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Abstract

As loss of circulation is still a major problem in the drilling industry, hundreds of lost circulation treatments are available on the market. The goal of this thesis is not to present a complete list of available products, but to give an overview of different treatments, investigating the level of effectiveness in different situations when exposed to high differential pressures.

The objective of this project was to investigate and compare the performance of three different commercial lost circulation materials; ONS-mixture, StopLoss and QuartzPack. All mixtures were tested in a simple water based mud system. The bridging and plugging capability was studied using a high pressure bridging apparatus, were the maximum applied pressure was 500 bar. To acquire a proper perception of each separate LCM system, the experiment was conducted with slots of different geometry and width openings, allowing further investigation. Firstly, slots that simulate the fracture mouth with openings of 1, 2, 3 and 4 mm were analysed. Secondly, cone shaped slots that simulate a fracture that has a specific length of 2.2 mm with openings of 3 - 1 mm, 3.5 - 1.5 mm and 4 - 2 mm. The intention for constructing the slots was to examine the principle of the stress cage and fracture closure models.

The results of the experiment is presented by pressure plots and analysed in regards of maximum pressure, average pressure, total number of pressure peaks and average peak pressure. Furthermore, the measured data is applied to a simulated well to relate the laboratory data towards a field specific application. Finally, a discussion that involves a review of important factors that might have a large impact on the results, namely, the particle size distribution, hardness of the particles and the principle of the fracturing models.

In this experiment, the key success factor for the various LCM mixtures were to hold the maximum pressure of 500 bar for an extended period. In other words, the performance accounted for can not include any pressure drops. The ONS-mixture was able to form an impermeable bridge for fracture opening widths of 1 and 2 mm, and the 3 - 1 mm and 3.5 - 1.5 mm. StopLoss could only create a solid bridge over the 1 mm opening fracture opening. Whereas for QuartzPack, a solid plug was formed in the slots with openings of 3 - 1 mm and 3.5 - 1.5 mm.

Acknowledgement

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I would like to use this opportunity to thank my supervisor, Bernt S. Aadnøy, and laboratory engineer, Sivert Drangeid, at the University of Stavanger, for providing me with guidance and encouragement throughout the process.

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Abbreviations

BHA	=	Bottom hole assembly
BHP	=	Bottom hole pressure
ECD	=	Equivalent circulating density
LCM	=	Lost circulation material
NPT	=	Non-productive time
OBM	=	Oil based mud
PSD	=	Particle size distribution
SG	=	Specific gravity
WBM	=	Water based mud

Chapter 1

Introduction

A lost circulation event is partial or entire loss of drilling fluid into the formation while drilling the well. If the loss rate is small and the fluid returns maintained, the drilling process may be resumed. However, if the losses are severe with no fluid returns to surface, the drilling operation must be stopped. Lost circulation may result in high non-productive time (NPT) and critical problems which can cost the companies millions of dollars [1], [2].

As large losses occur, the fluid level in annulus may drop. As the fluid level is reduced, there might not be a proper balance between the wellbore pressure and the formation pressure, resulting in a fluid flow from the formation into the wellbore. This event can induce a well control issue that may in worst case lead to a blow out. In addition, the lower wellbore pressure can induce wellbore collapse, were the consequence may be buried drilling tools and stuck pipe [3], [1].

A method to prevent loss of circulation events is the application of various particle additives known as lost circulation material (LCM). The LCM is either dispersed throughout the drilling fluid or spotted as a high concentrated pill, typically designed to plug fractures. For severe fluid loss it is common practice to use pill systems, were the particle additives can be flaky, granular or fibrous, available in a size range from nanometers to millimetres. By mixing larger and smaller particles, the bridging and plugging mechanism should be improved [4].

In a drilling operation, the fracture sizes may be highly variable and pressure in the wellbore may increase the fracture width of an existing or induced fracture. As these uncertainties are present in real life, it is difficult to predict the correct particle size distribution of the LCM. Therefore, the LCM systems needs to seal off a broad range of fractures. To verify the plugging or sealing mechanisms of these additives, laboratory test should to be performed. By amplifying the knowledge with regards to the subject of LCM, critical problems as losses might be mitigated [5].

Chapter 2

Theoretical review

Lost circulation can occur in any operation where a fluid is pumped into the well. Two conditions are necessary for fluid loss: a formation with flow channels that allows fluid to flow from the well and into the formation, and the fluid present in the well must be in overbalance. Both conditions must be present for a lost circulation scenario to occur, but the type of lost circulation scenario will be dependent on which of these conditions are predominating [6].

Lost circulation can be caused by different scenarios with various severity. The loss rate is frequently used to define the severity of loss events; seepage is approximately 3 – 30 liters/min, partial is 30 – 270 liters/min and severe losses are larger than 1300 liters/min. Seepage losses are most common in unconsolidated formations and gravel beds with high porosity and high permeability. Partial loss of returns might occur in unconsolidated sand, gravel, natural or induced fractures. A sudden and complete loss of returns is often associated with vugular or cavernous formations, heavily fractured rocks with large fracture width. Fig. 2.1 illustrates different lost circulation scenarios [7], [8].

An important parameter to consider in regards of lost circulation is the equivalent circulation density (ECD), particularly in wells with narrow fracture- and pore pressure gradient window. The narrow window can be induced by depleted zones, deep-water formations or naturally fractured formation. In depleted zones, the pore pressure gradient and the fracture pressure gradient is decreased. Whereas in deep-water formations, the substantial water depth can reduce the fracture gradient, making it demanding to maintain the wellbore pressure. These two scenarios are shown in Fig. 2.2.

Pre-existing fractures in the formation can have a significant effect on the pressure capacity of the wellbore. A small fracture can lead to a decrease in the tensile strength of the wellbore rock. This scenario can also contribute to a narrow pore- and fracture gradient window. If the mud weight exceeds the specific fracture gradient, the fracture may propagate, leading to severe loss of circulation [9].

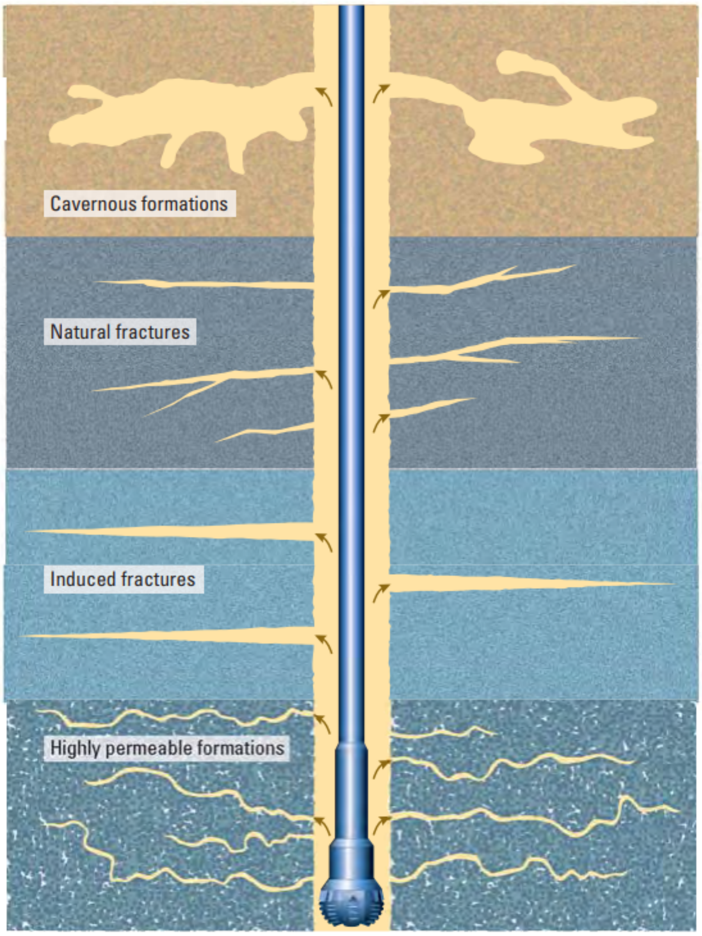


Figure 2.1: Lost circulation scenarios [4].

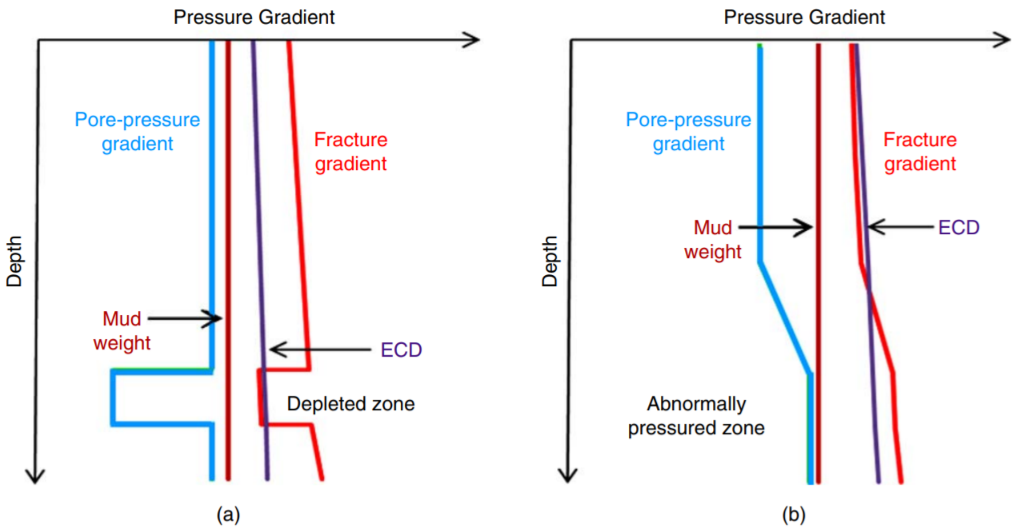


Figure 2.2: (a) Pore pressure and fracture gradient plot in depleted zone. (b) Pore pressure and fracture gradient plot in deep water formation with abnormal high pressure [10].

2.1 Lost circulation material

If the correct LCM is not used when drilling through fractured formations, critical problems may occur. To save drilling cost and improve safety it is important to have the knowledge on how the LCM plugs off the fracture. As the loss ranges from seepage to severe, the majority of LCMs are found in grades as fine, medium and coarse to accommodate a distinct scenario.

The conventional treatment for smaller losses is to add LCM into the entire active drilling fluid system. The continues treatment of the entire mud system is known as background LCM. As a result of the pressure difference in the weaker zones, the LCM is transported by the drilling fluid, bridges and eventually plugs the fracture. Background LCM systems are generally of moderate concentrations to avoid plugging of the bottom hole assembly (BHA) components. Severe lost circulation zones that do not respond to conventional treatments might be cured by spotting an LCM pill or spotting and squeezing a lost circulation plug at a desired depth.

The LCM has several functions which can be divided into the following stages [11]:

- **Dispersion**: The LCM should be pumpable and placed as intended.
- **Bridging**: The larger particles of the LCM creates a mechanical bridge across the fracture interface. This bridge is assigned to give an increased mechanical strength to the formation.
- **Sealing**: Small particles are deposited on/in the bridge which creates a in-permeable seal, preventing loss of fluid further into the formation.
- **Sustaining**: The strength of the seal is important. It is essential that it can withstand increased hydrostatic and dynamic pressure, which again results in the ability to drill ahead with a higher ECD.

2.1.1 LCM additives

The LCM additives are solids which can be added to the drilling fluid system or spotted as a pill to bridge across the pore throat or fractures, preventing fluid losses. The LCM can be divided into different categories based on their appearance and application: granular, flaky and fibrous.

Often, granular, flaky and fiber materials are mixed to enhance the sealing performance of an LCM. This might mitigate losses due to the diverse properties and particle size distributions. For a LCM to be fully optimized, it should be able to seal a wide range of fracture widths. To further comprehend the variety of the materials, a short explanation of each category is given below [12], [13].

Granular materials
Granular materials are defined as additives that are capable of forming a seal at the fracture opening or within the fracture to prevent losses into the formation. Three

commonly used granular LCMs includes graphite, sized calcium carbonate, marble, wood and nutshells, available in a wide particle size range.

Flaky materials
A type of lost circulation material that can be defined as thin and flat in shape, with a large surface area. This material may have a degree of stiffness and is capable of forming a permeable bridge over the fracture opening. The materials might include mica and flaked calcium carbonate.

Fibrous materials
Fibrous material can be defined as a long, slender and flexible material with a variety in size and lengths. This materials may be bark, mineral fibers, saw dust and shredded paper.

2.1.2 Particle size distribution

The particle size distribution (PSD) is one of the key parameters affecting the sealing capabilities of a LCM blend. Other laboratory tests show that the key factor for a successful LCM treatment is a broad PSD which enhances the sealing effect [7]. The main parameters used to describe the size of the particles are d_{10}, d_{50}, and d_{90}, usually measured in micron. By specifying these values, the percent of the particles are less than the d-number. For example, if the d_{50} is 0.5 mm, meaning that 50 % of the particles are smaller than 0.5 mm.

In 2016, Alsaba performed an experiment on fracture width limitations and concluded: "*The PSD has a significant effect on the seal integrities, especially the* d_{90} *value that is equal or slightly larger than the fracture width is required to initiate a strong seal. The presence of very fine particles in LCM treatments is recommended to fill the void spaces between other coarser particles, which in turn will result in a less permeable seal and higher seal integrity"* [14].

The Abrams' Median Particle-Size Rule [15], Ideal Packing Theory [16] and Vickers Method [17] are different theories regarding the PSD. Furthermore, the Halliburton Method states:"*The* d_{50} *of the PSD is set equal to the estimated fracture width to offset uncertainty in the estimation. In that situation, enough particles smaller and larger than the fracture are present to plug smaller and larger fracture width*" [18].

2.2 Wellbore strengthening treatments

Supplying wellbore strengthening materials or LCM into the well is an approach to achieve an enhancement of the formation‘s fracture resistance. In other words, the hoop stress in the treated zone is increased. As the formation gradient is increased, one may avoid fracture propagation. Also, the drilling mud window is enlarged. The strengthening materials are known to prevent fluid loss by plugging or sealing off the fractures [19].

In the drilling industry, there are two types of wellbore strengthening methods, the preventive and remedial methods. The preventive method aims at pro-actively strengthen the wellbore with LCM to avoid fracture initiation and prevent smaller pre-existing fractures from propagating. The remedial strengthening method is approached if the loss has already occurred. Here, the wellbore is strengthened as the LCM bridges, plugs or seals off the loss zone [10].

