University of Stavanger

Faculty of Science and Technology

MASTER'S THESIS

Study program/ Specialization: Masters of Science in Petroleum Engineering Specialization: Drilling and Well Technology	Spring semester, 2012 Open / Restricted access
Writer: **Anton Gerner**	………………………………………… (Writer's signature)
Faculty supervisor: Mesfin Belayneh External supervisor(s): None	
Title of thesis: **Lost circulation experimental study in Oil Based mud and analyzing experimental data**	
Credits (ECTS): 30 ECTS	
Key words: Lost circulation Bridging tests	Pages: 61 + enclosure: 1 Stavanger, 14.06.2012 Date/year

Acknowledgment

This thesis concludes the study of my Master of Science degree at the University of Stavanger.

First and foremost, I would like to thank my supervisor Mesfin Belayneh for a helpful guidance throughout the project and practical guidance in operating the experimental equipment.

Also, I would like to thank MI Swaco for the materials used in the experiments and the University of Stavanger for the laboratory facilities.

Abstract

The problem of lost circulation have for a long time occurred during the drilling operation. During the drilling through induced and natural fractures, huge drilling fluid losses lead to the higher operational expenses. That is why, it is vital to design the drilling fluid, so that it may minimize the mud invasion in to formation and prevent lost circulation.
Generally, the mud loss occurs in the cavernous and vugular formations, as well as naturally occurring or induced fractures, or fractures in permeable and low permeability formations. Historically, this problem was dealt with the help of the Lost Circulation Materials (LCM). These materials are added to the drilling fluid to seal the fractures and to increase fracture initiation or fracture propagation pressure. The lost circulation materials may be used in the form of pills, when the lost circulation zone is identified. In some cases, solutions to lost circulation may be obtained by the pretreatment of the drilling mud with the particles of the proper material and with the proper particle size distribution. Subsequent treatment is also important, as a form of lost circulation prevention, when the particles are efficiently added to the mud system in the correct size, shape and type.

Understanding the mechanisms of fracture sealing and the performance of the lost circulation materials is critical if the problem of lost circulation is to be mitigated effectively.

The objective of this thesis was to investigate the performance of the chosen lost circulation materials (i.e LC-Lube) in 60/40 and 80/20 oil/water ratio OBM mud systems. The bridging performance of LC-Lube was studied with the help of the bridging tests in the laboratory. The D50 of the particle size distribution was 310 µm. The slot openings used in the bridging tests were 100 µm, 250µm, 300 µm, 400 µm and 500 µm. The concentration of LC-lube additive were 16,85 lb/bbl and 8,49 lb/bbl. The results of the tests were compared and the performance of the bridging materials discussed and analyzed. The results have shown that the LCM performance in two different mud systems when it comes to bridging, was better with 60/40 OBM in the case of 250 µm and 300 µm slot openings and a concentration of 16,85 lb/bbl. In the case of a lower concentration of the LC-lube, the performance with the 60/40 was as well better with the slot openings of 250 µm and 300 µm, although the difference was less pronounced.

Table of contents

List of figures

List of tables

List of symbols

P_{wf} - Fracturing Pressure

σ_h, σ_H - Minimum and maximum in-situ horizontal stresses

P_0 - Pore pressure

σ_t - Tensile strength of the rock

P_0 - Pore Pressure

σ_t - Tensile strength of the rock

σ_h, σ_H - Minimum and maximum in-situ horizontal stresses

α - Biot poroelastic parameter and is defined as $\alpha = 1 - C_r/C_b$, where C_r is rock matrix compressibility and C_b is rock bulk compressibility

ν - Poisson's ratio for the rock

w - width of the fracture

R - Distance from the center of the wellbore

E - Young's Modulus

H_c - the height of the compressed specimen and

H_r - the height of the rebound specimen.

List of abbreviations

LC – Lost Circulation

LCM – Lost Circulation Materials

Lb/bbl (ppb) – Pounds per barrel

OBM – Oil Based Mud

ECD – Equivalent Circulating Density

1 Introduction

Lost circulation is a frequent problem during drilling and occurs when the formation fracture resistance is exceeded by the pressure in the wellbore. Lost circulation is defined as an undesirable loss of drilling fluids into the fractures and the voids of the formation during the drilling or cementing. The mud loss may occur in any formation and in every depth with a wide range of severity depending on the loss zone. Lost circulation severity is often categorized as seepage, partial, sever and total lost circulation. Mud losses happen in formations with high permeability, natural or induced vertical and horizontal fractures and also in case of the cavernous and vugular rocks. Small natural fractures are found in virtually any formation, however, some natural fractures found in limestones and chalks may result in very high mud losses. As far as the induced fractures are concerned, they result from the tensile failure of the formation in the vicinity of the wellbore and could occur in any formation where the pressure in the well exceeds the fracture pressure of the formation. Caverns and vugs are also very problematic type of loss zones which in most cases occur in limestones and dolomites.

Various techniques have been studied and applied to arrest the lost circulation, most of which may be grouped into preventive and corrective measures. The main focus, however, have also been concentrated on the Lost Circulation Materials, as an important means of preventing and correcting the problem of lost circulation. The particle size distribution together with the physical properties of the materials are important factors for the choice of lost circulation materials.

1.1 Back ground for the thesis

Extensive studies on lost circulation have been conducted at the University of Stavanger among which is the Experimental and Analytical Borehole Stability Study by Mesfin A. Belayneh, conducting numerous experiments on particle bridging with various water-based fluids[17]. The aim of the project was to evaluate bridging performances of individual and blending of particles with various slot openings. The results were compared and ranked in terms of sealing capacity, time required to seal and stability of the mud cake.

Another important background for the research was the Experimental and Mechanistic Modelling of Fracture Sealing Performance, conducted by researchers from University of Calgary and University of Stavanger[10].

1.2 Scope and objective

In this project, the performance of lost circulation particles is studied in two different oil based systems with different water oil ratio.

- First, the study of the literature is conducted and the information on the lost circulation, lost circulation materials and experiments on lost circulation and borehole stability is collected. The theoretical part gives the understanding of the lost circulation mechanisms and ways of mitigating it.
- The practical part of the project consists of preparing the two oil based mud systems, one with 60/40 oil water ratio and another with 80/20 oil water ratio. The rheology of the drilling fluid is tested in the laboratory. As a lost circulation material, the resilient graphite (LC Lube) is used with a certain particle size distribution. After the mud and particle preparation, the lost circulation bridging experiment in two mud systems is conducted and the pressure data is collected.
- The third stage of the project is the comparison of the two chosen mud system and the analysis of the experiment results.
- The last part of the thesis is the conclusion, summary of the project.

2 Literature study

The problem of lost circulation may be usually solved with the help of preventive measures, when it is addressed during the planning phase, or it could be also solved during the execution phase when the well is being drilled. These two ways are usually called Preventive and Corrective measures of treating the problem of the Lost Circulation[1]. The choice between the strategies is usually dictated by the "Pay now, or pay later" principle, but in some cases it may not be always cheaper to invest in the preventive measures. The choice however depends on each individual well.

