressure when the fluid injection rate was different. A higher fluid injection rate leads to faster pressure build-up, and when the injection rate was higher than 20 ml/min, the rupture of the filtercake can hardly be observed in the pressure plot due to the limitation of the pressure transducer. The injection rate was set to be 1 ml/min to better observe the pressure behavior with injection time. The test was stopped when the pressure reached 500 psi or after 20 min, whichever came first. Preliminary tests showed that achieving a pressure of 500 psi indicated complete sealing of the slots. In other words, if the pressure reached 500 psi, the seal would generally be stable enough to withstand higher pressure. The pressure can build up without significant oscillations to the pump pressure limit (2500 psi). The filtercake thickness was measured after each test. The filtercake was taken out and the extra mud was wiped away gently by a soft paper tissue. The filtercake thickness was measured by a digital caliper scale at different spots and the results were averaged.

Comparing to hydraulic fracturing tests in which rock or cement block samples are fractured, using PPA to evaluate the performance of filtercake in resisting rupture and sealing fracture is simpler and less costly. Although the tests using the metal discs with fixed slot width cannot quantitatively represent the process of fracture initiating and propagation process, nor can they quantitatively measure the tensile strength of the filtercake, the experimental approach can still be considered useful for qualitatively evaluating the effects of fracture aperture, filtercake thickness, yield strength in shear and solids concentration on filtercake performance.

3.2.2 Fluid Formulas

Three fluid groups were used in this investigation. Group I was for preliminary tests, which included fluid samples of 6 wt.% and 8 wt.% bentonite in tap water, and the same samples contaminated with 10 mL of 150,000 mg/L NaCl solution. NaCl was added to increase the filtrate loss rate and adjust the filtercake yield strength. The filtercake yield strength in shear can be characterized using a scratch tester or a rheometer. The addition of salt can increase the filtercake compressibility (Sharma and Zongming, 1991), and the higher compressibility of a material can potentially indicate its lower yield strength (McNabb and Boersma, 1993). It is also commonly known that salt-contaminated water-based mud produces softer and fluffier filtercakes, such "softer" character also suggests lower yield strength. More detailed filtercake yield strengthen discussion and measurement are presented in Chapter 4. Tests for group I were intended to explore the general pressure behavior during the tests, the relationship between filtercake rupture resistance and filtercake thickness, and the effect of filtercake yield strength on rupture resistance. Group II consisted of fluid samples with bentonite concentrations ranging from 6 wt.% to 9 wt.%. Group III contained 7 wt.% bentonite in tap water and with LCM content of 1, 2 and 3 wt.%. The LCM blend, here named Fiber Fluid Fine (FFF), possessed the size distribution (from sieve analysis) shown in Figure 3.5, which generates size parameters of d_{50} ~ 90 μm and d_{90} ~ 160 μm. The maximum particle size of the LCM (~ 840 μm) was comparable with the sand particles found in bentonite samples. Tests of this group were designed to explore the combined effects of filtercake and addition of small-particle LCM in fracture sealing.

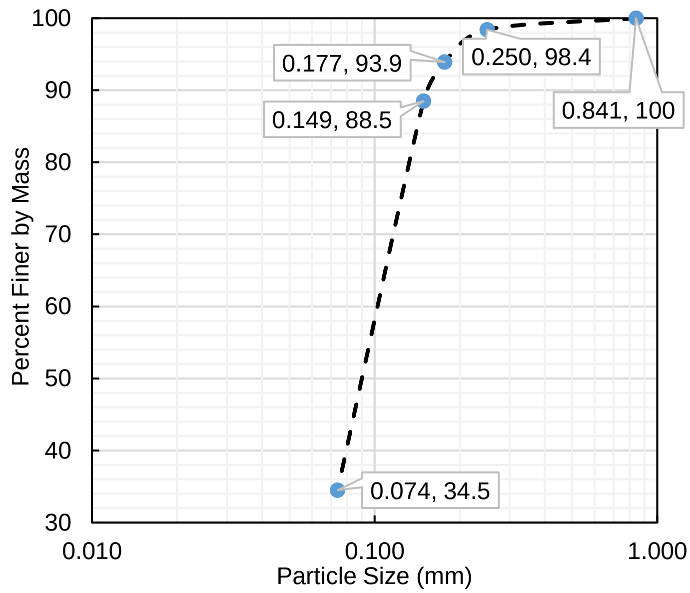


Figure 3.5. The LCM (Fiber Fluid Fine) used in group III, and its particle size distribution from sieve analysis.

3.3 Experiment Results Using Metal Slotted Discs and Discussion

3.3.1 General Pressure Behavior During Filtercake Rupture Tests

Figure 3.6 presents the filtercake rupture test pressure behavior from the sample of 8 wt.% bentonite in water. Filtration was conducted for 15.5 hours under a pressure of 100 psi, leading to a filtercake thickness of 0.356 in. The disc with a slot size of 0.008 in was used in this case.

After starting fluid injection during the filtercake rupture test, the injection pressure increased first since the pre-deposited filtercake could provide a pressure and fluid barrier over the open slots. In this stage, there was no fluid penetrating through the slots significantly. With the fluid injection, the first pressure-drop indicated the rupture of the pre-deposited filtercake, and the maximum pressure value before the pressure-drop was recorded as the filtercake rupture resistance. The filtercake rupture is defined as when the filtercake lost its integrity and fails to provide effective pressure and fluid barrier. The capacity of filtercakes primarily formed by bentonite and water to resist rupture depends on the filtercakes' capacity to resist deformation and flow over an open slot. As shown in Figure 3.6(A), the filtercake ruptured in the form of pinholes. After the first filtercake rupture, pressure spikes and oscillations were observed, the repeated pressure drop-down and increase indicated the filtercake break and reestablishment (Jeennakorn et al., 2017). Then, the pressure continued to build inside the cylinder with only minor fluctuations, which implies complete slot sealing. The slot seal was formed by a combination of filtercake and solid particles, as shown in Figure 3.6(B); in this case, the solid particles were the contaminating sand particles in the bentonite sample. These solid particles plugged the slots and bridged at the slot opening, forming a rigid skeleton of the sealing structure (Kageson-Loe et al., 2009); the bentonite particles swelled in water and then further deposited through filtration, filling the voids of the rigid skeleton and contributing to the establishment of the slot seal.

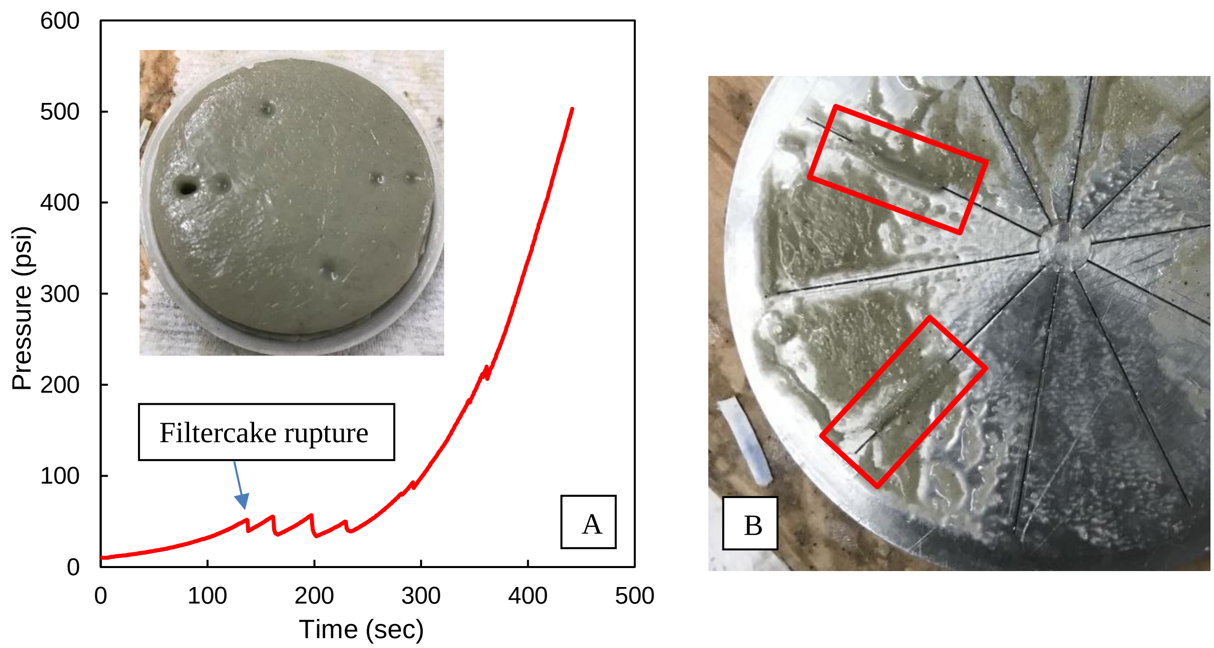


Figure 3.6. An example filtercake rupture test with 8 wt.% bentonite-water fluid and a slot size of 0.008in: (A) Pressure transients during the tests and an example of filtercake rupturing in the form of pinholes; (B) Example of slot seal formed by a combination of filtercake and sand particles.

The two slotted discs described in the experimental method section were used in this study. However, as shown in Figure 3.7, for the 0.02 in slotted disc, the pressure behavior was quite similar for all the cases tested except for the one with a long filtration time and a thicker filtercake of 0.232 in, which ruptured at a pressure of 22 psi. In other cases, the pressure curve was flat and stable, no significant pressure increase was observed during fluid injection, indicating that the filtercakes did not provide effective pressure isolation over such wide slots. The filtercakes lost their integrity shortly after fluid injection. And the relatively constant pressure was the pressure required to maintain the injection flow rate. It may be concluded that the opening size of 0.02 in is too large generally for the filtercake to affect sealing behavior, though the behavior with the thickest filtercake (8 wt.% bentonite, 8 hr) suggests that even thicker and less permeable filtercake may have provided higher and more sustainable pressure resistance.

No fracture sealing (pressure resistance to 500 psi) was observed if the slots were larger than 0.008 in and the fluid was untreated with LCM. All of the subsequent results reported in this chapter were collected using the 0.008 in slotted disc. Although it may appear that openings of 0.008 in are not representative of microfractures, the differences in filtercake rupture behavior and slot sealing time that result from different fluid formulations and filtration times using this size slotted disc can be of value, at least qualitatively.

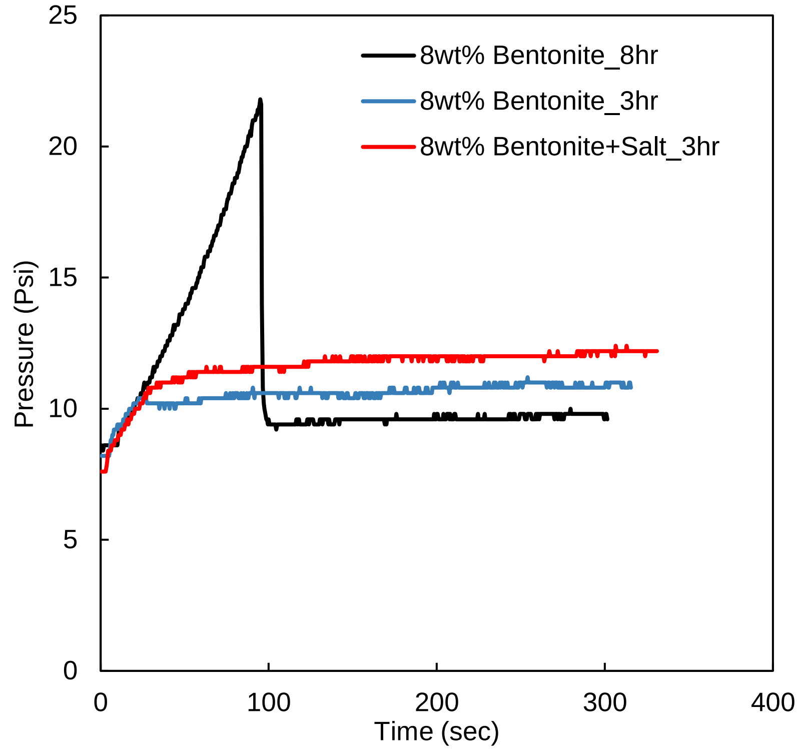


Figure 3.7. Pressure behavior during filtercake rupture tests with 0.02 in slots.

3.3.2 The Effect of Filtercake Thickness and Yield Shear Stress on Filtercake Rupture Resistance

Filtercake thickness can be increased by increasing the solid content in a drilling fluid, lowering fluid loss control, increasing exposure time and modifying the differential pressure (Cook et al., 2016). Filtercake thickness is also relative to filtercake permeability as introduced in section 3.1.2. Figure 3.8 shows the relationship between filtercake thickness and filtercake rupture resistance for different bentonite concentrations. It will be noted from the plots that filtercake rupture resistance varies approximately linearly with filtercake thickness. As summarized in Table 3.1, data points were collected from filtration tests of roughly 1, 3 and 15 hr. Longer filtration led to a larger fluid loss volume and thicker filtercake when the fluid formula was the same. For 8 wt.% bentonite, the filtercake rupture resistance increased from 13.4 psi to 55.5 psi as the filtercake thickness increased from 0.080 in to 0.356 in. Thickness of the filtercake increased with increasing bentonite concentration, as expected. And the addition of NaCl increased the fluid loss and produced a thicker filtercake for the same filtration time, while the corresponding filtercake appeared much softer than the one without salt contamination. The softness of the filtercake indicated a lower yield strength and generated a lower rupture resistance. This phenomenon qualitatively confirmed that the filtercake yield strength does affect the filtercake's capacity to provide a pressure barrier over fractures.

However, the effect of bentonite concentration on rupture resistance is a bit of a mystery. In these tests, rupture resistance was lower for the higher bentonite concentration samples. Further investigations to confirm the effects of bentonite concentration were conducted and the results are reported in the next section.

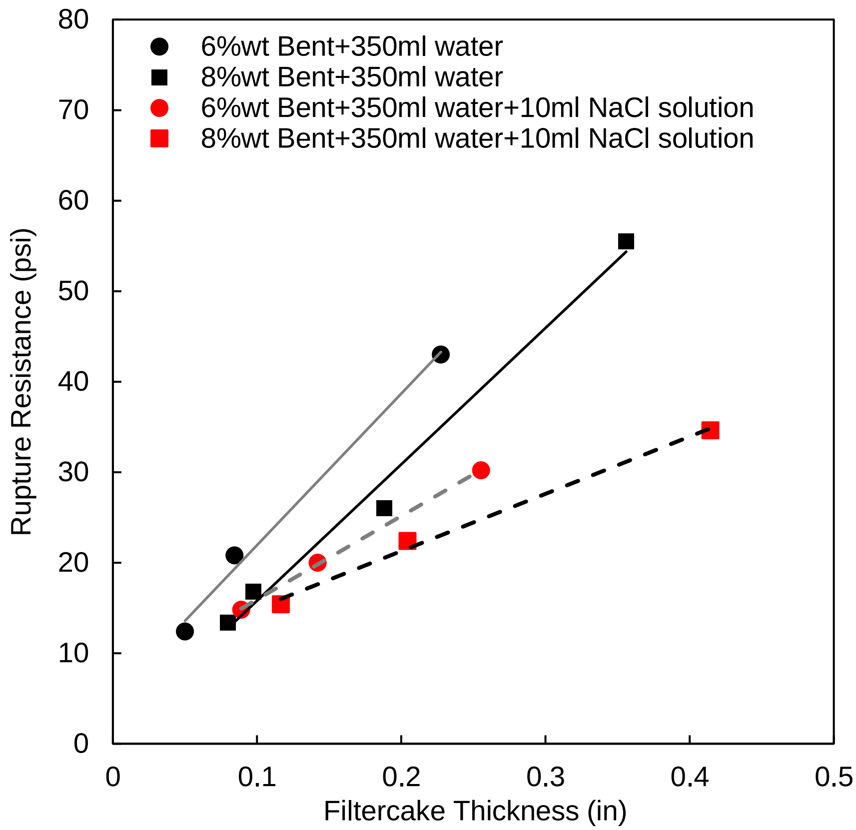


Figure 3.8. Filtercake rupture resistance vs filtercake thickness over 0.008 in slots for 6 wt.% bentonite (with and without NaCl)

Table 3.1. Summary of experimental results from fluid sample group I

Blend #	Fluid Content	Filtration Time	Start volume (ml)	End volume (ml)	Filtrate volume (ml)	Filtercake thickness (In)	0.008 in slot rupture pressure (psi)
1	8wt.% Bentonite+ 350ml water	0.5h	186.28	180.12	6.16	0.0800	13.4
2		1.2h	132.07	124.63	7.44	0.0975	16.8
3		3.0h	209.23	195.96	13.27	0.1885	26.0
4		15.5h	241.36	210.66	30.70	0.3560	55.5
5	8wt.% Bentonite+ 350ml water +10ml NaCl solution	1.2h	173.60	163.73	9.87	0.1165	15.4
6		3.0h	151.90	136.53	15.37	0.2045	22.4
7		15.0h	170.43	139.22	31.21	0.4145	34.6
8	6wt.% Bentonite+ 350ml water	1.2h	176.08	167.07	9.01	0.0500	12.4
9		3h	167.67	151.79	15.88	0.0845	20.8
10		17.5h	175.95	135.39	40.56	0.2275	43.0
11	6wt.% Bentonite+ 350ml water +10ml NaCl solution	1.2h	227.02	214.55	12.47	0.0890	14.8
12		3.0h	175.96	154.83	21.13	0.1420	20.0
13		15.0h	216.93	175.79	41.14	0.2555	30.2

3.3.3 The Effect of Bentonite Concentration on Filtercake Rupture Resistance

Bentonite concentration affects the bentonite hydration process and the interactions between the particles. The rheological properties of concentrated, aggregated fluid systems highly depend on the solids concentration. Again, 1, 3 and 15 h filtration times were used. As indicated by the test results in Figure 3.9 and Table 3.2, for the same filtration time, a higher bentonite concentration led to a thicker filtercake. However, for the same filtercake thickness deposited from different bentonite concentrations, the corresponding rupture resistance roughly varied inversely with the bentonite concentration. This is consistent with the results from Figure 3.8, which also showed lower rupture resistance for the higher concentration of bentonite. For low bentonite concentrations of 3wt.% and 4wt.%, the filtercake was as thin as about 0.15 in even after 15 hr of filtration due to low solid contents, while the rupture resistance was much higher than the filtercake of the same thickness made from a higher bentonite concentration. A 0.15 in filtercake made from a 9wt.% bentonite-water fluid had a rupture resistance of about 25 psi, which was almost 40% lower than it made from the 4wt.% sample. For a relatively higher bentonite concentration of 6wt.%

to 10wt.%, the slopes of the trend lines were similar but significantly less than the group of low bentonite concentration (3wt.% and 4wt.%). 7wt.% bentonite produced the highest filtercake rupture resistance for the same filtercake thickness while 9wt.% produced the lowest. The study of the underlying mechanism of this phenomenon is beyond the scope of this research. Based on experiment observation, the rupture resistance of the filtercake is affected by bentonite concentration, and in general, fluid samples with high bentonite concentration may not lead to an increased capability of making stronger filtercakes. To deposit filtercakes with the same thickness, the filtration time for low concentration fluid is much longer than it for high concentration fluid. Applying the filtration pressure across the filtercake may contribute to the consolidation of the filtercake. The longer the pressure has been applied onto the filtercake, the tighter the filtercake could be.

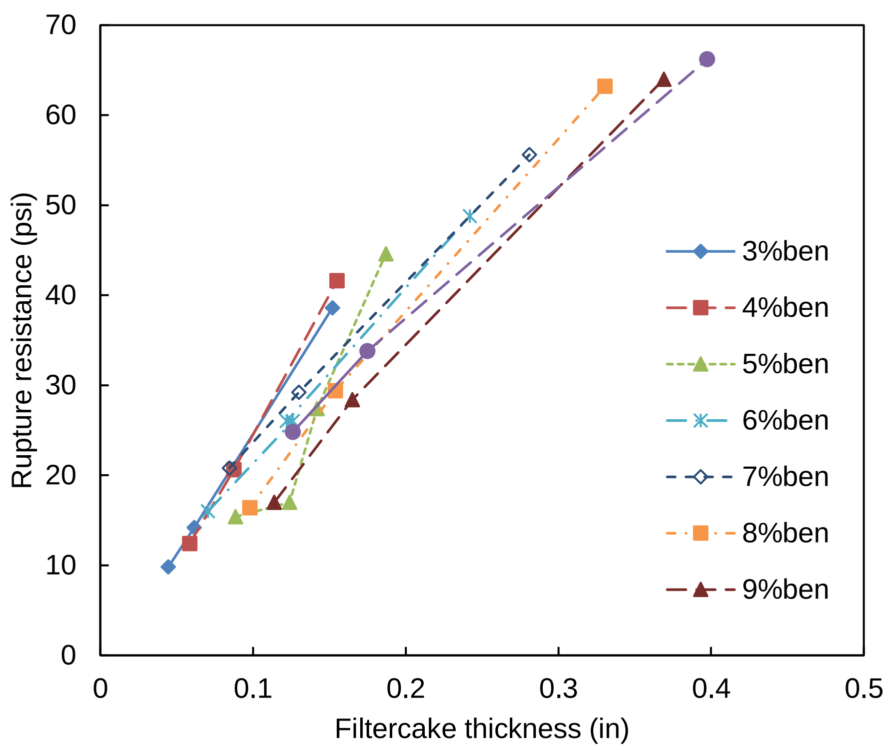


Figure 3.9. Filtercake rupture resistance vs filtercake thickness over 0.008 in slots for bentonite concentration of 3 wt.% to 10 wt.%

Table 3.2. Summary of experimental results from fluid sample group II

Blend #	Bentonite content (wt.%)	Filtration Time	Start volume (ml)	End volume (ml)	Fluid loss (ml)	Filtercake thickness (In)	0.008 in slot rupture pressure (psi)
14	3%ben	1h	143.80	126.80	17.00	0.0445	9.8
15	3%ben	3h	151.30	121.55	29.75	0.0615	14.2
16	3%ben	15h	175.35	103.60	71.75	0.1520	38.6
17	4%ben	1h	193.89	182.76	11.13	0.0585	12.4
18	4%ben	3h	178.37	154.73	23.64	0.0875	20.6
19	4%ben	15h	182.80	124.70	58.10	0.1550	41.6
20	5%ben	1h	182.20	170.47	11.73	0.0525	14.6
21	5%ben	3h	178.90	156.45	22.45	0.1240	17.0
22	5%ben	6h	200.80	170.23	30.57	0.1420	27.4
23	5%ben	15h	182.33	135.32	47.01	0.1870	44.6
24	6%ben	1h	205.10	194.22	10.88	0.0705	16.0
25	6%ben	3h	205.94	185.80	20.14	0.1260	26.0
26	6%ben	17.5h	202.86	157.94	44.92	0.2420	48.8
27	7%ben	1h	146.57	136.05	10.52	0.0845	20.8
28	7%ben	3h	173.52	156.41	17.11	0.1300	29.2
29	7%ben	15h	209.40	168.60	40.80	0.2810	55.6
30	8%ben	1h	208.36	199.28	9.08	0.0980	16.4
31	8%ben	3h	207.30	190.06	17.24	0.1540	29.4
32	8%ben	17.5	204.42	164.42	40.00	0.3305	63.2
33	9%ben	1h	172.60	163.69	8.91	0.1140	17.0
34	9%ben	3h	194.00	179.74	14.26	0.1650	28.4
35	9%ben	15h	206.30	173.28	33.02	0.3690	64.0
36	10%ben	1h	136.60	127.98	8.62	0.1260	24.8
37	10%ben	3h	149.73	134.32	15.41	0.1750	33.8
38	10%ben	15h	66.20	35.25	30.95	0.3975	66.2

Indeed, the effects of fluid bentonite concentration on filtercake rupture resistance are minor when the filtercake primarily consists of bentonite and water. It seems not practical to change the bentonite concentration of drilling fluids for significantly improving the filtercake quality, as the change of bentonite content will apparently affect the rheological properties of the fluids. The effectiveness of filtercakes to control fluid loss can depend on other more important factors, as discussed in the following sections.

3.3.4 The Effect of Filtercake Thickness on Complete Slot Sealing

For narrow slots of 0.008 in, the ruptured filtercake generally reduced the time required for complete slot sealing. Particles larger than bentonite may provide additional slot-sealing capability. Even the sand contaminant in the bentonite samples used in this study (and drilled cuttings) can aid in this regard. The sand particles, if of the appropriate size and concentration, can seal the slots after rupturing of the filtercake by either helping to bridge them or plugging them.

Complete slot sealing can be observed in most filtercake rupture tests using the 0.008 slotted disc. Figure 3.10 represents the pressure behavior of the 8 wt.% bentonite fluid during filtercake rupture tests after 1, 3 and 15 hours filtration, resulting in a filtercake thickness of 0.0975 in, 0.1885 in and 0.356 in, respectively. The pressure behavior of fluid without pre-made filtercake is also included in the figure. The results make clear that the thicker filtercake accelerated the process of complete slot sealing. The start pressure of filtercake rupture tests was about 10 psi in order to maintain the integrity of the filtercake after removing the 100 psi filtration test pressure. Preliminary tests indicated that there were no significant pressure oscillations after the differential pressure across the sealed slots was beyond 500 psi, indicating complete slot sealing. Thus, the filtercake rupture tests were stopped at a differential pressure of 500 psi. As summarized in Table 3.3, it took 9.9 min to reach 500 psi for the case of 1 hour filtration, where the filtercake thickness was 0.0975 in. And the time duration reduced to 7.4 min for the 15 hours filtration case, with a filtercake thickness of 0.356 in. It was a 25% time reduction.

The case without a pre-made filtercake was tested by flowing fluid directly through the slotted disc. The effort was made to start the test at 10 psi to be consistent with the other filtercake rupture tests; however, a high fluid flow rate through slots was observed at the pressure of 5 psi. With fluid flowing through the slots, bentonite and contaminant sand particles formed seals directly at the slot openings; at the conclusion of the test, a thin filtercake with a high concentration of sand particles was noted at the slot openings. For this “no cake” case, 3.3 min was required for the pressure to reach 10 psi and another 9.4 min (a total of 760 sec) was required to reach 500 psi.,

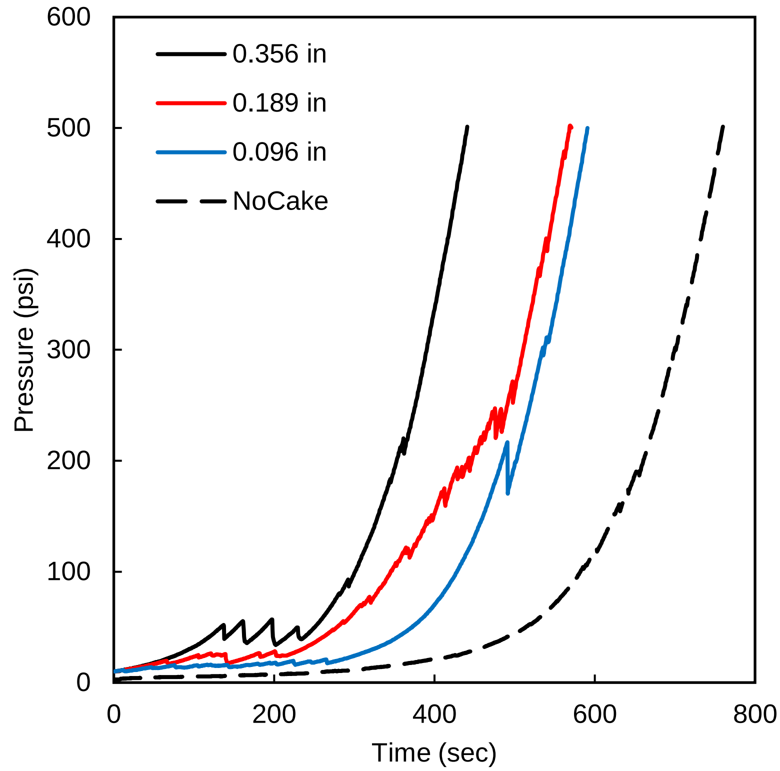


Figure 3.10. Pressure behavior during filtercake rupture tests over 0.008 in slots after 1, 3 and 15 hr filtration for 8 wt.% bentonite

Table 3.3. Summary of 8wt.% bentonite-water fluid filtercake fracture sealing tests

Filtration time	Filtercake thickness (in)	Time to 500 psi (min)	Time reduction comparing to the 1h case
0h	0	12.7	/
1h	0.096	9.9	0%
3h	0.189	9.5	3%
15h	0.356	7.4	25%

3.3.5 The Effect of LCM Solid Concentration on Complete Slots Sealing

As was discussed in the previous sections, the plugging/bridging by the fluid solids at the slot openings appears to be critical for the creation of a barrier that will withstand significant pressure differentials; in the field, this is expected to translate into a decreased potential and rate of fracture propagation. Other particulates such as LCMs are often used to supplement the standard drilling fluid solids and enhance their plugging/bridging potential. A small-particle LCM blend, Fiber Fluid Fine (FFF, as introduced in section 3.2.2) was selected and added into 7 wt.% bentonite-water fluid sample to explore the effect of LCM solid particle concentrations on sealing of the 0.008 in slots. LCM concentrations used were 1, 2 and 3 wt.%. Filtration was conducted for 3 hr at 100 psi for each case to make filtercakes of 0.120 in, 0.126 in, and 0.142 in thickness, respectively. Then the pump was started at an injection rate of 1 mL/min to gradually pressure up the fluid.

The test results with and without pre-made filter are plotted in Figure 3.11 to demonstrate the effect of the filtercake. For 1 wt.% FFF, the highest pressure reached within the test time frame was about 450 psi, while the pressure at the same time in the case without filtercake was less than 50 psi. This case indicates that the fluid sample with the addition of 1 wt.% FFF is not sufficiently capable to seal the slots effectively without a filtercake. Even with a filtercake, whose thickness was 0.120 in, a good stable seal of the slots was elusive. With FFF concentrations of 2 and 3 wt.%, the fluid can potentially remediate fluid loss even with no pre-made filtercake. With the addition of filtercake, however, the pressure build-up is considerably faster and the maximum pressure differential reached within the time frame exceeds 2000 psi. The filtercake thickness generated from 3 hr of filtration increases with increasing LCM concentration, and filtercake made from the fluid sample with higher LCM concentration accelerates pressure build-up and produces stable seals faster. It took 12.25 min to build up a differential pressure of 2000 psi when the LCM concentration was 2 wt.%, while it took 11.33 min for the case of 3 wt.% LCM. That is an 8% time reduction.