2.2.1 Preventive treatments

The preventive treatment is to add LCM into the fluid system while drilling to potentially reduce or stop a lost circulation event. This wellbore strengthening method has two designated intentions. Firstly, a filter cake should be developed on the wellbore wall to maintain the high fracture initiation pressure. Secondly, the filter cake shields any micro fractures that are present on the wellbore wall. These intentions prohibits fluid flow into the formation, thus increasing the fracture propagation gradient [10].

2.2.2 Remedial treatments

The remedial wellbore strengthening is a subsequent treatment for a loss of circulation event. The objective is to increase the wellbore strength by preventing fracture propagation. To prevent the fracture propagation, three distinct mechanisms have been developed and is shortly described below, and further discussed in Section 2.4:

Three physical models for remedial treatments:

- Bridge a fracture near the wellbore wall to increase the local compressive hoop stress and enhance fracture opening resistance [20].
- Widen the fracture‘s aperture and fill it with an immobile mass to enhance the fracture closure stress [21].
- Form a filter cake in the fracture near the fracture tip, to isolate the fracture tip from wellbore pressure to avoid fracture propagation [22].

2.3 Description of the fracturing process

Figure 2.3 illustrates the various steps in the fracturing process. Each event sequence is further explained below the illustration [23].

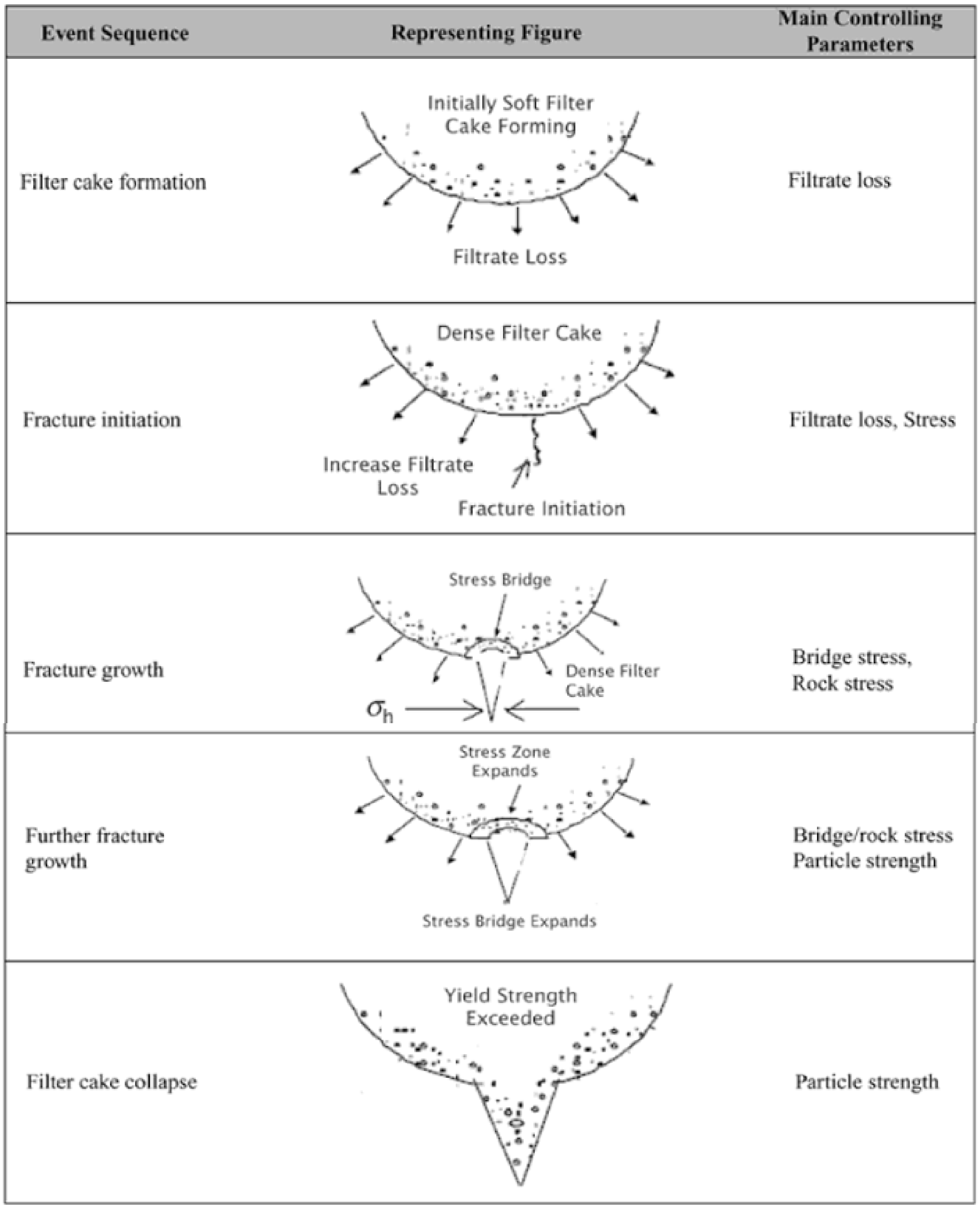


Figure 2.3: Description of the fracturing process [23]

Event 1: Filter cake formation
A filter cake is formed by the drilling fluid across permeable formations. The thickness of the filter cake depends on the equilibrium between the erosion due to the fluid flow and the filtrate attraction.

Event 2: Fracture initiation
As the wellbore pressure is increased, the hoop stress in the rock is in tension instead of compression. The filter cake is still in place, helping to resist the pressure in the borehole. As the pressure reaches a critical limit, the wellbore wall may start to fracture.

Event 3: Fracture growth
As the borehole pressure is increased, the fracture may be enlarged in width and start to propagate. The particles in the filter cake has a mechanical strength, preventing the bridge from collapsing. In this phase, both the rock stress and the strength of the filter cake resist failure.

Event 4: Further fracture growth
Enhanced pressure leads to further fracture opening. The stress bridge expands and become thinner. In other words, the filter cake is weakened.

Event 5: Filter cake collapse
As the critical pressure is reached, the filter cake does not have the strength to seal of the formation, resulting in a bridge collapse. Here, the yield strength of the particles in the filter cake is exceeded which establish mud flow into the formation. More specifically, a loss of circulation event is initiated.

2.4 Physical models for wellbore strengthening

Wellbore strengthening treatments are effective in mitigating lost circulation caused by drilling induced or natural fractures by increasing the fracture gradient. However, the strengthen treatment does not increase the strength of the rock, but alter stress distribution near the wellbore wall. Two of the models for the physical mechanism of wellbore strengthening are the stress cage model and fracture closure model. An explanation on how the models "strengthen" the wellbore is briefly described below [10].

2.4.1 Stress cage model

The stress cage model has been recognized as an effective method. The fundamental of the model is that larger particles are deposited at the fracture mouth, were the smaller LCM particles occupy the gaps, creating an impermeable bridge. This solid bridge near the fracture mouth results in an increased hoop stress near the damaged zone, preventing the fracture propagation. Fig. 2.4 shows the principle of stress caging [20].

2.4.2 Fracture closure stress model

The fracture closure stress model is an additional method to strengthen the wellbore. The essence of the model is to increase the fracture closure stress by widening the width of the fracture and fill it with an immobile mass. As the fracture is widen, the compressive strength or fracture closure stress in the rock is increased. Then, the LCM is forced into the fracture were it consolidates and finally turns into a immobile mass. The immobile mass isolates the fracture tip from wellbore pressures, preventing propagation. Fig. 2.4 illustrates the principle of the fracture closure model [21].

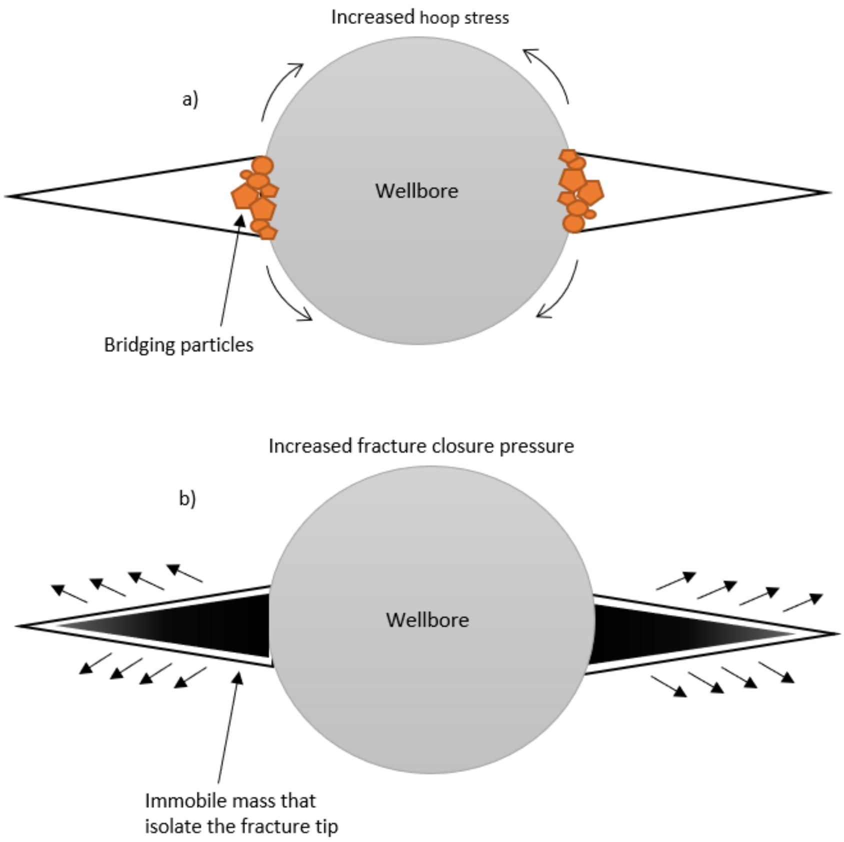


Figure 2.4: Two models for the physical mechanism of wellbore strengthening a) Stress cage model, b) Fracture closure model.

2.5 Drilling fluid

The most important function of the drilling fluid is to remove drilling cuttings from the bottom hole of the well, and keep the cuttings in suspension. If these two mechanisms fail, the pressure in the wellbore may exceed the fracture pressure of the formation and cause a lost circulation situation. Furthermore, a low permeable filter cake may be formed by the drilling mud on the wellbore wall. This filter cake seals pores and small fractures, thereby minimizing fluid loss into a permeable formation [6].

For this assignment two types of drilling fluids with different behaviour were considered; water-based mud (WBM) and oil-based mud (OBM). The OBM has in recent years gained popularity, but the present environmental concerns generates the demand of WBM. Environmental regulations restrict and prohibit the use of drilling fluids that have the potential to pollute the soil and ground water aquifers. As WBM is used in this experiment, that mud will be briefly discussed.

Water-based mud: The government prefers WBM due to environmental benefits. It does not contain harmful materials which makes it a preferred option. Also, it is cheaper. Another advantages using this mud is that LCMs have a better ability to build a seal which is generated by the filter cake. The disadvantage of WBM is that it can swell shale formation which may lead to borehole problems as decreased hole size with time [24].

2.5.1 Drilling fluid properties

Density is the mass per unit volume of a drilling fluid. The hydrostatic pressure in the wellbore is controlled by the mud weight and prevents unwanted flow into the well. Too high mud weight can fracture the formation and lead to lost circulation [25].

Viscosity is a very important parameter to consider in regards of fluid design, as it contributes to transport the cuttings from the bottom of the well to the surface. One can express viscosity as the muds resistance to flow. The flow properties of a drilling mud are often characterized by the following measurements:

- Apparent Viscosity
- Gel Strength
- Yield Point
- Plastic Viscosity

Apparent Viscosity is obtained by applying the instrumental parameters (RPM) measured by the rheometer. Generally, it tells us about the total viscosity of the fluid.

Gel strength is a measurement of the attractive forces in the drilling fluid and is measured at low shear rates after a static condition of 10 seconds and 10 minutes.

In this case, a high gel strength is preferred to keep the larger LCM particles in suspension.

Yield Point (YP) is the floating resistance caused by electrochemical forces between the particles. This measurement can be used to evaluate the ability to transport cuttings out of the annulus and plays a major part in preventing solid particles from settling as circulation is stopped. See Eq. 2.2 for calculations of YP.

Plastic Viscosity (PV) is the part of the flow resistance caused by the mechanical friction. If the PV increases, the solids content of the drilling fluid is most likely to increase. One can find the PV by subtracting the reading of 600 rpm and 300 rpm, as shown in Eq. 2.3.

Calculations of apparent viscosity, yield point and plastic viscosity:

$$AV = \frac{\theta_{600}}{2} \tag{2.1}$$

$$YP = 2 \cdot \theta_{300} - \theta_{600} \tag{2.2}$$

$$PV = \theta_{600} - \theta_{300} \tag{2.3}$$

Stokes law: a mathematical equation that expresses the settling velocities of small spherical particles in a fluid medium. By calculating the settling velocity of the particle one can ensure that the viscosity is high enough to keep the particles in suspension. For calculations, see Eq. 2.4. As the equation equals to zero, the particles has reached a steady state.

$$U = \frac{(\rho_{particle} - \rho_{fluid})d^2 g}{18\mu} \tag{2.4}$$

Chapter 3

Experimental equipment and setup

3.1 Fann 35 Viscometer

The Fann 35 viscometer is used to measure the viscosity and gel strength of a drilling fluid by measuring the shear stress at a certain shear rate. The data obtained from this apparatus is used to calculate the relevant fluid properties as plastic viscosity and yield point. The shear rate is measured in rates of 3, 6, 100, 200, 300 and 600 revolutions per minute (RPM) and the shear stress is measured as deflection angle in degrees. The gel strength is measured 10 seconds and 10 minutes after the viscometer is stopped to acquire a value of how the fluid would hold the particles in suspension.

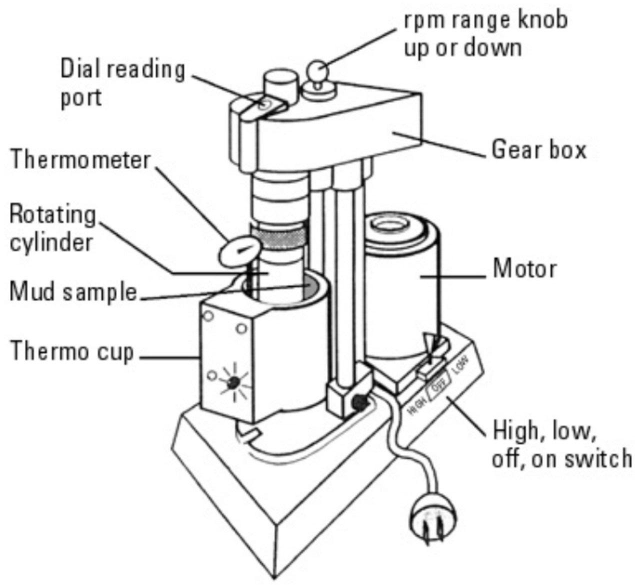


Figure 3.1: Fann 35 Viscometer.