Preventive Measures. The main reason why preventive measures are important, is purely economical, that is avoiding drilling non-productive time due to lost circulation. One important way to prevent the lost circulation is managing the wellbore stresses. The main idea of wellbore strengthening is to design and apply borehole stress treatments to increase the hoop stress around the wellbore.

This treatment can be described as placing a designed particle size distribution particulate treating pill across the interval, and then performing an open hole formation integrity test up to the maximum equivalent circulation density (ECD) expected while drilling, cementing and casing that interval[1]. A short fracture (fractures) is initiated but is plugged immediately by the particles which prevent further pressure and fluid transmission to the tip of the fracture and simultaneously propping the fracture to prevent closure. As a result, the hoop stress is increased around the wellbore and the strengthened wellbore can contain a higher ECD.

Software is used to predict the ECD over interval, the first module in the software is used to calculate the fracture width which could be initiated and the second module gives a proposition for the proper material and PSD that can prop and plug the fracture. Normally, borehole stress treatment materials are selected from sized resilient graphitic carbon and ground marble. Afterwards, the third module is used to predict the change in rheology, which is affected by the added LCM, and the new ECD is calculated[1].

LCM is not the only additive in the drilling fluid, special chemical sealant treatment is designed using the software for long fractures. Chemical sealant systems are designed to react with drilling fluid to make a highly viscous and cohesive sealant which is displaced into the fractures.

A particular example of preventive measures could be a depleted reservoir, where the Fracture initiation gradient is lowered to less than the mud weight. The drilling fluid is pre-treated with the selected particulates before entering the depleted formation. Particulates have to be present in the correct size and concentration before fractures are initiated by the excessive circulation pressures[2].

Corrective Measures. The well construction plan should not only address pretreatment and borehole stress treatments, but lost circulation mitigation if it occurs. In this situation both particulate and chemical sealant systems could be used. The design of these is based on the fracture widths estimated by the model.

One example of fighting the problem is the Combination Materials – which is basically a combination of resilient graphitic carbon and other sized components plus having a component that absorbs large amounts of water when it hydrates which increases volume and viscosity. It all turns into a hybrid chemical/particulate treatment[1]. When the treatment is pumped, it is not completely hydrated and has a lower viscosity, in the same time it can carry the LCM. When it enters the lost circulation zone, hydration continues and a viscous plug is created. The sized solids are also in place to plug the zone. This type of treatment is often more effective compared to the conventional LCM treatment.

It is also advised to add subsequent treatments in the form of sweeps, instead of adding into the active drilling fluid system in the suction pit. It will ensure the wellbore sees a higher concentration of particulate materials. It is also pointed out in the literature that one should have remediation materials on site for immediate application if needed.

2.1 Review on Lost Circulation and LCM

Lost circulation, or lost returns, is the loss to formation voids of whole drilling fluid or cement slurry used during drilling operations. The loss may vary from a gradual lowering of the pits to a complete loss of returns[14].

Mud losses vary in type, severity, and location in the hole. Even having the experience in the area, it is difficult to make valid standard recommendations. However, there is a systematic approach to controlling lost circulation that uses both preventive and corrective measures. It is mostly concerned with correct use of LCM such as bentonite, diesel oil and cement and a blend of bridging agents that are stocked on the location.

Types of Loss Zones.

Mud losses occur to the following types of formations[14]:

1. Unconsolidated or highly permeable formations (such as loose gravels)
2. Natural fractures
3. Horizontal induced fractures
4. Cavernous formations (crevices and channels)
5. Vertical natural and induced fractures.

Normally, loss zones are either horizontal or vertical. Induced and natural fractures are horizontal in shallower depths, as we go deeper, fractures are vertical. For inducement of horizontal fractures, one should overcome rock strength and overburden pressure. Vertical openings are formed without lifting overburden, and are formed at lower pressures.

Horizontal Loss Zones[14]

Porous sands and gravels. If the matrix of porous formation takes in whole mud or cement, it must have permeability of 10-100 darcies. Gravels and shallow sands often reveal such permeabilities and can accept cement or mud. The deeper sands normally don’t show the permeability more than 3,5 darcies, that is why their matrices are not often loss zones if they are not fractured. The pores of gravel constitute the loss zone, these can be filled with water with different pressures. For gravel widening, overburden must be lifted.

Natural or intrinsic horizontal fractures. A natural horizontal fracture can exist if the overburden is self-supporting. This is true for any width of the fracture, and for the widening of that, the overburden has to be lifted. The opening may be filled with water or air, so that the whole can transfer the drilling mud into the fracture.

Induced horizontal fractures

There may be some cases when the horizontal fracture can be induced. One of the most common is in shale. Another situation is offshore in an undercompacted sea bed.

Cavernous formations

A natural fracture of very large proportions which occurs in limestones, is called cavern. Cavernous formations are horizontal and overburden is self-supporting. Water can be flowing in horizontal caverns both within the fracture, and from an upper or lower zone into them, and it will make the sealing more difficult.

Vertical Loss Zones[14]

Natural vertical fractures. These fractures may exist in the deeper formations, but while the fracture is there, it has little or no width. That's why the mud losses to them are small until the fractures are widened. This widening happens more easily than horizontally induced ones. If the opening already exists, only the fracture propagation pressure must be overcome and widen the fracture.

Induced vertical fractures. The most difficult mud losses occur in caverns, but these are not the most common ones. Caverns form mainly in limestones, while the mud losses to induced vertical fractures may occur in essentially any formation. The reasons why the fractures are induced are: high mud weight, well irregularities, excessive back pressure or chokedown, closed hydraulic system or rough handling of the drilling tools.

Underground blowout. It is a condition where fluids (gas or water) are flowing from a lower active zone into a higher loss zone (normally an induced vertical opening).

Induced vertical fractures distinguish from natural vertical fractures in a way that mud loss to induced ones requires enough pressure to break the formation. The loss to natural fracture only needs the pressure to exceed the pressure of fracture propagation.

The plugging mechanisms in horizontal and vertical loss zones would be different since the borehole geometry of the fractures is different. While horizontal zones contact on a circle, the zone would be limited in height and lost circulation materials would pancake out in a horizontal plane or on the face of the hole. The vertical zones contact the hole in a line and can have vertical contacts up to 500 feet in height. Lost circulation materials would flow into a vertical plane and would not pancake but tend to drop or settle - extending rather than sealing the fracture.

Some of the ways of mitigating the lost circulation in different zones are analyzed by Messenger, these are summarized in the table 1.

Porous Sands and Gravels	Bridging agents which form a cake on the face of the gravel. Fiber component aids by binding the granular, the flake bridging agents with the gravel. (for example, plugging with sawdust with shredded leather fiber.	
Horizontal Fractures	Up to ¼ inch wide	Bridging agents approximately the width of the fracture The seal is more permanent if the bridge is out in the fracture and the fracture is packed with LCM and mud solids by dehydration.
	From ¼ inch to 1 foot	Cement slurries, if the slurry can be held till the cement sets. Soft plugs run before the slurry as a backup to hold the cement slurry in place. Soft/hard plugs.
Vertical Fractures	Fracture must be permanently pried apart by packing it with dehydrated mud solids and bridging materials Dehydration can only occur down the fracture if the fracture is in nonporous formation. Portland cements. The fracture must be pried apart by developing squeeze pressure and held apart while the cement slurry dehydrates and sets. Soft plugs	

Table 1: Lost Circulation in Different Zones [14]

There have been numerous different lost circulation materials used in the oil industry, some of them are presented in the table 2, with the evaluation test proposed by Howard and Scott.