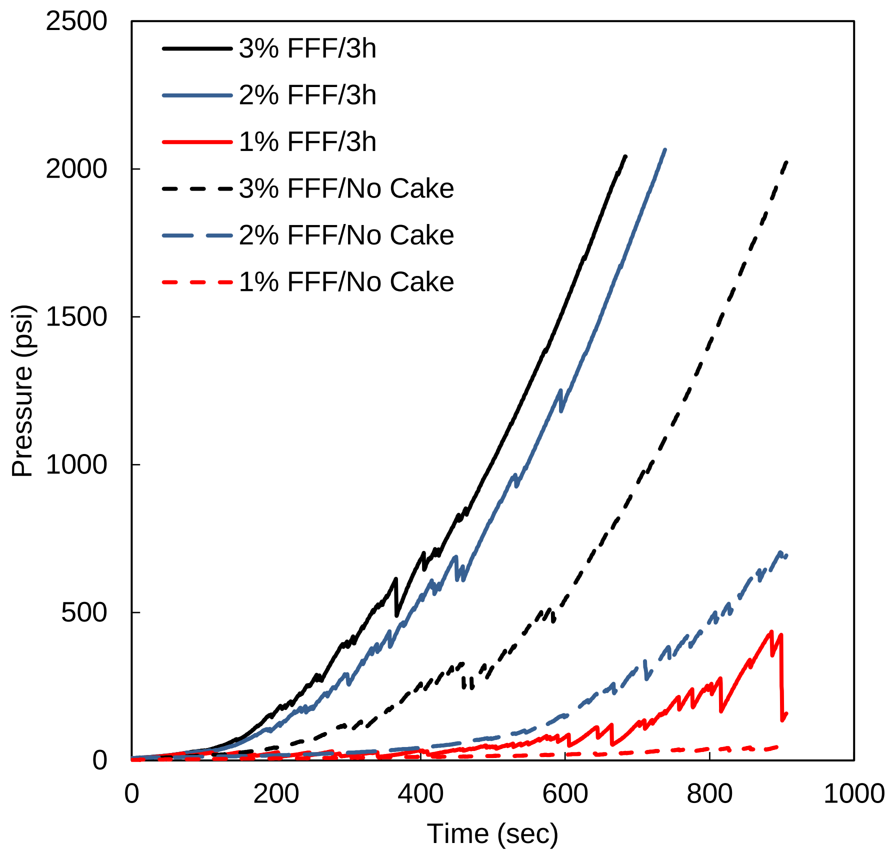


Figure 3.11. Pressure behavior during filtercake rupture tests over 0.008 in slots after 3 h filtration vs. Cases of no pre-made filtercake, 7 wt.% bentonite with 1, 2 and 3 wt.% LCM

Again, it can be noted that the solid particles in the fluids and filtercakes played important role in creating effective barriers to withstand high pressure over the open slots. All of slot seals observed in the tests were created by solid particles (sand particles in the bentonite, or fine LCM particles added intentionally). When the solid concentration in the fluids was low, it can be difficult to form the slot sealing structure, as indicated by slower pressure ramping up. Filtercake worked as a collection of solids that was capable to provide essential materials for immediate slot sealing, the solids retained in the filtercakes helped create the slot sealing structure. A more detailed discussion about the capability of solids to create filtercakes and physics of filtercake enhanced fracture sealing is presented in Chapter 4.

3.4 Conclusions and Recommendations

In this study, a modified PPA with slotted metal discs was used to simulate a wellbore with fine fractures, and tests were conducted to examine the effects of drilling fluid filtercake on the sealing of those fractures. This simple test method is more efficient than conventional hydraulic fracturing tests and was used to define a new parameter, filtercake rupture resistance, to describe the capacity of the filtercake to maintain its integrity over fractures. Filtercake rupture resistance, together with fracture sealing time was used to evaluate the filtercake performance in enhancing wellbore strengthening. The effects of fracture aperture, filtercake thickness, filtercake yield strength in shear, bentonite concentration, and fine-particle LCM concentration were investigated. The experimental results of this research indicate that:

- Slot opening size has a significant impact on filtercake rupture resistance. The filtercake can sustain higher differential pressures when the slot opening is small. Much higher filtercake rupture resistance is observed when the slot opening size is reduced from 0.02 in to 0.008 in.
- When filtercake thickness is related only to filtration time, filtercake rupture resistance increases with filtercake thickness, because in that situation the average filtercake permeability decreases and yield strength increases with filtration time.
- Bridging/plugging by drilling fluid solids plays an important role in sustaining high differential pressure and achieving fracture sealing. As with filtercake rupture resistance, a thicker and tighter (higher yield strength in shear) filtercake reduces the time required to achieve fracture sealing.

- Filtercake rupture resistance is affected by bentonite concentration. For filtercakes of the same thickness, lower bentonite concentrations appear to generate filtercakes with higher rupture resistance.
- The addition of fine-particle LCM makes a significant contribution to reducing the duration required for complete slot sealing. Filtercake made from the fluid sample with higher LCM concentration produces a stronger and faster seal.

In terms of field applications, the filtercake rupture resistance can potentially represent the capability of the filtercake to isolate pressure and fluid between the wellbore and the tiny fracture. When designing the drilling fluid for troublesome zones such as depleted zones, where there are high risks of lost circulation due to drilling-induced fractures, it is recommended to consider and evaluate the rupture resistance of the filtercake deposited by potential drilling fluids. And the drilling fluid design should be improved to enhance the filtercake rupture resistance to further improve the preventive wellbore strengthening performance. According to the test results, filtercake with high yield strength and low permeability is preferred. Bridging/plugging by drilling fluid solids plays an important role in sustaining high differential pressure and achieving fracture sealing. As with filtercake rupture resistance, a thicker and tighter (higher yield strength in shear) filtercake reduces the time required to achieve fracture sealing. In this study, the investigation of the LCM effects shed a light on how filtercake deposited by drilling fluid with LCMs can contribute to reducing the fracture sealing time. It should be noted that the experiments were conducted under the assumption that the fracture could be initiated and enlarged behind the filtercake, which has been claimed by Cook et al.(2016). The addition of LCM, in this case, is more related to lost circulation prevention treatment rather than remediation, so the LCM concentration was not as high as LCM pills. In this study, 3wt.% LCM consisting of a considerable amount of fine particles obviously improved the fluid's capability to deposit a high-quality filtercake and to seal the slots. When designing fluid with LCMs for lost circulation preventive treatment, it is recommended to incorporate the evaluation of its capability to deposit filtercakes. Further investigations of how LCM properties affect the capability of LCMs to build filtercakes are presented in Chapter 4.

The current experimental method and results have limitations and are subject to improvement. For example, filtercakes should be deposited dynamically at downhole pressure and temperature conditions. Drilling fluid samples and fracture geometry were simplified and should be modified to better reflect real applications. Other filtercake properties such as permeability, toughness, hardness and compressibility may also affect the filtercake rupture and fracture sealing process. These filtercake properties should be properly characterized and their effects in the process of filtercake rupture and fracture sealing should be investigated.

Chapter 4. The Effects of LCM Reinforced Filtercake on Lost Circulation Preventive Treatments

4.1 Introduction

The effect of filtercakes should not be overlooked in the understanding of WBS mechanisms and evaluation of LCM performance. Properly designed LCMs may facilitate the deposition of filtercakes with better quality, and the filtercake may, in turn, enhance the LCM fracture-sealing performance. Currently, there are limited studies regarding the capabilities of LCMs to deposit filtercakes and to promote fracture sealing. Especially for WBS preventive treatments, there may not be intact wellbores in real applications, the capability of the filtercake with LCMs to prevent the growth of pre-existing fractures and to seal induced fractures at the initial stage is crucial to “strengthen” the well, or in other words, to increase the lost circulation pressure. The evaluation of LCMs needs to consider the effects of the filtercake.

In this chapter, experimental investigations were conducted to understand the effects of LCMs on the creation of filtercakes and the facilitation of fracture sealing. The processes of filtercake rupture and fracture sealing were investigated by changing the differential pressure across the filtercakes. The performance of the filtercakes and LCMs in preventing and reducing fluid losses was evaluated based on the maximum sealing pressure, sealing structure stability, and total fluid loss upon the formation of an effective fracture seal. The effects of the filtercake thickness, shear yield stress, as well as the type, concentration, and particle size distribution of LCM on the filtercake rupture and fracture-sealing processes were investigated.

Parts of this chapter previously appeared as Mingzheng Yang, Mei-chun Li, Qinglin Wu, Frederick B. Growcock, and Yuanhang Chen. 2020. “Experimental Study of the Impact of Filter Cakes on the Evaluation of LCMs for Improved Lost Circulation Preventive Treatments.” *Journal of Petroleum Science and Engineering* 191 (August): 107152. Reprinted by permission of Elsevier

4.1.1 Role of the Filtercake in WBS Preventive Treatments

WBS treatments can be classified as preventive treatments or remedial treatments (Guo et al., 2014; Feng and Gray, 2017). The former incorporates lost circulation material (LCM) or loss prevention material to prevent the initiation of new fractures and seal pre-existing fractures to inhibit their growth; the latter is applied after the detection of considerable fluid loss and aims to bridge or plug the fractures using LCM. Preventive treatments are usually more cost-effective than remedial treatments.

The filtercake on the wellbore wall plays an important role in preventive WBS treatments. Under the assumption of an intact wellbore, a layer of tight and low-permeability filter cake may inhibit the increase in pore pressure, thus preventing the development of tensile stresses in the near-wellbore region and increasing the fracture initiation pressure of the formation (Salehi and Kiran, 2016; Feng et al., 2018; Liu and Abousleiman, 2018). The filtercake is also significant for strengthening a fractured wellbore, as it can provide a barrier to prevent the transmission of pressure and fluid between the wellbore and drilling-induced fractures at their initiation stage. This may increase the formation breakdown pressure and fracture propagation pressure (Cook et al., 2016). In experimental studies and real applications, it is often observed that the formation breakdown pressure is higher than that predicted by conventional continuum-mechanics theories. In some formation integrity tests and leak-off tests, multiple formation breakdown pressures can be observed in permeable formations when the drilling fluid has a high solid content. These observations may be explained by the effects of the filtercake acting to constantly seal the fractures (Morita et al., 1996b; Feng et al., 2016).

4.1.2 The Evaluation of LCMs

Many experimental studies have been conducted to evaluate the ability of various LCMs to remediate lost circulation and strengthen the wellbore. The most common criteria for LCM performance evaluations are the maximum fracture-sealing pressure and fluid loss before the effective seal breaks (Sanders et al., 2008; van Oort et al., 2011). The LCM type, concentration, particle size distribution (PSD), and shape are the key factors that affect the LCM fracture-sealing performance. A permeability plugging apparatus (PPA) has been widely used as a tool to assess LCMs (Kulkarni et al., 2012; Savari et al., 2016; Ezeakacha et al., 2017; Mansour et al., 2017). Typically, LCMs having different properties are mixed with water or drilling fluid samples and the mixture is injected through slotted disks. The slotted disks have different geometries to represent different fractures or vugs. Hydraulic fracturing tests are also commonly used to investigate WBS mechanisms and evaluate LCMs (Onyia, 1994; Morita et al., 1996a; Nwaoji et al., 2013; Guo et al., 2014; Razavi et al., 2016; Cao et al., 2018; Zhong et al., 2019). This is a comprehensive experimental approach that aims to present the overall process of fracture initiation, formation breakdown, and fracture propagation. The effects of LCMs for sealing fractures and preventing fluid loss may be revealed; however, these tests require complex experimental facilities and may not be efficient for investigating multiple LCM properties.

LCMs need to be designed to include both preventive and remedial strategies. While studies have been carried out regarding the effects of filter cake properties on the pore pressure increase and the effects of LCM properties on bridging/plugging fractures, there is very limited research on the performance of LCMs for creating filter cakes and sealing small fractures. The evaluation of LCMs always overlooks the effects of the filter cake.

4.2 Experimental Material and Procedure

The experiments in this study were designed to test the capability of filtercakes with LCMs for sealing a fracture with a known aperture width. This represents a transient stage in which a fracture has been initiated behind a filtercake and the filtercake ruptures owing to overbalanced pressure; the fracture can then be sealed as the fluid carrying the LCMs continually flows through the fracture. The experimental setup was similar to it in the previous chapter, a conventional slotted metal disc with a slot aperture of 0.02 in (0.5mm) was used to represent fractures.

Filtercakes were created as the way in the previous chapter. After the filtercake was deposited, the syringe pump increased the differential pressure across the filtercake and the slotted disc at a constant injection rate of 2 ml/min. The pressure behavior was recorded every 0.5 seconds by the pump pressure transducer during the process. Tests were stopped when the pressure reached 2500 psi or after 15 min of injection. The maximum slot-sealing pressure, fluid loss volume before effective sealing, and stability of the seal in different tests were compared to evaluate the performance of the LCM and filtercake in sealing the slots, which may represent their performance in lost circulation and WBS preventive treatments.

The effects of filtercake thickness and yield stress in fracture sealing were investigated in this study. The thickness of the filtercakes was measured by a caliper scale. Filtercake yield stress is an important property of filtercake and it can be measured by different approaches such as scratching test (Cerasi et al., 2006) or using a rheometer (Suri and Sharma, 2016)(Savari et al., 2013). Note that a filtercake is not a homogenous structure, and thus its yield stress varies with the distance to the filtration medium. The measurement results obtained using a rheometer ignore this property, and can thus be considered the average filtercake yield stress or apparent filtercake yield stress. The filtercake yield stress can be considered as the stress at which the filtercake will be strained indefinitely. A TA Instruments AR2000ex rheometer with a cone-plate measuring geometry (shown in Figure 4.1) was used to measure the filtercake yield stress. The upper measuring plate is 40 mm in diameter with a cone angle of 2°. The gap between the two measuring plates was set as 0.5 mm, which is larger than the maximum particle size in the LCM. Preliminary tests indicated that similar measurement results were obtained for plate gaps of 0.4 mm, 0.5 mm, and 0.6 mm. Two measuring modes, flow and oscillating, are commonly used for the yield stress measurements. In the flow mode, a continuously increasing shear rate from 0.001 to 0.05 s-1 was applied to the filtercake sample, and the corresponding stress was recorded. The filtercake was considered to have yielded when the stress decreased or approached a steady value with increasing shear rate. In the oscillating mode, the elastic modulus, G', viscous modulus, G", and phase angle were recorded when a frequency sweep was implemented. The yield stress can be approximated by determining the stress value when G' is equal to G" with increasing strain.

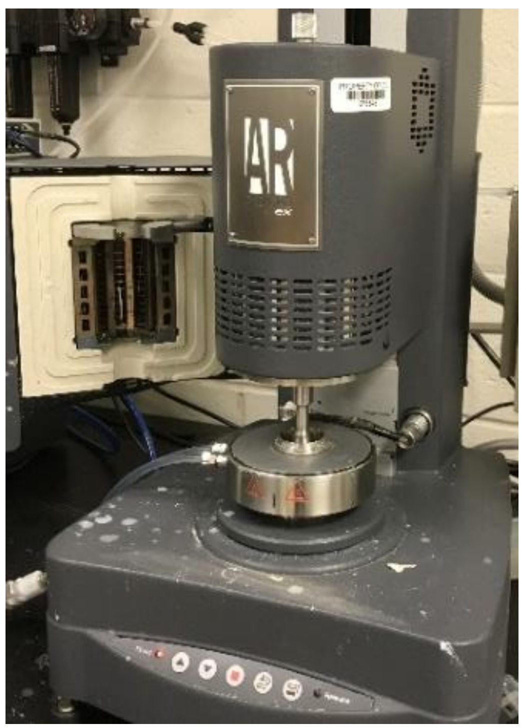


Figure 4.1. TA Instruments AR2000ex rheometer used for filtercake yield stress measurements

The base fluid consisted of 7 wt.% bentonite in water. It can suspend the LCM particles tested in this study, and the fluid formula was kept simple to avoid possible effects of other additives on LCM performance (Alsaba et al., 2017). The filtration time was varied to deposit filtercakes with different thicknesses. The types of LCMs evaluated were granular-fibrous, fibrous, granular, and flaky LCMs. Figure 4.2 shows the appearance of the LCMs with their corresponding particle sizes. The granular-fibrous LCM was a commercially available LCM with a product name of *FIBER LCM*, which is a blend of granular-shaped highly resilient fiber. Its PSD is listed in Table 4.1. The fibrous LCM used in these tests is a blend of slender and flexible fibers with different lengths and sizes. Blends of granular calcium carbonate with certain PSDs were used as the granular LCM. Finally, flaked calcium carbonate combinations named Primo Flake were used for the flaky LCM.

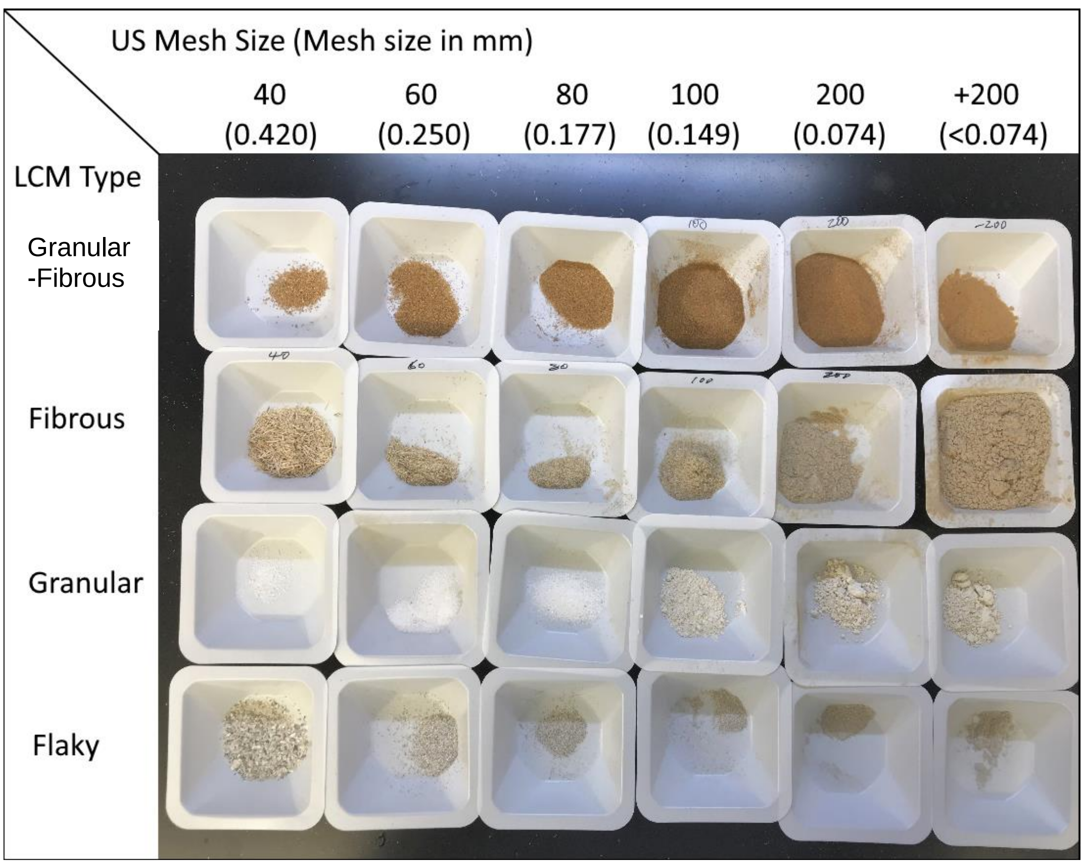


Figure 4.2. The appearance of the LCM samples with corresponding particle sizes

Table 4.1. Particle size distributions of the granular-fibrous LCM samples (Fiber LCM Regular)

Fiber LCM Regular PSD Screen Analysis						
U.S. Mesh #	40	60	80	100	200	+200
Mesh Size (mm)	0.420	0.250	0.177	0.149	0.074	<0.074
Typical % Retained	5	19	13	12	20	31

When testing the effect of LCM type, the LCM concentration for each type is 2% by weight. The PSD of each LCM sample was allocated to be the same according to Table 4.1. Filtration was conducted for 2 h to deposit filtercakes before the fracture-sealing test.

To investigate the effects of the filtercake thickness and LCM concentration, the base fluid was mixed with the granular-fibrous LCM at LCM concentrations of 1 wt.%, 2 wt.%, and 3 wt.%. The LCM concentration was kept relatively low to be inconsistent with lost circulation preventive treatments. Filtration test times of 2 h and 6 h were used to develop filtercakes with different thicknesses.

To investigate the effect of the filtercake yield stress, 150,000 mg/L NaCl solution or silica nanoparticles were added to the base fluid. The base fluid in these tests was 7 wt.% bentonite with 2 wt.% granular-fibrous LCM. A 10 ml volume of 150,000 mg/L NaCl solution was added to 390 ml of base fluid to reduce the corresponding filtercake yield stress. Then, 0.5 wt.% silica nanoparticles was added to the base fluid in the third case, and the corresponding filtercake appeared tougher. Filtration tests were carried out for 2 h to produce the filtercake.

To investigate the effect of the LCM PSD, the granular-fibrous LCM was tested with two PSDs and two concentrations. The PSD was measured using simple sieve analysis. Sieves with mesh sizes of 40, 60, 80, 100, and 200 were used; the corresponding sizes in SI unit are listed in Table 4.1. The sieve analysis results are shown in Figure 4.3: granular-fibrous LCM Mixture I consists of a broader PSD, and Mixture II removes the fine particles relative to Mixture I. The fluid formulations used to test the effects of the LCM PSD are listed in Table 4.2. The majority of the particles in the LCM samples were smaller than the slot size of 0.5 mm in order to explore the potential of the filtercake to enhance the LCM slot-sealing performance. The fluid samples in PSD tests 1 and 2 had almost equivalent amounts of LCM particles with sizes of 0.420 mm, 0.250 mm, and 0.177 mm. There were more fine particles in the fluid in test 1. In Table 4.2, particles larger than 0.177 mm are referred as Coarse, and particles smaller than 0.177 mm are labeled Fine. The fluids in tests 3 and 4 had higher LCM concentrations than those in tests 1 and 2. Filtration tests were conducted for 2 h to produce the filtercake.

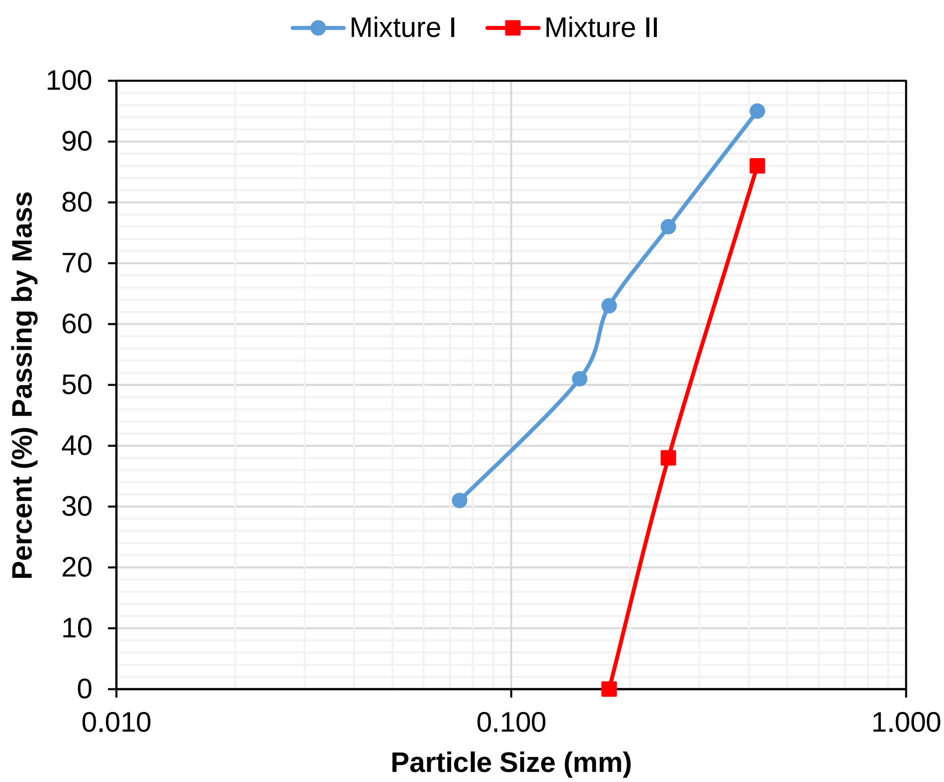


Figure 4.3. Particle size distributions of the two LCM mixtures

Table 4.2. Fluid recipes for testing the effects of LCM particle size distribution

PSD-Test #	Fluid Recipe			
	Water (ml)	Bentonite (g)	LCM Mixture I	LCM Mixture II
1	364	28	8g (3g Coarse, 5g Fine)	-
2	364	28	-	3g (3g Coarse)
3	360	28	12g (4.5g Coarse, 7.5g Fine)	-
4	360	28	-	4.5g (4.5g Coarse)

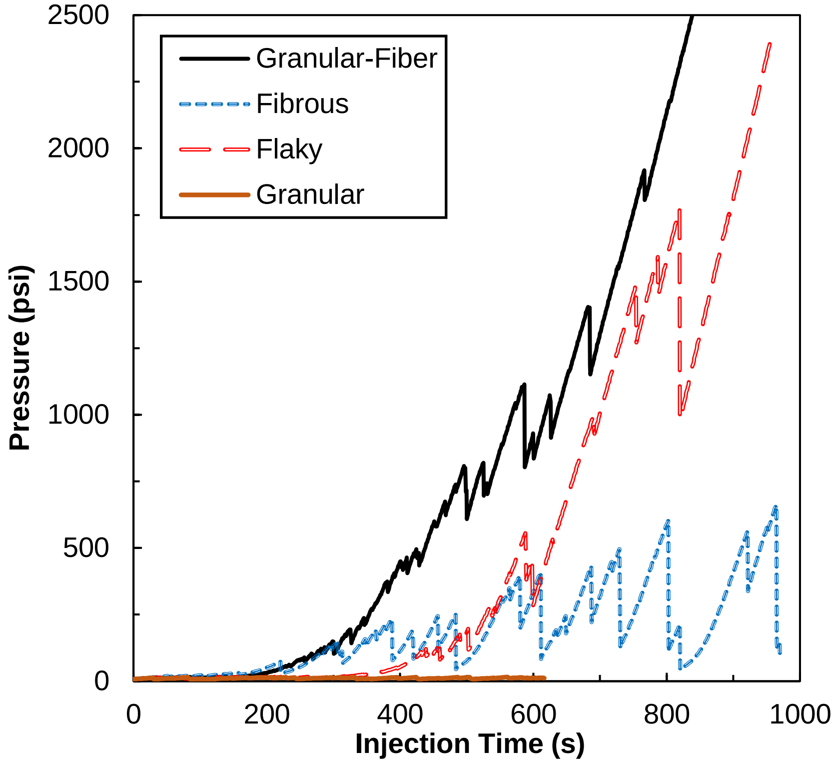
4.3 Experimental Results and Discussion

4.3.1 The Effects of LCM Type

The filtercake thickness after 2 h of filtration with granular-fibrous, fibrous, flaky, and granular LCMs was 0.105 in (2.667 mm), 0.131 in (3.327 mm), 0.109 in (2.769 mm), and 0.112 in (2.845 mm), respectively. The fibrous LCM developed the thickest filtercake among the four types of LCM because it was the lightest material and occupied the largest space in the fluid and filtercake for the same mass of fibrous LCM as the other LCMs in the tests.

As shown in Figure 4.4, with increasing injection time, the differential pressure across the filtercake and slotted disc built up and fell off repeatedly. As differential pressure increased, the filtercake ruptured and pressure fell, but almost immediately LCM and filtercake particles rushed in to bridge and plug the slots, stopping the pressure fall-off and enabling pressure to continue to build. This process appeared to take place repeatedly, but with a general upward trend in the differential pressure the seal could withstand. The saw-shaped pressure oscillations indicated the instability of the seal. Fewer spikes in the pressure behavior curve mean the LCM is capable of providing a more stable seal over the slots; similarly, the greater the differential pressure that is attained, the more effective is the seal. The Granular-Fibrous LCM performed the best with the smoothest pressure build-up and highest attained differential pressure. Indeed, at an injection time of 800 sec, the differential pressure reached the limit of the instrumentation, 2500 psi. Generally, attainment of a differential pressure of 500 psi was considered acceptable for a decent seal. The total fluid loss for Granular-Fibrous LCM at that differential pressure was 14.7 mL. Flaky LCM exhibited a good ability to plug the slots at later times, and the maximum sealing pressure reached 2500 psi within 15 min after the beginning of the test. However, there were more severe pressure drop-offs in the pressure behavior curve compared to that obtained with the Granular-Fibrous LCM. The flaky LCM thus lacks the capability to form a high-quality filtercake, as at early times (before 400 s), there were no indications of slot sealing in the pressure curve. In contrast, with the Granular-Fibrous LCM, the pressure started to build up after approximately 250 s, which can be attributed to the contribution of a better filtercake that sustained a higher pressure before rupture and facilitated the slot-sealing process. The fibrous LCM also formed a strong filtercake, which facilitated a pressure build-up until the first drastic pressure drop-off at approximately 70 psi. The maximum slot-sealing pressure of the fibrous LCM used in the tests was approximately 500 psi. This much lower sealing pressure may be due to the flexible property of the fibrous material, which may not be strong enough to form a firm seal. The granular LCM (calcium carbonate) has the highest density, and thus the granular sample had the least amount of LCM particles for the mass compared to the other samples. Thus, there were not enough particles present in the fluid to form a seal over or inside the slots with the addition of 2 wt.% calcium carbonate. As a result, fracture sealing by the calcium carbonate cannot be clearly observed in the plot.

The Granular-Fibrous LCM had the capability to form a strong filtercake, which facilitated the pressure build-up process. This material could also form a stable seal with minimal pressure fluctuations, demonstrating its considerable capability to seal the fractures on a wellbore continuously.