3.2 Static bridge apparatus

The effectiveness of LCM treatments was investigated using a static bridging apparatus, which is manufactured to evaluate the sealing integrity. The main objective of using this setup was to closely analyse the strengthening mechanism on a wide range of slot widths were each slot simulates a fracture.

In preparation of the equipment, the first step was to place the LCM mixture into the high pressure cell. In this step, the top of the pressure cell is exposed to atmospheric pressure. In order to increase the pressure, the excess air in the cell was displaced with water. To do this, the Gilson pump was started at a rate of 6 ml/min, continuing until water was observed at the top opening. The top opening is then closed off, and the pump was restarted at a rate of 3 ml/min. Now, the LCM particles should start to settle and form a bridge over the slot opening. As a bridge is built, the pressure should rapidly increase. To obtain the results from this experiment, a computer recorded the pressure measurements and stored the data in Lab-View. The maximum pressure allowed for the system is 500 bar. An illustration of the static bridging apparatus is shown in Fig. 3.2.

The slots consist of two steel half cylinders which has an opening of a known size and shape. A variation of slots were conducted resulting in 21 pressure analysis. Two types of slots were fabricated; four cylindrical and three coned slots. The cylindrical slots simulates the fracture mouth with width openings of 1, 2, 3 and 4 mm. As for the coned slots, simulating a fracture with a specific length of 2.2 mm with width openings of 3 - 1 mm, 3.5 - 1.5 mm and 4 - 2 mm. Fig 3.3 illustrates the two type of fractures conducted in the experiment.

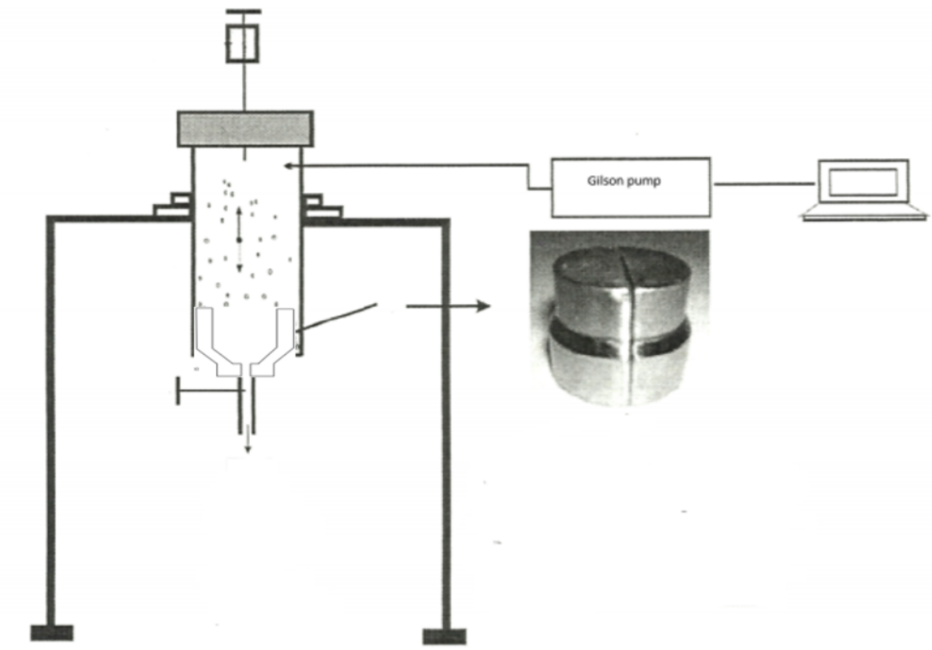


Figure 3.2: High pressure bridging apparatus containing a cylindrical slot [26].

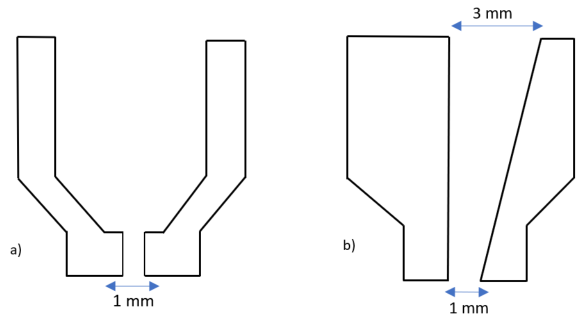


Figure 3.3: a) Cylindrical slots with openings of 1, 2, 3, and 4 mm. b) Coned slots with openings of 3 - 1 mm, 3.5 - 1.5 mm and 4 - 2 mm.

3.3 Test sieve shaker

The sieve shaker is a dry vibrating shaker with a series of sieves with a known size, used to analyse the particle size distribution of the LCMs. The first step for accurate measurements is to weigh each sieve separately. Then, stack the sieves in the right order before adding the LCM. As the particles were distributed throughout the shaker, each sieve was weighed, acquiring the correct amount of particles contained in each sieve. The sieves used in this experiment were stacked in the order of: 63, 90, 125, 180, 280, 355, 500, 1000 and 2000 micron.

Figure 3.4: Test sieve shaker to determine the particle size distribution of LCM.

3.4 Drilling fluid formulation

As the LCM is of dry material, the first step was to develop a drilling fluid. Whereas WBM seems to be the future of drilling fluid and is less harmful to handle, it was decided to perform the experiments with water-based mud. The lost circulation materials contains large particles up to 2.5 mm in diameter with a density of 2.5 sg. Therefore, the focus has been to produce a drilling fluid that can keep the larger particles in suspension.

The WBM used in this experiment contains:

1. Tap water (350 gram)
2. NaOH (0.5 ml)
3. Bentonite (10 gram)
4. Xanthan Gum (XG) (1.6 gram)
5. Barite (150 gram)

Bentonite was added to increase the viscosity of the drilling fluid as it swells considerably when exposed to water. To enhance the performance of the bentonite, a polymer named Xanthan Gum were supplemented. As the water, bentonite and XG was mixed, the density was measured to be 1.02 sg, which is considered too low. To increase the density of the fluid, barite was supplied which increased the density to 1.3 sg.

3.5 Lost circulation material

For this thesis, three separate LCM pills were tested; one is premixed, meaning the material has already been added to a fluid phase. The other two are added to a produced drilling fluid. The goal is to compare the sealing mechanisms as the products contains different material, mineral and particle size distribution. The information given below is acquired from the data sheets, and is presented to describe the LCMs contents.

The LCM products are provided by three companies:

1. MI Swaco: Mixture of OptiSeal, NutPlug Fine and SafeCarb 2500
2. DrilChem: StopLoss
3. Flopetrol: QuartzPack

Mixture of OptiSeal, NutPlug and SafeCarb (ONS-mixture): the lost circulation material mixture consist of 50 % OptiSeal, 25 % NutPlug and 25 % SafeCarb. The recommended amount of LCM to be added in the drilling fluid is 350 g/litre. As these are three different materials, a short explanation of each product is necessary:

- OptiSeal consist of graphitic material and marble where d_{50} is 0.50 - 0.60 mm.
- NutPlug is cellulose comprises ground walnut where d_{50} is 0.40 - 0.50 mm.
- SafeCarb is calcium carbonate used as a bridging agent where d_{50} is 2.50 mm.

StopLoss: a blend of naturally occurring organic fibres and particles, primarily developed from hardwood and softwood. Here, the d_{50} is 0.125 mm. The amount of LCM material recommended to be added in the drilling fluid is 100 g/litre.

QuartzPack: this lost circulation material is premixed. It consists of 0 - 25 % microsilica and 50 - 70 % quartz particles, together with approx. 30 % water and loss control additives. The mixture hardens over a short time period, but will fluidize if affected by mechanical stress. For this product the d_{50} is 0.50 mm.

Fig. 3.5 illustrates the three different lost circulation materials.

Figure 3.5: The three different lost circulation materials used in this experiment. A) ONS-mixture, B) StopLoss, C) QuartzPack

3.6 Hydraulic simulation setup

An hydraulic simulation is applied to estimate the dynamic bottom hole pressure (BHP) in a hypothetical wellbore to illustrate at which depths the LCM pills can be applicable. It is assumed that the drilling process is resumed after spotting an LCM pill across the fractured formation. The objective of this simulation was to relate the laboratory results towards specific field application which is presented in Section 4.5. The result from the simulated BHP is shown in Fig. 3.6.

The experimental vertical well utilized for this simulation varies in depths from 2000 - 4500 meters. At each depth the flowrate is increase from 500 l/min to 3500 l/min. As illustrated in Figure 3.7, the constructed well consists of a 9 5/8 " casing followed by a 8 1/2 " open hole. The drill string consists of a 5 " drill pipe and a bottom hole assembly. Furthermore, the drilling fluid has a density of 1.7 sg and the pore pressure gradient is 1.03 sg to assume worst case. The different pressure across the bridged fracture has been assumed as ECD - pore pressure.

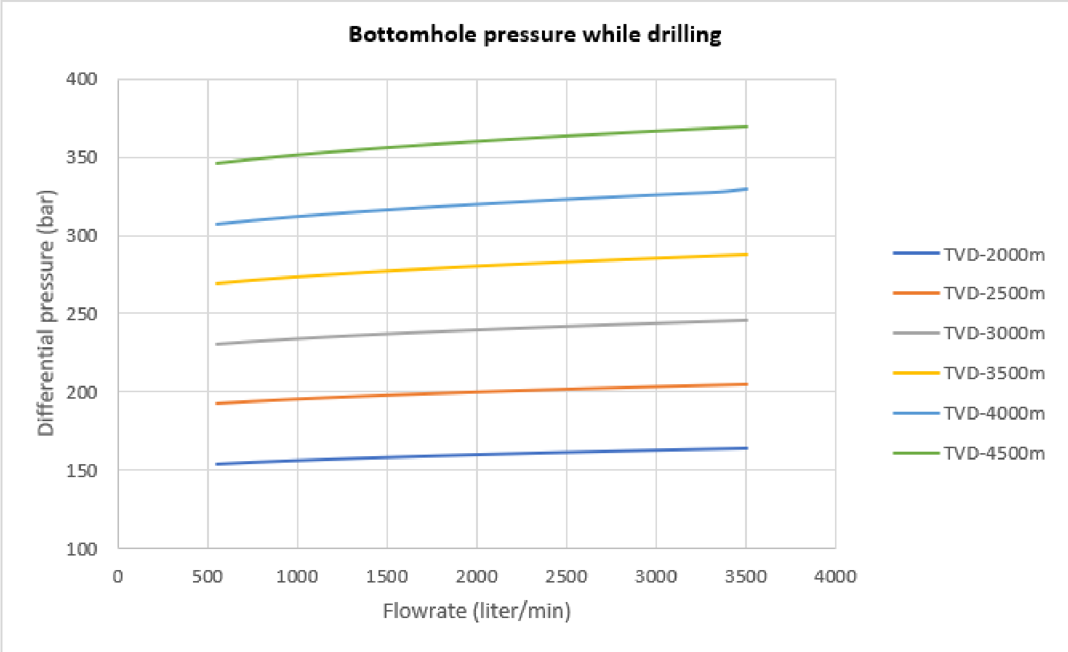


Figure 3.6: The simulated BHP at varying depths.

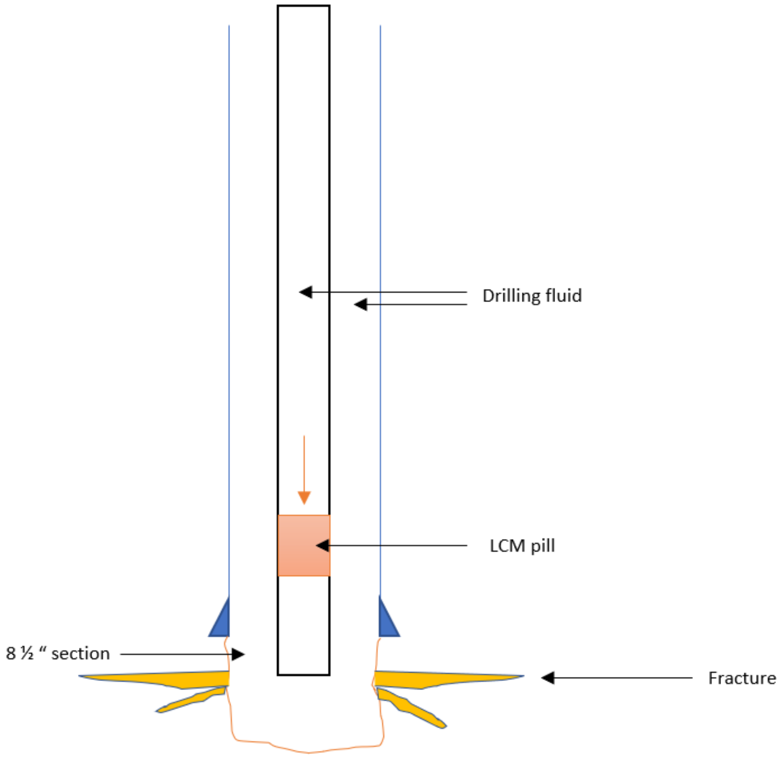


Figure 3.7: Hypothetical well used for hydraulic simulation.

Chapter 4

Experimental results

4.1 Rheology measurements of drilling mud

As two of the LCM mixtures were of dry material, it was necessary to produce a drilling fluid. The amount of LCM added to the fluid is considerable as the objective was to study a pill system. Additionally, the particles contained in the LCMs are large in size. Therefore, the focus was to produce a drilling fluid that could keep the larger particles in suspension. The rheology measurement was performed on the Fann 35 viscometer and the obtained data is plotted in Fig. 4.1.

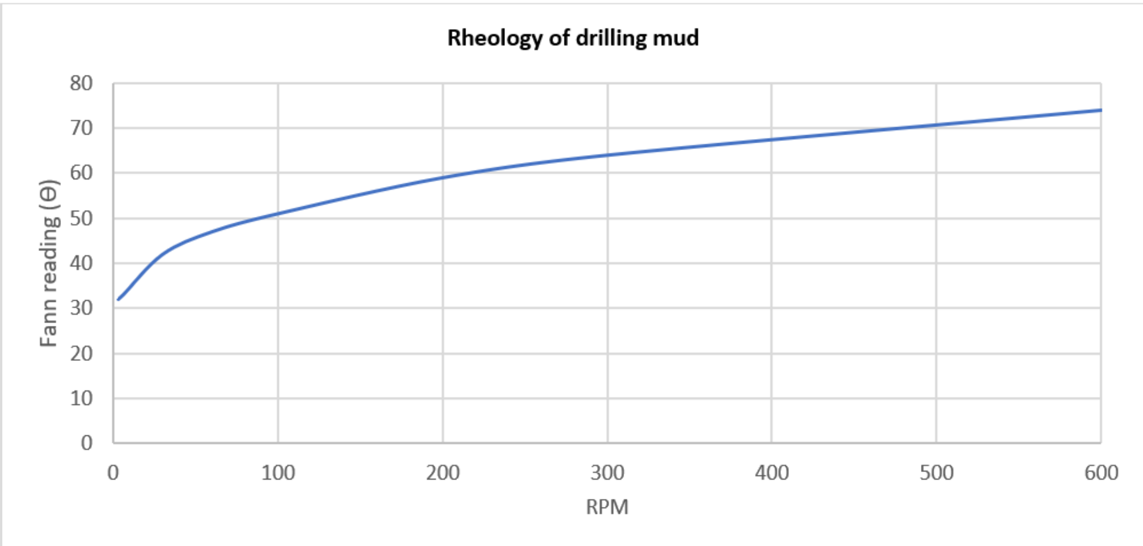


Figure 4.1: Measured rheology of the drilling mud.