Various Bridging Materials and their Evaluation tests (after Howard and Scott)

Material	Type	Description	Concentration lb/bbl	Largest fracture sealed, in.
Nut Shell	Granular	50% 3/16 + 10 mesh 50% 10 + 100 mesh	20	0,2
Plastic	Granular	50% 3/16 + 10 mesh 50% 10 + 100 mesh	20	0,2
Limestone	Granular	50% 3/16 + 10 mesh 50% 10 + 100 mesh	40	0,13
Sulfur	Granular	50% 3/16 + 10 mesh 50% 10 + 100 mesh	120	0,13
Nut shell	Granular	50% 10 + 16 mesh 50% 10 + 100 mesh	20	0,13
Expanded Perlite	Granular	50% 3/16 + 10 mesh 50% 10 + 100 mesh	60	0,11
Cellophane	Lamellated	¾ in. flakes	8	0,11
Sawdust	Fibrous	¼ in. particles	10	0,11
Prairie hay	Fibrous	½ in. fibers	10	0,11
Bark	Fibrous	¾ in. fibers	10	0,07
Cotton Seed Hulls	Granular	Fine	10	0,06
Prairie Hay	Fibrous	¾ in. particles	12	0,05
Cellophane	Lamellated	½ in. flakes	8	0,05
Shredded wood	Fibrous	¼ in. fibers	8	0,035
Sawdust	Fibrous	1/16 in. particles	20	0,02

Table 2: Different Lost Circulation Materials [15]

Among the lost circulation materials used nowadays are the Resilient Graphite, Ground Marble, different fibers and chemical sealants used for the lost circulation problem. Some of these are described here, whereas the main attention is drawn to the resilient graphite which is used in the experiment.

Resilient Graphitic Carbon Material[6]

The most important characteristic of graphitic carbon is its resiliency (up to 150% at 10000 psi). There is no other LCM that when put in a press at 10000 psi , still yields free-flowing beads. All other LCM will compact. This resiliency allows the product to compress when pressure is applied and rebound when the pressure is released, whereby maintaining the seal at different pressures.

In addition to its resilient characteristics, graphitic carbon is available in various grades which allows to design the pill to design the requirements of the seal.

Fibers[7] are often used as LCM during cementing. Fiber evolution began with 2 – in. long natural fibers, and glass fibers 3-mm long are available to the industry for lost-circulation issues.

Losses before cementing can be controlled by treating mud with LCM. Losses can also occur after running and setting the liner. Fibers are generally organic polymers and are added to cement slurries after preparation. Fibers are inert and do not affect slurry properties, like fluid loss, thickening time etc. But there are mixing issues associated with large concentrations of fibers related to bridging and plugging at mixing and pumping units, float equipment etc. It has also been observed that specific gravity of conventional fibers is less than water, that is why they may float on the surface after mixing, causing the slurry to be inhomogenous.

The new types of fibers have been developed for use with cement slurries. Some of these fibers are brittle, so any bridging can be unplugged after applying higher pumping pressures. Some elastomers can assist in minimizing loss by helping to bridge off the porous formation or fracture when combined with these new fibers. These fibers are smaller in sizes (1/8-in. length) and can be used in larger quantities than the conventional fibers. They increase fluid viscosity and special devices are required for rheology measurements.

Ground Marble and combinations of LCM. [8]

In many cases, it is a combination of several lost circulation materials that works better in arresting mud losses compared to just one type of LCM. Traditionally ,the combination of

Ground Marble and resilient graphitic carbon is reported to perform due to synergetic effect between the two. In the case of reservoir zones, operators usually recommend the use of particles that minimize or have no impact on formation damage. The usual definition used by many operators is equate the "non-damaging" to "acid soluble". Ground marble is, as of now, the most widely used as non-damaging LCM in the reservoir zones. Particles like GM alone might be good enough in arresting fluid losses, but in the case of highly permeable formations or formations with large fractures or vugs, they often fail, particularly if a wide PSD is not maintained, but the combination of high aspect ratio materials like fibers with GM demonstrate a complete plugging.

The presence of high permeability features in the formation, such as large naturally occurring fractures or an extensive interconnected vugular porosity system, represent a significant challenge for overbalanced drilling operations with respect to rapid and deep invasion and significant permeability impairment. In this case one may use a mixture of ground marble, unique resilient graphitic carbon and fibers.

2.2 Review well stress

2.2.1 Well fracture models

2.2.1.1 Non-penetrating fracture model

In rocks like shale with low permeability, the bridge will need extremely low permeability to prevent the transmission of the pressure into the fracture. In situations like these, one needs mud cakes with extremely low fluid loss. Aston et al have analyzed fluid loss mechanisms in oil muds and described ways for achieving those muds.

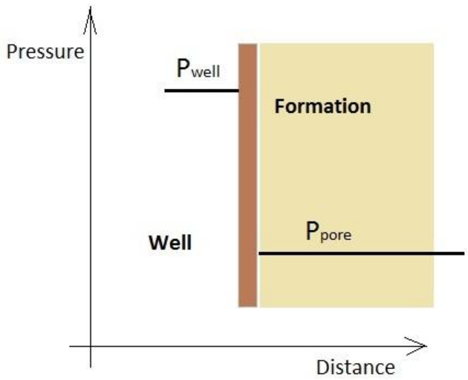


Figure 1: Non-Communicating Boundary Condition [18]

The bridge formation across a shale opening should be considered in detail. The beginning flow of fluid into the fracture when it is formed will put the bridging solids at the opening mouth, but a difference in pressure across the bridge should hold the bridge stable. Pressure decay into the shale matrix behind bridge will be minimal especially with oil muds, which have additional sealing action because of the interfacial tension. In water based muds, a slow pressure leak off into the shale will occur. The challenge will become to engineer the water based fluid with a very low fluid loss, so that the permeability of the bridge at the opening would be minimal[12]. Figure 1 shows the situation with the low permeability rocks.

Aadnøy and Chenevert (1987)[19] obtained elastic solutions linking the hydraulic fracturing initiation pressure P_{wf}(breakdown pressure) and the two principal horizontal stresses σ_h and σ_H and for this derivation, the Kirsch solution can be used. As is marked earlier, the pore pressure in the surrounding formation remains same during hydraulic fracturing, that is fracturing fluid does is not entering the formation. When one of the principal effective stress components is larger than the tensile strength of the rock (σ_t), the hydraulic fracturing is initiated. As far as tangential stress is concerned, it will be perpendicular to the minimum horizontal stress[17]. Thus, the initiated hydraulic fracture will be extended in the direction of the maximum horizontal stress and formation breakdown pressure will be related to the stress according to Kirsch's equation:

$$P_{wf} = 3\sigma_h - \sigma_H - P_0 + \sigma_t \qquad 1$$

Where:

- P_{wf} - Fracturing Pressure
- σ_h, σ_H - Minimum and maximum in-situ horizontal stresses
- P_0 - Pore pressure
- σ_t - Tensile strength of the rock

This equation is a function of in-situ rock and reservoir parameters and experimental work show that the fracturing pressure also depends on the drilling fluid used.