LCM Type	Max. Sealing Pressure	Fluid loss before 500 psi / 3.45 MPa	Filtercake Quality
Granular-Fibrous	2500 psi / 17.24 MPa	14.5 (ml)	Strong
Fibrous	596 psi / 4.11 MPa	26.3 (ml)	Strong
Flaky	2500 psi / 17.24 MPa	19.5 (ml)	Weak
Granular	N.A.	N.A.	Weak

Figure 4.4. Pressure behaviors of different LCM types during slot sealing tests.

4.3.2 The Effects of Filtercake Thickness and LCM Concentration

The tests on the effects of filtercake thickness and LCM concentration were all run using the Granular-Fibrous LCM. Three filtercake thicknesses were used: 0 (no filtercake) and those created with filtration times of 2 and 6 hours. Three LCM concentrations were used: 1, 2 and 3 wt.%.

The LCM concentration was found to have a very limited effect on filtercake thickness. After 2 hours of filtration, the filtercake thickness for 1 wt.%, 2 wt.%, and 3 wt.% LCM were 0.103

in (2.616 mm), 0.105 in (2.667 mm), and 0.102 in (2.591 mm), respectively; after 6 h, the corresponding filtercake thicknesses were 0.153 in (3.886 mm), 0.159 in (4.037 mm), and 0.160 in (4.064 mm), respectively. In static filtration tests, erosion of the cake (as occurs under downhole conditions) is not simulated, and the filtercake continues to thicken with exposure time. Permeability of the cake decreases as the filtercake thickens; indeed, bentonite filtercakes are highly compressible, and particulates that make up the cake rearrange continuously to reduce its permeability. Since the flux of liquid through the cake is proportional to cake permeability and inversely proportional to cake thickness, the liquid flux drops dramatically with increasing exposure time, i.e. much faster than the increase in cake thickness.

The resulting pressure behavior curves during slot sealing tests for 1, 2 and 3 wt.% LCM are shown in Figure 4.5. The pressure curves were compared with those obtained by injecting the fluid sample directly with no pre-formed filter cake (denoted by “No Cake” in the plot legends). Fluid samples with 3 wt.% LCM produced the most stable seals, and pressure fluctuations occurred less frequently than with 1 and 2 wt.% LCM. Thus, higher LCM content could develop more stable seals. The maximum sealing pressures within the timeframe of the tests also varied for different LCM concentrations. For 1 wt.% LCM, the sealing pressure was less than 1000 psi in all cases. For 2 wt.% and 3 wt.%, on the other hand, the maximum sealing pressure reached 2500 psi in all cases except 2 wt.% LCM with no filtercake, where the maximum pressure recorded after ~ 15 min was 2000 psi. These results indicate that a sufficient population of particles was available to bridge/plug the slots when an LCM concentration of at least 2 wt.% was used.

Filtercake appears to aid in the ability of LCM to maintain a seal of the slots. The capability of the pre-made filtercake itself to withstand differential pressure may enable the pressure to build early as well as provide some additional integrity to the seal formed by the LCM. A thicker (and less permeable) filtercake enables pressure to build more rapidly and reduces fluid loss volume before the formation of an effective seal (pressure reached 500 psi). As summarized in Figure 4.6, for the case of 2 wt.% LCM with a 0.159-in-thick (4.064 mm) pre-formed filtercake, the total fluid loss through the slots before the pressure reached 500 psi (3.45 MPa) was 12.4 ml; with a 0.105 in (2.667 mm) pre-formed filtercake, the fluid loss increased to 14.3 ml. If there was no pre-formed filtercake, the fluid loss began at the time of injection, and the total loss volume was 20 ml. For a higher LCM concentration of 3 wt.%, the effect of the filtercake on reducing the fluid loss was more significant. The total fluid loss volumes were 8.4 ml, 10.7 ml, and 13.3 ml with pre-formed filtercakes having thicknesses of 0.160 in (4.064 mm), 0.102 in (2.591 mm), and no pre-formed filtercake, respectively.

The intrinsic properties and concentration of the LCM appeared to dominate the slot sealing performance of the LCM at longer injection times. The effects of the filtercake were not always clear. For all three LCM concentrations, the primary effect of the filtercake was to decrease the threshold injection time before the rise in differential pressure. This was most evident for the case of 3 wt.% LCM. For 1 and 2 wt.% LCM, filtercake thickness did not have much of an effect, though the mere presence of filtercake decreased that threshold injection time significantly. In general, the formation of a filtercake over the slots promoted the pressure build-up and reduced the total fluid loss before an effective seal was formed.

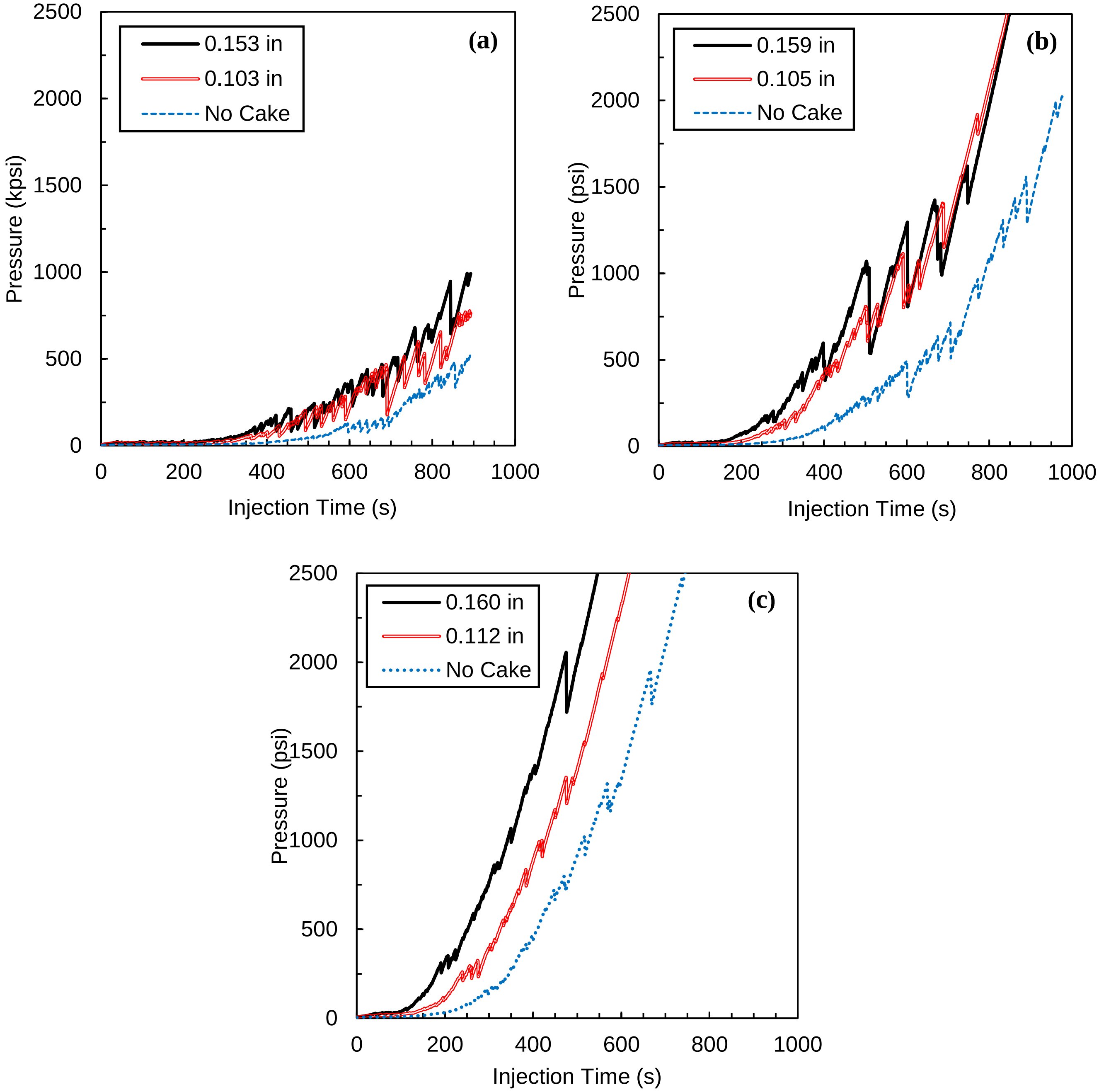


Figure 4.5. Pressure behavior during slot-sealing tests with varying filtercake thicknesses and granular-fibrous LCM concentrations of: (a) 1 wt.%, (b) 2 wt.%, and (c) 3 wt.%

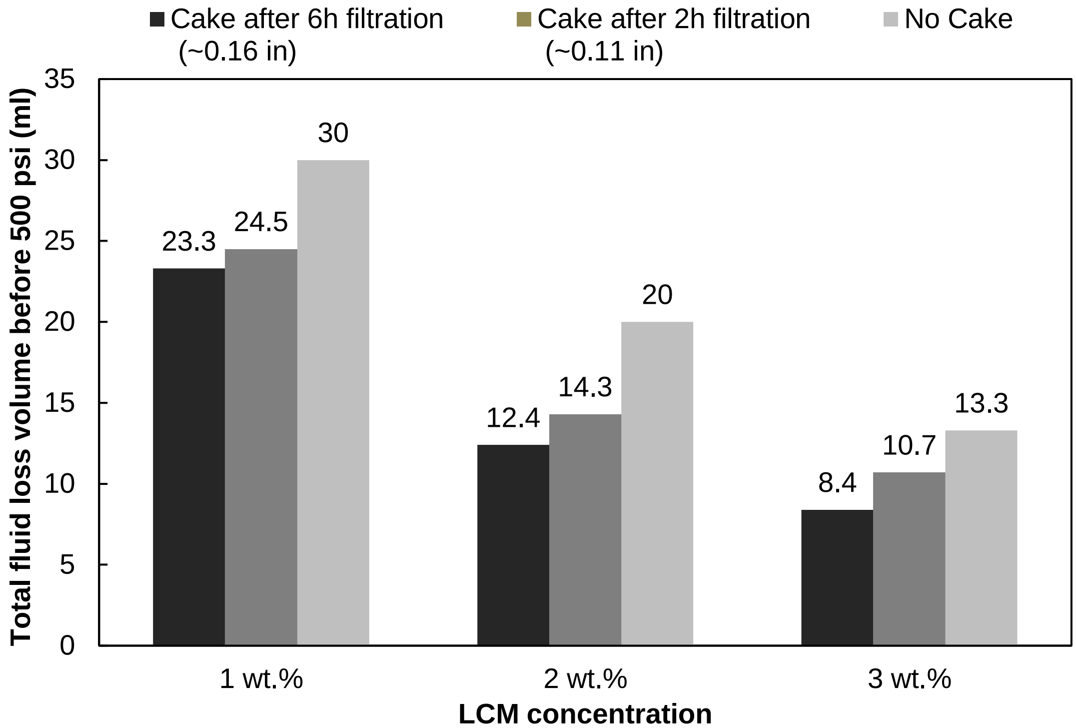


Figure 4.6. Total fluid loss volume before a differential pressure of 500 psi (3.45 MPa) was reached for different filtercake thicknesses and LCM concentrations

4.3.3 The Effects of Filtercake Yield Stress in Shear

The filtercake thickness for the base case, with the addition of NaCl, and with the addition of Nanoparticles were 0.105 in (2.667 mm), 0.114 in (2.896 mm), and 0.125 in (3.175 mm), respectively. The thickness of the filtercakes may be considered similar, however, the filtercake yield stresses were quite different.

The filtercake yield stress results obtained using the rheometer flow mode are shown in Figure 4.7; the stress decreasing or approaching a steady value with increasing shear rate indicated yielding of the tested filtercake. In other words, the stress applied to the filtercake exceeded the stress threshold marking the transition between the elastic region and plastic flow, and the filtercake was strained indefinitely without a significant increase in stress. For the base case, the filtercake yielded at a shear rate of 0.009 s^{-1} with a stress of 1711 Pa. The addition of saline reduced the filtercake yield stress to 1444 Pa, and the filtercake yielded at a shear rate of 0.025 s^{-1}. When 0.5 wt.% nanoparticles was added, the corresponding filtercake yielded at a shear rate of 0.019 s^{-1} with a yield stress of 2566 Pa.

As shown in Figure 4.8 and summarized in Figure 4.9, the effects of the filtercake yield stress can be observed at early times during the slot-sealing tests and were significant before the pressure reached 500 psi. With a stronger filtercake, the pressure built up faster; when the filtercake was softer, the pressure built up more slowly. For the base case, the total fluid loss before the pressure reached 500 psi was 14.7 ml, while the tougher filtercake reduced the total fluid loss to 12.8 ml, and the softer filtercake increased the total fluid loss to 17.7 ml. A higher filtercake yield stress indicated a better ability of the filtercake to maintain its integrity over the slots. A possible explanation is that a strong filtercake can potentially provide better bonding between the LCM particles to promote the bridging and plugging processes. The maximum sealing pressure was not significantly affected by the filtercake yield stress. A potential reason for this phenomenon is that the sealing structure skeleton was constructed from LCM particles, and thus the LCM particle properties will determine the strength of the sealing structure.

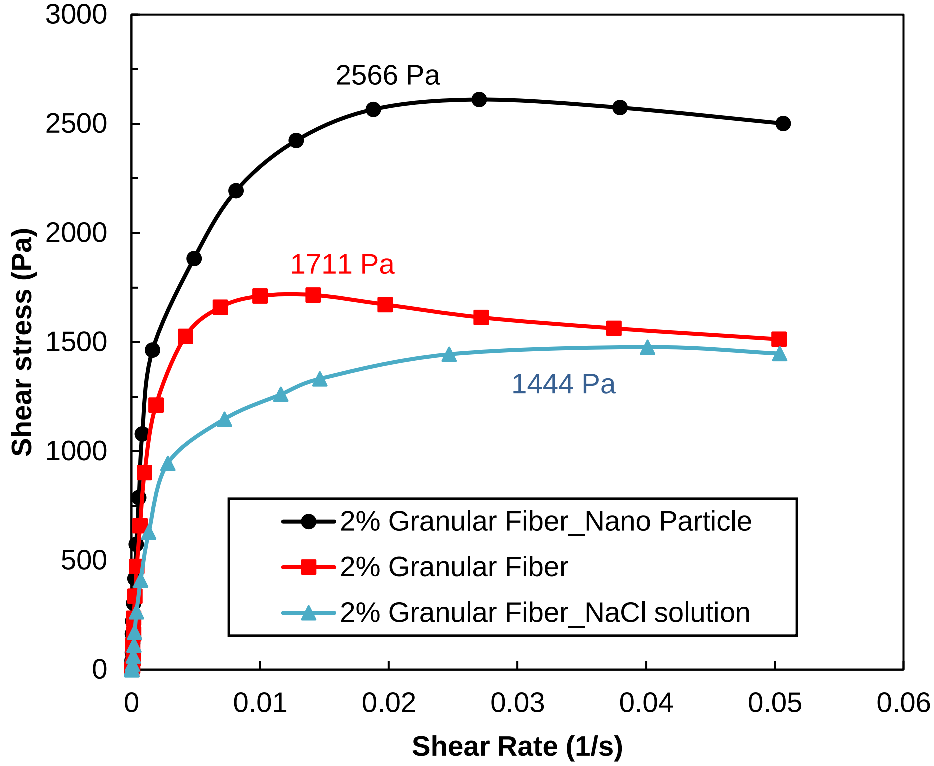


Figure 4.7. Filtercake yield stress measurement results using flow mode of the rheometer

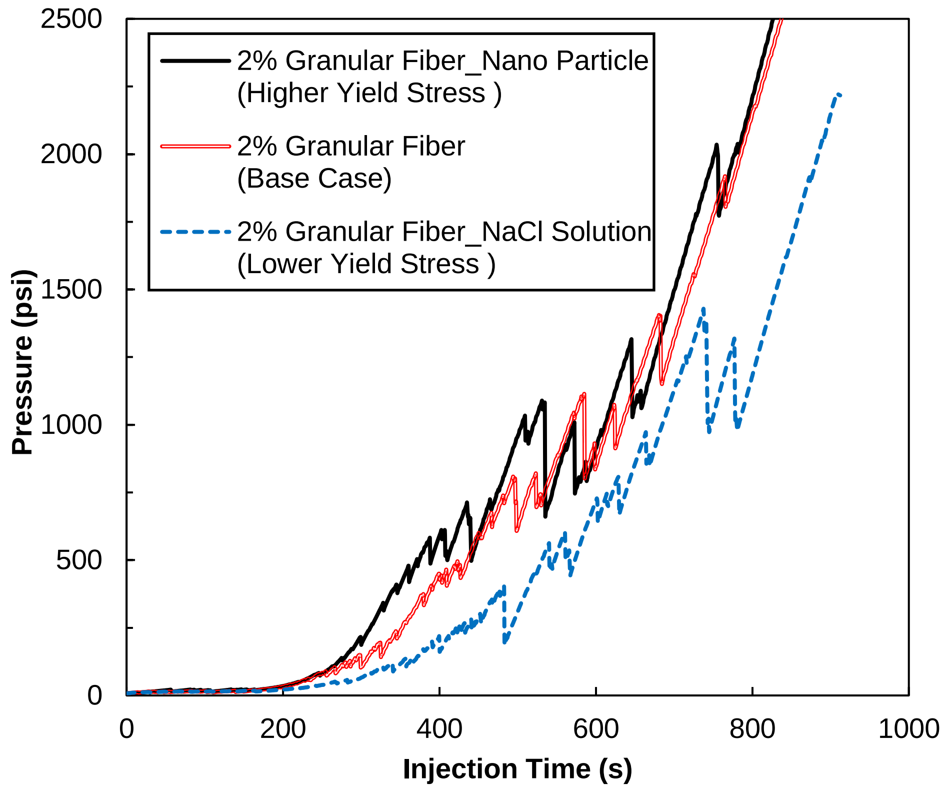


Figure 4.8. The effects of filtercake yield stress in slot sealing tests

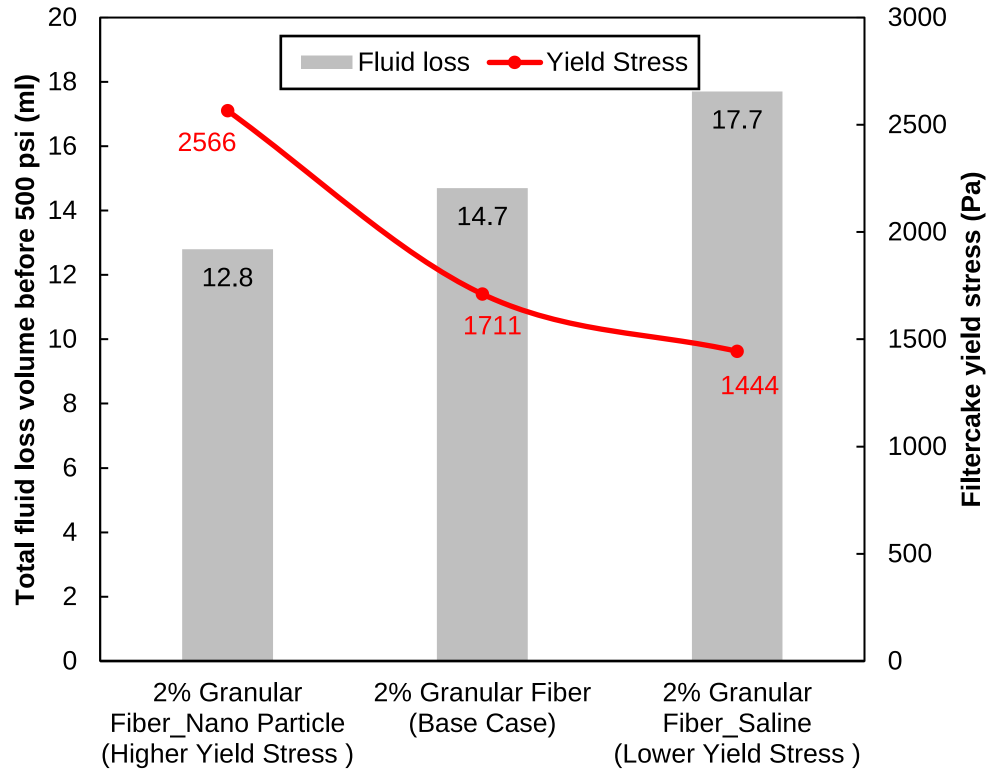
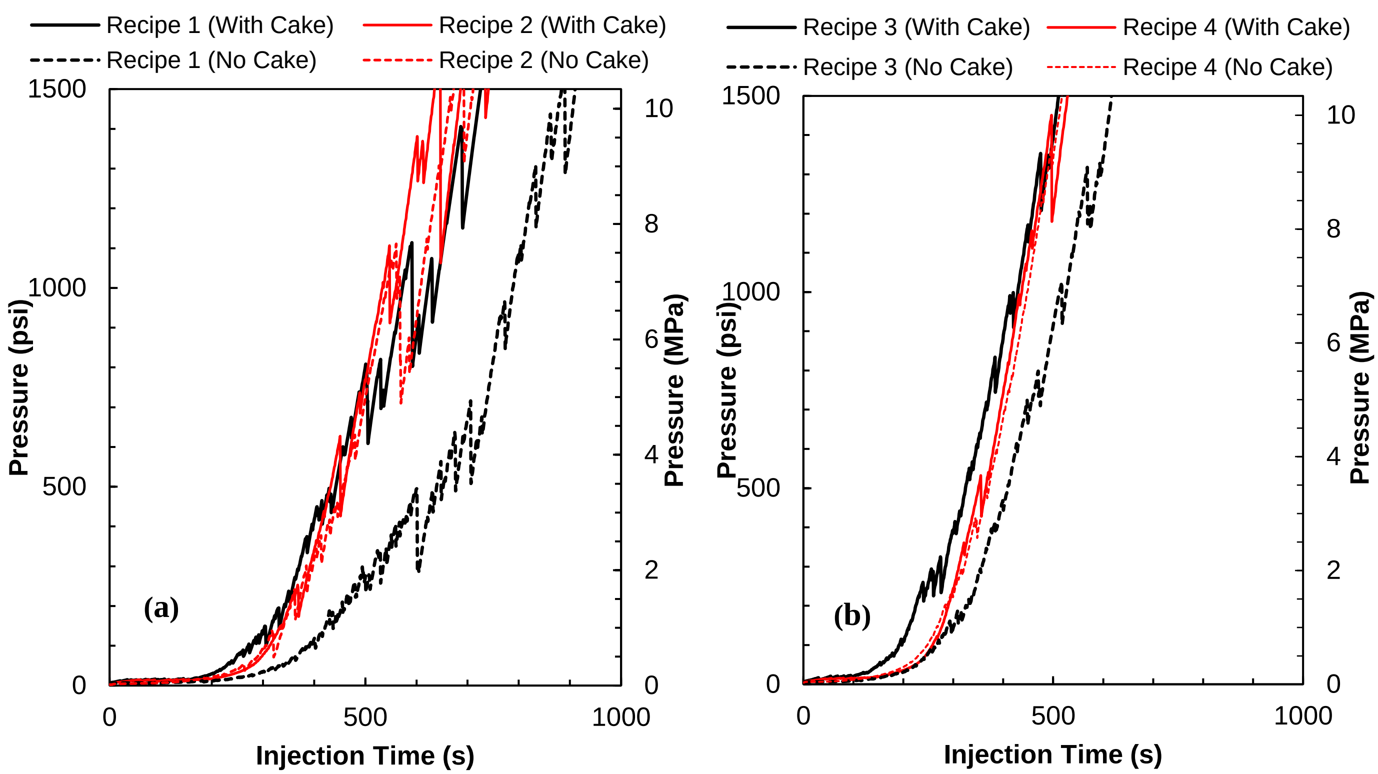


Figure 4.9. Total fluid loss volume before a differential pressure of 500 psi (3.45 MPa) was reached with filtercakes having different yield stresses

4.3.4 The Effect of LCM Particle Size Distribution

The LCM mixtures and fluid formulas for tests in this section were introduced in Section 4.2. The filtercake thicknesses for PSD tests 1 to 4 are 0.105 in (2.667 mm), 0.104 in (2.642 mm), 0.112 in (2.845 mm), and 0.108 in (2.743 mm), respectively. The slot-sealing test results are shown in Figure 4.10. When the LCM concentration was 2 wt.% with recipe 1, the particles were able to bridge/plug the slots gradually as the fluid flow through the slots without a pre-formed filtercake. When a layer of pre-formed filtercake was present, the pressure build-up was accelerated, and the fluid loss was reduced. When using fluid samples prepared according to recipe 2, which had an absence of fine LCM particles, the pressure built up faster than that with recipe 1 for the cases without a pre-formed filtercake. However, there was no significant difference between the cases with and without pre-formed filtercakes when recipe 2 was used. The test results for recipe 1 with a filtercake and recipe 2 with and without filtercakes were similar.



Test Cases	Fluid Loss before 500 psi / 3.45 MPa (ml)	Test Cases	Fluid Loss before 500 psi / 3.45 MPa (ml)
Recipe 1 (With cake)	14.0	Recipe 3 (With cake)	10.7
Recipe 2 (With cake)	13.7	Recipe 4 (With cake)	11.3
Recipe 1 (No cake)	21.7	Recipe 3 (No cake)	13.5
Recipe 2 (No cake)	14.3	Recipe 4 (No cake)	12.0

Figure 4.10. Effects of the LCM PSD and filtercake in slot-sealing tests: (a) low LCM concentration, with no LCM particles retained by the No. 100 screen in recipe 2; (b) high LCM concentration, with were no LCM particles retained by the No. 100 screen in recipe 4.

When the LCM concentration was 3 wt.% with recipe 3, the pressure built up faster and was more stable than the cases with lower LCM concentrations, and the effect of the filtercake on accelerating the process was more obvious. When using recipe 4 (no fine LCM particles), the effects of the filtercake could not easily be observed. The absence of the fine LCM particles weakened the capability of the fluid to deposit a strong filtercake. It should be noted that when comparing the LCM performance for sealing fractures without considering the filtercake, the fluid sample without fine LCM particles might provide a faster seal. However, when taking into consideration the effects of the filtercake, the fluid sample containing fine LCM particles provided better performance for slot sealing and reducing fluid loss before the pressure reached 1000 psi.

4.4 Experiment Limitations and Error Analysis

4.4.1 Experiment Limitations

The current experimental method can be improved to better reflect the physics of actual wellbores. The filtercake is formed on the wellbore wall, and there is an increase in the overbalanced pressure that can cause fracture initiation behind the filtercake; the filtercake has the ability to maintain its integrity and provide pressure and fluid isolation when the fracture aperture is small. With increasing overbalanced pressure, the fracture aperture will be enlarged, tearing the filtercake apart; the fluid in the wellbore then tends to infiltrate into the fracture and push the filtercake into the fracture. The filtercake ruptures owing to the combined effects of shear and tension. The filtercake is a layer of thickened mud that incorporates higher concentrations of LCMs and solids (compared to mud), which has the potential ability to plug the fracture immediately after its initiation and to undergo the process of fracture sealing after rupturing.

One of the significant limitations of the experiments in this study is that they neglect the potential tensile failure of the filtercake as the fracture widens. The formation properties and fracture geometry is simplified for the tests by using non-permeable metal disks with straight slots, and sealing of the fracture was achieved mainly through plugging/bridging by solids at the fracture mouth. However, during field operation, the permeable formation matrix may enhance the process of filtercake reconstruction, and tapered fractures with rough fracture surfaces may also enable fracture-sealing structures to form both at the fracture mouth and inside the fracture. The deposition of the filtercake on the wellbore is a dynamic process that combines filtration and filtercake surface shear due to the fluid flow in the well, and thus the filtercakes in the tests should be deposited dynamically under downhole pressure and temperature conditions. Other filtercake properties, such as the permeability, hardness, compressibility, and tensile strength, can also affect the ability of the filtercake to resist rupture and accelerate the fracture-sealing process. As discussed by Cook et al.(2016), the filtercake tensile strength can be one of the most important factors affecting the filtercake's capability to resist rupture as the fracture widens under overbalanced pressure. Future studies with improved experimental equipment/methods are suggested to explore the effects of filtercake tensile strength, as well as the bonding between filtercakes and formation rocks, in the process of filtercake rupture and fracture sealing. The drilling fluid and LCM design in this study are simplified, and drilling fluid additives that can improve the filtercake quality and the fracture-sealing performance should be further explored.

Nonetheless, the current experimental methods and results provide an efficient approach for evaluating the quality of a filtercake and the ability of LCMs to form a strong filtercake and promote fracture sealing. When designing drilling fluid and LCM systems for prevention of lost circulation, it is recommended to consider the effects of the filtercake on promoting fracture sealing.

4.4.2 Error Sources

The test results were repeatable in terms of general trends, but the time required to achieve fracture sealing may differ when testing similar fluid formulas under similar experimental conditions, especially with low LCM concentrations, where the corresponding pressure build-up process was quite unstable. The pressure oscillations during the pressure build-up process indicate the instability of the pressure-sealing structure, and the pressure oscillations and spikes may be due to repeated reconstruction and breakage processes of the sealing structure. Such processes seem complex, and two pressure results from similar fluid formulas and test conditions can differ in terms of the number of pressure spikes and the pressure amplitude at each crest and trough. These differences can be considered experimental error and can potentially be caused by different contents of the fluids, as it was difficult to ensure that the LCMs were added with exactly the intended PSD. The LCM samples are a blend of particles with different sizes, and although the LCM samples were added to the fluid at almost the same weight percent in the repeated tests, the LCM content for each particle size can differ. It may be difficult and unnecessary to accurately measure and control the portion of each LCM particle size.

The pressure transducer in the current experiment setup has an accuracy of ±18.75 psi (0.13 MPa, 0.5% Full Scale), the flow meter has an accuracy of 0.5% of the set point, and the syringe pump displacement resolution is 31.71 nL. If the pressure reaching 500 psi (3.45 MPa) can be considered as establishment of an effective seal, there is the risk of a 3.75% pressure measurement error. The error in the fluid injection volume is small enough to be neglected. In general, for different fluid recipes, the differences in the test results were consistent. More precise test results can be expected with pressure transducers with even higher measurement precision and higher precision in the control of the fluid recipe, especially the LCM PSD.