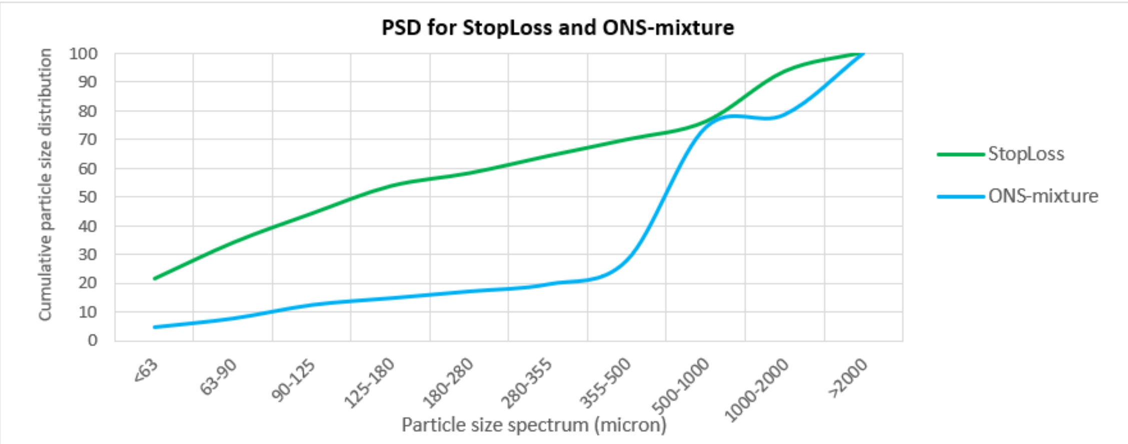
Table 4.1: Measured and calculated drilling fluid properties.

Fluid properties	
Density (sg)	1.30
Plastic viscosity (cp)	10
Yield point (lbf/100ft^2)	54

4.2 Particle size distribution of the LCM mixtures

To study how the particle size distribution correlates with the sealing integrity, a PSD analysis was conducted. Fig. 4.2 represent the cumulative percentage of the mixture against particle size. Samples from the ONS-mixture and StopLoss were sieved through a series of stalked sieves as these were of dry substance. Whereas for QuartzPack, Flopetrol specified the PSD data as the pre-mixture was unfeasible to measure with the sieve shaker. It should be noted that the dry sieve used were only able to determine particle sizes below 2 mm. Based on the ONS-mixture and specifications of d_{50}, it can be calculated a d_{90} value of approximately 2.5 mm.

As a result of the PSD measurements, it was decided to investigate the bridging effect on larger fracture widths, resulting in cylindrical slots with openings of 1, 2, 3 and 4 mm. For further study, cone slots with opening widths of 3 - 1 mm, 3.5 - 1.5 mm and 4 - 2 mm were conducted.



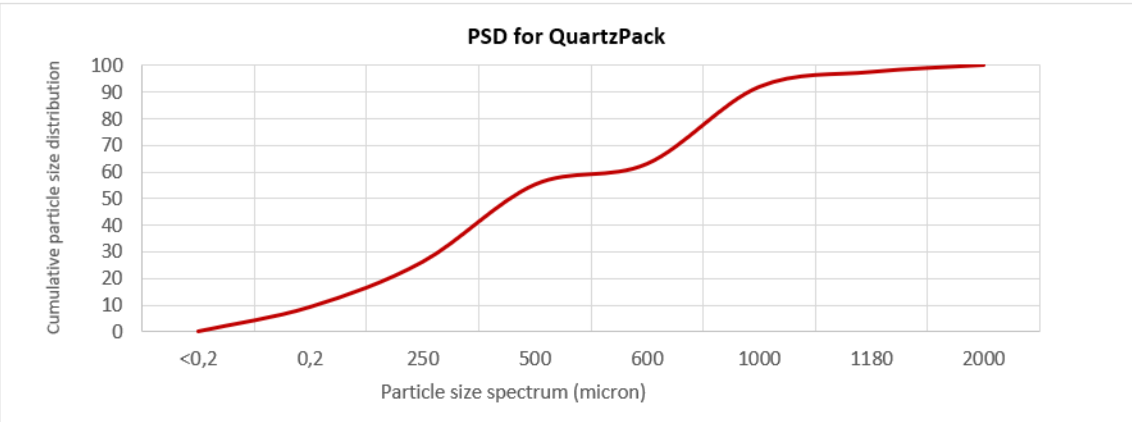


Figure 4.2: Measured particle size distribution of StopLoss, ONS-mixture and QuartzPack.

Table 4.2: Approximately particle size distribution of the various LCM mixtures.

PSD (micron)	d_{10}	d_{50}	d_{90}
ONS-mixture	90	500	2500
StopLoss	< 63	125	1200
Quartzpack	0.2	500	1000

4.3 Bridging test results

This experiment was performed to observe the LCMs sealing effect on a wide range of slot widths. Observations from the results will be discussed below. As described previously, the experiment was conducted with slot openings of 1, 2, 3 and 4 mm. Also, cone slots with openings of 3 - 1 mm, 3.5 - 1.5 mm and 4 - 2 mm were used.

4.3.1 Experimental data for each LCM system

In this subsection, experimental results for the LCM systems are presented and discussed. The data obtained from the experiment is plotted to illustrate the bridging capacities as the slot widths vary in size.

Experimental test with ONS-mixture

In Fig. 4.3, the experimental data using the cylindrical slots of 1, 2, 3 and 4 mm is shown. From this plot it is observed that the ONS-mixture can quickly create a solid bridge over the 1 and 2 mm slot opening, holding a maximum pressure of 500 bar. The initial build-up rate for these two openings are nearly identical but starts to deviate at the 3 minutes mark. As the slot openings are enlarged to 3 and 4 mm, a substantial decrease in sealing pressure is observed. The maximum pressure for the larger openings are 500 bar and 180 bar, which shows that the particles are still able to resist a relatively high pressure before collapsing.

The performance of bridging the cone slots is shown in Fig. 4.4. Here, the ONS-mixture can establish an endurable bridge within four minutes in the 3 – 1 mm and 3.5 – 1.5 mm slots. There is a major distinction in the pressure capacity as the cone increases to 4 – 2 mm. The pressure peaks are low and the time intervals wide, indicating an incapability of sealing off higher pressures.

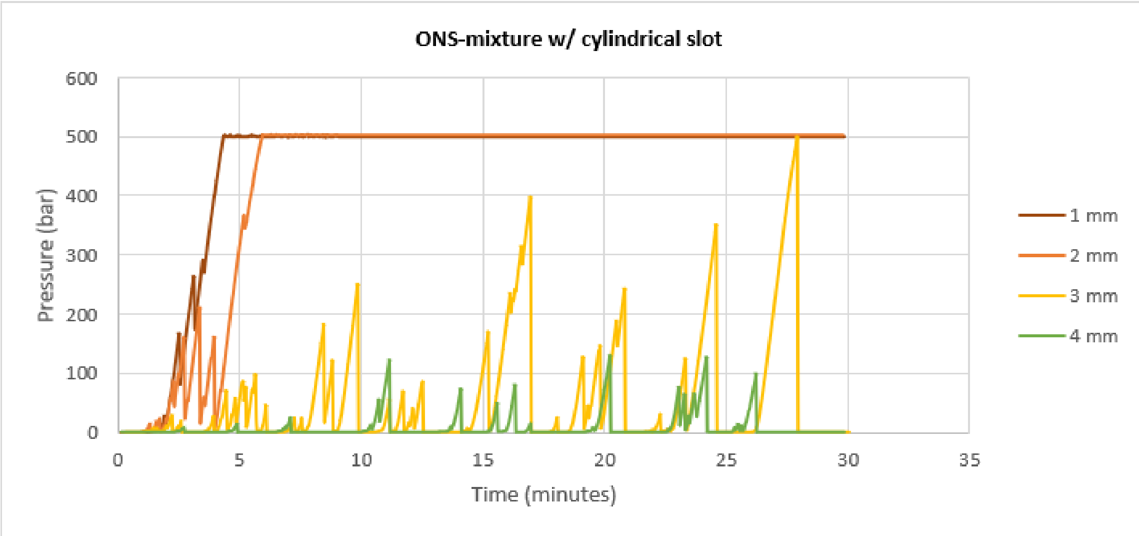


Figure 4.3: Data from the experimental bridging test with cylindrical slots for the ONS-mixture.

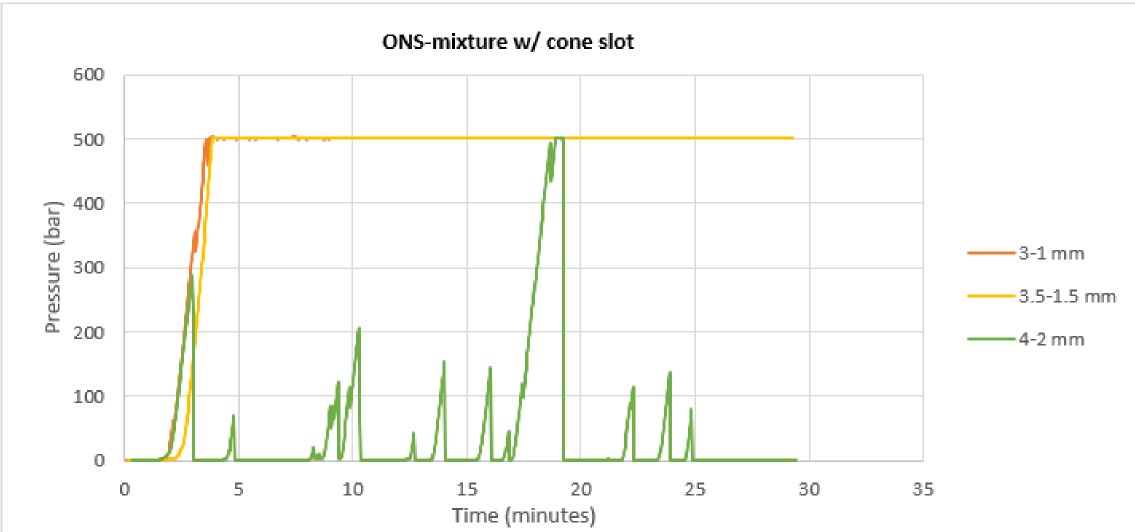


Figure 4.4: Data from the experimental bridging test with cone slots for ONS-mixture.

Experimental test with StopLoss

For StopLoss, there is a major variety on the ability of sealing the cylindrical slots with widths of 1, 2, 3 and 4 mm, as shown in Fig. 4.5. The initial bridging capacity emerges closer to the 10-minute mark, meaning that the bridging particles is slowly transported to the fracture opening. For the opening of 1 mm, the pressure build-up increases until it hits the maximum pressure of 500 bar. Hereafter, the pressure is kept constant. Considering the 2 mm opening, the pressure build-up is far less compared with the 1 mm opening. Here, the bridge struggles to hold the pressure. In the time interval between 20 to 25 minutes, the maximum pressure of 450 bar is reached followed by a pressure drop to zero. Furthermore, the 3 and 4 mm pressure readings are low. For the 3 mm opening there are two peaks reaching a pressure of 100 - 150 bar. Once more, as these peaks are reached, the pressure breaks down to zero as the bridge is further weakened by the increased slot. For the 4 mm opening, signs of not being able to establish a stable bridge is shown, as the slot width is too large.

As for the coned slots shown in Fig. 4.6, the performance of StopLoss is highly erratic. The pressure readings for the 3 – 1 mm opening has periodically high values, but the time interval between each peak indicates a slow bridging process. As the cone increases in width, the performance of StopLoss is further inhibited in containing the pressure in the cell.

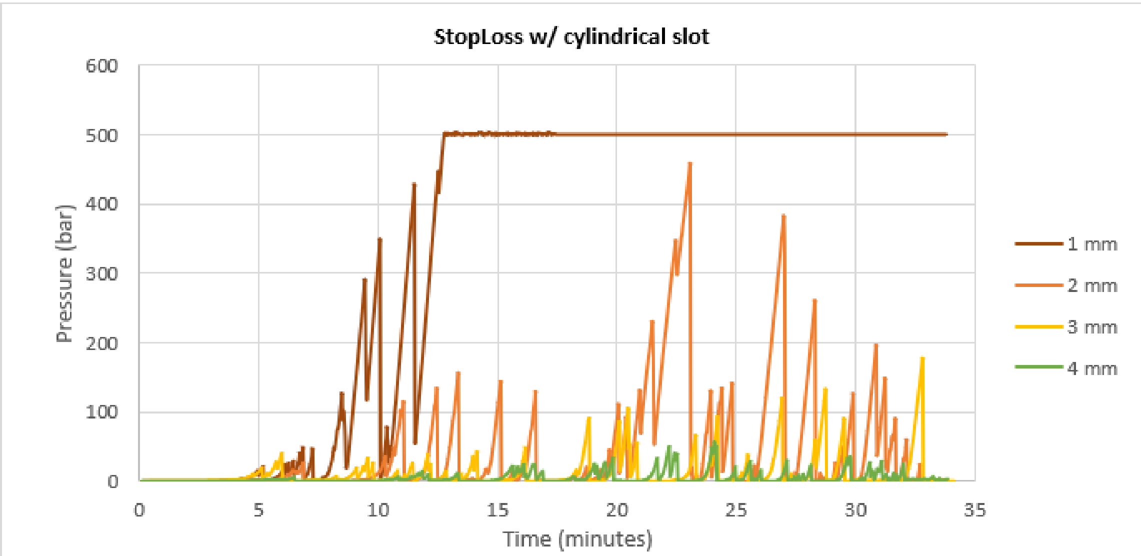


Figure 4.5: Data from the experimental bridging test with cylindrical slots for StopLoss.