Experiments have shown that for penetrating fluids without filtrate control, a Kirsch equation works well. Fracture initiation during well stimulation can be modeled with Kirsch equation, which simplest form is:

$$P_w = \sigma_h \qquad 2$$

This simplest form stated that borehole will fracture when minimum in-situ stress is exceeded, in case the there is a penetrating fluid. During the drilling operation, the filter cake barrier is formed by the fluids.

2.2.1.2 Penetrating fracture model

In permeable rocks particle bridge doesn't need to be perfect because the passing fluid will leak away from within the fracture into the rock matrix. That is why there will be no pressure build-up in the fracture and the fracture will not develop. If a mud cake forms initially on the walls of the fracture, the opening could grow slowly to expose new surface and relieve the pressure. Afterwards, the pressure will decline first behind the bridge when the fracture forms. That will increase the effective stress across the fracture and cause closure behind the bridge. That will become a stable foundation for the bridge[12].

If mud contains the particles that are very small to bridge near the opening, the fracture can become sealed by a mud cake build up inside the fracture. In this situation, the sealing will be slower and the fracture length may extend too far, and the useful stress cage effect may not form. Fracture gradients observed in sands are usually higher than predicted by theoretical models. The reason might be the presence of mud solids and mud cake deposition[12].

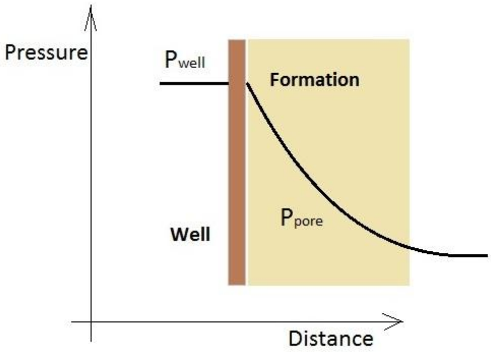


Figure 2: Communicating Boundary Condition [18]

It is illustrated that there exists a fluid flow and pressure communication between formation and the well. The flow of the fluid inside the formation adds to the stress field in around the wellbore. So in clean open holes without mud cake, this is the situation[17]. This effect of fluid permeation on the stress distribution in the vicinity of the wellbore has been studied by Haimson and Fairhurst (1968) using the theory of poroelasticity and obtained the following equation:

$$P_{wf} - P_0 = \frac{3\sigma_h - \sigma_H + \sigma_t}{2 - \frac{\alpha(1-2\vartheta)}{1-\vartheta}} \qquad 3$$

Where:

- P_{wf} - Breakdown Pressure
- P_0 - Pore Pressure
- σ_t - Tensile strength of the rock
- σ_h, σ_H - Minimum and maximum in-situ horizontal stresses

α - Biot poroelastic parameter and is defined as $\alpha = 1 - C_r/C_b$, where C_r is rock matrix compressibility and C_b is rock bulk compressibility

ν - Poisson's ratio for the rock

2.2.2 Stress cage theory

The principle of the Stress Cage Theory is to deposit solids at or close to the face of the induced fractures which will act as a proppant and also isolate fluid pressure in the wellbore from the majority of the fracture. The dissipation of the filtrate into the formation beyond LCM plug will lead to dissipation of the pressure. Solid particles plugging the fracture keep it open, and near wellbore tangential stress increases[5]. An equation for a penny shaped fracture with strengthening effect is as follows

$$\Delta P = \frac{\pi w E}{8R(1-\vartheta^2)} \quad (4)$$

where

- w- width of the fracture
- ν- Poisson Ratio
- R- Distance from the center of the wellbore
- E- Young's Modulus

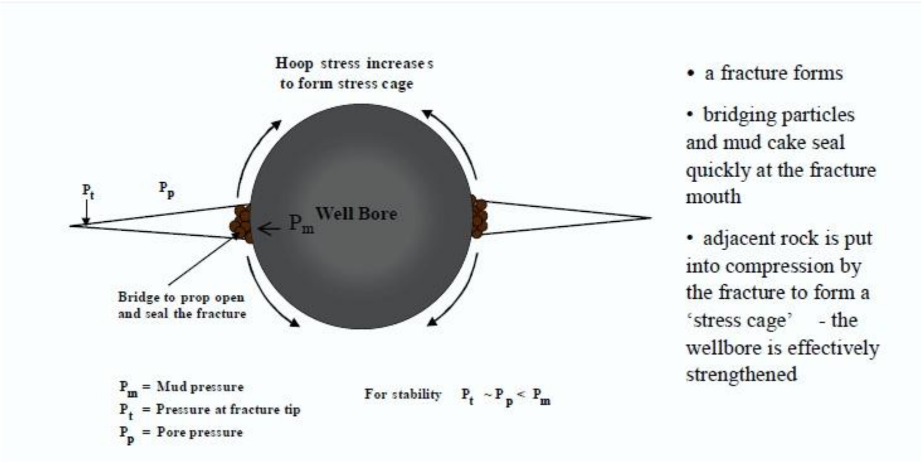


Figure 3: Stress cage concept to enhance wellbore strength [12]

Stress cages result in a wellbore strengthening with the help of changing the stress state in the vicinity of the well. This is accomplished by allowing the fractures to form in the wellbore formation and sealing them with the lost circulation material of the sufficient size and concentration. The materials act as wedges compressing the formation within the zone of stress caging around the well.

The lost circulation particles should hold the fracture open near the fracture mouth and to seal efficiently to provide pressure isolation to prevent the propagation of the opening. In case when the induced opening is created and sealed at or close to the wellbore, the hoop stress is established in the vicinity of the well. However, the stress cage applications are specific for a field and formation that is mud additives used for the stress cage effect are custom designed for each specific well[6].