4.5 Summary and Conclusions

In this study, the performance of LCMs for sealing fractures was evaluated while considering the effects of filtercakes. The variables considered include the filtercake thickness and yield strength, as well as the type, concentration, and PSD of LCM. A modified PPA with a slotted disk containing four 6.35-mm-deep straight 500-mm-long slots was used to measure the efficiency of fracture sealing. The test results obtained using a 7 wt.% bentonite suspension treated with various LCMs indicate the following:

- For the same LCM mass percent concentration, different types of LCM exhibit significantly different fracture-sealing capabilities. The high resiliency granular-fibrous LCM exhibits the best performance, providing a tough filtercake and the most reliable external seal. The other types of LCMs tested in this study can neither form a tough filtercake with bentonite nor provide a seal strong enough to withstand high differential pressures.
- The stability and rapidity of the slot seal formation is affected by the LCM concentration. A higher LCM concentration results in more rapid pressure build-up and fewer pressure fluctuations.
- The filtercake generally improves the initial rate of seal formation and stability of the seal, although the specific properties of the LCM and the effects of LCM on the filtercake properties can vary. A lower filtercake permeability (indirectly measured here as the inverse of the filtercake thickness) reduces the fluid loss, especially when the LCM concentration is relatively high.
- Addition of NaCl solution to the fluid reduces the yield strength of the filtercake, whereas addition of silica nanoparticles results in a tougher filtercake than the base case. A higher filtercake yield strength reduces the fluid loss volume. These effects are especially noticeable during the initial states of fracture sealing.
- Even when the majority of LCM particles are smaller than the slot size, the Granular-Fibrous LCM can still seal the slots without a pre-formed filtercake. Removing the fine

LCM particles enhances the ability of the mixture to provide a faster seal in the absence of a pre-formed filtercake. However, the fine LCM particles enhance the quality of the filtercake, and a pre-formed filtercake containing fine LCM particles facilitates the pressure build-up process and reduces fluid loss during the early stages of fracture sealing.

- It is recommended that the effects of filtercakes be considered when evaluating the fracture-sealing performance of LCMs. In addition, the ability of LCMs to help build stronger and less permeable filtercakes should be considered during the drilling fluids design process.

4.6 Improved Experimental Methods and Proof-Test Results

In Chapters 3 and 4, it is assumed that the filtercake forms on a fracture-free wellbore wall and a fracture can initiate behind the filtercake before filtercake ruptures. With the increase of the overbalanced pressure, the fracture can be widened and the filtercake is gradually torn apart. Eventually the filtercake lost its integrity under shear and tensile stresses. The solids such as sands, LCM particles and drill cuttings that are retained in the filtercake and contained in the fluid can bridge at the fracture aperture, or seal the fracture when being pushed into and accumulate in the fracture. The experimental method for simulating filtercake rupture and fracture sealing processes was simplified for efficiency. The filtercake was created and then placed against an already open slot. This method can only represent filtercake failure due to shear stress, while it overlooked filtercake failure due to tensile stress. To better represent the filtercake rupture process, and to prove the concept that the fracture can initiate and propagate before filtercake ruptures, the experimental method was improved and several proof-of-concept tests were conducted.

Ceramic discs with a mean pore throat of 20 μm were used as filtration medium to create filtercakes. The discs were cut into two halves by a water jet cutting machine with a kerf size of

0.030 in. The cutting surfaces were polished using sandpapers and then the two half-disc were put together in the testing cylinder with rubber pieces holding them in place. The filtercakes were then created onto this closed slot through filtration. During the filtration process, there was no mud penetrating through the slot, indicating that the slot was effectively closed. After the filtercake was created, a thin piece of metal sheet with a thickness of 0.012 in (0.305 mm) was carefully inserted into the closed slot to split it open. This is to simulate the fracture widening. The process was briefly shown in Figure 4.11. Then the fluid was injected again at a low flow rate, the filtercake rupture and fracture sealing processes were observed.

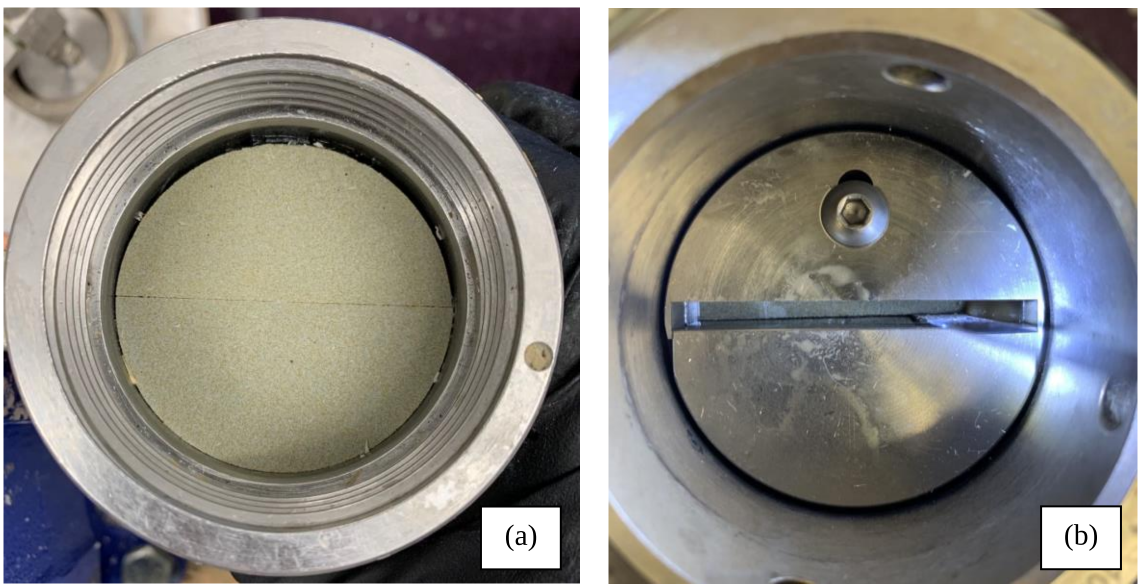


Figure 4.11. Illustrations of simulating fracture widening with filtercake: (a) ceramic disc with closed slot; (b) the slot is opened by a metal sheet after creating the filtercake.

Two sets of tests were conducted, the fluids used for creating filtercakes were bentonite-water fluids with and without LCMs. The LCMs added were 2wt.% Fiber LCM Regular (FLR) with a D90 value of 0.35 mm and a D50 value of 0.149 mm. The filtration for making filtercake lasted for 3 h, the filtercake thickness with and without LCMs was 0.21 in (5.33 mm) and 0.18 in

(4.57 mm), respectively.

Figure 4.12 shows the pressure curves when injecting LCM-free fluid through the open slot. It was obvious that when there was a layer of pre-deposited filtercake, the pressure increased stably after fluid injecting until reached 8.8 psi, there was no mud observed at the slot outlet at this point. Then the mud penetrated through the slot, indicating that the filtercake ruptured and lost its capability of pressure and fluid isolation. When there was no pre-deposited filtercake, the fluid directly flowed through the slot and no obvious pressure increase was observed. Figure 4.13 shows the ruptured filtercake after testing, the fluid flowed through the ruptured filtercake and then the slot, eroding the filtercake near the slot aperture. Here for a straight slot after fluid penetration, the filtercake on the fracture surface was not obvious.

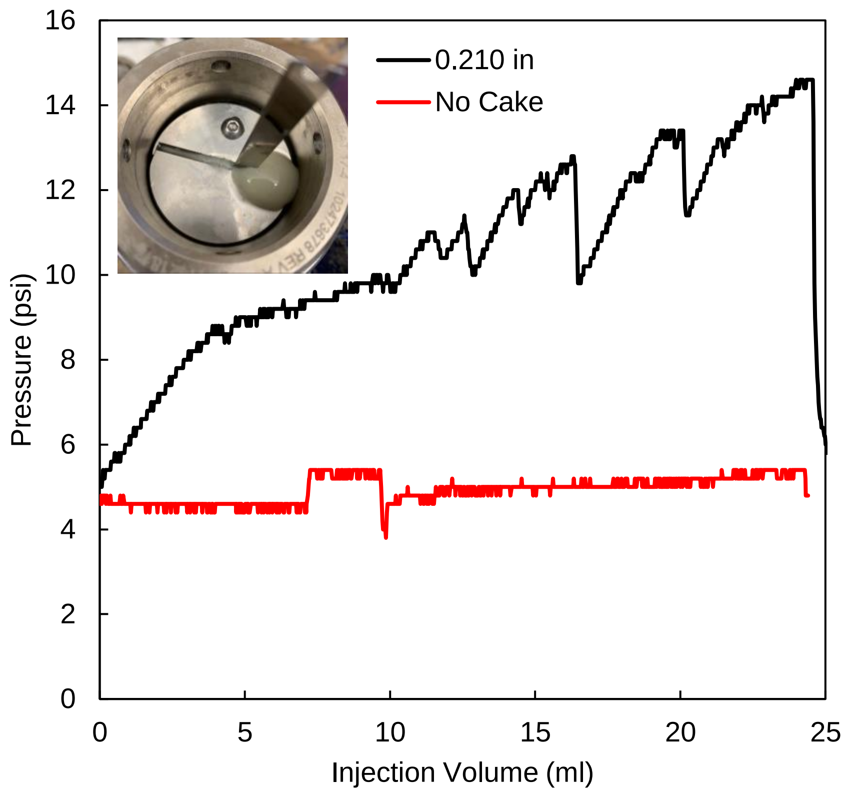


Figure 4.12. Pressure behavior when injecting LCM-free fluid through the open slot

Figure 4.13. Ruptured filtercake (without LCMs) after testing.

Figure 4.14 shows the pressure curves when injecting fluid with LCM through the open slot. When there was a layer of pre-deposited filtercake, the pressure built faster than it when there was no filtercake, thus the filtercake reduced the fluid penetration/loss volume before an effective seal formed. With the presence of LCMs, much less fluid was observed at the slot outlet than in the case without LCMs, the pressure increased smoothly without significant drop. The filtercake with LCM worked as a much better pressure-isolating barrier. With the pressure increase, the filtercake ruptured and was squeezed out from the slot as shown in the figure, the filtercake can still contribute to fracture sealing after rupturing over the slot aperture, the LCM particles with the paste-like filtercake inside the slots can work as sealing agents that prevented fluid penetrating. Figure 4.15 shows the ruptured filtercake after testing, there can be LCM particles and filtercake residuals on the slot surface. Also at the slot aperture, the LCM particles accumulated to form the slot bridging/sealing structure that enabled effective fluid and pressure isolation.

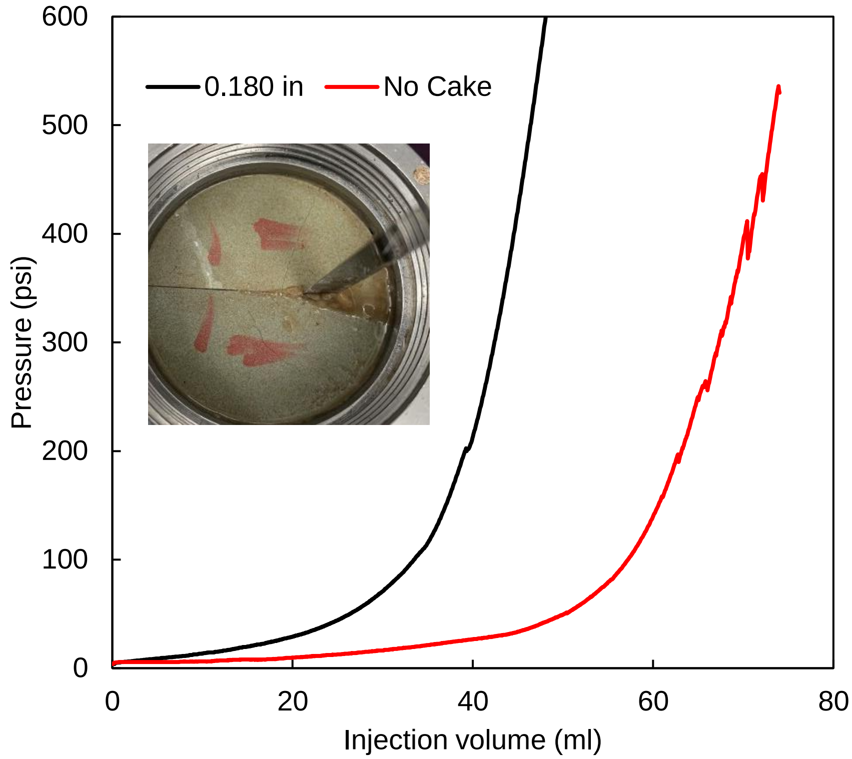


Figure 4.14. Pressure behavior when injecting fluid with LCMs through the open slot

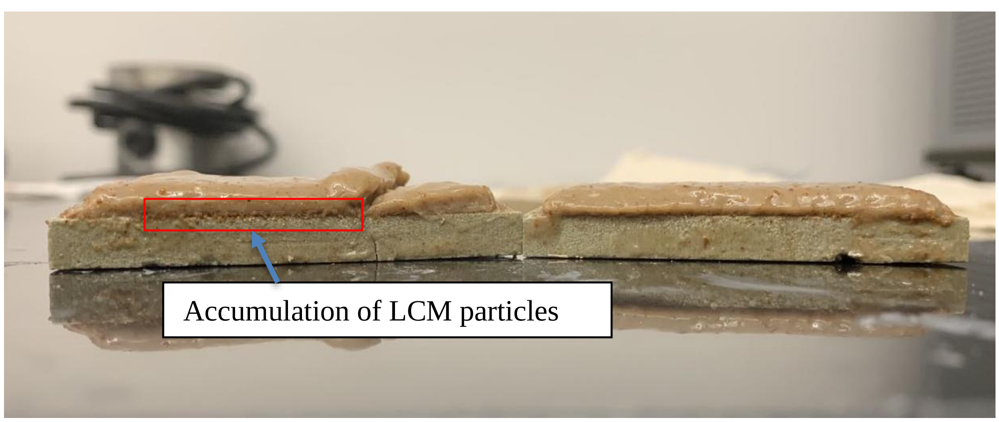


Figure 4.15. Ruptured filtercake (with LCMs) after testing.

4.7 Discussion about Filtercake Rupture and Fracture Sealing Processes

It was validated by the improved experimental methods and results that a layer of filtercake can work as a pressure barrier over a fracture. The filtercake rupture process is defined and discussed in a relatively idealized situation that a layer of filtercake loses its integrity over an open fracture. Once the filtercake loses its integrity, or ruptures, as termed in this research, the fluid will penetrate into the fracture, exerting pressure on the fracture surface and significantly increase the risk of further fracture propagation and fluid loss. The filtercake rupturing and fluid penetrating can easily be observed when the filtercake was created by simply bentonite clay with water, as shown in Figure 4.12. In such cases, the filtercake withstood the differential pressure by its mechanical capabilities to maintain its integrity and resist deformation/flow. The differential pressure to rupture the filtercakes can be as low as around 10 psi unless the fracture width is very small. In actual situations, the filtercake is a complicated system that contains solid particles such as sands, LCMs and drill cuttings. The effectiveness of filtercakes in providing pressure barriers can be primarily attributed to fracture plugging by those solids. Unlike LCM-free filtercakes, the rupture point of filtercakes with a considerable amount of solid particles may not be easily identified in the pressure curves. The solids retained in the filtercake can immediately seal the fracture upon its initiation, and create a stable seal to withstand the differential pressure. As shown in Figure 4.14, the pressure smoothly increased with fluid injection, indicating that the slot seal was stable. As the differential pressure increases during fluid injection, the filtercake is squeezed into the fracture, we may consider that the pre-deposited filtercake has lost its integrity, but since a stable seal can be created and there is no significant fluid invasion into the fracture, the filtercake is still effective in reducing the risks of fracture propagation and lost circulation.

In brief, when there are few solid particles in the filtercake, the effectiveness of filtercake in providing pressure barriers depends on its capability to resist deformation or flow, the filtercake can rupture at a low differential pressure unless the fracture width is very small; when there are a considerable amount of solid particles in the filtercake, the filtercake provides effective pressure barrier by creating a stable sealing structure to immediately seal the fracture upon its initiation. The solid particles retained in the filtercake play a critical role in creating the slot seal.

Chapter 5. Investigation of LCM Soaking Process on Fracture Plugging for Fluid Loss Remediation and Formation Damage Control

5.1 Introduction

The previous two chapters discussed the effects of filtercake, as a sealing structure on a wellbore, in WBS and lost circulation prevention. In this chapter, the sealing structure created by LCMs inside a fracture for effective lost circulation remediation is discussed.

When drilling through naturally fractured reservoirs, the remediation of drill-in fluid loss needs to be designed with taking both fracture plugging and formation damage into account. The fractures provide channels and spaces for fluid loss, it is required to seal the fractures when drilling through the fractured pay zones. The fractures can also provide channels for oil and gas production, the preservation of the high-permeability fractures is of prime importance. Even if the LCM fracture-plugging systems are designed removable, it is still important to efficiently implement the LCMs to create the desired plug, since reduced solid particle invasion leads to lower risks of fracture permeability damage.

This study investigated the effects of three LCM deployment factors: injection rate, soaking time, and soaking pressure, on the total fluid invasion volume and plug breaking pressure. Full factorial experimental design and statistical analysis were conducted to study the statistical significance of each factor. Scanning Electron Microscope (SEM) and Micro Computed Tomography (MicroCT) were applied to visualize the plug structures for the understanding of the soaking effects.

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5.1.1 Drill-in Fluid Loss Remediation in Naturally Fractured Reservoirs

The design of drilling fluid lost circulation remediation strategies is more complicated in naturally fractured reservoirs. The presence of high-permeability channels such as natural fractures can be a challenge for overbalanced drilling, there is a high risk that drilling fluids leak off and invade through these channels(Xu et al., 2016b). The invasion of fluid and suspended particles into the fractures can cause significant and often permanent permeability impairment (Qutob, 2004; Restrepo et al., 2010; Selvadurai et al., 2018; Xu et al., 2018; Dong et al., 2019). In most situations, these high-permeability channels provide conduits for gas or oil production from tight source matrices. The preservation of the high-permeability fractures is of prime importance (Salimi and Alikarami, 2006).

To remediate severe drill-in fluid losses through pay zones and limit formation damage, “non-damaging” fluid solutions such as crosslinking system, solid-free polymetric pill or acid soluble cement may be required (Savari et al., 2017; Vasquez and Fowler, 2013; Seymour and Santra, 2013). Other solutions such as drilling with air, form or aerated fluids, drilling with special low-density fluid such as aphrons or with low weight solid additives such as hollow spheres may also be applied with success. Most of these solutions aims at remediating fluid loss and formation damage by controlling the pressure difference between wellbore and formation. However, these solutions may require specialized personnel or equipment (Gianoglio et al., 2015). A more common solution is to use degradable or acid soluble LCMs (Singh and Sharma, 1997; Nana et al., 2016). The biggest limitation of conventional particulate-based LCMs is their dependency on particle size distribution, which needs to be designed according to the opening size of fluid loss channels. Most of the time, the information of the opening sizes is not available and cannot be accurately predicted. Trial-and-error process by changing LCM particle size distribution and concentration can greatly increase non-productive time. The addition of fibrous LCM helps increase the overall strength of the LCM plug. Calcium-carbonate particles with a large particle size distribution, in conjunction with acid-soluble fibrous LCMs may be used for mitigating severe fluid losses (Droger et al., 2014). High-fluid-loss defluidizing systems are designed to defluidize rapidly when differential pressure is applied, which can create sealing structures to seal channels that causes severe fluid losses (Sanders et al., 2010). Conventional defluidizing systems depends on the formation permeability to develop the filter plug. New type of these systems with reticulated form can be used to seal fractures in low-permeability formations like shale (Savari and Whitfill, 2019). Hesitation squeeze is commonly required for the application of defluidizing systems in severe fluid loss zones (Murray et al., 2014; Savari et al., 2016; Hegazy et al., 2018).

5.1.2 LCM Implementation Strategies: Hesitation and Soaking Process

LCM implementation strategies can be a broad concept that involves the design of LCM properties such as types, concentration, particle size distribution, etc.; it also includes the LCM pumping schemes that are compatible with the LCM-laden fluids. Hesitation squeeze is applied for squeezing cement and also LCMs whereby a portion of the fluid is pumped, then soaked under differential pressure against the zone of interest for a certain duration. Currently, there seems to be no well-defined terminology to describe the soaking process. "Soaking" (Soliman et al., 2015; Gooneratne et al., 2017; Olsen et al., 2019) and "hesitation wait" (Savari et al., 2016; Al-saba et al., 2014) are commonly used to refer to the process of the plug being exposed to differential pressure for a specific time. In this study, "soaking" is used for consistency. The soaking process is indeed a dehydration/defluidization process for high-fluid-loss systems (Murray et al., 2014). LCM particle accumulating may enable the development of a low-pressure-bearing plug at the fracture mouth or inside the fracture. Soaking the initial plug can strengthen the plug and increase the lost circulation pressure by increasing the plugging zone length and decreasing the plugging-zone permeability (Xu et al., 2017a; Xu et al., 2017b). The plug strengthening process through soaking is analogous to filtration process, the initial plug works as part of the filtration media. Being exposed to differential pressure, the LCM-laden fluid filtrates though the temporary plug, leaving suspended LCMs and other solids to strengthen the plug.

When plugging the fractures in pay zones, the less amount of LCMs being used, the easier the fractures can be unchoked for production. Forming the plug near the fracture mouth is preferable than deep into the fracture. Acid soluble LCMs do not ensure complete cleanup. Less amount of LCM-laden fluid invading into the fracture leads to less LCM residue and less formation damage risk (Lietard et al., 1999). The LCM implementation strategies should be carefully designed to effectively utilize the materials to achieve desired fluid loss remediation and formation damage control (Ghalambor et al., 2014; Xu et al., 2016).

In summary, the application of LCMs is one of the most common practices for fluid loss remediation. The design of LCM systems and deploying schemes are more complicated in naturally fractured reservoirs, where the preservation of the high-permeability fractures is of prime importance. Effective LCM treatment design is required to limit the volume of LCM-laden fluid invasion into the fractures when creating the desired plugs. Soaking/hesitation is a common practice for strengthening the LCM-plugs designed for curing severe fluid losses. Some studies discussed lab evaluations and field cases of applying LCM systems using a hesitation squeeze method (Al-saba et al., 2014; Savari et al., 2016; Savari and Whitfill, 2019), however, there is limited information about the design methods of the hesitation/soaking processes. The LCM plug breaking pressure and total fluid invasion before sealing are important factors for evaluating the performance of an LCM system in fluid loss and formation damage control (Kang et al., 2014; Xu et al., 2016a). Most studies focused on optimizing LCM performance by improving LCM properties and formulas (Kumar and Savari, 2011; Xu et al., 2016a), however, the design of LCM implementing schemes should be discussed in more detail.

5.2 Experimental Method and Procedure

The experimental setup consists of three main components as shown in Figure 5.1: (a) a permeability plugging apparatus (PPA) test cell with a 0.04 in (1 mm) slotted disc to hold the fluid sample and to simulate the fracture; (b) an LCM evaluation receiver to collect the filtrate and fluid loss; (c) a Teledyne Isco 500D Syringe Pump connected to the inlet of the PPA test cell to control and monitor the fluid injection rate and pressure. Data were recorded by the pump build-in transducer and logged into a computer. The LCM evaluation receiver has an orifice size of 0.28 in (7 mm), it can handle larger particles than the original PPA outlet cap without plugging.

In brief, the experimental procedure included three stages: the creation of initial plug, strengthen the plug by soaking, and then continue injection to test the ultimate plug breaking pressure and the fluid loss volume to develop the desired plug. For each test, the LCM-laden fluid was injected at a constant rate through the slotted disc, the LCM particles could create a structure that can withstand a relatively low differential pressure with the fluid injection, such structure is referred to as initial plug in this study. The initial plug was soaked by maintaining this low differential pressure for different period, and then the fluid was injected at a constant rate again. The injecting pressure was monitored and recorded for the understanding of the plug building and breaking processes. The first pressure drop after the soaking process indicated the breaking of the initial plug after soaking. The fluid loss volume before the establishment of the desired plug (indicated by the pressure reaching 1200 psi) was recorded and the total volume of fluid invasion can be calculated.

The design of experiments (DoE) is a 2^3 factorial design (3 independent variables, each variable has 2 levels). Factorial designs are more efficient and cost effective than one-factor-at-a-time experiments, and enable the detection of the interactions between independent variables. The dependent variable in this experiment design is the fluid invasion volume during the plug building and breaking processes, and it is a key factor to consider when evaluating LCMs, the less fluid invasion, the less formation damage risk. The independent variables are fluid injection rate, soaking time and soaking pressure. The fluid injection rate represents the speed of the fluid being displaced and it is closely related to the speed of the fluid flowing through the slot; the soaking time can be considered as hesitation time, it represents the duration that the initial plug was exposed to the soaking pressure; the soaking pressure is the differential pressure maintained to strengthen the initial plug. Note that for field hesitation squeeze application, the pump is stopped during hesitation period, the differential pressure across the plugging structure can gradually dissipate due to filtration process. The change of the pressure depends on formation properties and it may be difficult to characterize it experimentally. In this experimental study, the pump was set in constant pressure mode to maintain the differential pressure to investigate if it has a significant impact on the soaking process.

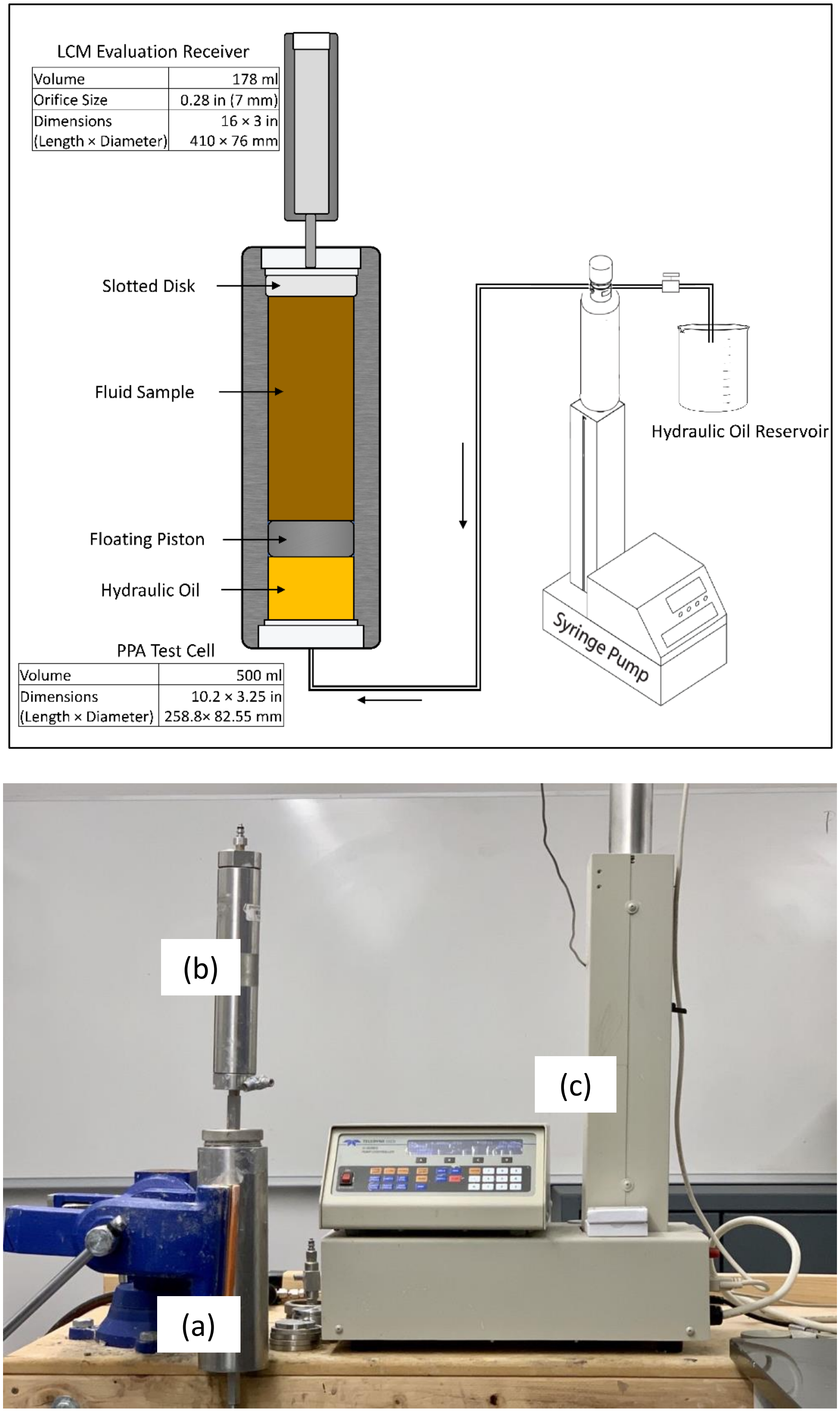

Figure 5.1. Schematic diagram of experimental setup and actual apparatuses

The test matrix is shown in Table 5.1 and Table 5.2. The fluid used in this section was formulated using water and 7 wt.% bentonite with 2 wt.% traditional fibrous LCM, named OKCG. The D10 and D50 for OKCG mixture is around 0.27 mm and 0.84 mm. It should be noted that the base fluid formula in this research is simplified for efficient experimental investigation. Bentonite is an essential viscosifier for water-based mud that provides LCM suspending capacity of the fluids. Other drilling fluid additives are avoided to eliminate their possible effects on LCM performance (Alsaba et al., 2017). In actual operational designs, the LCM candidates should be tested with the fluids applied on-site.

Table 5.1. 2^3 factorial design of experiment (DoE) to test factors influencing LCM implementation

Factors	Notation	Low level (L)	High level (H)
Soaking Pressure	P	200 psi	400 psi
Soaking Time	T	1 hr.	2.5 hr.
Injection Rate	Q	5 mL/min	20 mL/min

Table 5.2. Full factorial design, 3 Factors, 2 Levels test matrix

Run #	P	T	Q
1	L	L	L
2	H	L	L
3	L	H	L
4	H	H	L
5	L	L	H
6	H	L	H
7	L	H	H
8	H	H	H

The effects of soaking process can heavily depend on the LCM type and particle size distribution. Four LCM combinations consist of other LCM types were tested: Fiber LCM Coarse (FLC), Grinded Medium Fiber (GMF), Magma Fiber™ (MF), Calcium Carbonate (CC). The FLC is a granular shaped high resilient LCM. GMF is a traditional fibrous LCM with wooden fiber appearance, there are more fine/shot fibers than those in OKCG. MF is a specially formulated, extrusion-spun mineral fiber, which can be sheared and dispersed within the base fluid and creates a lattice network of fibers. CC is a traditionally used granular type LCM. The appearance of each LCM is shown in Figure 5.2.