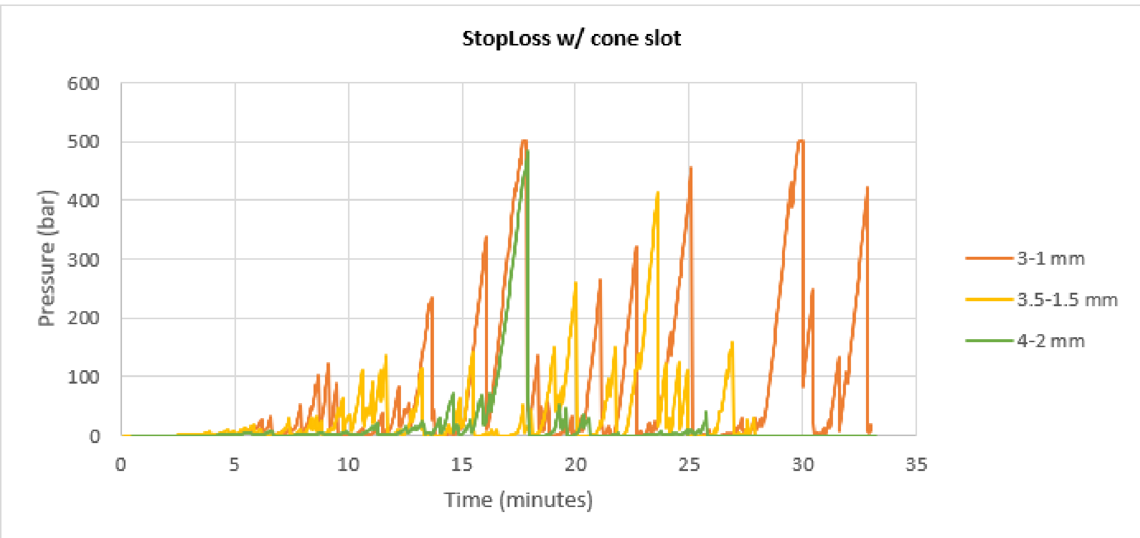


Figure 4.6: Data from the experimental bridging test with cone slots for StopLoss.

Experimental test with QuartzPack

QuartzPack could not contain the pressure inside the cell for the cylindrical slots. Therefore, no data will be presented form these experiments. For the analysis conducted on the coned slots, the performance of QuartzPack accelerated rapidly, capable of withstanding a maximum pressure of 500 bar with the cone width of 3 – 1 mm and 3.5 – 1.5 mm. As the cone width of 4 – 2 mm was utilized, fluid loss emerged.

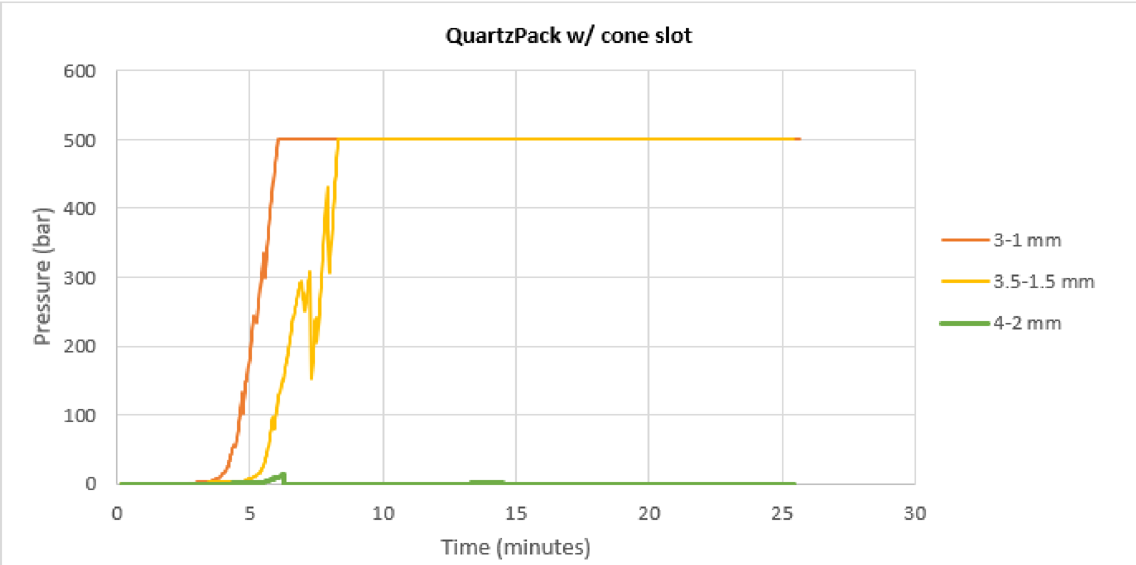


Figure 4.7: Data from the experimental bridging test with cone slots for QuartzPack

4.3.2 Comparison of LCM systems

In this subsection, the bridging results of the LCM systems will be compared and discussed for each slot width to further investigate and compare the bridging performance.

Comparison of 1 mm slot opening

As shown in the plot, both the ONS-mixture and StopLoss are able to withstand the maximum pressure of 500 bar, whereas QuartzPack could not hold any pressure. The bridging process for the ONS-mixture starts approximately after two minutes were a couple of pressure drops occur before the bridge is stable. The bridging process for StopLoss begins five minutes subsequent to the applied pump pressure. Here, there are frequent pressure drops prior to fully sealing off the slot opening. As shown in the plot, QuartzPack was not able to hold any pressures.

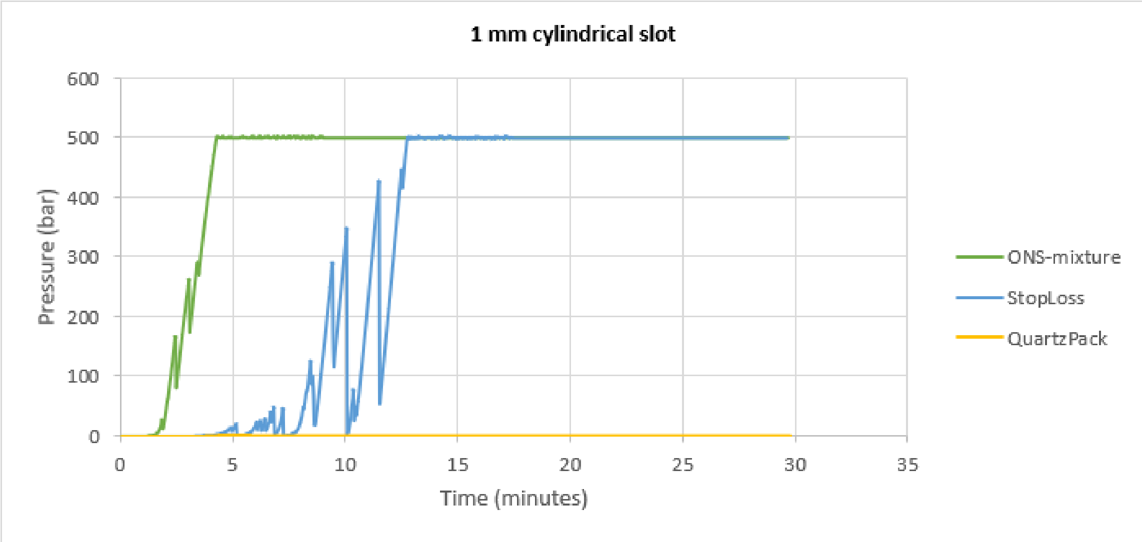


Figure 4.8: Comparison of LCM systems with 1 mm slot opening.

Comparison of 2 mm slot opening

For the slot width of 2 mm, the ONS-mixture could hold the pressure of 500 bar, but StopLoss appears to struggle in achieving a resistant bridge as the pressure frequently drops to zero. As for QuartzPack, the pressure remains zero throughout the experiment.

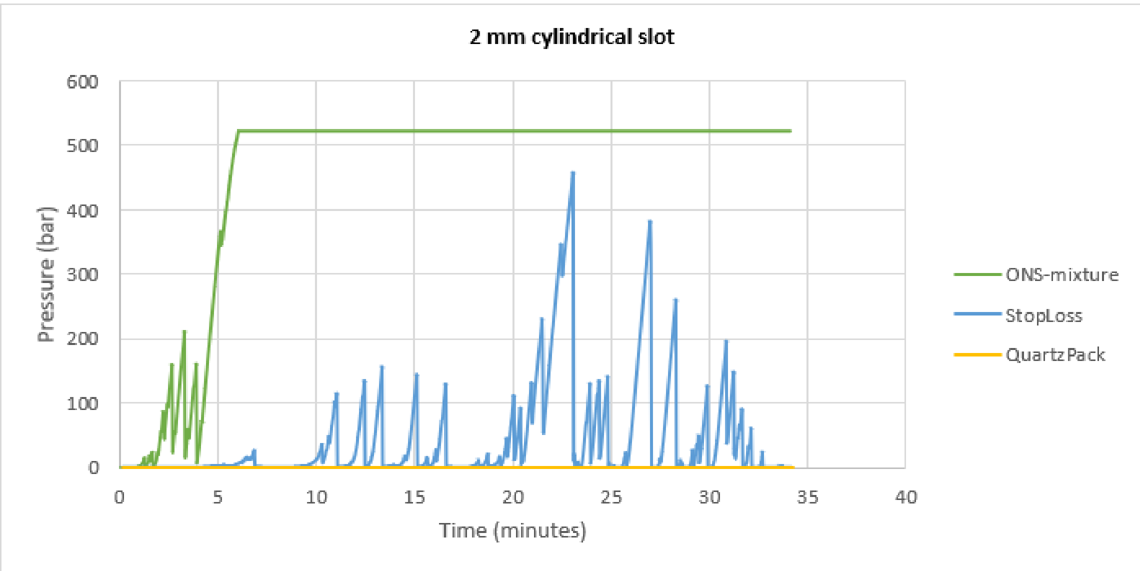


Figure 4.9: Comparison of LCM systems with 2 mm slot opening.

Comparison of 3 mm slot opening

For the cylindrical slot with width of 3 mm, the bridges become fragile. The LCMs have frequent pressure peaks which indicates an unstable bridging process. The bridges formed by the ONS-mixture frequently collapses but rebuilds throughout the experiment, able to withstand higher pressures. The same trend is observed for StopLoss, but at significantly lower pressures. As expected, QuartzPack was unable to achieve any pressure build-up.

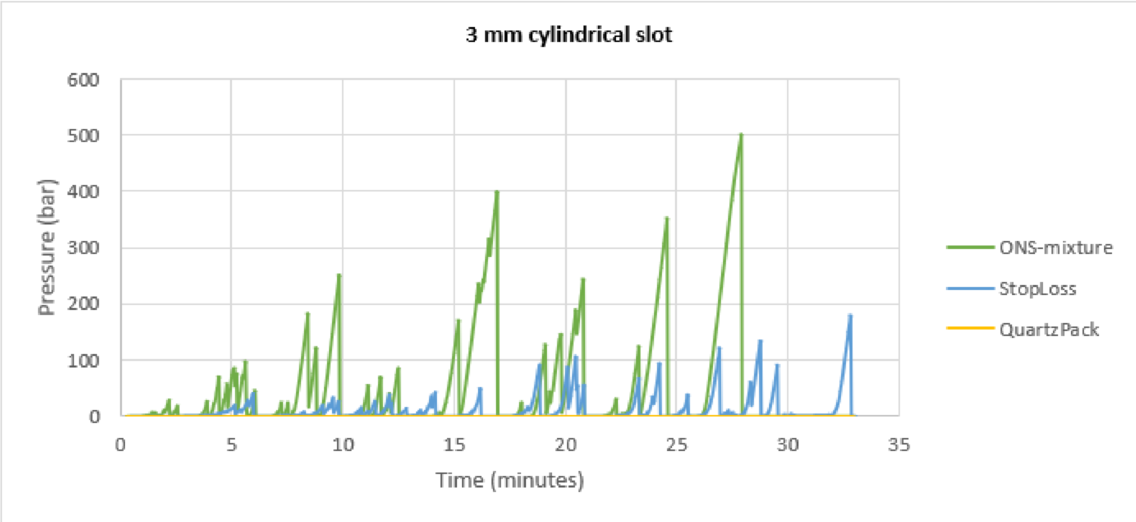


Figure 4.10: Comparison of LCM systems with 3 mm slot opening.

Comparison of 4 mm slot opening

The bridges are still able to form over the 4 mm slot opening but are more fragile, caused by the increased slot opening. As seen on the plot, there is a significant difference between the pressure resistance for the two systems. The ONS-mixture can hold a maximum pressure of 120 bar, and StopLoss achieves a maximum pressure of 50 bar.

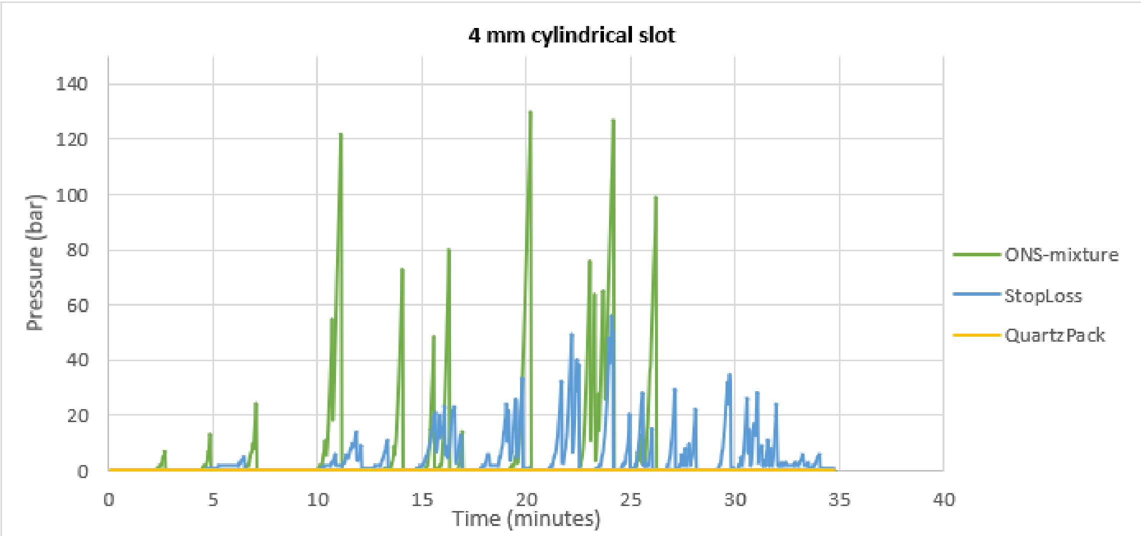


Figure 4.11: Comparison of LCM systems with 4 mm slot opening.