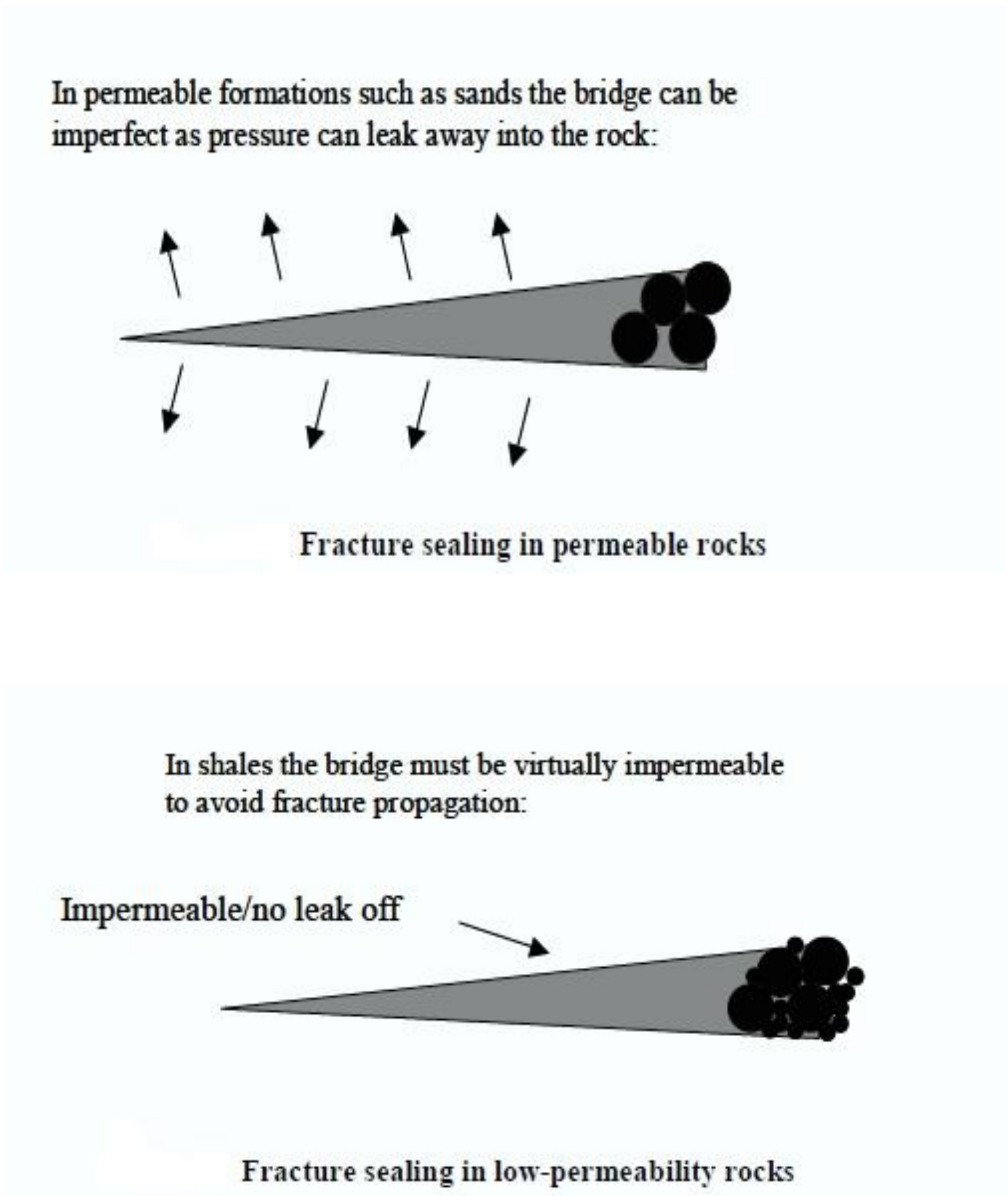


Figure 4: Fracture sealing in permeable and in low-permeability rocks [12]

2.2.3 Review particle size selection methods

There have been several models for the selection of the lost circulation materials, which are based on the size for the purpose of keeping mud loss at minimum. Here is the list of several models:

1. **Abrams' Median Particle-Size Rule** [21] **(Abram 1977)**. According to Abram the median particle size of the bridging material has to be equal or slightly greater than 1/3 the median pore size/fracture size of the formation. D (50) = $\lambda/3$. This rule addresses the size of particle to initiate a bridge. It is important to note that the rule doesn't give an optimum size for ideal packing sequence for minimizing fluid invasion and optimizing sealing.

2. **IPT (Ideal Packing Theory)(Dick 2000)** [22]**.** The IPT addresses either pore sizing from thin section analysis or permeability information, combined with PSD of bridging material, to determine ideal packing sequence.

3. **The Vickers Method (Vickers 2006)** [23]. This method tries to exceed the bridging efficiency gained in IPT. It was decided to match target fractions. For minimal fluid loss in the reservoir, the following criteria should be met:

   D(90) = largest pore throat

   D(75) < 2/3 of largest pore throat

   D(50) +/- 1/3 of the mean pore throat

   D(25) 1/7 of the mean pore throat

   D(10) > smallest pore throat

4. **Halliburton Method (Whitfill 2008)** [24]. 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.

Aston [12] has noted several observations, concerning the lost circulation materials:

- The fluid should contain a smooth/continuous range of particle sizes ranging from clay size (around 1 micron) to the required bridging width
- Ideal packing theory (the d1/2 rule) is useful for selecting the optimum size distribution in low weight muds.
- High particle concentrations are best and at least 15 ppb of bridging mix is required for an effective seal.
- Mud weight is not a critical factor in forming a successful bridge.

Less studied LCM properties [5].

The size of the particles is not the only aspect of the LCM selection, there are several physical characteristics that are to be taken into account.

Crushing resistance Determination

LCM in the plug is subjected to wellbore stresses, one of these is Fracture Closure Stress, which is generally equal to minimum horizontal stress. That is why, the opening of the fracture depends on the difference between ECD and FCS. The LCM bridge is expected to have good crush resistance for it to be durable. To study the crushing resistance, the Tinius Olsen Hydraulic Tester may be used, when the sieving is used for measuring the particle size distribution before and after crushing.

Resiliency determination

LCM plug needs to have resiliency to accommodate fracture width changes due to pump operations. Resiliency can be defined as the extent to which a material rebounds when the applied force is removed. The resiliency is determined normally at 10,000 psi. The formula for resiliency is:

$$\%Resiliency = \left(\frac{H_r}{H_c} - 1\right) \times 100 \qquad 5$$

Where H_c is the height of the compressed specimen and H_r is the height of the rebound specimen.

Shape and size

Sphericity - is a measure of how spherical a particle is. Mathematically, it is the ratio of the surface area of a sphere (with the same volume as the given particle) to the surface area of the particle.

$$\varphi = \frac{(6Vp)^{2/3}\pi^{1/3}}{A_p} \qquad 6$$

Convexity. The projected area of the object divided by the area enclosed by an imaginary "rubber band" wrapped around the object. The values of convexity is from 0 to 1. Convex shape has convexity 1.0, concave shape has a lower value, close to zero. This characteristic also tells about the particle surface roughness[5].

In addition to PSD, other mechanical properties like crush resistance and resiliency of LCM also have an important role in the remediation of lost circulation and wellbore strengthening.

Many of the physical parameters for different LCM are however similar. It was observed that Ground nutshells undergo permanent deformation, but there is no significant change in particle size. Resilient graphite undergoes elastic deformation and regains its actual shape once the pressure is removed, particles undergo reduction in size, but it is significantly less than ground marble. In fact, two LCM may perform better when used together, for example, the combination of ground marble and resilient graphite, provide a better result. LCM like ground shells and ground rubber does not undergo any change in particle size at 5000 psi, but the resiliency is not exhibited.