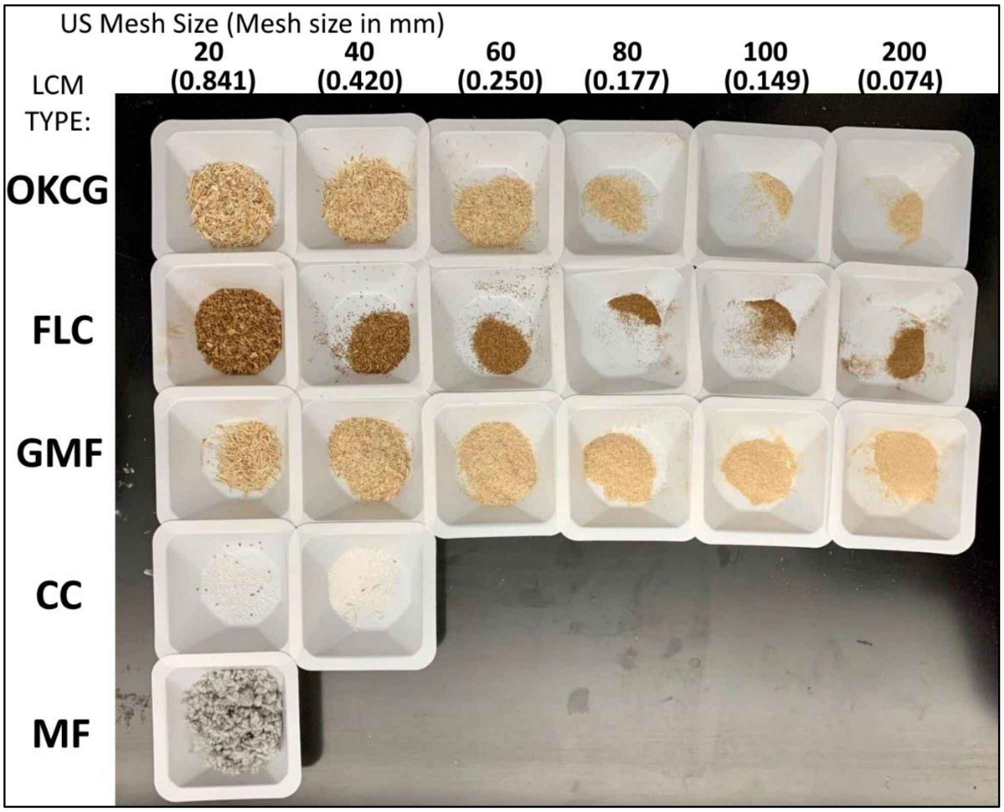

Figure 5.2. Appearance of LCMs samples of different types and particle sizes

The D10 and D50 for the FLC mixture is around 0.36 mm and 1.51mm; The D10 and D50 for GMF is around 0.08 mm and 0.32 mm; MF can be sheared and dissolve in base fluid; The CC mixture is basically a combination of 20% 1.19 mm particles and 80% 0.40 mm particles. The base fluid is 7 wt.% bentonite water, the LCMs were added by different weight percent and by different type combinations to formulate the fluid samples. The initial plug was soaked at 200 psi for 1 hour and the pressure curve during the plug building and breaking processes was compared to that without soaking.

The soaking process in the tests was indeed a filtration process through the plugs. Since the non-porous stainless-steel discs were used, there is no filtration into the surrounding media such as formation rocks in real applications. Permeable formation will make the soaking effects more noticeable than shown in the lab test results.

5.3 Results and Disscussion

5.3.1 Effects of LCM Injection Rate, Soaking Time and Soaking Pressure

The differential pressure across the slotted disc was recorded along with the fluid injection. Figure 5.3 shows a comparison between the pressure curve with and without soaking process during the plug build-up. The curve with soaking has been trimmed and the pressure during initial plug building and fluid injection after soaking were presented. In general, the soaking process can enable the consolidation of the temporary plug, creating a dense collection of LCMs at the fracture mouth or inside the fracture. Such structure provided a more stable pressure increase when the injection resumed, represented by a relatively straight line with few fluctuations in the pressure curve. Again, the pressure fluctuation was a cyclical process of sealing structure break and reestablishment. The pressure drop indicated sealing structure break and the pressure increase indicated sealing structure reestablishment. A stable pressure increase can potentially reduce the amount of fluid entering the fracture before the desired plug is built. The less amount of LCM-laden fluid enters the fracture, the less damage it may cause to the fracture permeability (Lietard et al., 1999).

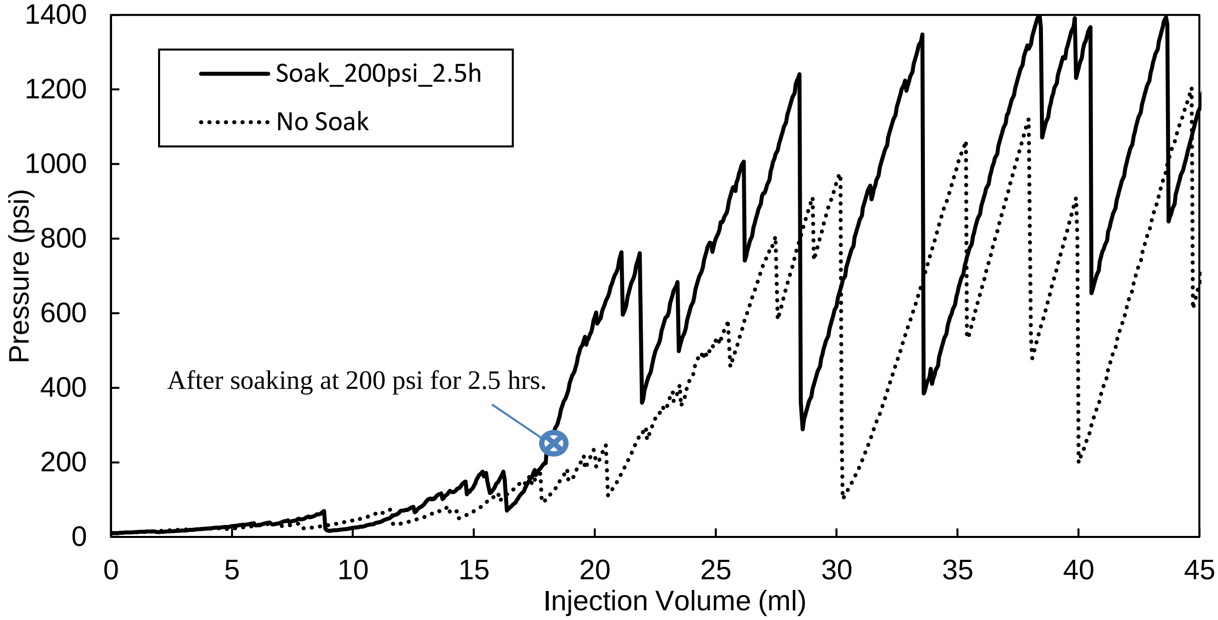

Figure 5.3. Example pressure curves for tests with and without soaking

The effects of LCM injection rate without soaking are shown in Figure 5.4. A faster fluid displacement rate resulted in a slower plug development and thus a slower pressure buildup. A potential explanation is that a higher flow rate through the fracture tends to flush the LCM and shear the blocking structure apart (Al-saba et al., 2014). When the flow rate is low, there is less shear force exerting on the LCM particles/fibers and there can be a higher chance that the LCM being retained to form a blocking structure. When implementing the LCM pill without soaking, a low displacing rate can potentially create the desired fracture seal with less amount of fluid and LCM entering the fracture.

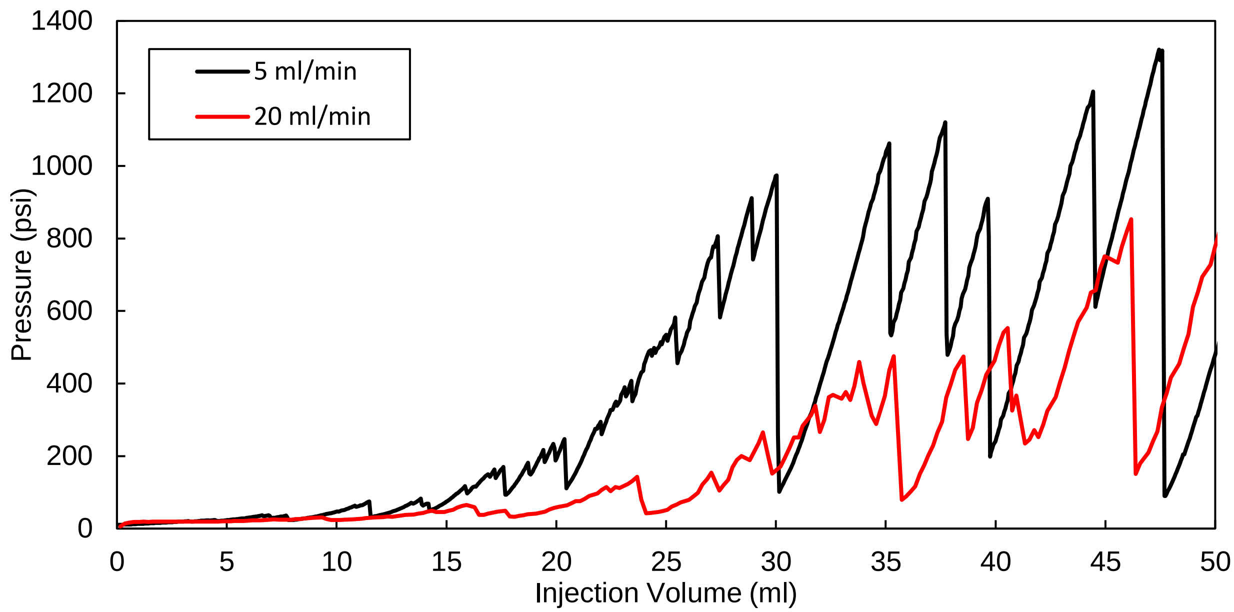

Figure 5.4. Effects of LCM fluid injection rate on plug development

The pressure curves with different soaking time and pressure were shown in Figure 5.5, where the pressure with resumed injection after soaking is plotted. In general, the soaking process is analogous to the filtration process where a layer of filtercake is formed onto a permeable medium. In the soaking process in the tests, the initial plug provided the permeable medium, and in the real applications, the LCM carrying fluid filtrates through the plug and the permeable formation (Savari and Whitfill, 2019). A longer soaking time resulted in an increase of the plug strength, reflected by the increase of the pressure magnitude at which the first significant pressure drop occurred.

The effects of soaking time and soaking pressure on the initial plug breaking pressure were summarized in Figure 5.6. For the materials tested in this experiment, 2.5-hours soaking generally increased the plug breaking pressure by 150 psi compared to 1-hour soaking. Similar to the filtration process, in which a higher differential pressure may compact the filtercake, a higher soaking pressure can enhance the plug strength, thus reduce the total fluid loss after the injection resumes. As for the plugs soaked at 400 psi, the initial plug breaking pressure was 969 psi and 863 psi after soaking for 2.5 h and 1 h, respectively. That was a 569 psi and 463 psi increase compared to the pressure at which the plugs were soaked. And for the plugs soaked at 200 psi, the initial plug breaking pressure was 752 psi and 591 psi after soaking for 2.5 h and 1 h, respectively. That was a 552 psi and 391 psi increase compared to the soaking pressure. However, to soak the initial plug at a higher pressure requires a longer initial plug development process, which requires more LCMs and results in more fluid invasion before soaking.

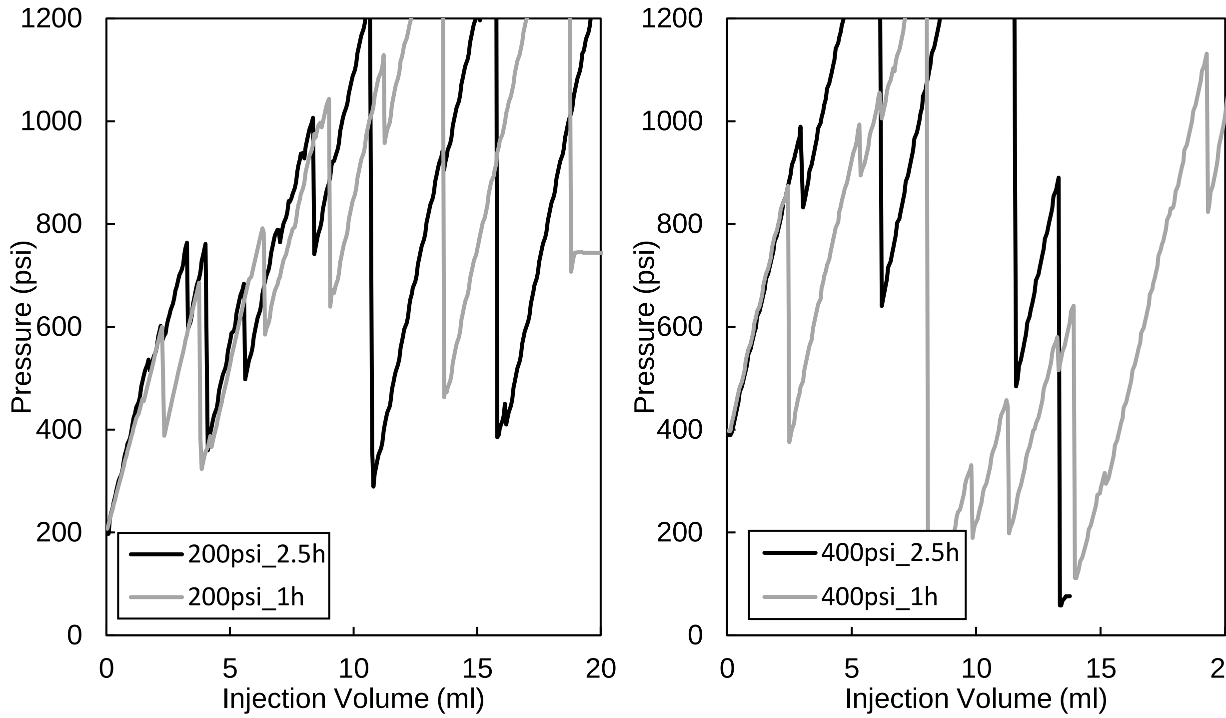

Figure 5.5. Pressure curves with different soaking time and pressure, with an injection rate of 5 ml/min.

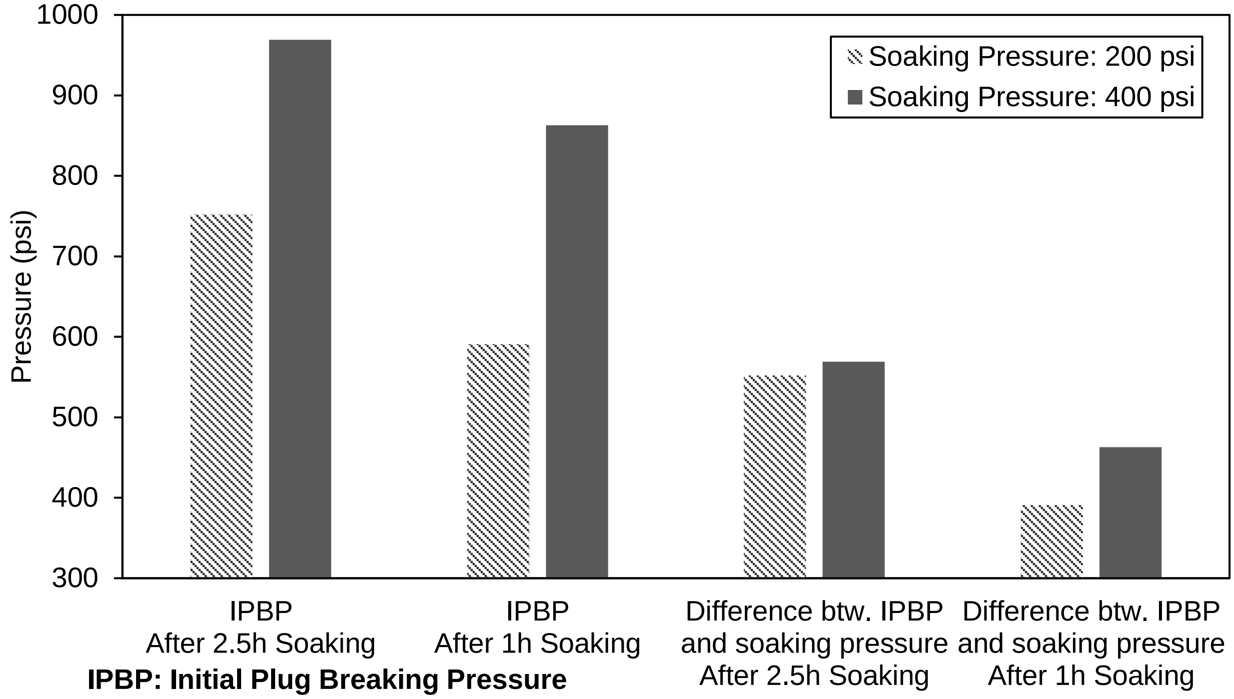

Figure 5.6. Effects of soaking pressure and time on initial plug breaking pressure

Figure 5.7 shows the summary of the effects of injection rate, soaking pressure and soaking time on fluid invasion volume. The fluid invasion mainly consists of the LCM-laden fluid flowed through the slots during the processes of building the initial plug before soaking and building the desired plug after soaking. The filtration loss during soaking was neglected since the fracture permeability damage is mainly caused by the invasion of fluid and suspended particles into the fractures (Qutob, 2004; Selvadurai et al., 2018). As summarized in the figure, a lower injection rate led to a less fluid invasion volume; soaking for a longer time may also reduce the fluid invasion volume; the effects of soaking pressure seem unnoticeable.

Three factors were involved in these tests, whether the effect of each factor is statistically significant, and whether there is a combined effect of the factors are discussed in the flowing section.

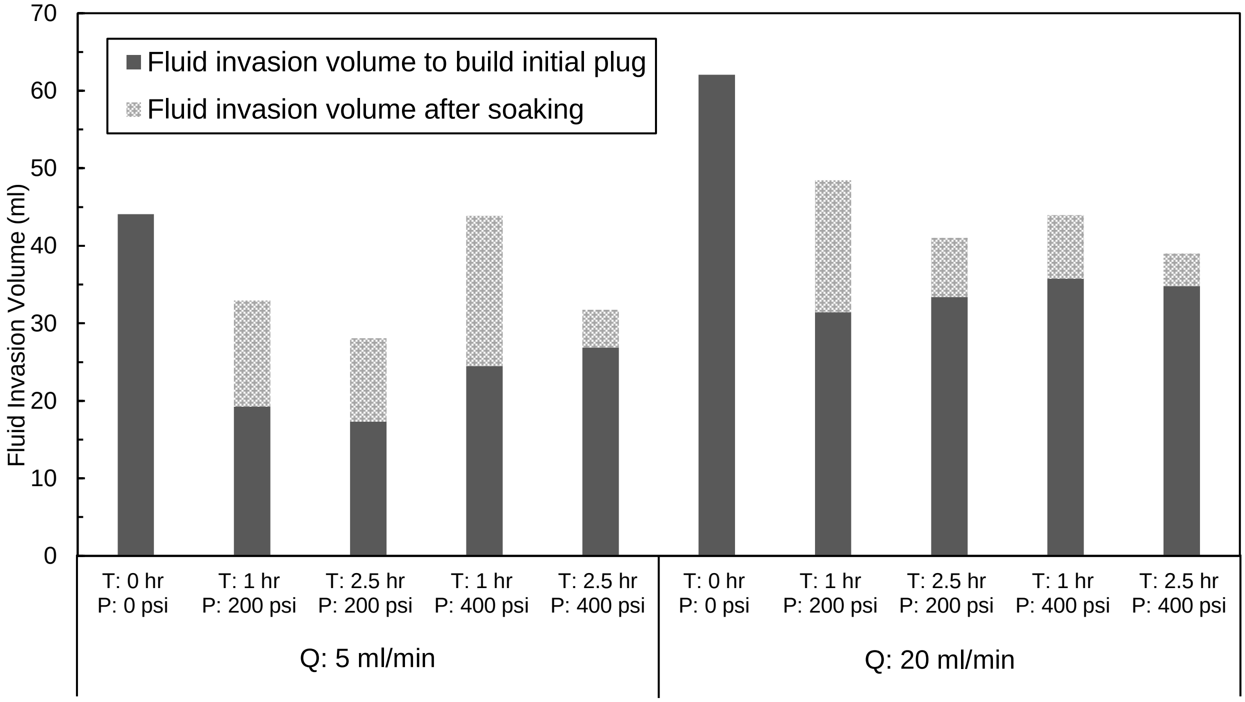

Figure 5.7. Summary of the experimental results: the effects of injection rate, soaking time and pressure on fluid invasion volume.

5.3.2 Statistical Analysis of the Test Results

Single and Multiple Factor Effect:

Statistical analysis can be a useful tool for analyzing drilling related problems (Ezeakacha and Salehi, 2018; Ezeakacha and Salehi, 2019; Meng et al., 2019). The interaction effects are plotted in Figure 5.8. . If the line is horizontal, then it means there is no main effect, in other words, as the independent variable level shifts from low to high, there is no significant change in the dependent variable. When the line is not horizontal, there is main effect presenting and a steeper slope indicates a greater magnitude of the main effect. For example, in this figure, as the dependent variable, T, shifts from low level to high level, every single line in “T(min)*P(psi)” and “T(min)*Q(ml/min)” is pointing downwards with a steep slope, indicating a potential significant main effect of T(soaking time), and a longer soaking time can lead to a less amount of fluid invasion volume. And also in the plot of "T(min)*Q(ml/min)", as the injection rate, Q, shifts from 5 ml/min to 20 ml/min, there is a noticeable increase in invasion volume, indicating a potentially significant effect of injection rate.

Interactions occur when variables act together to impact the output of the process. Nonparallel lines indicate possible interactions. For example, in the figure of "P(psi)*Q(ml/min)", which shows the interaction of soaking pressure and injection rate, as the soaking pressure shifted from 200 psi to 400 psi, the fluid invasion volume (denoted LOSS in the figure) decreased when the injection rate was 20 ml/min, and the fluid invasion volume increased when the injection rate was 5 ml/min. These two lines have a potential to intersect with each other, indicating possible variable interactions.

While the plots help to identify possible interaction effects, a hypothesis test like ANOVA is needed to examine whether the interaction effects are statistically significant.

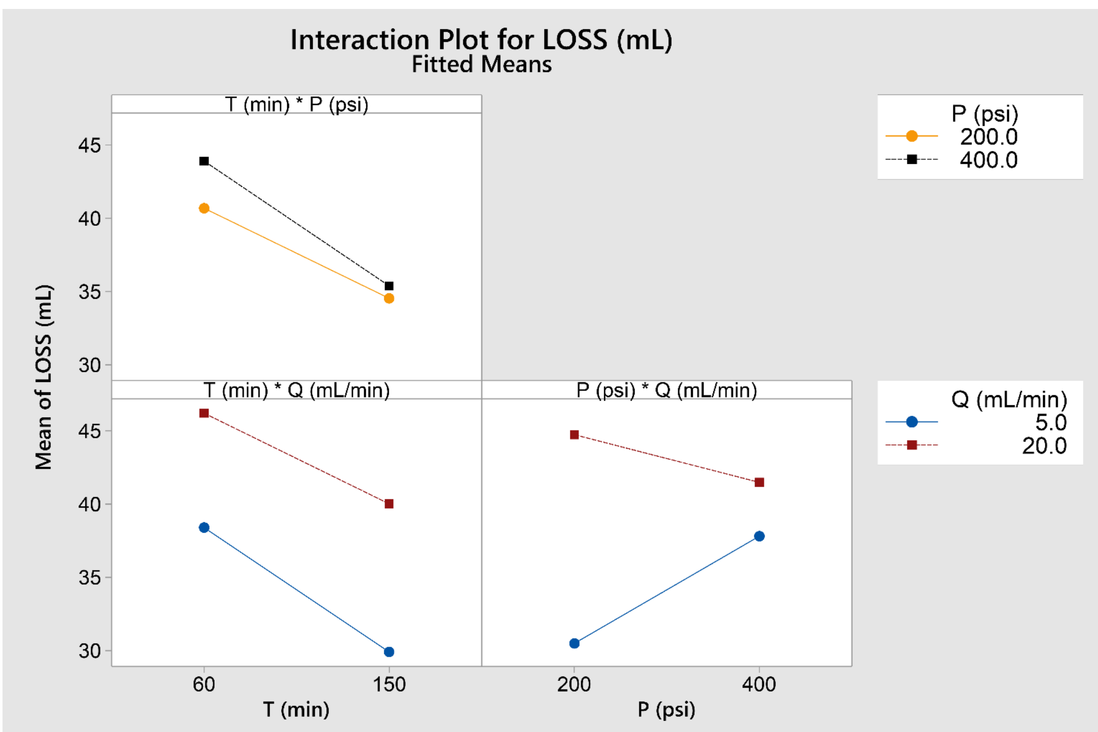

Figure 5.8. Effects of injection rate (Q), soaking time (T) and pressure (P) on fluid invasion volume, and the interactions of the variables

Analysis of Variance (ANOVA):

ANOVA is a statistical method used to compare the means between each group and test whether any of the means are significantly different from others. The ANOVA test can help to sort out the real effects from sampling error and other noises. In this test, we analyze the effects of injection rate (Q, ml/min), soaking pressure (P, psi) and soaking time (T, min) on the fluid invasion volume before the establishment of the desired plug. It is originally hypothesized that these independent variables have no effects on the dependent variable, in other words, the population means are all equal (null hypothesis). With a significant level of 0.05 (5% risk of concluding that a difference exists when there is no actual difference), a p-value less than 0.05 indicates that the null hypothesis is rejected, the conclusion is that the variable is statistically significant. The ANOVA results are shown in Table 5.3, it can be concluded that the soaking time and injection rate are statistically significant in affecting the fluid invasion volume, while there is no enough statistical evidence to show that the soaking pressure and the combination of each two variables have significant effects on the results.

Table 5.3. Analysis of variance results

Source	DF	Type I SS	Mean Square	F Value	Pr > F
T	1	415.1995	415.1995	36.93	0.009
P	1	1.944178	1.944178	0.17	0.706
Q	1	290.09	290.09	25.8	0.015
T*P	1	15.62712	15.62712	1.39	0.323
T*Q	1	9.002298	9.002298	0.8	0.437
P*Q	1	80.39755	80.39755	7.15	0.075

Multiple Linear Regression Analysis:

Regression analysis is a mathematical approach that attempts to model the relationship between variables by fitting a curve to observed data. It can be used for the prediction of a dependent variable from independent variables in a certain range. Before attempting to fit a linear model to the results, it has already been tested that the independent variable: soaking time (T) and injection rate (Q), are statistically significant in affecting the dependent variable: fluid invasion volume (LOSS). And there are no variable interactions that are statistically significant. The method of least-squares is the most commonly used for fitting a regression line. This method calculates the best fitting line by minimizing the sum of the squares of the vertical deviations from each observed data point to the line

Multiple linear regression analysis is applied to predict the invasion volume by soaking time and injection rate of the fluid used and within the test condition range. The ANOVA p-value for the regression is 0.0019 (<0.05), which is small enough to reject the null hypothesis and conclude that the regression is statistically significant. For multiple linear regression, the regression model follows a form of $\hat{y} = \mathrm{b}_0 + b_1 x_1 + b_2 x_2 + \cdots b_n x_n$. Table 5.4 shows the intercept of the model and coefficient of each variable. The following p-values are less than the significant level 0.05, which indicates that the coefficient for the predictor does not equal zero. The sign of a regression coefficient indicates whether there is a positive or negative correlation between each independent variable and the dependent variable. The coefficient value signifies how much the mean of the dependent variable changes given a one-unit shift in the independent variable while holding other variables in the model constant. The regression model is shown in equation (1), this implies that while the other variable is kept constant, as the soaking time increases 1 unit (minute), there will be 0.11077 ml less fluid invasion volume, and as the injection rate increases 1 unit (ml/min), there will be 0.71813 ml more fluid invasion volume. It should be noted that this regression model is not generic, it is only applicable to the experimental setup and test range in this research. However, the statistical tools and analyzing methods can provide guidelines for general experimental design and result interpretation.

Table 5.4. Parameter estimates for regression

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|	95% Confidence Limits	
Intercept	1	41.84982	3.43286	12.19	<.0001	33.7324	49.9673
Time (T)	1	-0.11077	0.02437	-4.54	0.0027	-0.1684	-0.0531
Injection Rate (Q)	1	0.71813	0.18903	3.8	0.0067	0.27114	1.16513

$$\mathrm{LOSS} = 41.85 - 0.11077\ \mathrm{T} + 0.71813\ \mathrm{Q} \ldots\ldots (1)$$

5.3.3 Sensitivity Analysis of Major Factors

Previous sections revealed that soaking time and injection rate are major factors affecting the total invasion volume during the plug development process. Sensitivity analyses were conducted to confirm and further explore the effects of the major factors. When investigating the effects of soaking time during the plug development process using 2 wt.% OKCG, the injection rate was 5 ml/min and the initial plug was soaked at 200 psi for 30 min, 60 min, 150 min and 240 min. When investigating the effects of injection rate, the LCM-laden fluid was injected at a constant rate of 2 ml/min, 5 ml/min, 10 ml/min and 15 ml/min without soaking for simplicity, given that the interaction between soaking time and injection rate was not significant. Each test was repeated three times and the results were plotted with 95% confidence interval error bars in Figure 5.9 and Figure 5.10.