Comparison of 3 – 1 mm cone opening

With the cone opening of 3 - 1 mm, the ONS-mixture and QuartzPack have a similar trend. The bridges of these LCM systems can withstand a maximum pressure of 500 bar. The systems packs off the inside of the cone, creating a solid bridge. Whereas, the performance of StopLoss shows a repeated initial collapse pressure, but within 14 minutes higher pressure peaks are observed.

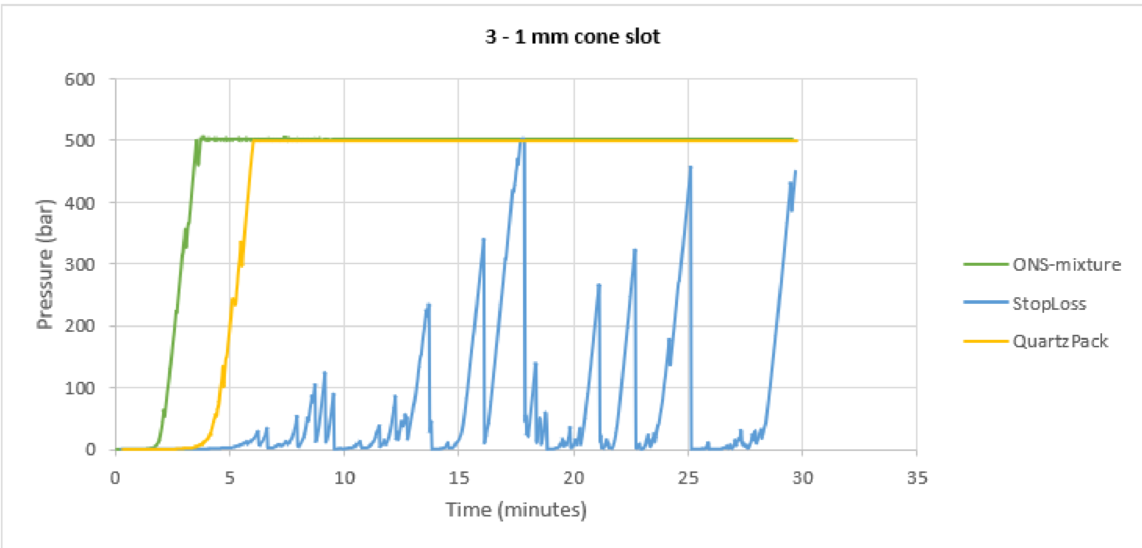


Figure 4.12: Comparison of LCM systems with 3 – 1 mm cone opening.

Comparison of 3.5 – 1.5 mm cone opening

As for the enlarged cone opening of 3.5 – 1.5 mm, the ONS-mixture and QuartzPack are still able to create a stable bridge that can hold the maximum pressure. At the three-minute mark the ONS-mixture has a rapid pressure increase prior to hitting the pressure of 500 bar. This solid bridge is formed in just over 1 minute.

For QuartzPack, the pressure build-up is of some delay compared with the ONS-mixture. The pressure starts to build up within five minutes, reaching a maximum pressure within three minutes. Furthermore, StopLoss is unsuccessful in the attempt to pack off the cone throughout the experiment, causing instability in the bridging process.

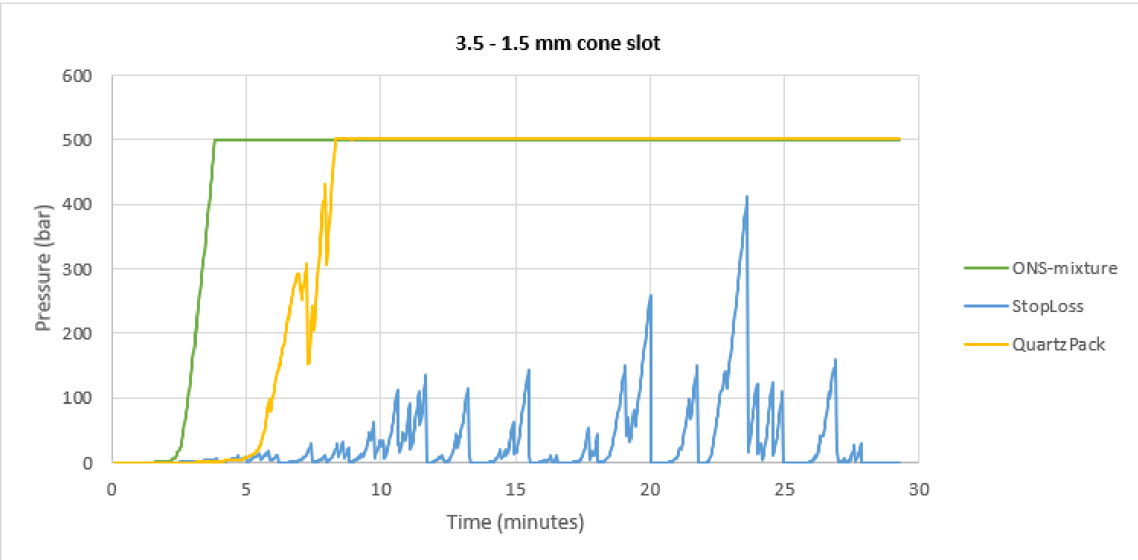


Figure 4.13: Comparison of LCM systems with 3.5 – 1.5 mm cone opening.

Comparison of 4 – 2 mm cone opening

For the cone opening of 4 – 2 mm, the sealing ability decreased for all three LCM systems. The ONS-mixture has a peak just a couple of minutes prior to pump start. After the first pressure drop, there is a larger time interval until the next bridge is established, which continues throughout the experiment. The bridging process for StopLoss is barely seen until the 15 minutes mark. Here, the pressure builds up to 500 bar before it drops to zero resulting in no further pressure build-up. As for QuartzPack, the pressure inside the cell remains zero.

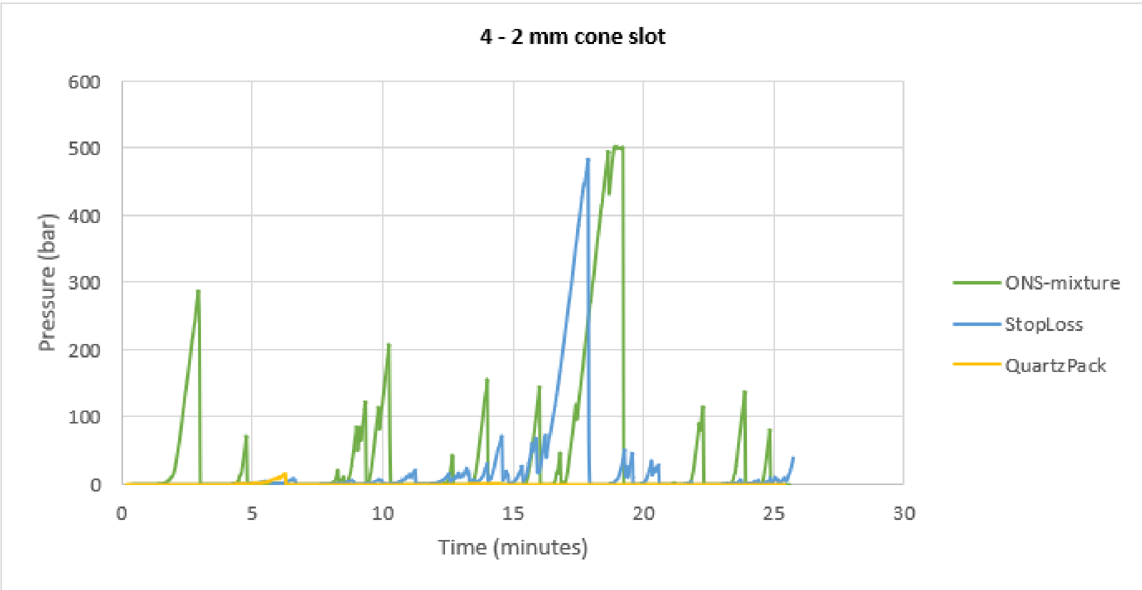


Figure 4.14: Comparison of LCM systems with 4 – 2 mm cone opening.

4.4 Analysis of bridging test results

Toroqi (2012) defined a new set of parameters for the particle plugging tests. The parameters provide additional information on the performance of the particles in terms of plugging and pressure resistance. This data may be used for a thorough comparison of the LCM systems. To be able to evaluate the data obtained from the bridging tests, the terms are briefly presented below [27]. Furthermore, in the following subsection, graphs are used to emphasize the results of the analysis.

Maximum pressure (P_{max}): The maximum pressure obtained by the particles, which is influenced by the particle distribution.

Average pressure (P_{avg}): The average pressure obtained in the cell gives information about the average strength capacity of the bridge.

Total number of peaks (N): Each developed pressure peak gives a number of collapsed bridges, regardless of the particles strength. A numerous of peaks indicates unstable bridging capacity.

Average peak pressure (P_{Pavg}): The average peak pressures is the average strength retained in the cell prior to a pressure drop.

4.4.1 Analysis of maximum pressure

In Fig 4.15 and Fig. 4.16, the maximum pressure for each LCM system is compared. Firstly, observations obtained from the plot with the cylindrical slots are presented. The ONS-mixture is able to reach a maximum pressure of 500 bar for 1, 2, and 3 mm slot openings. A rapid decrease in the maximum pressure is shown as the slot opening increases to 4 mm. As for StopLoss, there is a slight decrease in maximum pressure from 1 to 2 mm, but a steep decline is observed with openings of 3 and 4 mm. As a result of enlargement in the fracture size, more particles flow through the opening and the probability of forming a sufficiently resistant bridge reduces. Whereas for QuartzPack, the pressure is zero.

Secondly, maximum pressure readings from the plot with the cone shaped slots is reviewed. Here, the ONS-mixture was able to reach a maximum pressure of 500 bar for all cone openings. StopLoss also had an overall high maximum pressure value of 500 – 400 bar. QuartzPack holds a maximum pressure at the widths of 3 – 1 mm and 3.5 – 1.5 mm but has a steep decrease with the 4 – 2 mm, where the pressure build-up remained zero.

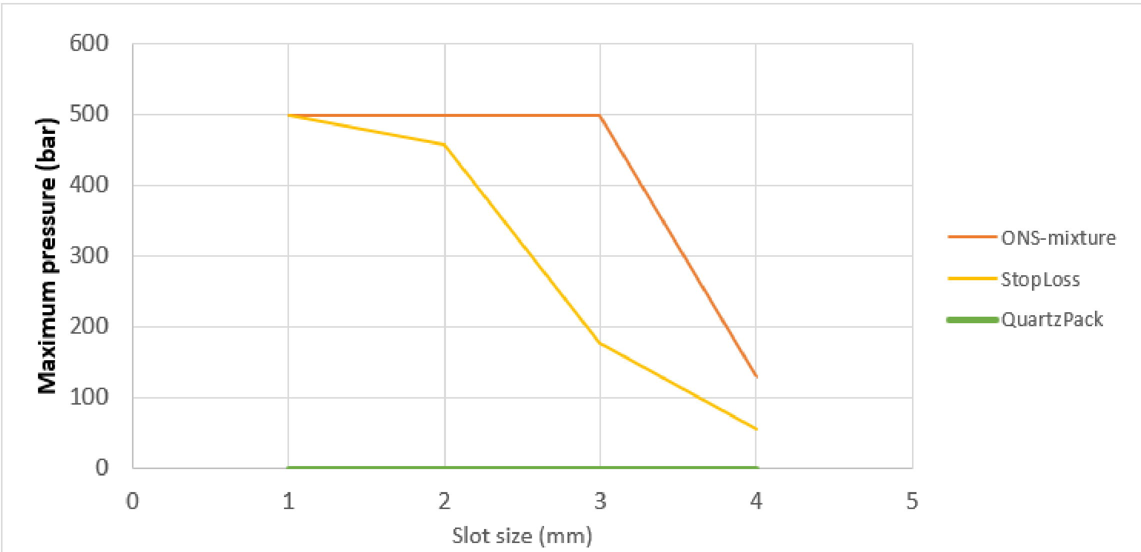


Figure 4.15: Analysis of the maximum pressure with cylindrical slots.

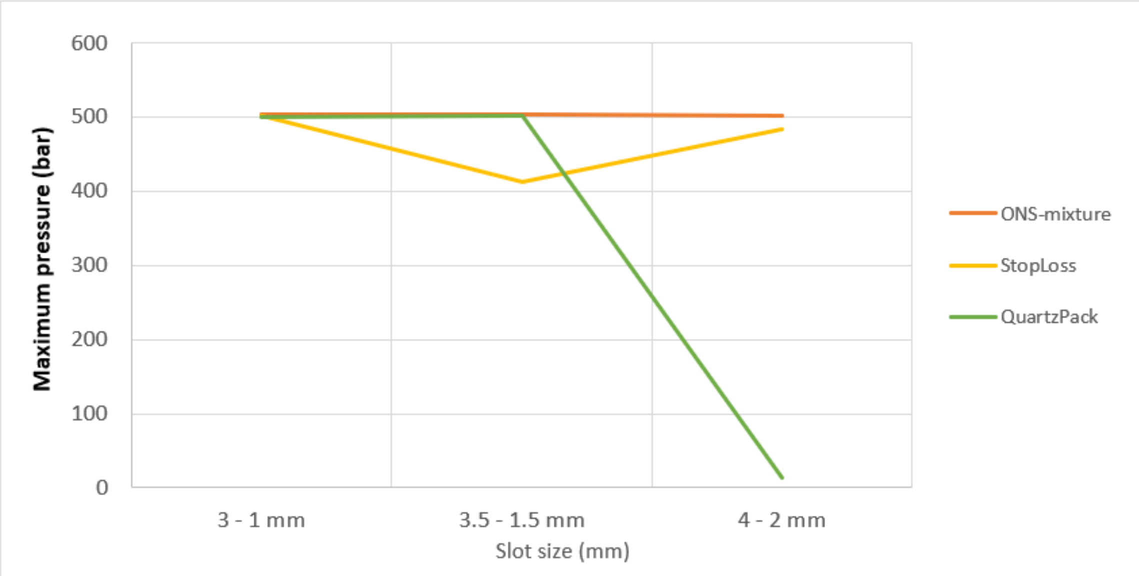


Figure 4.16: Analysis of the maximum pressure with cone slots.

4.4.2 Analysis of average pressure

The average pressure for the LCMs are shown in Fig. 4.17 and Fig. 4.18. First off, observations from the plot with cylindrical slots are discussed. The ONS-mixture is able to withstand high average pressure, while StopLoss has lower average pressure reading. This implies that the average strength of the bridges in these systems are quite incompatible. The ONS-mixture is considered the most ideal system of building a solid bridge for fracture widths of 1 and 2 mm, while StopLoss only has a resilient bridging strength over the 1 mm fracture width. The observations confirm that the average pressure declines as the slot width is increased.