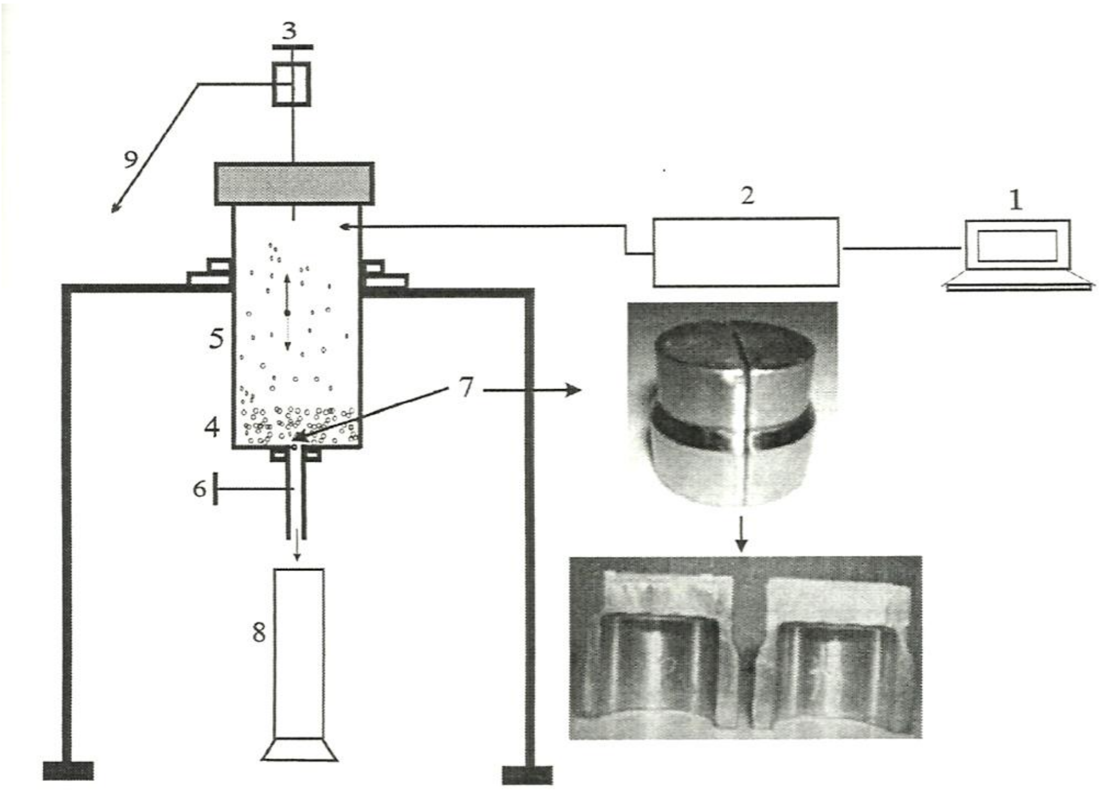
3 Experimental lost circulation study

3.1 Experimental set up

The experiments have been conducted at the laboratory of the University of Stavanger. Two types of oil-based mud have been prepared: one with 60/40 oil-water ratio and another type with 80/20 oil-water ratio. After sieving the particles and constructing the particle size distribution, the particles have been mixed with two different types of mud in two different concentrations. Afterwards, the two different types of mud were tested in a particle bridging system.

The system is schematically shown in figure 5. The system is constructed of steel vessel which is filled with the drilling fluid before the experiment starts. Firstly, the vessel is connected to atmospheric pressure through an opening in the upper part of the system. When the experiment is started, water is pumped through the opening in the system at a rate of 6 ml/min. The water is pumped on the top of the drilling fluid until there is no air in the system. When the vessel is completely filled, the vessel is closed and the pressure can be increased using the water pump. The flow of the drilling fluid out of the vessel is only restricted by the opening in the lower part of the system and the particles, mixed in the fluid. In the process of the experiment, the lost circulation particles in the mud manage to build bridges on the lower opening and it leads to a pressure increase in the vessel. As the pressure builds up, the particle bridges collapse, however the pressure variation is recorded using the computer data acquisition system. During the experiment, several bridging and collapse occurs until all the mud from the vessel has left it. It can also occur, that the opening is permanently plugged and the maximum pump pressure of 60 MPa is not enough to break through the bridge. In that situation, the experiment is terminated by stopping the pump and relieving the pressure in the vessel.

The slots used during the testing are 100µm, 250 µm, 300µm, 400µm and 500µm. Dimensions of the high-pressure cylinder are 35 mm inner diameter, 64 mm outer diameter and 150 mm long. The rate of the water injection during testing was 4 ml/min and the duration of the test was around 30 min each, or until all the mud had exited the pressure vessel. The results of the pressure variation is graphed. The experiment is run at a room temperature, which does not simulate the reservoir temperature.



(1) Lab-View (2) Gilsen pump (3) Valve to control air/fluid flow (4) Cake (5) Drilling fluid with suspension (6) Valve to control mudflow (7) Opening slots (8) Cylinder (9) Fluid/air outflow

Figure 5: Schematic particle bridging testing experimental set-up [17]

3.2 Lost circulation particles

In the experiment, all the lost circulation materials added to the mud have been thoroughly mixed just before placing the mud in the high-pressure cylindrical vessel; that is why it is possible to assume that before the pressure is applied, the particles are uniformly distributed in the fluid. The particle size distribution of the filter cake in static situation should be representative of the particle size distribution of the mud itself. However, when the mud cake builds up the situation can be different since each opening requires a certain combination of the particle size and form.

During the course of the experiment, LC – lube have been used as a lost circulation material, chemical drilling fluid additive, namely, specially formulated resilient graphite used to control loss of circulation, partial loss and seepage loss of drilling fluid. The size, shape and durable nature of LC-Lube make it a good agent for pre-emptive use in highly depleted reservoirs, sand and limestone sections. Its bridging properties come from the deformable nature of this material. Resilient graphite also functions as a solid lubricant and used as a sliding agent. It is chemically inert, thermally stable and may be applied in water, synthetic or oil-based fluids maintaining its durability and high compressive strength.

The most important characteristic of graphitic carbon is its resiliency (up to 150% at 10000 psi). There is no other LCM that when put in a press at 10000 psi , still yields free-flowing beads. All other LCM will compact. This resiliency allows the product to compress when pressure is applied and rebound when the pressure is released, whereby maintaining the seal at different pressures.

In addition to its resilient characteristics, graphitic carbon is available in various grades which allow making the pill to design the requirements of the seal.

The particles used for bridging tests in the project are products of MI-SWACO. The particle size distribution is given below and the D50 of the distribution is approximately 310 µm. One of the slots used in the experiment is 300 µm, and with this Particle Size Distribution it corresponds to the Halliburton Method (Whitfill 2008). However, other slots used in the experiment are either larger or smaller than D50 of the Particle Size Distribution. This allows investigating the effect of the change in the fracture width.