As shown in Figure 5.9, in general, the total fluid invasion volume was less when the initial plugs were soaked for a longer time. The soaking process is analogous to the filtration process, the plug length can increase as the fluid leaks off through the plug and constantly deposits LCMs. The soaking process may also contribute to reducing the plug porosity. As revealed by Xu at al. (2017a; 2017b), a longer and less porous plug has a higher plug breaking pressure, a higher plug breaking pressure indicates the ability of the plug to sustain a higher differential pressure and support further plug development.

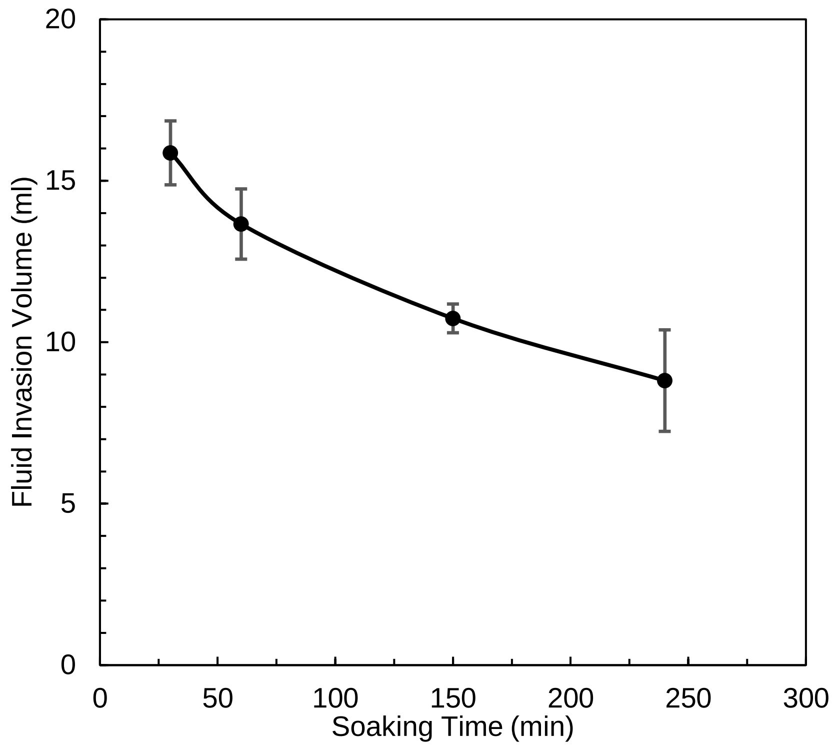

Figure 5.9. Effects of soaking time on total fluid invasion volume

As shown in Figure 5.10, the fluid invasion volume was generally higher when the LCM-laden fluid was injected at a higher rate. The difference in total fluid invasion volume was more evident when there was a significant difference in injection rate. According to Razavi et al. (2017), due to the lack of fluid leak-off in low-permeability formations, the fluid penetration rate can be faster, and a faster penetration rate can prevent the deposition of LCMs along the fracture. In this research, formation fracture was simulated by nonpermeable steel slots and the penetration rate was controlled by pump injection rate, the trend of the experimental results was consistent with the modeling results shown in Razavi's research. A potential reason is that for certain types of LCMs like OKCG, a faster fluid penetration rate disturbs the LCM particle accumulation and consolidation processes. It is difficult to retain fast-moving LCM particles and fast-moving fluid may rupture the accumulated structures (Al-saba et al., 2014).

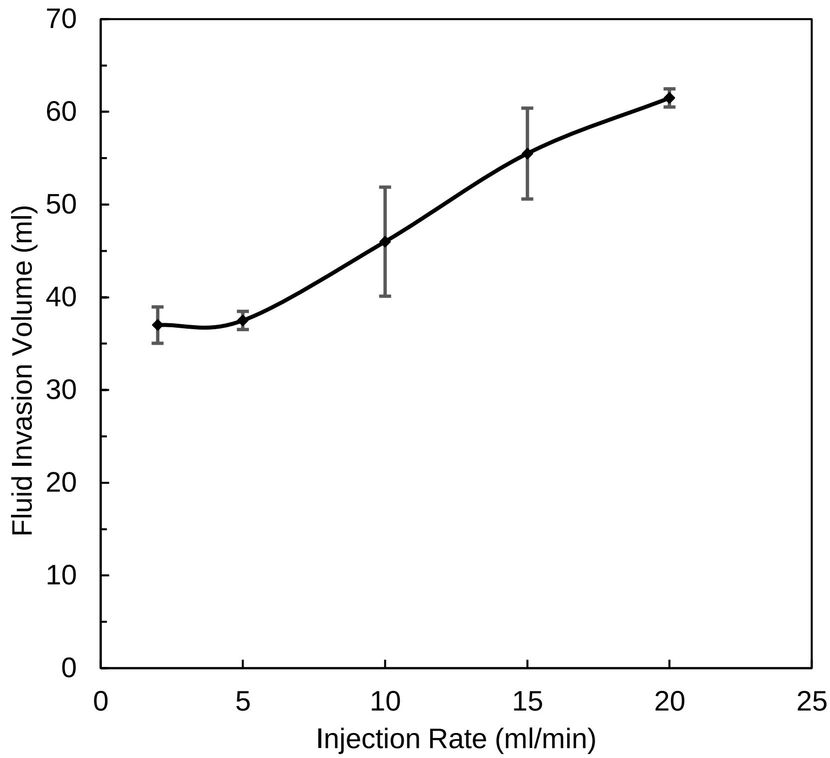

Figure 5.10. Effects of injection rate on total fluid invasion volume

5.3.4 The Effects of Soaking on LCMs with Different Types

The results of the statistical analysis presented in previous sections are valid for the specific LCM been tested. Not all LCMs are made equal, they come with different materials and different properties such as shape, PSD and resiliency. When designing the LCM implementing strategy, the LCM properties should be carefully evaluated and considered.

In this section, four combinations of LCMs were evaluated by soaking the corresponding initial plug at 200 psi for 1 hour, the pressure curve during the followed fluid injection was compared with the non-soaking case starting from 200 psi. The four LCM combinations added to 7 wt% bentonite water fluids are: (a) 1 wt% FLC with 1 wt% GMF; (b) 2 wt% FLC; (c) 1 wt%

FLC with 1 wt% MF; and (d) 1 wt% FLC with 1 wt% CC.

As shown in Figure 5.11, for different LCM combinations, the effects of soaking were different: in plot (a), it is obvious that the soaking process compacted the initial 200 psi-bearing plug and increased the initial plug breaking pressure to around 500 psi. A drastic pressure drop occurred when the pressure climbed to around 700 psi. In this case, the soaking process did not contribute much to build the desired 1200 psi plug. The GMF contains more fine and short fibers and these fibers can accumulate at the initial plug during soaking, which increased the initial plug breaking pressure. However, the GMF fibers are flexible and may not provide the structure that was strong enough to sustain 700 psi just after soaking; In plot (b), the soaking process increased the initial plug breaking pressure and also advanced the buildup of the desired plug; The effects of soaking are the most noticeable in plot (c), without soaking, the peaks of the pressure spikes were around 500 psi, while after soaking, the initial plug breaking pressure was increased and the peaks of the pressure spikes reached 1000 psi. This can be attributed to the MF's unique property, it is soluble in the base fluid when being sheared and can aggregate when being dehydrated. The soaking process filtrated the liquid and created a dehydrated structure, the MF aggregated and aided in increasing the overall structure strength; In plot (d), the soaking effects were not significantly noticeable for a combination of FLC and CC.

The effects of soaking on LCMs with different types tested in this study confirmed that the soaking process works best on LCM systems like Magma Fiber, the soaking or dehydration process facilitates the consolidation of the dehydrated mud plug. The soaking effects were not significant for granular type LCMs like calcium carbonate, the solid particles may not considerably compact and strengthen the accumulated plugging structure through the soaking process.

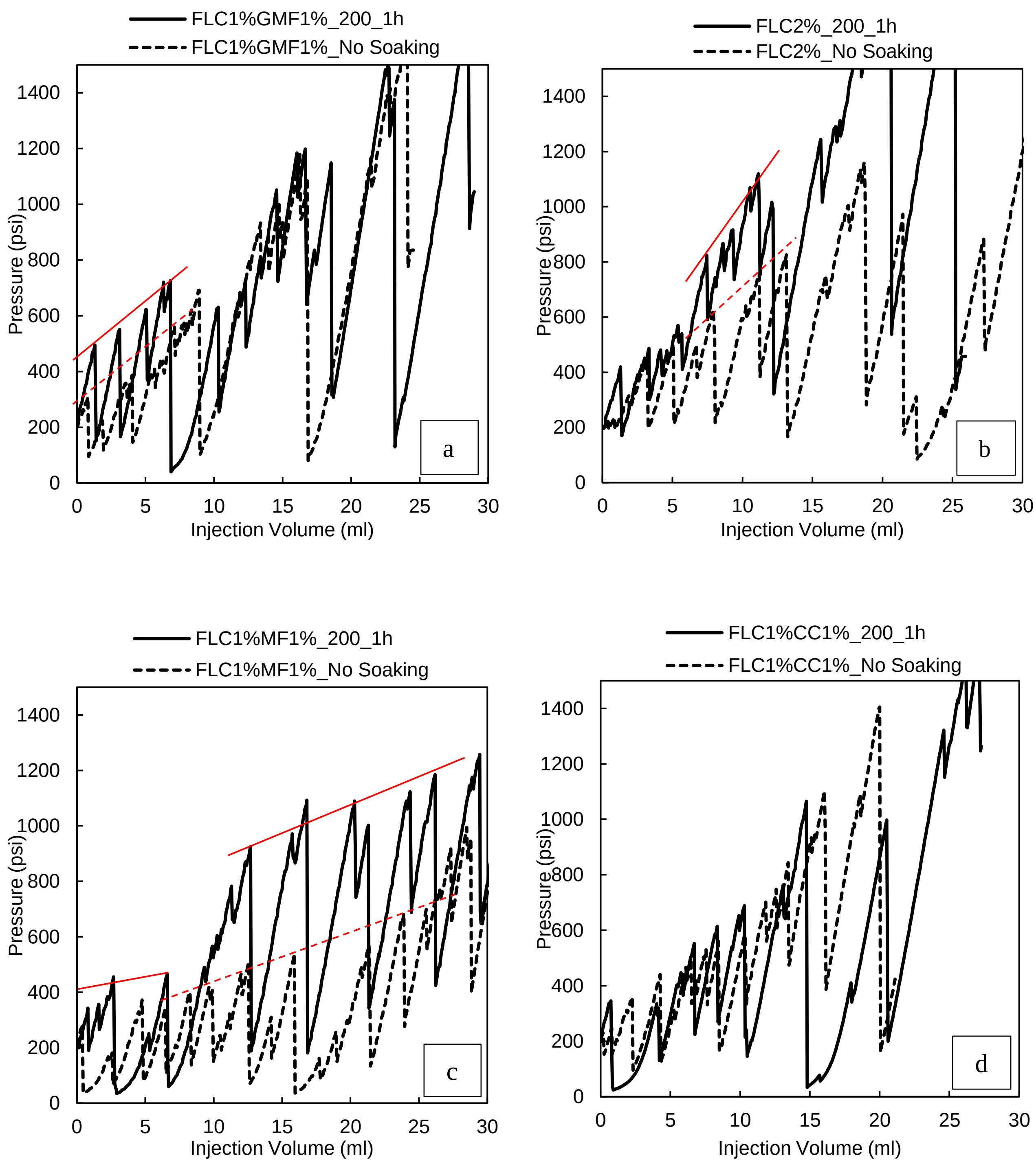

Figure 5.11. The effects of soaking process on different LCM combinations (with red solid and dash lines showing the differences in pressure trend between soaking and no soaking cases)

5.4 Visualization of the Plug Structure

Previous modeling studies indicated that the plug breaking pressure can be increased by increasing the plug zone length and reducing its permeability (Xu et al., 2017a; Xu et al., 2017b). Similar to the development of drilling fluid filtercakes, in which a longer filtration time can produce a thicker filtercake, a longer soaking time enabled further establishment of the plugs and increased the plug volume. For visualizing the effects of soaking on the plug internal structure, the techniques of Scanning Electron Microscope (SEM) and Micro Computed Tomography (MicroCT) were applied to characterize and image the plug soaked for 0.5 h and 6 h. The plugs were created using fluids formulated by water and 7 wt.% bentonite with 2 wt.% OKCG, through an adjustable slotted disc fixed at 0.04 in (1 mm). Each plug was carefully separated from the disc after being soaked for desired time.

JSM -6610 LV SEM was used to take the SEM images (as shown in Figure 5.12 a & b). To prepare the plugs before scanning, the plugs were sliced and dried on a hot plate, then coated with a conductive layer of metal on the sample surface. It should be noted that the status of the plugs can be different from their original status after the essential sample preparation processes. The drying process may enlarge the pore spaces and make them more obvious in the SEM image. Figure 5.12a shows the cross-section of the plug soaked for 0.5 h at 200 psi and Figure 5.12b shows it soaked for 6 h. The dark void spaces in the image show the pore spaces in the dried plugs. It is noticeable that the plug soaked for a shorter time had a less consolidated structure than it soaked for a longer time, as reflected by more and larger void spaces in Figure 5.12a than those in Figure 5.12b.

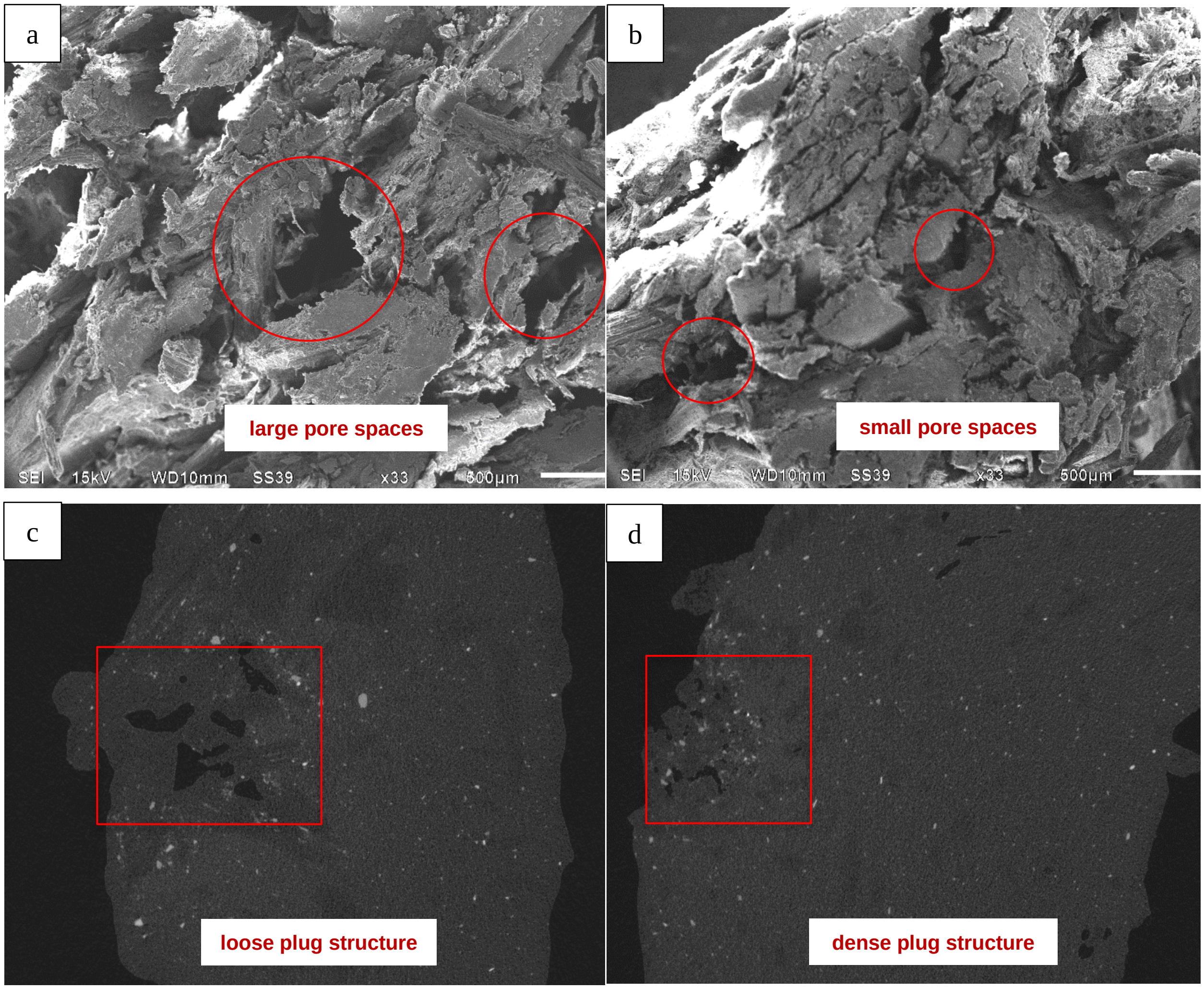

Figure 5.12. SEM and MicroCT image showing the effects of soaking time: (a) SEM image of the cross-section of the plug soaked for 0.5 h; (b) SEM image of the cross-section of the plug soaked for 6 h; (c) MicroCT image of the cross-section of the plug soaked for 0.5 h; (d) MicroCT image of the cross-section of the plug soaked for 6 h.

MicroCT is a non-damaging technique that enables the visualization of the sample cross-sections without physically slicing the sample. It has been an effective tool for analyzing fracture sealing structures (Yang et al., 2019). The MicroCT scans were done on a SCANCO Medical AG (Switzerland) MicroCT 40 system. The plug sample soaked for 0.5 h was scanned in a 15mm diameter tube and the one soaked for 6 h was scanned in a 20 mm diameter tube, with a voltage of 55 kVp, a current of 145 µA, and a voxel resolution of 8 µm. The images are shown in Figure 5.12 c & d. The differences in gray scales of each image reflect the differences in densities of materials.

The brighter parts indicate dense materials/mixtures, the darker parts indicate loose structures. For example, the bright dots can be the images of the sand particles in bentonite samples and the black background is the image of air. As it was indicated in the pictures, the plug soaked for 0.5 h were less dense than the plug soaked for 6 h, as a larger portion of the image of the former was darker than it of the latter. And there were more dark void spaces in the plug soak for less time.

As visualized by the images, a longer soaking time led to a more consolidated plug structure, such less porous structure contributed to increased plug breaking pressure.

5.5 Limitations

In this research, the effects of soaking on the fracture plug development and fluid invasion volume were investigated using a modified permeability plugging apparatus under room temperature. The current experimental method can be improved to better reflect actual operating conditions and processes. The design of LCM and its implementation strategies should take into consideration the field conditions such as formation temperature and fracture geometry. To further improve the experimental setup, a heating jacket should be incorporated to simulate the formation temperature. The stainless slotted disk should be replaced by fractured rock cores if available. The LCM-carrying fluid should be formulated by actual working fluid and the effects of fluid additives and the fluid properties in the processes of fracture plug development during soaking can be further investigated. Other LCM properties such as their concentration, particle size distribution and sphericity can affect the soaking process and should be further investigated. This research investigated the effects of one soaking stage, the effects of multiple soaking stages can be explored in the future. The plug structure visualizing techniques such as SEM and MicroCT scan have their advantages and limitations (Meng and Qiu, 2018), better imaging techniques and sample preparation methods should be considered to observe the plugs in their original status.

Despite the limitations, the current experimental setup and investigation results provide insights into the understanding of the LCM soaking process. The analyzing methods can be references for further experimental design and results interpretation.

5.6 Conclusions and Recommendations

Implementing LCMs to remediate fluid loss through naturally fractured reservoirs requires effectively plugging the fractures and minimizing the damage to fracture permeability. In this research, experimental investigations and statistical methods were applied to test and quantify the effects of fluid injection rate, plug soaking time and soaking pressure. Sensitivity analysis was conducted to analyze the impacts of major factors. SEM and MicroCT imaging techniques were used to visualize the effects of soaking time on plug development. Based on the experiments and statistical analysis, the following conclusions are made:

- In general, a lower LCM pill injection rate results in a less fluid invasion volume upon the establishment of an effective fracture plug.
- For fluids blended with fibrous LCMs, soaking the initial plug for a longer time can increase the corresponding plug strength and reduce the total fluid invasion volume.
- The effects of soaking depend on the property of the LCM combination. The soaking process increases the capability of the Granular-Fibrous and soluble fiber (MF) mixture in creating desired plugs.
- Similar to the development of filtercakes through filtration process, the volume of the plug can be increased through soaking process. As visualized by SEM and MicroCT techniques, the soaking process can strengthen the plug structure by reducing its porosity. A larger plug volume and lower plug porosity contributes to a higher plug breaking pressure.

- It is recommended to displace LCM-laden fluids at a lower rate and soak fibrous LCM blends for a longer time if conditions permit.

Chapter 6. Modeling of Fracture Plug Development During Filtration Process: Reduction of Plug Permeability

6.1 Introduction

6.1.1 Fracture Plugging Zone and Its Properties

As stated in previous chapters, lost circulation material plays important role in plugging fractures and preventing fractures from propagating. Although there are different explanations about wellbore strengthening mechanism, one important agreement is that stabilizing existing fractures is necessary to ensure WBS effects. After the fractures are plugged by the LCMs, the fracture and the fracture sealing structure can be considered as a system, as illustrated in Figure 6.1(Xu et al., 2017b). The stability of the fracture system depends on the plugging-zone strength and fracture propagation pressure. Lost circulation treatments become unsuccessful when the fracture plugging zone fails due to structural failure, and when the induced fracture propagates due to higher plugging-zone permeability than the critical permeability of the system.

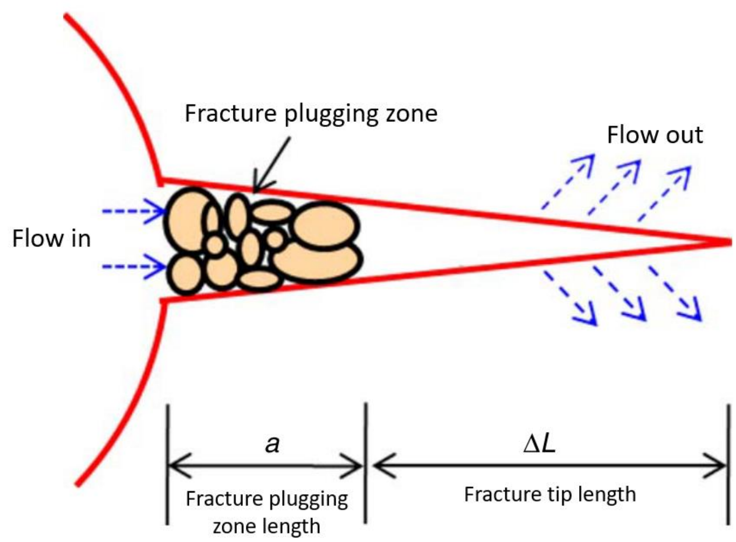

Figure 6.1. Illustration of the fracture system consists of an induced fracture and fracture plugging zone, modified after (Xu et al., 2017b)

The critical permeability of the system, K_c, as shown in the following equation, is a function of K_i(formation-matrix permeability), ΔL(fracture-tip length), a (fracture-plugging-zone length), σ_h (minimum horizontal principal stress), P_i (initial formation pressure), I_d (distance for fracture tip pressure to decay to formation pressure), W (width of fracture plugging zone or fracture) and P_w (wellbore pressure):

$$K_c = \frac{2K_i \Delta L a(\sigma_h - P_i)}{I_d W(P_w - \sigma_h)}$$

It was developed based on the principle of mass conservation between the inflow rate and the outflow rate within the fracture system(Xu et al., 2017b). When the plugging-zone permeability is lower than the critical permeability, and the fracture-tip pressure is lower than the formation minimum horizontal principal stress, the pressure can not significantly transmit from the wellbore to the fracture tip through the plug, and the fracture can not propagate before plugging-zone failure. In this case, plugging-zone-strength failure is the only reason for fracture system instability. When the plugging-zone permeability is higher than the critical permeability, the pressure at the fracture tip can increase and cause fracture propagation without plugging-zone failure. The fracture-system instability can be caused by both plugging-zone failure and fracture propagation. In brief, a low plug permeability is critical for a stable fracture system. When the plug permeability is lower than the critical permeability, the maximum pressure that a fracture system can hold is determined by the plugging-zone strength; When the plug permeability is higher than the critical permeability, the pressure that causes fracture system instability is determined by both plugging-zone strength and the fracture propagation pressure.

In actual WBS and lost circulation treatments, fracture propagation pressure is primarily determined by the geomechanical properties of the formation. Changing formation properties and further increasing fracture propagation pressure seems not practical. It is easier for the operators to decrease the plugging-zone permeability until it is lower than the critical permeability of the system, and then increase the plugging-zone strength.

Despite the importance of plugging-zone permeability, it seems that there are limited researches and methods about plugging-zone permeability characterization. In this chapter, a model for evaluating the permeability of an LCM plug is introduced.

6.1.2 Models for Filtration Process and Permeability Calculation

As discussed in the previous chapter, the soaking/filtration process can contribute to the reduction of plug permeability. Developing models to describe filtercake permeability with filtration process has been a research focus for many years. Bourgoyne (1986) provided the classic filtration model for static API filtration test based on Darcy's law and assumed a constant mud cake permeability. Meeten and Sherwood (1994,1997) pointed out that the permeability of a filtercake is difficult to measure directly due to a large porosity range and small magnitude of porosity and permeate flux. They reported methods to determine filtercake permeability based on cake void ratio and desorptivity. The methods may require a step increase in the filtration pressure. Elkatatny et al.(2011, 2012, 2013) used CT scan and SEM scan to characterize filtercake thickness and permeability after HPHT filtration. Vipulanandan et al.(2014, 2020) proposed to fit filtration test data using a Kinetic Hyperbolic Model instead of the classic linear API model, to characterize filtercake permeability change. Besides these studies that focus on the filtration process and the characterization of filtercake properties, other researches seek to estimate the permeability of packed particles based on information such as the porosity of the packed particles and the particle median diameter (Carman, 1997)(Huang et al., 2019). These studies can provide inspiring information on permeability calculation of the medium with known geometry, however, they may have limited capability to track the permeability change during filtration.

Previous studies on the filtration of drilling fluids have provided models that capture how filtercake properties change as filtration progresses (Chenevert and Dewan, 2001)(Jaffal et al., 2017) (Jaffal et al., 2018). In general, these models split the system into two parts: (1) the filtration medium with known permeability and geometry, such as the ceramic discs; and (2) the filtercake developed onto the filtration medium. For each part, Darcy's law was applied to correlate the change of permeability and filtration rate. Mass balance and filtercake compressibility were considered to calculate the filtercake thickness. Filtercake is a layer of heterogeneous consolidated combination of solids and liquids, its permeability varies from the layer near the filtration medium to the layer exposed to the fluid. The calculated filtercake permeability is actually the average or apparent permeability.

6.2 A Model for Calculating LCM Plug Permeability Change with Filtration Process

Based on these models, we aim at developing a model that captures the length growth and permeability change of a fracture plug during the filtration process. An initial plug that can hold a relatively low differential pressure was created first and then the initial plug was soaked under constant pressure for a certain time. The average plug permeability can be calculated using Darcy's law. The plug length can be calculated stepwise based on the filtration rate, solid volumetric content of the fluid, plug porosity and plug compressibility. The physical process is illustrated in Figure 6.2. The model simulates a physical process that the LCM-laden fluid filtrates through the plug and leaves a layer of solids to add up the plug length.

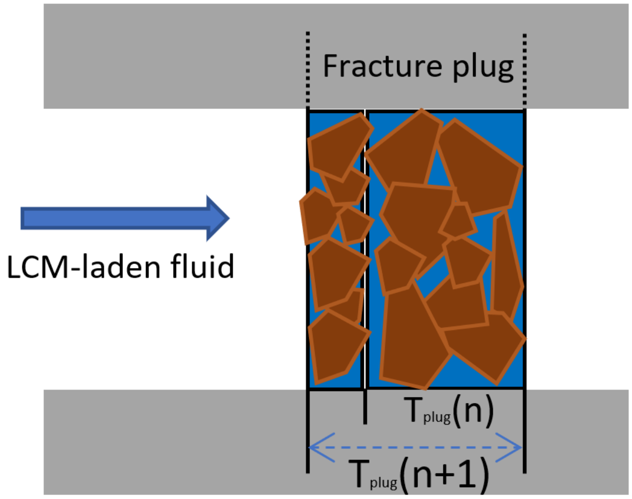

Figure 6.2. Illustration of fracture plug development during filtration process.

The main equations of the filtration models are:

$$k_{plug}(t) = 14700 \cdot \frac{q(t) \cdot T_{plug}(t) \cdot \mu}{P} \text{ [md]} \tag{1}$$

$$T_{plug}(n+1) = T_{plug}(n) + \frac{q(n) \cdot s \cdot \Delta t}{1 - s - \frac{\emptyset_{mc0}}{P^{\delta\nu}}} \text{ [cm]} \tag{2}$$

Where, $k_{plug}(t)$ is the average permeability of the plug at time t; $q(t)$ is the volumetric filtration flux at the filtration outlet; $T_{plug}(t)$ is the plug length at time t; P is the differential pressure across the plug; μ is the viscosity of the filtrate; n is the time step; s is the volumetric solids content of the fluid; Δt is the interval between each time step; $\emptyset_{mc0}$ is the reference porosity of the plug; ν is the compressibility exponent of the plug; δ is a multiplier for compressibility exponent. Detailed model inputs are described as follows:

- $q(t)$, $[cm^3/(cm^2 \cdot s)]$, is the flux or discharge per unit area. It is calculated by dividing the volumetric filtration rate, Q $[cm^3/s]$, by the cross-sectional area of the plug, $A[cm^2]$.

Q can be estimated using the injection flow rate recorded at the constant pressure mode of the pump. A can be estimated using the width of the straight slot in which the plug forms.

- $T_{plug}(t), T_{plug}(n)$, [cm], is the length or thickness of the plug at time t, and at time step n, respectively. $T_{plug}(0)$ is the length of the initial plug. It can be measured after creating the initial plug.
- P, [psi], is the differential pressure across the plug during the filtration process.
- μ, [cp], is the viscosity of the filtrate. It can be measured using a viscometer.
- s, is the volumetric solids content. It can be estimated using the following equation:

$$s = \frac{\sum_{i=1}^{k} \frac{W_s(i)}{SG_s(i)}}{W_{water} + \sum_{i=1}^{k} \frac{W_s(i)}{SG_s(i)}} \tag{3}$$

Where W_s and W_{water} is the weight of solid and water contents for preparing the fluids, SG_s is the specific gravity of the solid. k represents the total number of solid kinds.