The results from the test conducted with the coned slots shows an alternating behavior when compared with the cylindrical slots. The ONS-mixture and QuartzPack has virtually the same trend for all the three cone widths. The maximum average pressures are approximately 450 bar for 3 – 1 mm and 3.5 – 1.5 mm openings but as the width is increased, the pressure resistance has a sudden drop. Here, the ONS-mixture can hold an average pressure of 45 bar, but QuartzPack is not capable of withstanding any pressure. For StopLoss the average pressure readings are low. An average pressure of 60 bar is recorded for the 3 - 1 mm slot opening. There is a clear decreasing trend as the slot width is increased.

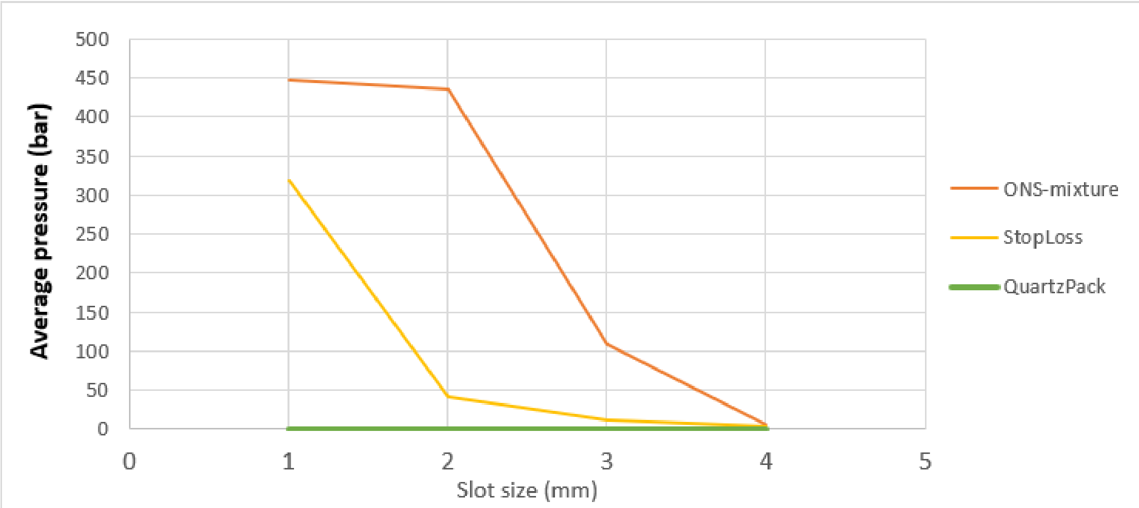


Figure 4.17: Analysis of the average pressure with cylindrical slots.

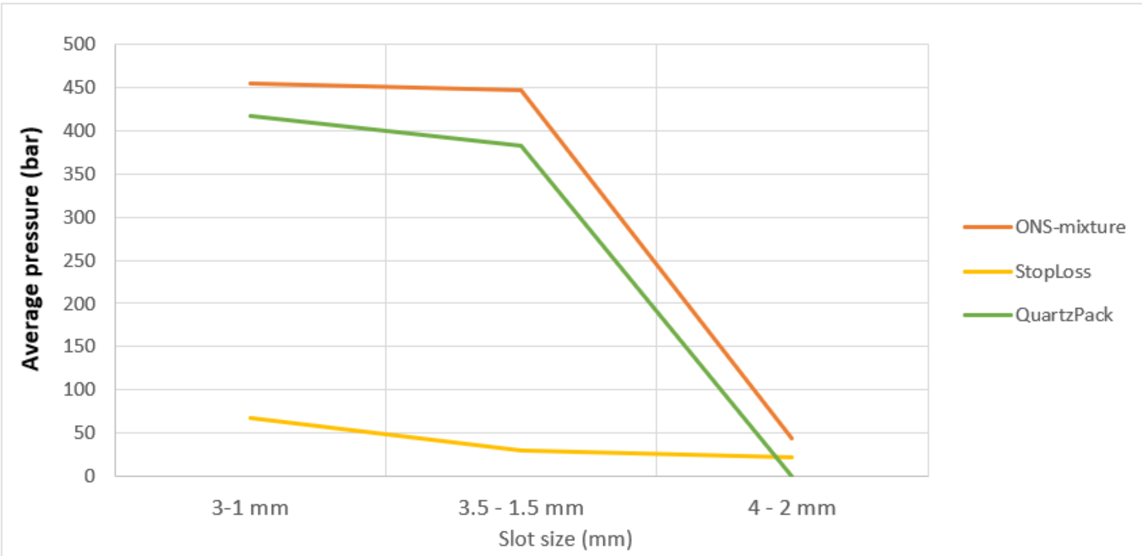


Figure 4.18: Analysis of the average pressure with cone slots.

4.4.3 Analysis of total number of peaks

In Fig. 4.19, and Fig. 4.20, the LCM systems ability to build a bridge over the fracture is shown. A large number of peaks can be interpreted as instability in the bridging capability, but a small number of peaks may indicate two scenarios: the LCM is able to withstand the higher pressure, or is not able to form a bridge at all.

Observations obtained from the diagram with cylindrical slots is that StopLoss has a large increase in peaks from 1 to 2 mm slot opening. As mentioned, StopLoss is able to build a stable bridge for the 1 mm slot but is striving to hold the pressure as the width is increased. This may result in an increase in the number of peaks. The number of peaks for the ONS-mixture are low for the slots of 1 and 2 mm but increases as the slot is widen. The total number of peaks decreases again for the 4 mm slot opening. Form earlier observations, one may say that the number is reduced as the LCM is unsuccessful of plugging the cell. As for QuartzPack, the pressure remained zero for the cylindrical slot, therefore no data is presented in Fig. 4.19.

Fig. 4.20 shows the number of peaks for the coned slots. For StopLoss the number of peaks is remarkably higher compared with ONS-mixture and QuartzPack. These values denote that StopLoss is unable to seal off the cones. The ONS-mixture has no peaks for the 3 – 1 mm and the 3.5 – 1.5 mm cone widths as it completely seals off the cell. As the width is further increased, ONS- mixture is inadequate of forming a stable seal, resulting in an increased amount of pressure peaks. QuartzPack has a low sum of peaks for all the widths. For the two smaller openings the pressure peaks are followed by an stable bridge that could resist a pressure of 500 bar. As for the large width of 4 - 2 mm, QuartzPack was not able to hold any pressure.

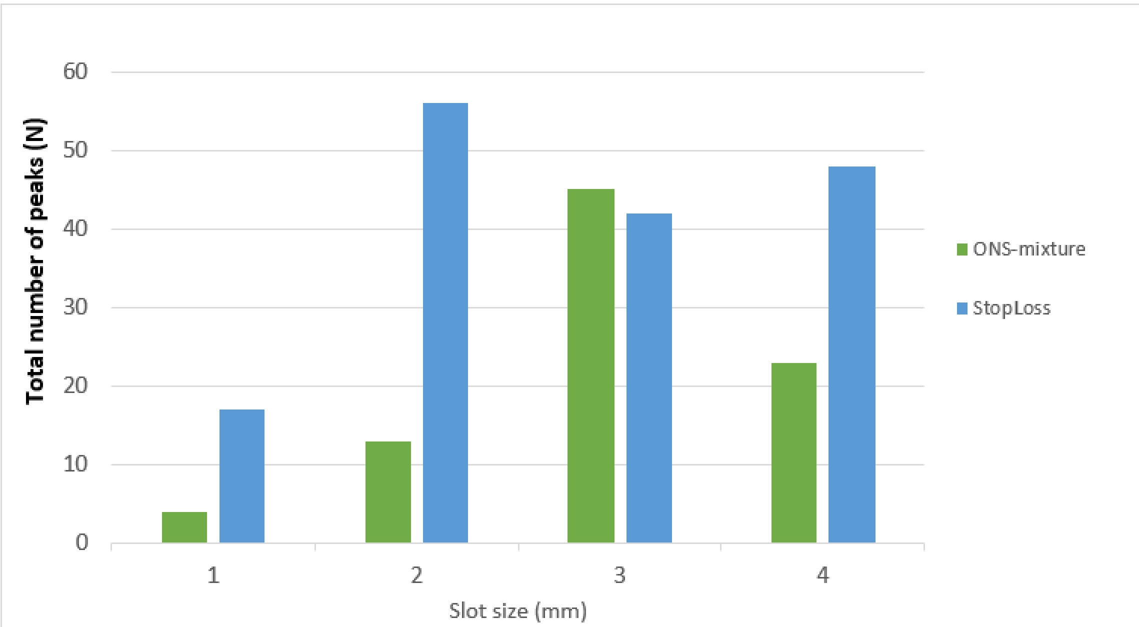


Figure 4.19: Analysis of the total number of peaks with cylindrical slots.

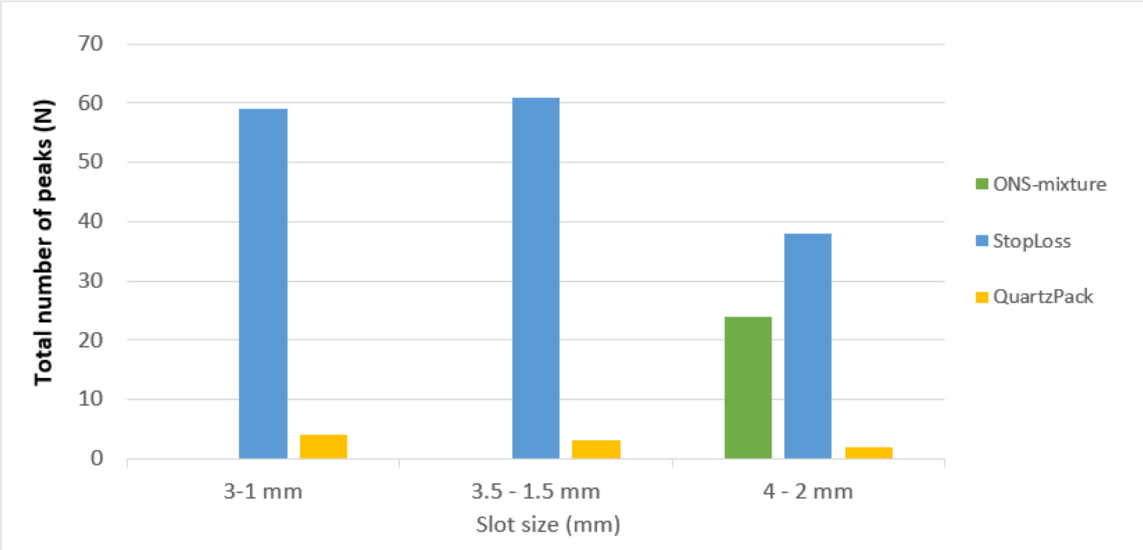


Figure 4.20: Analysis of the total number of peaks with cone slots.

4.4.4 Analysis of average peak pressure

The average peak pressure is a parameter containing information about the average strength of the bridge prior to a pressure drop. Fig. 4.21, shows the average peak pressure for the cylindrical slots. The plot indicates that the ONS-mixture can resist the highest pressure as it has a maximum average peak pressure of 150 bar and minimum of 50 bar. Furthermore, StopLoss has a maximum of 130 bar and minimum of 20 bar.

As for the coned slots, shown in Fig. 4.22, the results show that the ONS-mixture has an average peak pressure of zero for the widths of 3 – 1 mm and 3.5 – 1.5 mm. The pressure of zero is an outcome of no pressure peaks, as confirmed in the diagram that presents the total number of peaks in subsection 4.4.4. Whereas for the opening of 4 – 2 mm, the ONS-mixture has frequent pressure peaks as it struggles to build a bridge, causing an increase in the average peak pressure.

StopLoss has a gradual decrease in the average peak pressure. As the average peak pressure readings are low, and the total number of peaks are high it may indicate that the average strength of the bridge is weak. For QuartzPack, the average peak pressure is high at 3 – 1 mm and 3.5 – 1.5 mm, but has a decline for the 4 – 2 mm width as the material did not accomplish to generate the sealing ability. It should be noted that the average peak pressure is a poor indication for mixtures which successfully builds a solid bridge instantly, as indicated by the ONS-mixture results in Fig. 4.22.

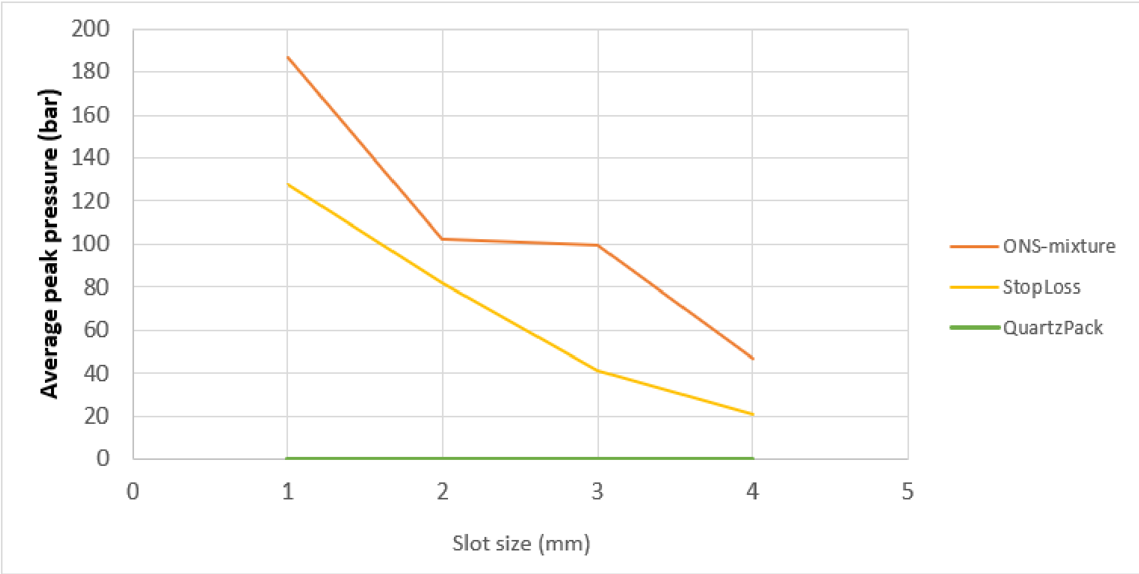


Figure 4.21: Analysis of the average peak pressure with cylindrical slots.