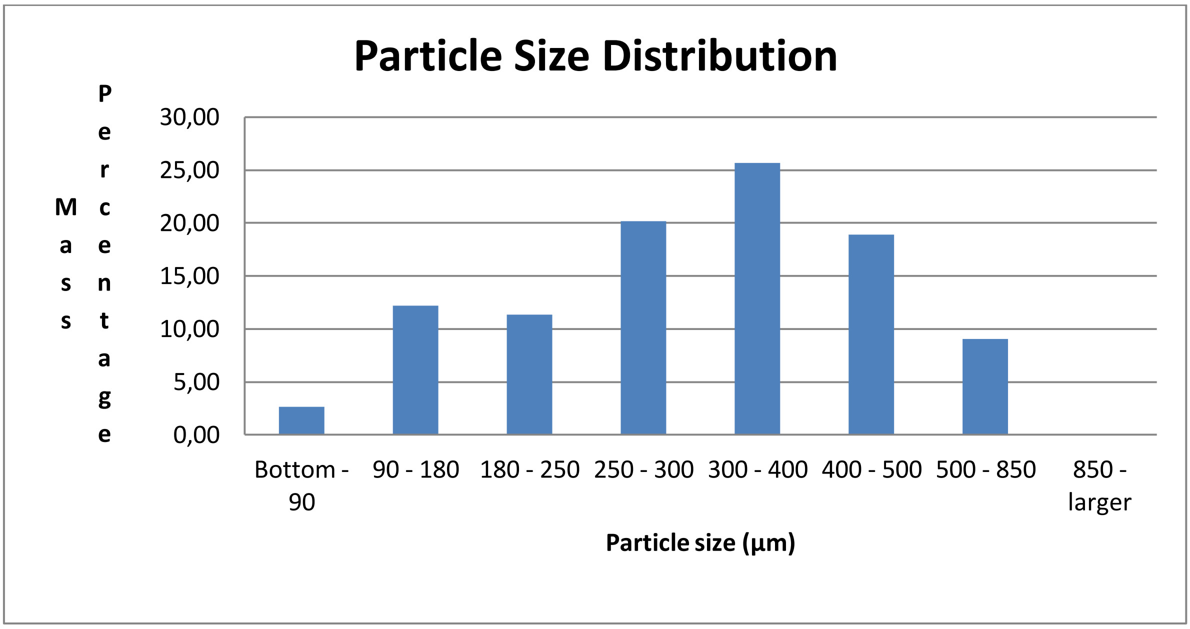


Figure 6: LC-Lube particle size distribution

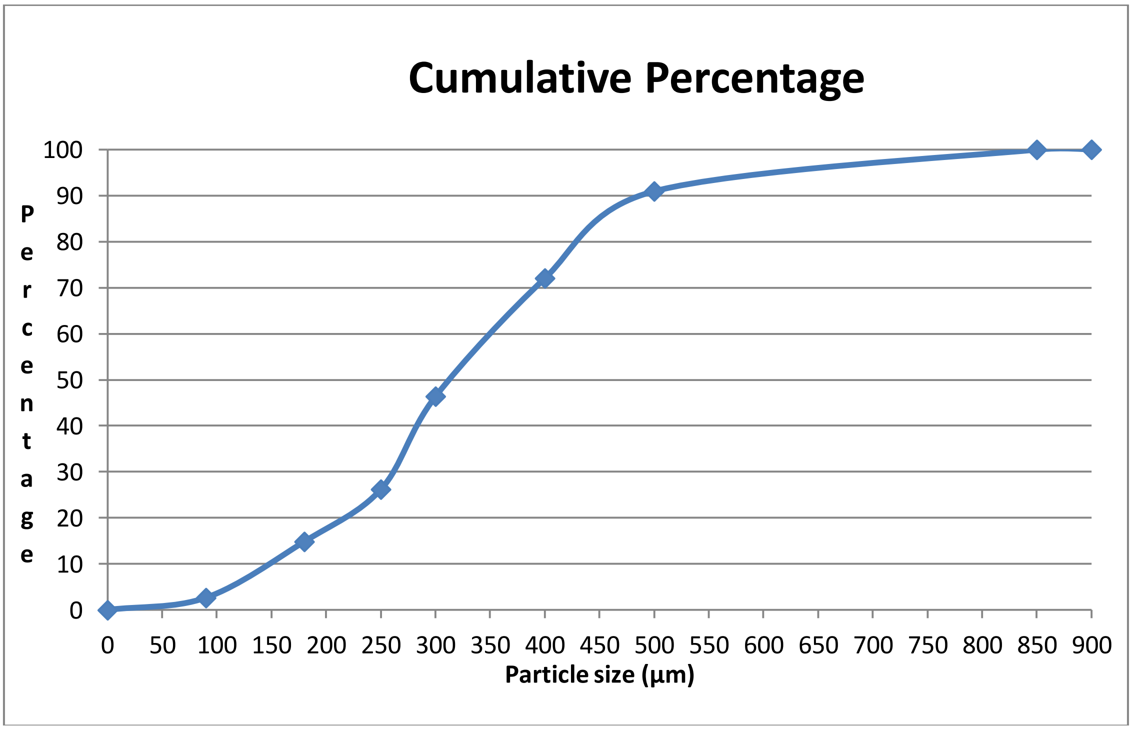


Figure 7: LC-Lube cumulative particle size distribution

3.3 Mud preparation

In the course of the experiment, two types of oil-based mud have been prepared: one with 80/20 oil water ratio and another type with 60/40 oil water ratio. The procedure and components are shown in a table below. Both fluids have the same density, but different rheology.

Traditionally, viscometer is used to measure the rheological properties of the drilling mud. The measurements done with the viscometer were made in conditions of the room temperature. In some cases, the drilling fluid may be warmed up to simulate the well conditions.

One of the problems of drilling in North Sea is that formations contain very reactive clay which swells very easily. That is why the drilling fluid is used, which prevents clay swelling. Oil based mud is an alternative to inhibitive water based fluids. It is also used in cases when different friction forces are expected, for instance in deviation wells, with risk for differential sticking, etc. Oil-based mud is actually invert emulsion drilling fluid.

In oil emulsion drilling fluid one have water drops emulsified in oil. These oil drops are acting in the same manner as solid particles in drilling fluid. Water content may vary from 5-50% in the oil based mud. The oil phase is wetting all the solid particles in the mud. That is the reason why drilling fluid with high weight or many particles needs a higher oil-water ratio.

Besides the three phases (oil, water, particles), the additives in oil based mud are:

- Emulsifiers
- Viscosifiers
- Filter control substances

The mud has been prepared especially for the experiment using the chemicals from MI SWACO and UIS laboratory. The preparation procedure and the viscosity information is documented in the tables 3 and 4.