- Δt, [sec], is the time interval between each time step n.
- $\emptyset_{mc0}$ is the plug porosity after removing the plug from the filter cell. It can be estimated using the following equations:

$$\emptyset_{mc0} = \frac{V_l}{V_l + V_s} = \frac{\frac{M_l}{\rho_l}}{\frac{M_l}{\rho_l} + \frac{M_s}{\rho_s}} = \frac{M_l}{M_l + M_s \frac{\rho_l}{\rho_s}} = \frac{\frac{M_l}{M_s}}{\frac{M_l}{M_s} + \frac{\rho_l}{\rho_s}} = \frac{\alpha}{\alpha + \frac{\rho_l}{\rho_s}} \tag{4}$$

$$\alpha = \frac{M_l}{M_s} = \frac{plug\ net\ wet\ weight}{plug\ net\ dry\ weight} - 1 \tag{5}$$

where V denotes volume, M denotes mass, ρ denotes density, subscript l denotes liquid, subscript s denotes solid. The LCM plug is removed from the filter cell immediately after each test and weighted to get the weight of the wet plug. The wet plug is then heated dry, and the plug net dry weight is considered as the total weight of the solids. It is assumed that the volume of the liquids equals the volume of the pore spaces in the plug. The weight of the liquids equals the weight difference between the wet and dry plug.

- ν is the compressibility exponent or “pressure-up” index of the plug. It is a fitted value and it is defined and described in previous publications (Chenevert and Dewan, 2001)(Jaffal et al., 2017). In this research, ν is determined by fitting the calculated final plug length, $T_{plug}(t = end\ of\ filtration)$, to the experimentally measured value after filtration, as introduced in (Jaffal et al., 2017).
- δ is the multiplier for compressibility exponent. Changing δ does not affect actual mud cake properties (Jaffal et al., 2017). In this research, ν and δ come together as an exponent of P, changing δ will only affect the fitted value of ν. The value of δ was set as 0.1 for all the cases. Keeping both ν and δ as parameters in the model is to be consistent with the original model equations.

6.3 Laboratory Experimental Methods

In this chapter, the experiments were aimed at investigating the changes of plug permeability with the filtration process. The experimental facilities were similar to those shown before. A 1-in-thick stainless-steel disc with a 0.2 in (5 mm) slot was used to simulate the fracture, as shown in Figure 6.3. The LCM-laden fluid was injected through the slot to build an initial plug that can withstand a targeted differential pressure, then the pump was set to constant pressure mode to soak the initial plug. The injecting flow rate during filtration was recorded for the calculation of plug permeability.

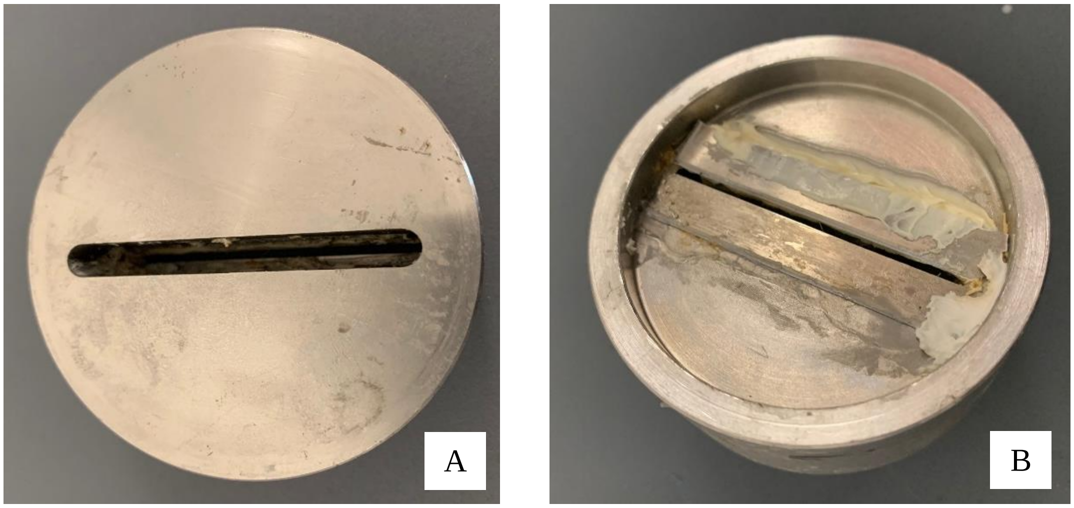

Figure 6.3. The 1-in-thick stainless-steel slotted disc for simulating the fracture: (A) The inlet of the slot; (B) The outlet of the slot with restriction.

Ideally, an extended and transparent fracture should be used to better simulate and observe the constructing process of the LCM plug inside a fracture. In this research, the aperture of the slot outlet was restricted to approximately 0.06 in (1.5 mm) to capture the LCMs, the 1-in-long and 0.2-in-wide slot provided a space with known geometry that constrained the development of the plug. Although the restriction at the outlet can induce a fluid pressure drop during filtration, it is reasonable to neglect this pressure drop since the filtration flow rate was quite small. A typical flow flux in the filtration/soaking experiments was approximately 0.0005 cm/s, and the corresponding local pressure drop was approximately 0.04 psi as estimated by Bernoulli's equation. A plug with a known geometry can simplify the permeability calculation process. In this case, the cross-sectional area of the plug equals the area of the slot inlet aperture.

Similar to previous chapters, the fluids were prepared by mixing bentonite–water fluids with different LCMs. The fluid contents and other testing conditions are listed in Table 6.1. For a more straightforward denoting, OKCG is denoted by CoarseF since it contains relatively coarser fibrous materials; GMF is denoted by FineF since it contains relatively finer fibrous materials. The materials are shown in Figure 6.4. Test 1 and 2 aim at comparing the performance of coarse and fine fibers in creating fluid-isolating plugs; Test 1 and 3 aim at checking the effects of fine particles like bentonite clay in building the plugs; Test 2 and 4 aim at testing the effects of higher differential pressure.

Table 6.1. Fluid contents and filtration pressure for each test to evaluate plug permeability

Test #	Fluids	Filtration Pressure (psi)
1	7.0% ben + 2% CoarseF	60
2	7.0% ben + 1% CoarseF + 1% FineF	60
3	6.5% ben + 2% CoarseF	60
4	7.0% ben + 1% CoarseF + 1% FineF	100

Figure 6.4. Coase and fine LCMs for plug soaking tests and model calculation: (A) OKCG, denoted by CoarseF; (B) GMF, denoted by FineF.

For each test, the fluid was prepared and then placed into the PPA fluid chamber. Then the fluid was injected at 10ml/min through the slotted disc, the LCMs accumulated at the slot outlet restriction and formed the initial plug. The injection was stopped when the differential pressure across the initial plug reached the desired value, for example 60 psi or 100 psi. The test apparatus was then disassembled for measuring the initial plug length. The average initial plug length was estimated by subtracting the length in the slot that was not occupied by the initial plug from the total depth of the slot. The test was then resumed by setting the pump at constant pressure mode to soak the initial plug. The injection rate during the filtration process was recorded every second by the pump. Note that ideally the filtration rate should be measured at the outlet of the filtration medium. In this study, the injection flow rate was used as an estimation of the filtration rate. After soaking the initial plug for a desired time, which was 30 min in this study, the test was stopped and the final plug length was measured. The plug was taken out from the slot and weighted immediately to get its wet weight after filtration. Then it was dried on a hot plate to get its dry weight. Another initial plug was created and measured under the same conditions to get the wet and dry weight of the plug before filtration.

6.4 Results and Discussions

6.4.1 Plug Porosity

The plug porosity can be estimated using equations 4 and 5 after getting the wet and dry weight of the plug. The plug porosity before and after filtration was summarized in Figure 6.5. In general, the plug porosity reduced with filtration, as expected. At a higher filtration pressure of 100 psi, the porosity reduction was not as obvious as it when the filtration pressure was 60 psi. A possible reason is that the plug is further compressed under higher pressure, the higher differential pressure contributes to the reduction of porosity. It also seems that the finer the LCM was, the smaller the porosity was, as indicated by test 1 and test 2; and more clay content also led to smaller porosity, as indicated by test 1 and test 3.

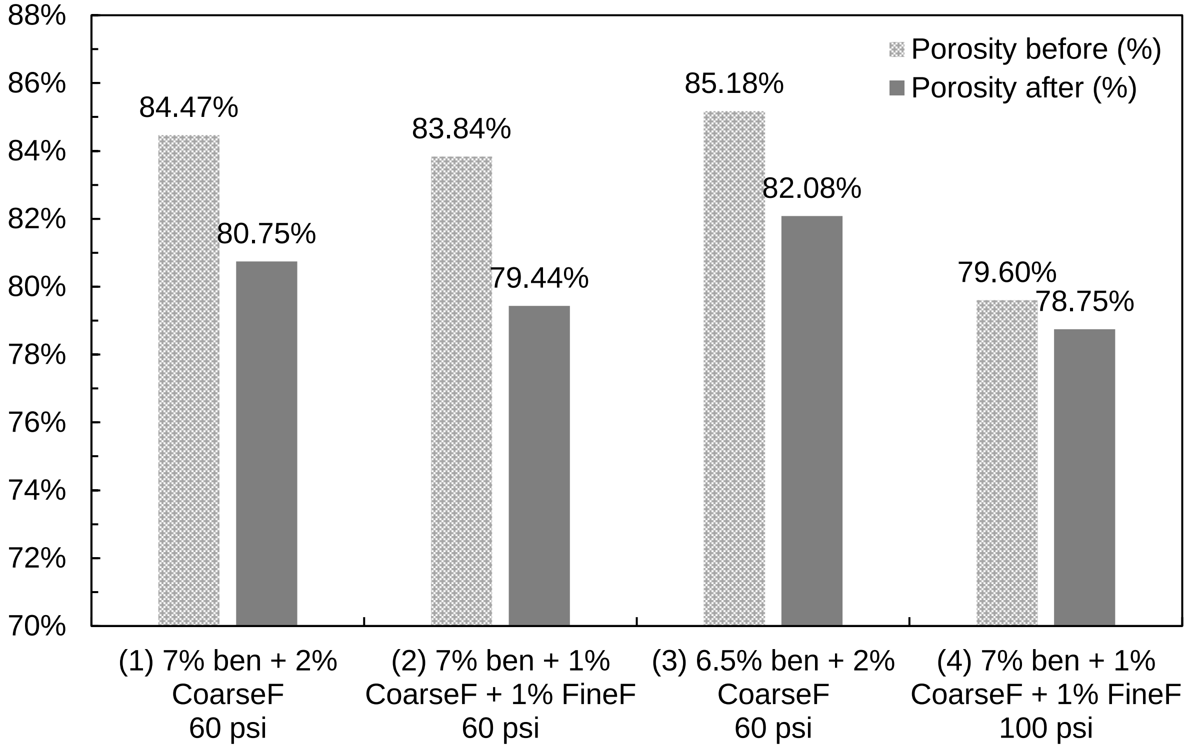

Figure 6.5. Estimated plug porosity before and after filtration

6.4.2 Plug length

The length of the initial and the final plug was measured, and the plug length growing during the filtration process can be calculated using the model. During filtration, the LCM-laden fluid filtrates through the plug, leaving solid materials to add up the plug length. The results are shown in Figure 6.6.

In general, when holding the same differential pressure, coarse LCMs created thicker plugs, as indicated by test 1 and test 2. This is because the coarse LCMs have relatively larger particle sizes than the fine LCMs (as shown in Figure 6.4), these larger particles can augment the corresponding plug length. Also for plugs with the same length, the one created by the coarse materials have higher porosity and higher permeability than it formed by fine materials. To prevent fluid from flowing at the same differential pressure, it requires more coarse LCMs piling up to create the plug. And as indicated by test 1 and test 3, clay particles were critical in creating low-permeable plugs. An effective plug should be formed by a combination of large LCM particles and fine clay particles. The large LCM particles can provide the skeleton of the plug structure, it requires fine particles to fill the voids to create tight plugs. If the fine clay particles were not adequate, as in test 3, the fluid system will lack the capability to form a tight plug, the fluid kept flowing through and the large LCMs kept accumulating, eventually a much thicker plug was created to hold the desired pressure. Lastly, as indicated by test 2 and test 4, a thicker plug was needed to hold a larger differential pressure, as expected.

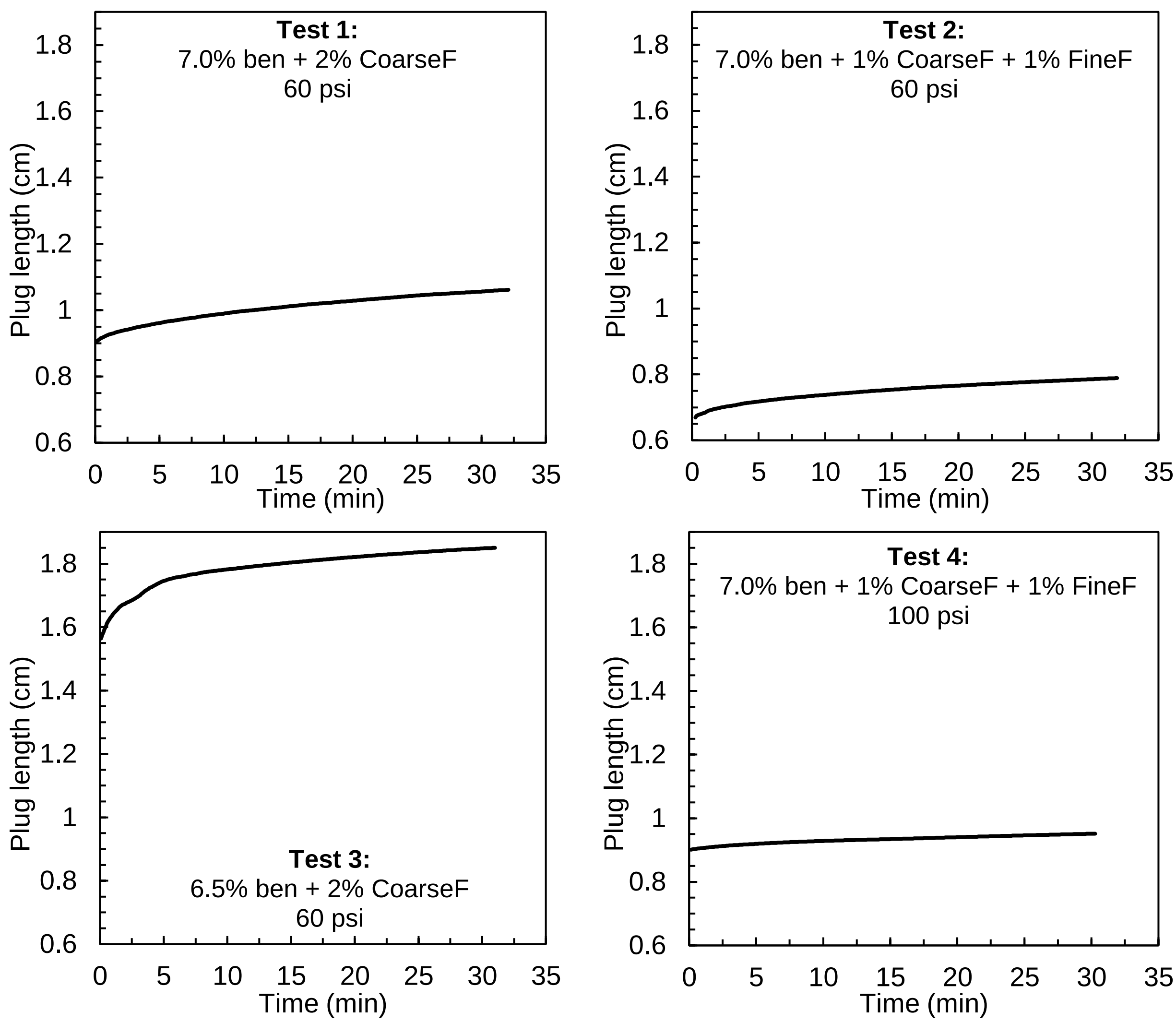

Figure 6.6. The change of plug length during filtration process for each test

6.4.3 Plug Permeability

The permeability change of the plugs with filtration process was calculated using the model developed in this chapter, the input parameters and values are listed in Table 6.2, the results are plotted in Figure 6.7 to Figure 6.9. The fluid injection rate to maintain the filtration pressure was recorded every second, the calculated permeability was averaged every 30 seconds for a clearer plot presentation and to reduce abnormal data due to pump sensor measurement error.

In general, the permeability of the plug declined quickly in the first 5 mins, and tended to be "stabilized " after 10 min. In the first few minutes, although the plugs were able to withstand the desired differential pressure, the structures of the plugs could still be loose and spongy, which led to a relatively high rate of filtration. As the LCM-laden fluids filtrated through the plugs, more solids were deposited to consolidate the plugs, reducing the plug permeability. After 10 min, the plug permeability still declined with filtration but the change was not as noticeable as it was in the early minutes. The more consolidated plug with lower permeability slowed the filtration rate and the solid deposition rate so the permeability reduction was less noticeable.

Table 6.2. Input parameters for the plug permeability calculation model

Test #		1	2	3	4
Parameters	Unit	Values			
A	cm^2	2.5	2.5	2.5	2.5
P	psi	60	60	60	100
μ	cp	1.0	1.0	1.1	1.0
s		6.15%	6.15%	5.91%	6.15%
∅_mc0		80.75%	79.44%	82.08%	78.75%
T_plug (t=0)	cm	0.897	0.660	1.544	0.900
T_plug (t=30 min)	cm	1.060	0.790	1.824	0.950
δ		0.1	0.1	0.1	0.1
v		0.25	0.28	0.25	0.5
∆t	sec	5	5	5	5

Figure 6.7 shows the calculated permeability difference due to the difference in LCM particle size. The plug formed by finer LCMs was less permeable than it formed by coarse materials. The coarse LCM formed the plug skeleton and it was the fine LCMs that helped fill the void spaces among the skeleton and contributed to the reduction of plug permeability.

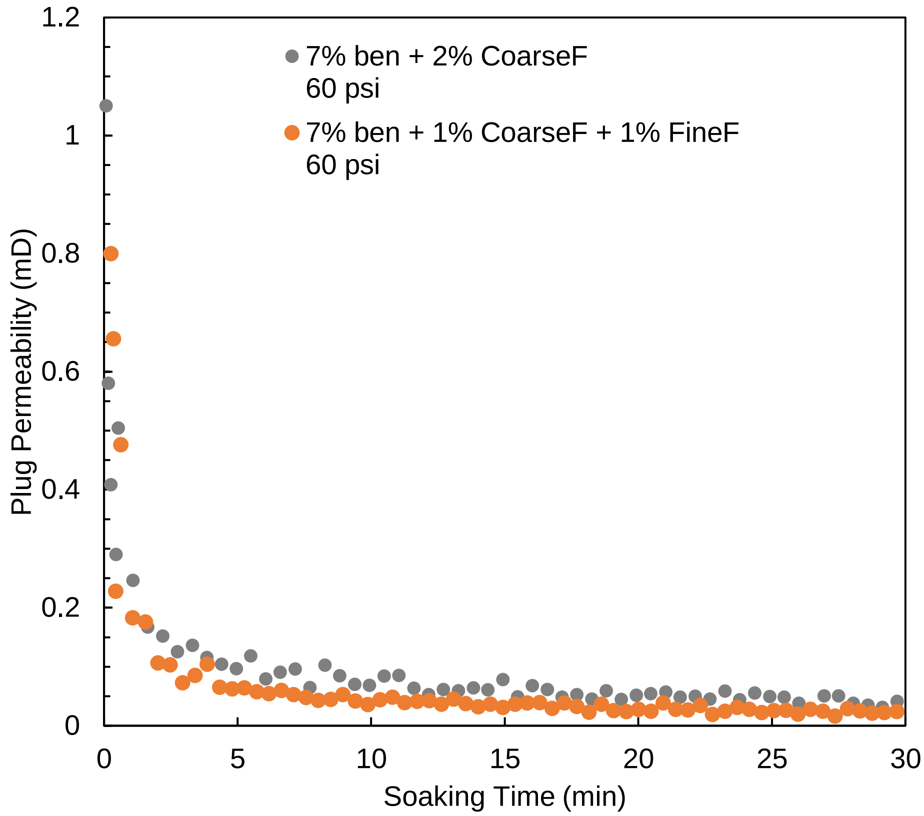

Figure 6.7. Calculated plug permeability of test 1 and test 2: the effects of fine LCMs

Figure 6.8 shows the calculated permeability difference due to the difference in bentonite content. Bentonite is a fine-particle clay that can inhibit the invasion of drilling fluid by its ability to assist in mud cake formation. It is shown in the figure that with less bentonite in the fluid, the permeability of the initial plug was much higher. The fluid flowed fast through the loose initial plug, leaving more solids onto the plug. And in the plotted case, the permeability "jumped" at around 4 min since the initial plug was loose and weak, there was a partial plug breaking that caused fluid penetration. During filtration, the loose initial plug became tighter when more LCM and clay particles were deposited. When the plugs were consolidated with adequate solids, the permeability of the two cases was similar. The fine clay particles played important role in creating tight initial plugs.

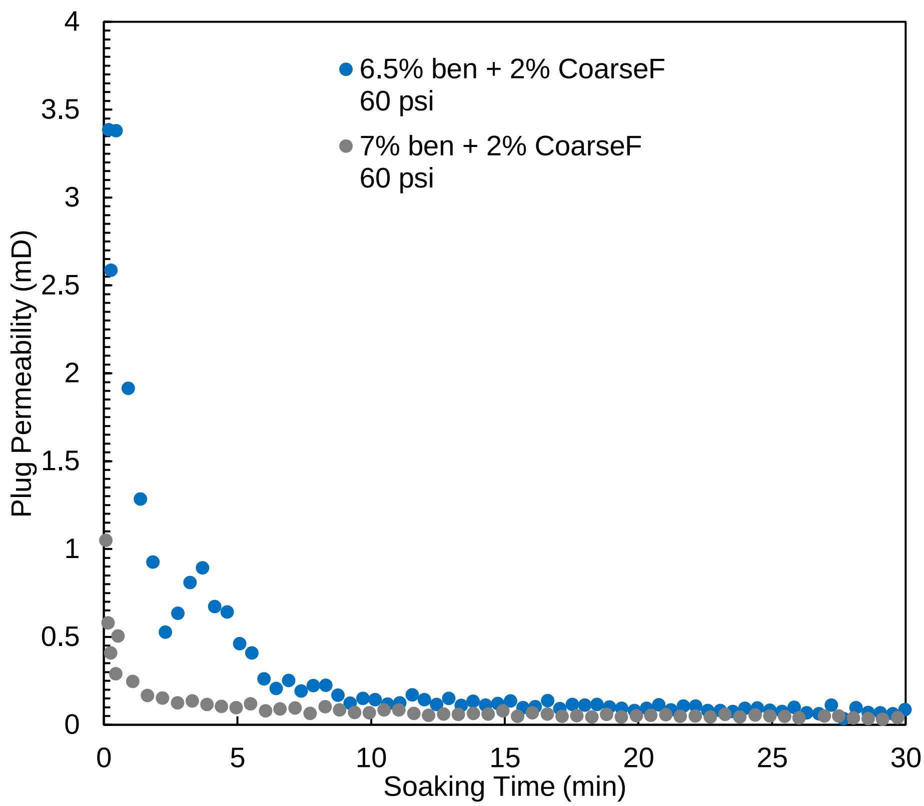

Figure 6.8. Calculated plug permeability of test 1 and test 3: the effects of fine clay particles

Figure 6.9 shows the calculated permeability difference due to the difference in filtration pressure. For a higher pressure of 100 psi, the change of plug permeability was mild; and for a lower pressure of 60 psi, the decline of plug permeability was relatively drastic. This is because a thicker and more compact plug was needed to hold a higher differential pressure. The initial plug that holds 100 psi was already quite impermeable compared to the initial plug that holds 60 psi.

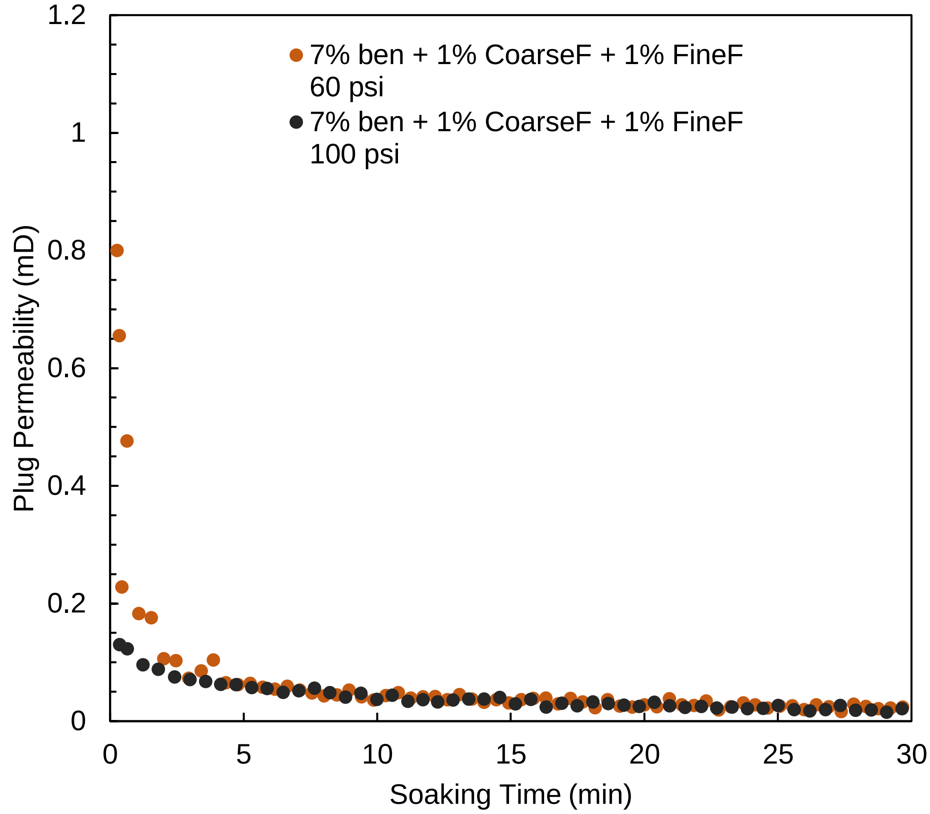

Figure 6.9. Calculated plug permeability of test 2 and test 4: the effects of filtration pressure

6.5 Summary and Conclusions

A model to calculate plug permeability change with filtration time was developed to provide a solution for evaluating the performance of LCMs in creating low-permeability fracture plugs and the effects of filtration. This model is developed based on Darcy's law, and uses information of LCM-laden fluid content, property and filtration rate, to calculate the fracture plug length and permeability. This model enables quantification of fracture plug permeability, which provides key parameter inputs for wellbore strengthening and lost circulation prevention models, and provides references for LCM-laden fluid design for fracture plugging. Experimental tests with model calculations were conducted to evaluate the effects of LCM particle sizes, clay contents and filtration pressure on plug length, porosity and permeability. The experimental tests and model calculation results indicated that:

- In general, the permeability of the initial plug can be relatively high, and it declined relatively fast at the beginning of filtration. Then the permeability change was mild after adequate solids were deposited. The model can help determine the optimal filtration time.
- The coarse fiber LCM provided the plug skeleton, and when there was a higher percentage of fine LCM fibers, the plug was thinner, less porous and less permeable.
- The clay particles were important for creating a low-permeability plug. When the bentonite content is 6.5wt.%, the permeability of the initial plug can be 6 times higher than that when the bentonite content is 7.0wt.%.
- Higher differential pressure can compact the initial plug, thus the permeability declined mildly at the beginning of filtration.

Chapter 7. Summary and Future Works

In this research, we aimed at discussing the effects of filtercakes and fracture plugs in lost circulation prevention and remediation. We experimentally simulated the filtercake rupture process over fine fractures, and investigated the effects of filtercakes on sealing fractures. A simple and efficient test method was proposed together with a new parameter – filtercake rupture resistance, to investigate and characterize the capability of filtercake to maintain its integrity over fractures. It was disclosed that filtercakes can provide pressure isolation and promote the fracture sealing process. After emphasizing the role of filtercake in WBS, the performance of LCMs in sealing fractures was evaluated while considering the effects of filtercakes. LCM type, concentration, PSD affected the LCMs' capability of creating filtercakes and forming a stable fracture seal. Besides investigating the filtercakes over fractures, sealing structures inside fractures were also studied. LCM implementation schemes were optimized for effectively creating fracture plugs and reducing formation damage risk in fractured pay zones. Experimental investigations and statistical methods were applied to test and quantify the effects of fluid injection rate, plug soaking time and soaking pressure on the development of fracture plugs. A mechanistic model to calculate plug permeability and length with filtration was developed. Experimental tests with model calculations were conducted to evaluate the effects of LCM particle sizes, clay contents and filtration pressure on plug length, porosity and permeability.

The main conclusions of this research include:

- Filtercakes can withstand higher pressure over the slots when the slots were narrower. Filtercake rupture was defined as when the filtercake lost its integrity over open slots. Filtercake rupture resistance represents the capacity of filtercakes to provide pressure and fluid barrier. The capacity of filtercakes with a very low concentration of solid particles to maintain their integrity depended on their capacity to resist deformation. Solid particles in the filtercakes played an important role to create slot seals and sustain high differential pressure, filtercakes with a considerable amount of solid particles can create stable slot seals.

- Different types of LCM exhibit significantly varied slot sealing capability. The high resilient granular-fibrous LCM performs the best by providing a tough filtercake and the most reliable seal. A higher concentration of LCM contained in the fluid and retained in the filtercake contributed to establishing a stable slot seal. Fine LCM particles can promote the quality of the filtercake and thus facilitate the slot seal creation. The effects of filtercake should be considered when evaluating the LCMs for fluid loss preventive treatments.
- LCM-laden fluid should be displaced at a lower rate if conditions permit. Soaking/hesitation process can enhance the strength of the LCM plug by increasing its volume and reducing its porosity. The effects of soaking depended on LCM types and were more significant on high-fluid-loss LCM systems. Statistical methods can help design LCM deploying schemes.
- As implied by the model calculation results, the permeability of the initial plug can be relatively high and it declined fast at the beginning of soaking/filtration. A higher filtration pressure can compact the initial plug so it can be less permeable, and the reduction of permeability under higher filtration pressure was relatively mild. The coarse LCM provided plug skeleton, the fine LCM and clay particles contributed to reducing the plug porosity and permeability.