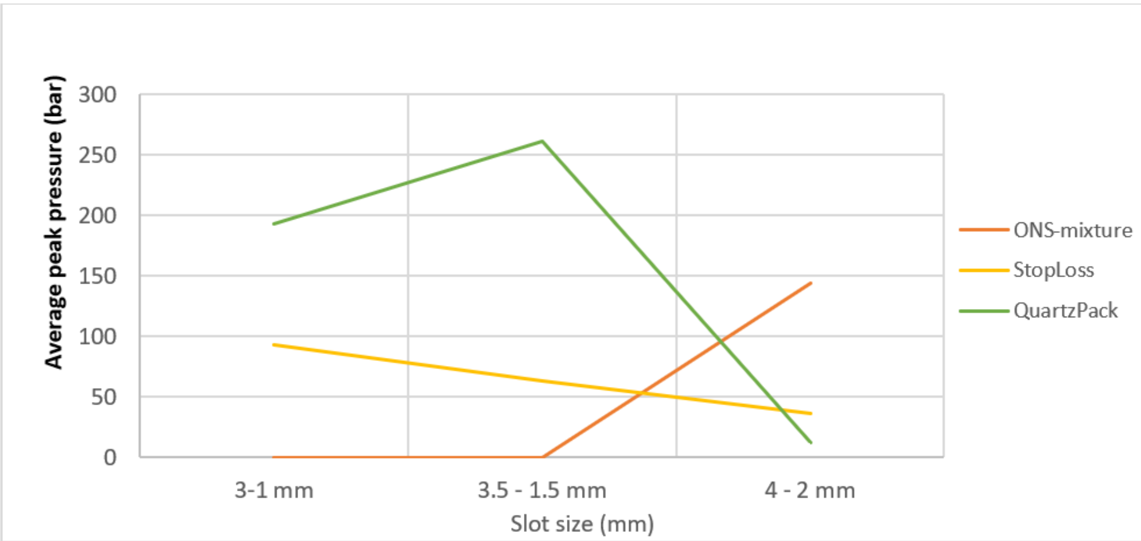


Figure 4.22: Analysis of the average peak pressure with cone slots.

4.5 Application of measured data

The results obtained from the bridging experiment have been applied in a wellbore simulation to further illustrate the application and performance of the LCMs. A hypothetical well, as described in Section 3.6, has been set up to simulate the bottom hole pressure at varying depths. The main assumption is that the various LCM mixtures have been spotted across the fractured formation and the drilling operation is about to continue. The objective of the simulation is to relate the laboratory data towards specific field applications. More specifically, at which depths are the LCM pills effective considering differential pressure between dynamic wellbore pressures and pore pressure (seawater gradient).

To conduct a reliable simulation, the average pressure of each LCM system was used to estimate the sustainable depths and pressures to make further recommendations of which system is most practicable. The Fig. 4.23 shows the strength of the bridge over cylindrical fracture openings. Whereas, Fig. 4.24 highlights the strength of the bridge/plug formed in a cone shaped fracture. The same assumptions for flow rates, depth and dynamic pressure applies for both figures.

Observations from Fig. 4.23 show is that the ONS-mixture is able to withstand a pressure of more than 400 bar, sealing a fracture width of 1 and 2 mm. Therefore, the LCM system can be operated in a depth of 4500 meters. As for StopLoss, the highest sealing pressure is approximately 300 bar over the 1 mm fracture width, resulting in an effective drilling depth of 3500 meters. As the fracture width increased to 3 and 4 mm, the LCM systems could not withstand the higher pressures.

In Fig. 4.24 the bridging strength for the coned fractures are presented. As the ONS-mixture and QuartzPack are capable of sealing 3 – 1 mm and 3.5 – 1.5 mm fractures at 400 – 450 bar, the obtainable drilling depth is 4500 meters. As measured in the bridging experiment, StopLoss has the maximum average pressure of 70 bar which is not enough strength at any depth of this simulation. None of the LCM mixtures are able to seal off a fracture of 4 – 2 mm at the given differential pressures.

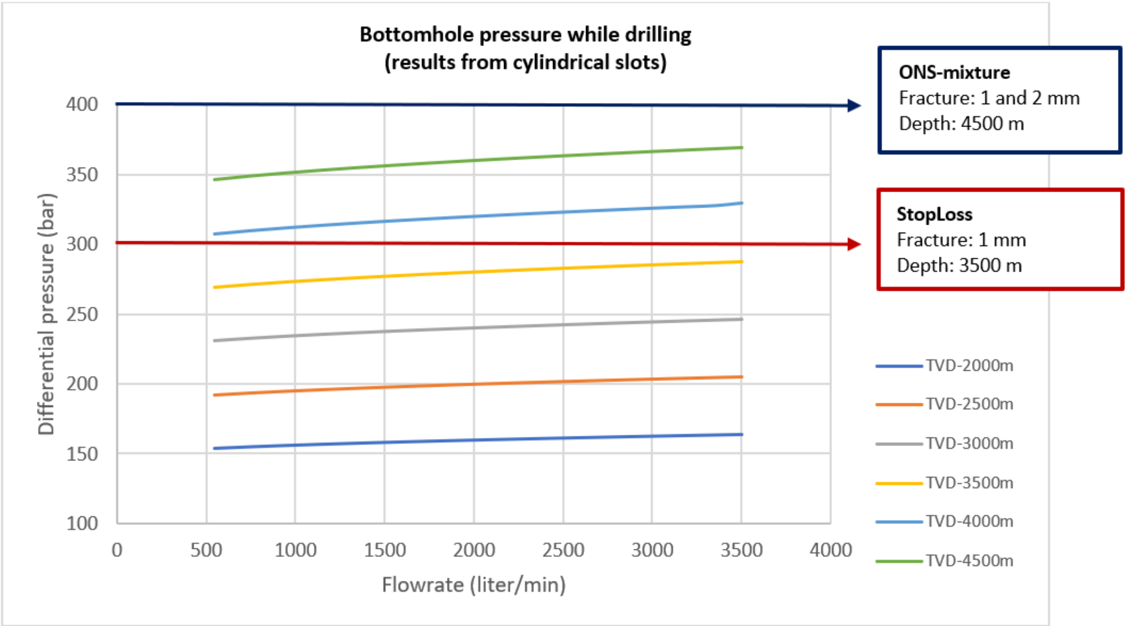


Figure 4.23: A simulated wellbore to illustrate the sealing strength of the bridges. The results conducted in this simulation is obtained form the cylindrical slot analysis.

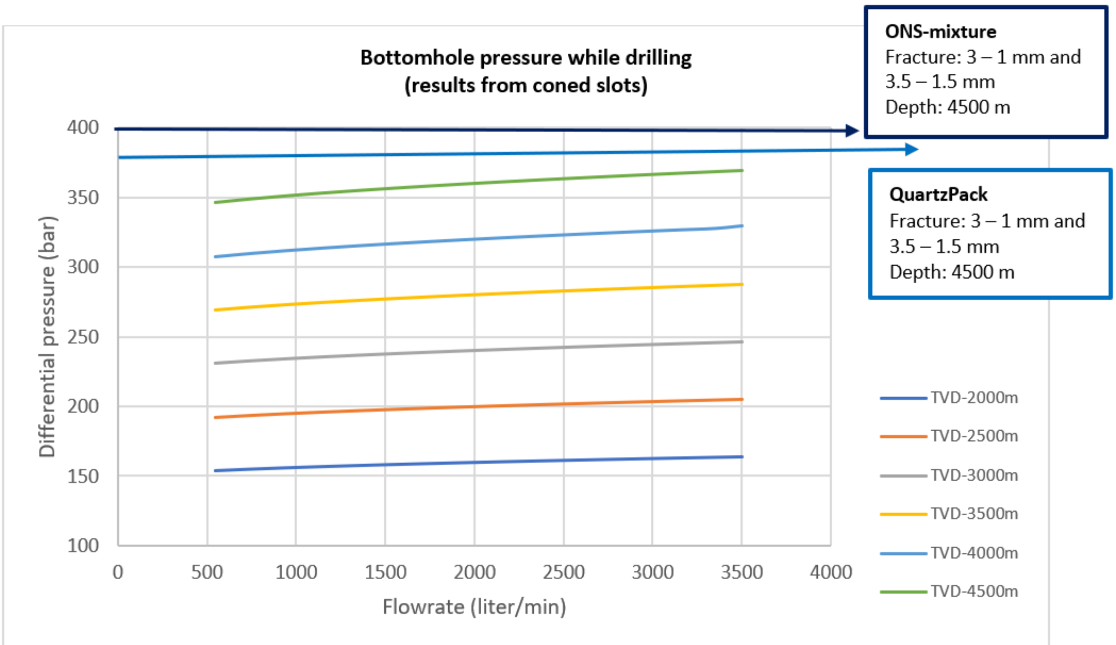


Figure 4.24: A simulated wellbore to illustrate the sealing strength of the bridges/plugs. The results conducted in this simulation is obtained form the cone slot analysis.

4.6 Summary of results

- The ONS-mixture was able to withstand the highest pressures for the cylindrical and coned slot openings. The system can create a stable bridge for the widths of 1 mm, 2 mm, 3 – 1 mm and 3.5 – 1.5 mm with a maximum differential pressure of 500 bar. As the fracture width increased to 3 mm, 4 mm and 4 - 2 mm the ONS-mixture was partially able to bridge the slot openings. However, as the pressure was increased towards the target of 500 bar, the ONS-mixture was still able to reach higher pressure peaks.

- StopLoss could build a solid bridge and hold the maximum pressure over the cylindrical slot with a fracture width of 1 mm. For the larger fracture widths, including both the cylindrical and coned slots, StopLoss was only partially able to create a bridge capable of sustaining moderate pressures for a short period of time.

- For QuartzPack a constant filtrate loss emerged as the particle in the LCM was not able to build a bridge or hold any pressure for the cylindrical slots. For the coned slots with widths of 3 – 1 mm and 3.5 – 1.5 mm, QuartzPack could hold the maximum differential pressure of 500 bar. As the cone width increased to 4 – 2 mm, the mixture was unable to hold any pressure.

Chapter 5

Discussion

A wide variety of lost circulation materials are found in the market. These have a distinct performance as the products and mixtures contain different material, concentration and hardness of particles, combined with various particle size distributions. To enhance the knowledge of three distinguished LCM systems, a bridging experiment with high differential pressure was conducted. As the results were presented, a discussion is essential to comprehend the results of the experiment.

The discussion involves a review of three important factors that may have a large effect on the results:

1. Particle size distribution
2. Hardness of the particles
3. Physical models for wellbore strengthening

To acquire a thorough perspective of the impact that the particle size has on the results, data obtained from the PSD measurements is presented below. It appears that the ONS-mixture consist of a minor amount of particles ranging from 63 – 355 micron, but a high quantity of particles within the range of 400 – 1000 micron. As for StopLoss, the system contains a higher quantity of smaller particles that gradually increase in size. Furthermore, QuartzPack has particle sizes ranging from nano-scale to larger particles of 1000 micron.

Table 5.1: Review of PSD.

PSD (micron)	d_{10}	d_{50}	d_{90}
ONS-mixture	90	500	2500
StopLoss	< 63	125	1200
Quartzpack	0.2	500	1000

For the cylindrical slot analysis, the LCM systems ability of stress caging is implemented as the fracture mouth is bridged. Here, the ONS-mixture and StopLoss showed results in regards of bridging fractures that are equal to or larger than the d_{90} value. However, QuartzPack were not able to bridge over the fracture mouth, which likely is caused by the mixture‘s particle size distribution. As there were clear indications of filtrate losses, the PSD may not be optimal.

The coned slot analysis was conducted to simulate a fracture with a specific length, to investigate two fracture models; the stress cage model as a bridge can form over the fracture mouth, and the fracture closure stress model that is achieve by plugging the fracture with an immobile mass. The results from this analysis showed that the ONS-mixture and QuartzPack were able to hold higher pressures over an extended period. Whereas for StopLoss, the small pressure peaks repeatedly dropped to zero as a stable bridge was not able to form. These results may emerge as the hardness of the particles in each mixture varies. The ONS-mixture and QuartzPack contains harder materials like granite, marble and quartz. The main content in StopLoss is wood which is a softer material. The hardness might increase the strength of the seal as the LCM is mechanically compressed downwards in the cone by higher pressures.

Also, another observation involving the plugging performances should be discussed, namely the physical models for wellbore strengthening. Results obtained for QuartzPack showed no sign of any pressure build-up with the cylindrical slots. But for the coned slot, the pressure resistance reached the maximum pressure of 500 bar. It is therefore assumed that QuartzPack fills the fracture, consolidates and turn into a immobile mass, which relates to the fracture closure stress model. Whereas for the ONS-mixture and StopLoss, it is assumed that both systems creates a bridge over the fracture mouth, following the principle of the stress caging model.

Chapter 6

Conclusion

In this thesis the bridging performance of three LCM systems have been tested. The LCMs were exposed to high differential pressure as the bridging performance was investigated with a variety in cylindrical openings of 1, 2, 3 and 4 mm, and coned slots of 3 - 1 mm, 3.5 - 1.5 mm and 4 - 2 mm were assessed. Based on the results from the bridging experiment, the following conclusions can be drawn.

It is distinctly observed that the d_{90} value has a significant impact on the overall seal integrities as the larger particles contributes in developing a stable bridge. More specifically, d_{90} has to be equal to or larger than the fracture opening to create a strong seal, which is an agreement with previous research [14]. Also, based on observations from the results, it is recommended to used particles with a high compressive strength if high differential pressure is expected.

Fig. 6.1 represent an overview that present the LCM's capacity of developing a stable bridge that can withstand the maximum pressure of 500 bar. The overall performance of the ONS-mixture is substantial, compared with StopLoss and QuartzPack.

Slot opening (mm)	ONS-mixture (d_{90} = 2.5 mm)	StopLoss (d_{90} = 1.2 mm)	QuartzPack (d_{90} = 1.0 mm)
1	√	√	
2	√		
3			
4			
3 - 1	√		√
3.5 – 1.5	√		√
4 – 2			

Figure 6.1: Overview of LCM mixtures able to withstand maximum pressure of 500 bar. Several of the experiments showed partial bridging at lower pressures which has not been included.

6.1 Recommendations for future work

Recommendations for further investigation of the LCM systems may be:

- Perform the high pressure bridging experiment as the pressure is gradually increased. To improve the accuracy of the experiment the pump should be stopped and pressure held at predetermined intervals to gather more exact data of bridging capacity of the LCM systems.
- Conduct an experiment on a low pressure API cell filled with gravel to analyse how the LCM mixtures can seal off a fractured formation.
- Construct slots with more diverse opening widths to obtain a thorough investigation.
- Add a smaller or larger amount of the ONS-mixture and StopLoss to the drilling fluid to analyse the optimal combination.
- Perform field study to correlate experimental results and well model. The width a fracture carries a high level of uncertainty and must be estimated from for example core samples or downhole logging measurements.

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