Based on the research methodology, results and discussions, the following recommendations can be made for future works:

- The current experimental methods can be improved to better reflect actual physics and processes. The interactions between filtercakes, fluids, formation matrix and fractures should be considered and studied comprehensively under actual temperature and pressure conditions.
- The effects of other filtercake properties such as permeability, tensile strength and the bonding with formation rock in the processes of filtercake rupture and fracture sealing should be considered.
- Simple bentonite-water fluids were used in this study for simplification. For more practical results, the fluids should be formulated according to actual situations.
- Drilling fluid properties may affect the particle transportation and accumulation process, thus affect the creating of filtercakes and LCM plugs. Primary drilling fluid properties that make LCM more efficient in creating filtercakes and promoting fracture sealing should be investigated.
- Other LCM properties such as shape and resilience can be further explored to understand their effects in creating filtercakes and facilitate fracture sealing.
- To better study LCM transportation, LCM plugging and LCM plug soaking processes, long and permeable plates with rough surfaces can be used to simulate fractures. The effects of multiple soaking stages can be future explored.
- The mechanistic model was developed based on geometry with a defined dimension. The model can be improved for characterizing the permeability of irregular-shaped structures.

Appendix A. Supplemental Data for Filtercake Rupture Tests

This appendix provides experimental methods and results of the exploratory tests using ceramic discs, intending to explore filtercake rupture behavior over narrower slots than those made in stainless steel discs. Using porous ceramic filtration media is one step closer to actual situations.

A.1 Experimental Setup and Procedure (Porous Ceramic Slotted Disc)

The ceramic discs used for the exploratory tests are shown in Figure A.1a. The average pore throat diameter of the porous ceramic disc is 20 microns, and each disc is 1.25 in thick with a diameter of 2.5 in. The ceramic discs were cut in halves by a waterjet cutting machine and then stick back together to create slots along the diameter. A thickness gauge (shown in Figure A.1b) consists of stainless-steel sheets with different thicknesses was used to assist in creating a slot with the desired width or determine the slot width range. The process to create filtercakes was similar to previous sections. The injection rate during the filtercake rupture test was 5 ml/min. Preliminary tests indicated that the injection rate in this range does not greatly affect the filtercake rupture process. The fluid for investigating LCM-free filtercake is 7wt.% bentonite. 1wt.% fine LCM particles with a diameter less than 0.003 in (76.2 um) were added to the fluid to check the effects of fine particles in the filtercake rupture and fracture sealing process. A major issue for these exploratory tests was to control the slot properties when making a new slotted disc, especially when the target slot width was less than 0.003 in (76.2 um), the glue between the two half-discs can take some space, and the thickness gauge is thin and very flexible. It was not easy to make two discs with identical slots.

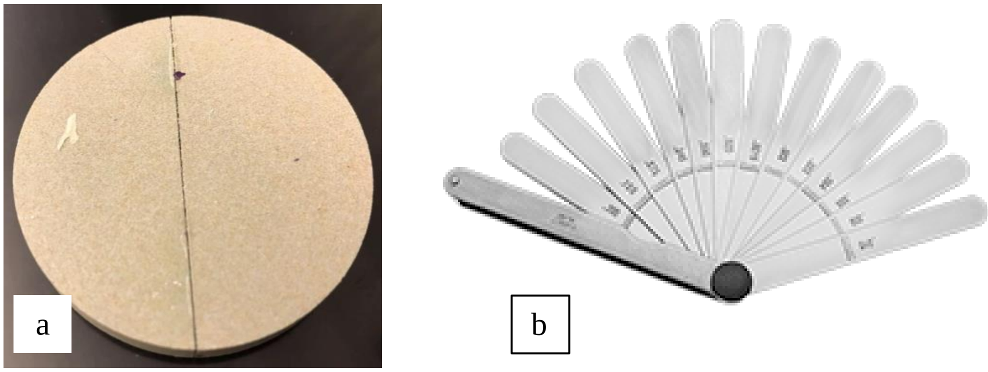

Figure A.1. (a): Sample slotted ceramic disc; (b):Feeler thickness gauge set (inch thickness 0.0015, 0.002, 0.003, 0.004, 0.006, 0.008, 0.01, 0.02, 0.03, 0.04, 0.075, 0.1, 0.2)

A.2 Experiment Results Using Ceramic Discs and Discussion

These experiments provide supplemental data to the results presented in Chapter 3, showing filtercake rupture behavior over narrower slots.

A.2.1 The Effect of Slot Opening Size on LCM-Free Filtercake Rupture Resistance

Two straight slots with an opening size of 0.003 in (76.2 um) and 0.006 in (152.4 um) were made to simulate the tiny fractures. Fluid filtration was conducted for 1.5 hrs to create the filtercakes, the corresponding filtercake thickness was around 0.075 in (1.905 mm). As it is shown in Figure A.2, for a tinier fracture size, the 0.076 in filtercake ruptured at around 120 psi, and for a relatively wider fracture, the filtercake with a similar thickness ruptured at around 50 psi, indicating that the filtercake had a much better capability to resist rupture over small fractures. Again the pressure spikes indicated sealing structure breaking and reestablishment. The filtercake reconstruction process can be better observed over a porous medium, as reflected by the more frequent pressure fluctuation in the pressure curve. The fluid sample was not 100% pure bentonite and water, there were a few relatively larger particles such as sands incorporated. These larger particles can help build slot bridging/plugging structures that withstand higher pressure. The filtercake reconstruction process can be a combined process of fluid filtration, filtercake deposition, particle bridging/plugging, filtercake rupture and bridge breaking. Similar to filtercake rupture pressure, the maximum differential pressure during the overall testing process was also greatly affected by the slot width. For the 0.003 in slot, the maximum pressure was around 300 psi; and for a wider slot of 0.006 in, the maximum pressure could just reach around 100 psi.

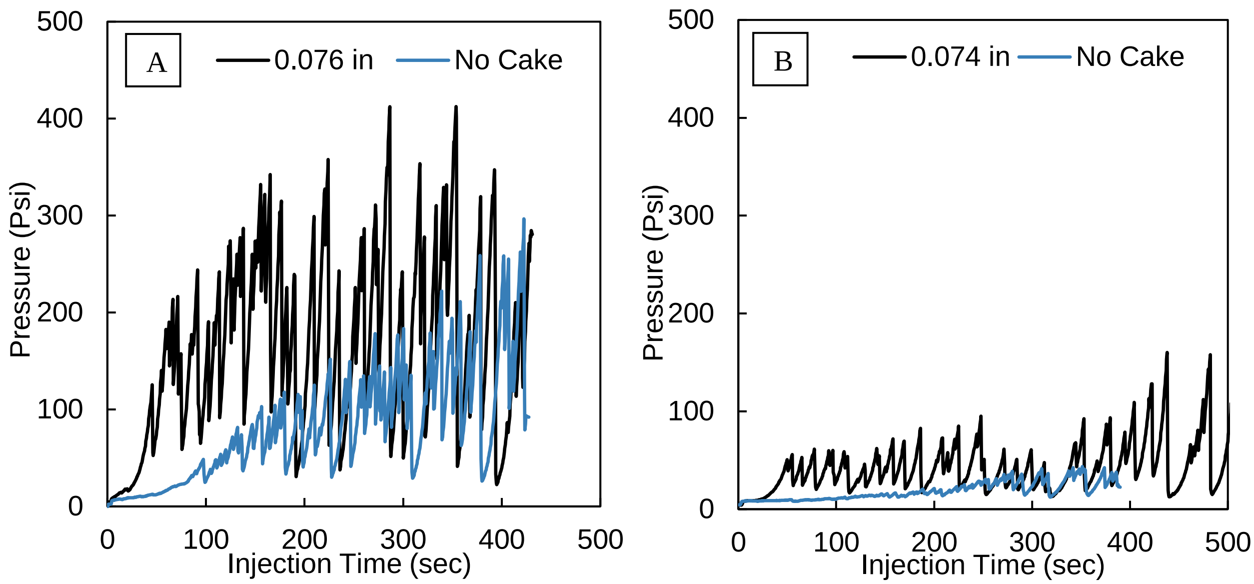

Figure A.2. Filtercake rupture pressure behavior over porous medium with: (a) a 0.003in straight slot; (b) a 0.006in straight slot

In short, even when the fluid and filtercake are almost free of LCM particles, the filtercake will play a role in isolating pressure and fluid over small fractures. The tinier the opening size is, the higher pressure the filtercake can withstand. More intensive sealing structure reconstruction processes were observed when using the porous ceramic disc.

A.2.2 The Effect of Filtercake Thickness on LCM-Free Filtercake Rupture Resistance

In this section, a tapered slot was made to simulate a fracture with tapered shape, and such slot geometry is a better simulation of drilling-induced fracture. The opening size of the slot entrance is 0.005 in (127 um) and the tip is 0.0015 in (38.1 um), crossing a disc with a thickness of 1.25 in. The tiny end of the slots enabled the creation of an initial plug during fluid injection. The initial plug was created by fluid filtration and bridging/plugging of the fine sand particles. The initial plug can be considered as a filtercake with a higher solid particle concentration compared to the filtercake formed on the disc surface.

In this section, the filtercake was created in a way similar to soaking/hesitation. The fluid was injected directly through the tapered slot, the creation of the initial plug enabled the pressure build-up. When the pressure reached the desired value (200 psi and 300 psi in this section), the injection pump was set to constant pressure mode to hold the pressure for a certain period (4 hrs), to enable further fluid filtration and filtercake deposition. Then the pump was set to constant flow mode to inject the fluid again, the pressure behavior during this fluid injection stage was recorded.

As it is shown in Figure A.3, directly injecting the fluid through the tapered slot without pre-deposited filtercake, the pressure could reach around 400 psi, indicating that the tiny fracture tip enabled the establishment of the initial plug. The pressure was held at 300 psi and 200 psi for 4 hrs, the corresponding filtercake thickness was 0.161 in and 0.150 in, and the filtercake rupture pressure was around 700 psi and 530 psi, respectively. The difference between the rupture pressure and the filtercake deposition pressure was above 300 psi for both cases. These results indicated that a pre-deposited filtercake can effectively increase the pressure at which the fluid drastically invades into the fracture.

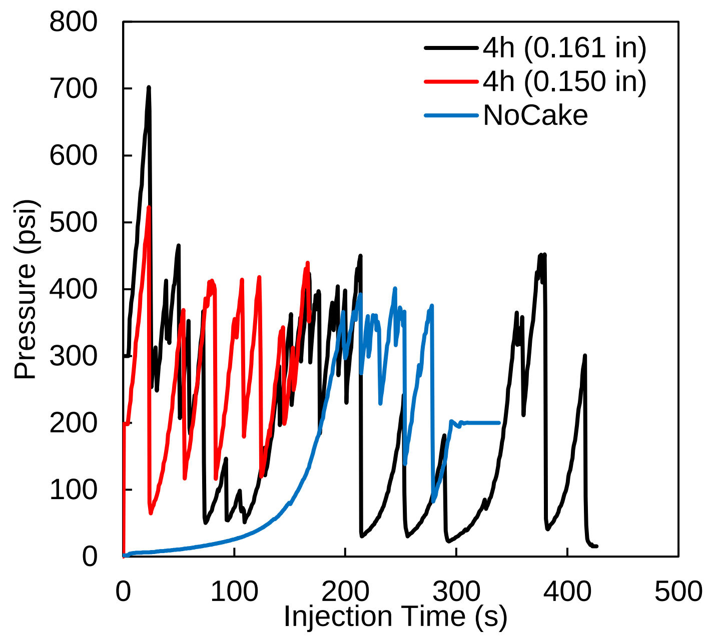

Figure A.3. Filtercake rupture pressure behavior over porous tapered slot (0.005 in - 0.0015 in, 127 um - 38.1 um).

A.2.3 The Effects of Filtercake Thickness and Fine Solid Particles on Filtercake Rupture Resistance

Filtercakes are mixed solid structures, and it is impractical to form a filtercake that is free of solid particles. Indeed, it is the solid particles that provide the skeleton of the structure that withstands high differential pressure. In this section, 1wt.% fine fiber particles with diameters less than 0.003 in (76.2 um) were added to 7wt.% bentonite-water fluid, to test the effects of fine particles in filtercake rupture and fracture sealing process. Ceramic discs with a 0.006 in (152.4 um) straight slot were used for the tests in this section. The test results of fluids with and without additional fine particles are presented.

The filtration was conducted for 14 hrs and 2.5 hrs to make the filtercakes, the corresponding filtercake thickness for the LCM-free case was 0.237 in and 0.102 in, and for the LCM case was 0.194 in and 0.101 in, respectively. The added fine particles could slightly reduce the filtration volume and the filtercake thickness. The pressure behavior during the filtercake rupture and fracture sealing process is shown in Figure A.4. For the LCM-free case, the filtercake ruptured at low pressure and the maximum pressure within the test period is less than 200 psi. With the addition of fine particles, the filtercake rupture can hardly be observed in the pressure curve. As shown in Figure A.4(b), with a 0.194 in pre-deposited filtercake, the pressure continuously built up after fluid injection. The test was stopped when the pressure reached around 600 psi and the PPA fluid cell was opened to check the status of the filtercake. A pinhole was observed in the filtercake, indicating the filtercake was already ruptured. But the ruptured filtercake with the solid particles sealed the fracture instantly. The disc was placed back, and the fluid was injected again to continue the test. The maximum pressure during this process was over 1200 psi, and there was no fluid observed at the cell outlet, indicating that the seal was effective to prevent fluid penetration. Such instant sealing after filtercake rupture was not observed when there was a 0.101 in pre-made filtercake. The filtercake needs to be thick enough, or needs to contain enough solid particles to build the effective fracture seal.

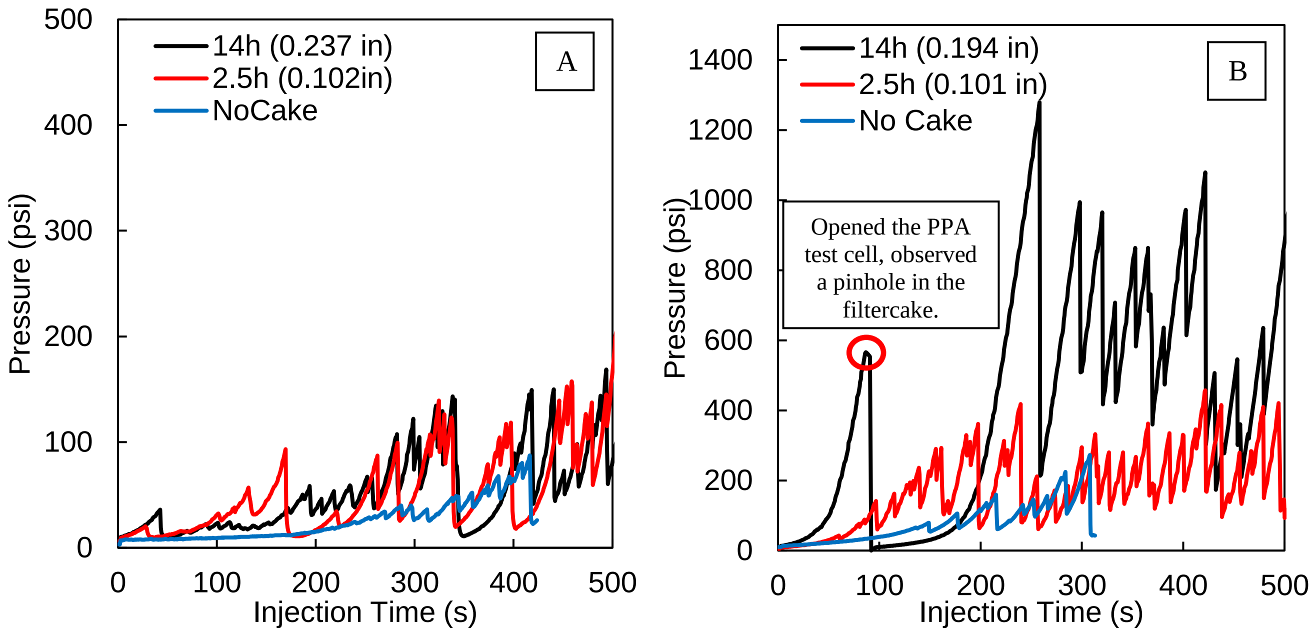

Figure A.4. Filtercake rupture pressure behavior over porous medium with a 0.006-in-straight slot: (a) filtercake was made from bentonite and water fluid, no added fine LCM particles; (b) filtercake was made from bentonite and water fluid with added fine LCM particles.

Appendix B. Supplemental Data for the Effects of Filtercakes with Drill Cuttings on Fracture Sealing Pressure and Cumulative Fluid Loss

Drilling fluid is a complicated system that consists of different components. During drilling, drill cuttings are created and transported by the drilling fluid, the filtration of the mud into the formation will leave the cuttings onto the wellbore to be part of the filtercakes. With the filtercakes, the drilling cuttings can play a role in sealing the fractures at their initiation stage as the LCMs. This section includes exploratory tests aiming to qualitatively observe the effects of drill cuttings in fluids and filtercakes during the filtercake rupture and fracture sealing process.

B.1 The Effects of Drill Cutting Size

Two mixtures of calcium carbonate (CC) particles were used in this part. One mixture is a combination of particles with diameters of around 16 and 40 US mesh size (1.19 mm and 0.42 mm), the other consists of particles with diameters of around 40 and 200 mesh size (0.42 mm and 0.074 mm). These two mixtures represented coarse and fine cuttings, respectively. The stainless-steel disc with 0.008 in (2 mm) slot was used to simulate the small fractures. 1wt.% CC mixtures were added to 7wt.% bentonite and water system to formulate the fluid and make the filtercake.

A Hamilton Beach mixer was used to prepare the fluid. When mixing at high rpm, the calcium carbonate particles suffered from degradation and it can be easily observed after mixing. The effects of degraded coarse cuttings were also tested and compared with the cases using the other two mixtures.

The filtration was kept for 4 hrs to make the filtercake, the corresponding filtercake thickness for the coarse (CC 16.40) cutting case and the fine (CC 40.200) cutting case was 0.133 in and 0.130 in, respectively. As it is shown in Figure B.1. when directly flowing the fluid through the slots, the simulated drill cuttings could bridge or plug the slots and enable the pressure buildup with the continuous fluid injection. When there was a pre-made filtercake, the pressure built up faster than directly flowing the fluid, as indicated by the pressure curve in the first 50 s of fluid injection. The filtercake maintained its integrity and enabled the pressure to build up steadily. The filtercake also prevented the fluid from penetrating the slots as there was no drastic fluid flow observed at the cell outlet. The size of the CC mixture seems to have limited effects in the filtercake rupture and fracture sealing process. A possible reason is that for 0.008 in (0.2 mm) slots, the 1.19 mm particles are too large and the 0.074 mm particles are too small to assist in sealing the slot. The 0.42 mm particles with filtercake played the predominant role in this process.

Figure B.2 showed the effect of degraded coarse CC particles. The degraded particles worked better than the original ones in both no filtercake case and pre-filtercake case. This is because degraded particles can have a broader PSD that better matches the slot sealing requirements. In real applications, it is difficult to control or predict the cutting size and the cutting content in the filtercake, this section just provided a qualitative indication of the cutting's contribution to facilitating the fracture sealing process.

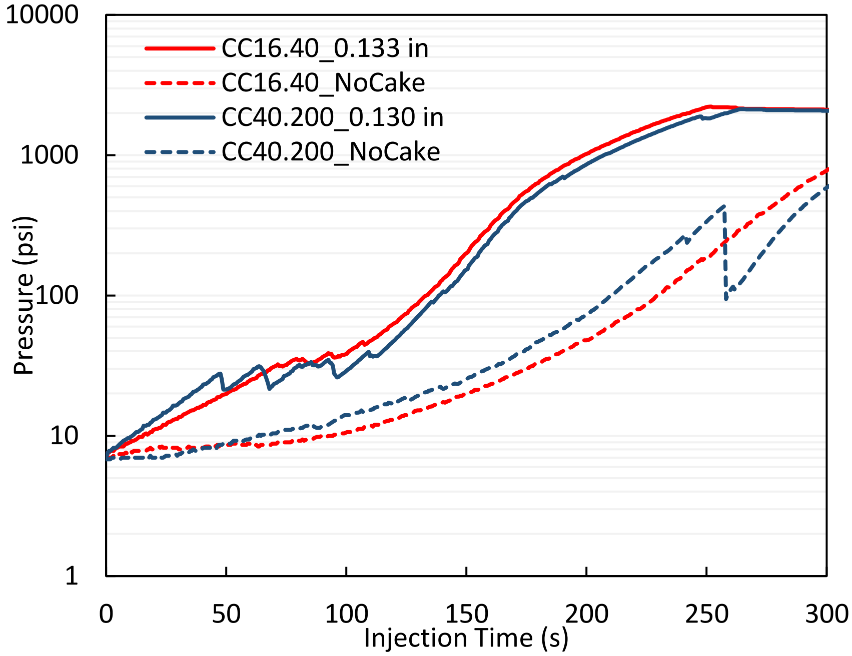

Figure B.1. The effects of cutting size (Coarse and Fine) on corresponding filtercake rupture resistance and fracture sealing time

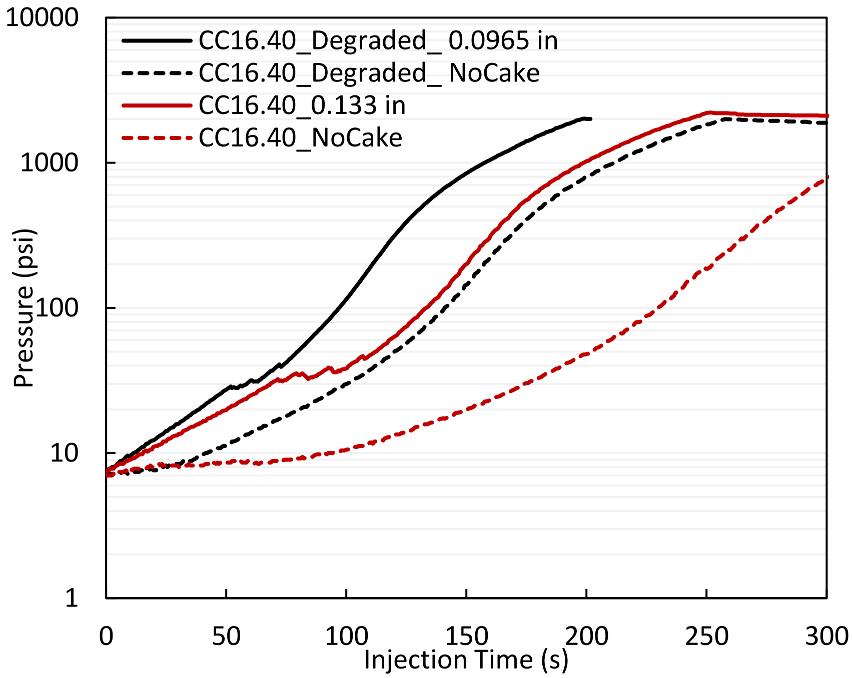

Figure B.2. The effects of cutting size (Coarse and Degraded coarse) on corresponding filtercake rupture resistance and fracture sealing time

B.2 The Combined Effects of Drill Cuttings and LCMs

The previous section indicated that the cuttings worked effectively in sealing small slots. In this section, the combined effects of drill cuttings and LCMs in sealing wider slots (0.02 in, 0.5 mm) are presented.

Figure B.3 indicates the effect of incorporating cuttings in the filtercake. With a layer of filtercake made from the fluid containing 1wt.% coarse cuttings, the pressure went up faster than directly injecting fluid with 2wt.% coarse cuttings. And the fluid with a higher cutting concentration performed better in plugging the slot. In these tests, due to the poor design of the fluid formulation, the slot sealing process was slow, even with a pre-deposited filtercake.

2wt.% Fiber LCM Fine (FLF, same as Fiber LCM regular) was added to mix the fluid with both LCM and cuttings. Cutting-facilitated fracture sealing is shown in Figure B.4. The fastest and most stable pressure increase was achieved by the combined system incorporating LCM and cutting. Directly injecting this fluid through the slot can seal the slot faster than the cases with pre-made filtercakes containing only CC or FLF. The filtercake made from the combined FLF and CC, as always, provided a faster seal than directly flowing the fluid. These results indicated that the cuttings in the fluid and filtercake can indeed facilitate the fracture sealing process. In field applications, the design of LCM should consider the combined effects of cuttings and LCM. The LCM that works better with on-site cuttings should be considered as a better choice for lost circulation preventive treatment.

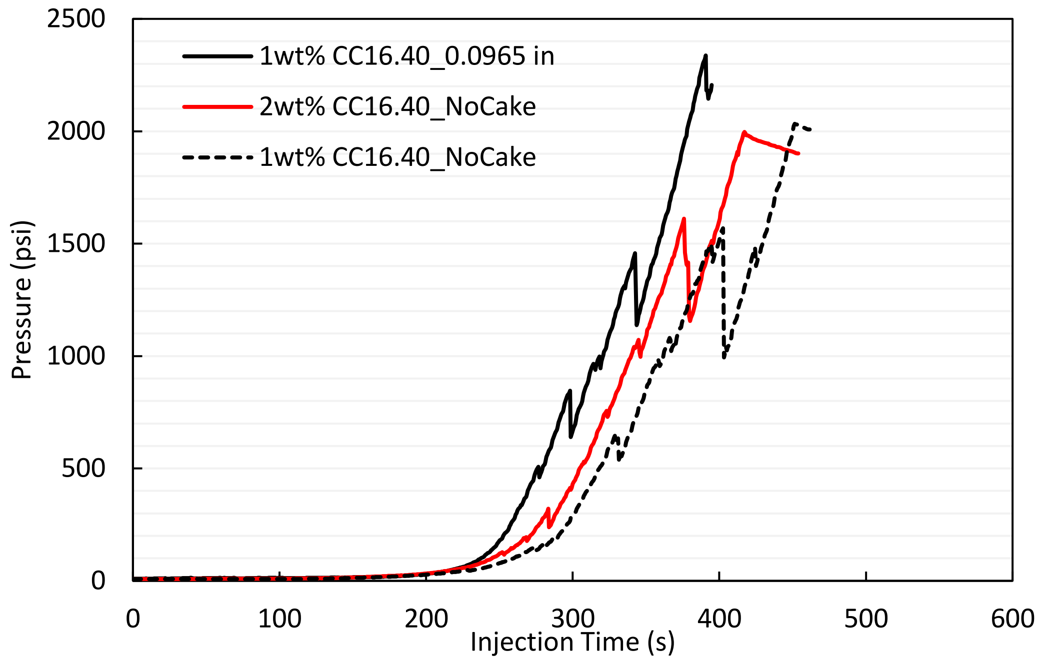

Figure B.3. The effects of cutting concentration on slot sealing

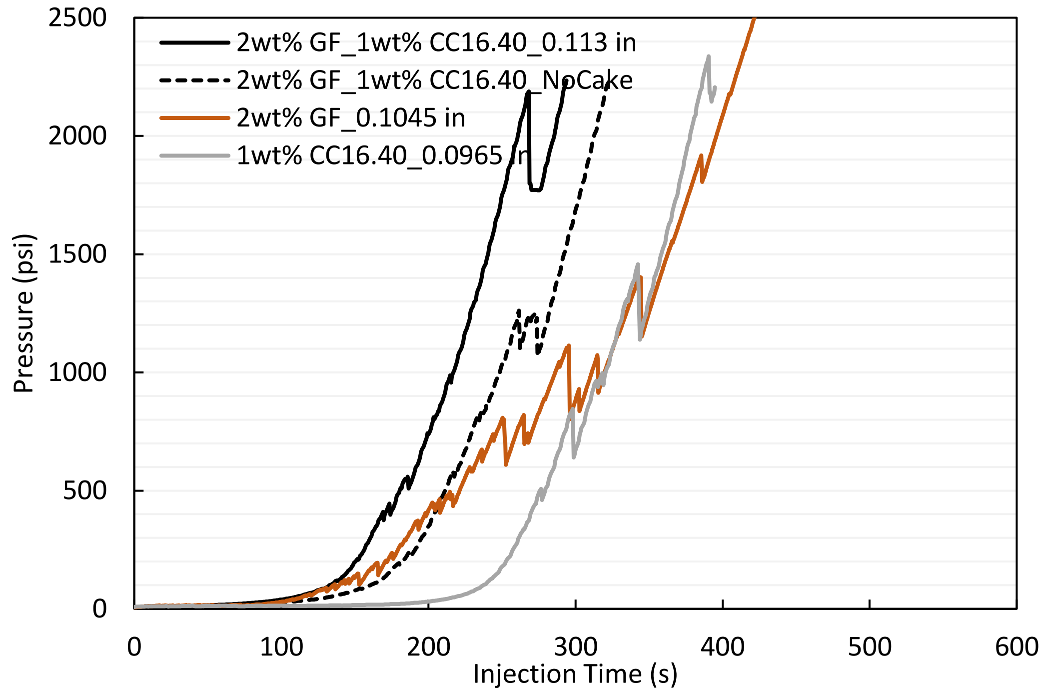

Figure B.4. The combined effects of cuttings, LCMs and the corresponding filtercake on slot sealing

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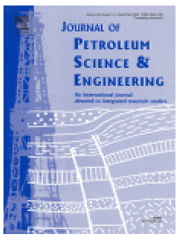

Experimental study of the impact of filter cakes on the evaluation of LCMs for improved lost circulation preventive treatments

Author: Mingzheng Yang,Mei-Chun Li,Qinglin Wu,Frederick B. Growcock,Yuanhang Chen

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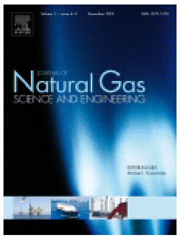

Investigation of LCM soaking process on fracture plugging for fluid loss remediation and formation damage control

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