Mud formulation per liter

Product name	Use	80/20 OBM	60/40 OBM	Mixing time
EDC 95/11	Base Fluid	440	321	
Paramul	Emulsifier	20	30	
Parawet	Wetting agent	8	8	5 min
Lime(Hydratkalk)	pH modifier	20	25	5 min
Water (mix water + salt separately and add the brine mixture)		137	279	
CaCl2 (mix water + salt separately and add the brine mixture)	Osmotic control	37	75	10 min
Versatrol M	Fluid loss control	10	10	5 min
Benton 128	Viscosifier	9	4	5min
Barite (All Grades)	Weighting agent	1065	997	25 min

Table 3: Test Mud Formulation

	MUD RHEOLOGY	
	80/20 OBM	60/40 OBM
θ_{600}	160	261
θ_{300}	98	161
θ_{200}	76	124
θ_{100}	50	81
θ_{6}	17	23
θ_{3}	15	19
SG	1,75	1,75
AV (cP)	80	130,5
PV (cP)	62	100
YP (lb/100sq ft)	36	61

Table 4: Test Mud Rheology

The apparent viscosity, plastic viscosity and yield point are important viscosity parameters giving information about the drilling fluid:

Apparent Viscosity (AV).

This value is obtained by applying the instrumental equations used in obtaining the viscosity of a Newtonian fluid to viscometer measurements of a non-Newtonian fluid. Generally it tells us about the total viscosity of the fluid. In our case the 60/40 drilling fluid has a remarkably higher apparent viscosity than the 80/20 one as a result of smaller percentage of oil.

Plastic Viscosity (PV) is the resistance caused by mechanical friction:

- Friction between the particles in the mud
- Friction between particles and fluid phase
- Friction between fluid elements

Plastic viscosity is dependent on the concentration, size and particle configuration in the drilling fluid.

Yield Point (YP) is the amount of flow resistance which results from the adhesive forces between the particles as a result of electrical charges (electrostatic forces).

3.4 Bridging tests

This part presents an overview of the bridging experiments conducted with the 60/40 and 80/20 oil-based mud and LC Lube. The tests have been carried out with various slot openings and different concentration of the bridging particles. The usual time of the test was set 30 minutes, however, during some tests, the slot became plugged and the maximum pressure of 60 MPa was not able to collapse the bridge formed, causing the time of the test to be shorter than 30 min.

The test results are compared according to the pressure behavior during the experiments

Program of the bridging tests		
Mud and additives	Slot µm	Remark
60/40 OBM + 16,85 LC Lube	200	good
60/40 OBM + 16,85 LC Lube	300	plugged after 10 min
60/40 OBM + 16,85 LC Lube	400	good
60/40 OBM + 16,85 LC Lube	500	good
80/20 OBM + 16,85 LC Lube	200	plugged after 23 min
80/20 OBM + 16,85 LC Lube	300	good
80/20 OBM + 16,85 LC Lube	400	good
80/20 OBM + 16,85 LC Lube	500	good
60/40 OBM + 8,49 LC Lube	200	good
60/40 OBM + 8,49 LC Lube	300	good
60/40 OBM + 8,49 LC Lube	400	good
60/40 OBM + 8,49 LC Lube	500	good
80/20 OBM + 8,49 LC Lube	200	good
80/20 OBM + 8,49 LC Lube	300	good
80/20 OBM + 8,49 LC Lube	400	good
80/20 OBM + 8,49 LC Lube	500	good
60/40 OBM + no LCM	100	good
80/20 OBM + no LCM	100	good

Table 5: Overview over the bridging experiments

3.4.1 Test with 80/20 OBM

3.4.1.1 Particle additive- LC-Lube 16,85 ppb

In the experiment with 80/20 OBM, a peculiar attention was drawn by the test with a 300 µm slot opening. Right at the start, the pressure started to escalate at a higher rate than in the cases of the other slots, even the 250µm one which is narrower. In the same time the sealing becomes more effective since the bridge withstands the pressure of 50 MPa and it was decided to allow a higher pressure and the strongest bridge in this section collapses only at a pressure of 57 MPa. As is seen from the test, the method of the PSD choice, which is based on the D50 being equal to the fracture size have worked here and have shown the best sealing result, since the D50 of the particle size distribution used has been very close to 300 µm.

As for the 250µm slot opening, effective bridging was initiated later in time compared to the 300 µm slot. The pressure build up observed was much smoother in the beginning of the test but the pressure peaks and the frequency of the peaks observed was approximately the same as in the case of 250 µm slot.

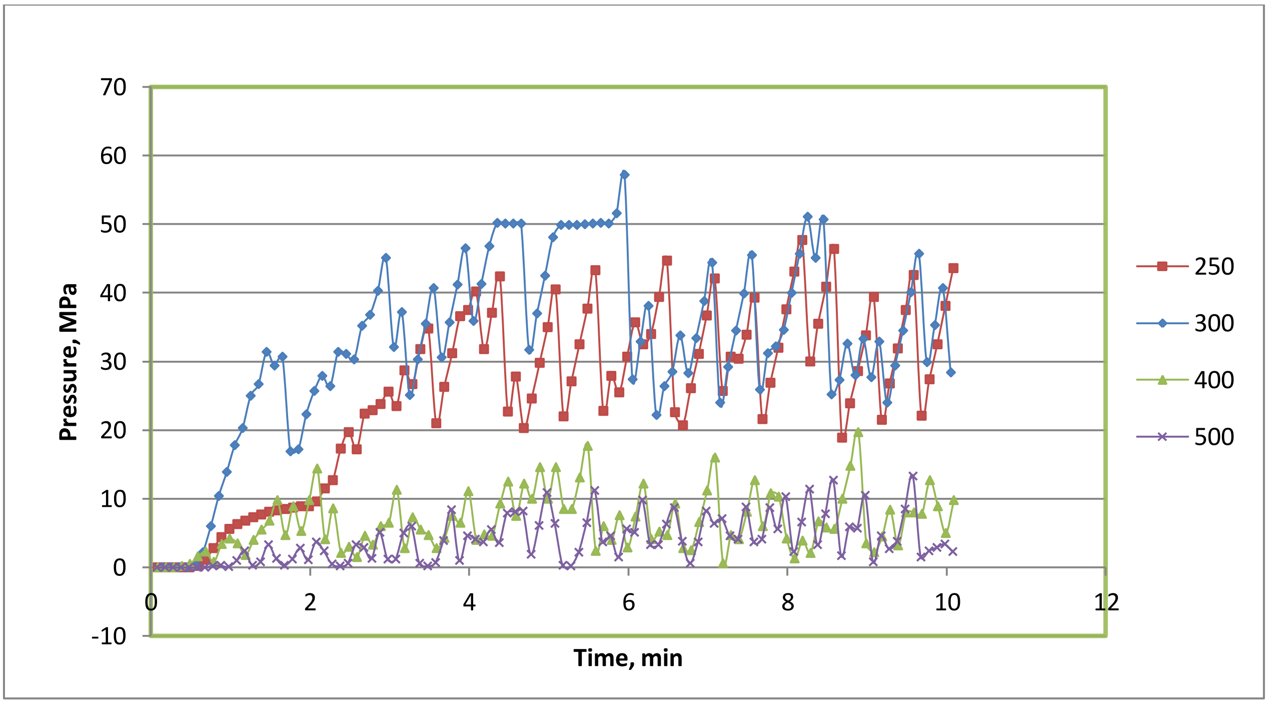


Figure 8: 80/20 OBM + 16,85 ppb LC-Lube

The slot openings of 400 µm and 500 µm showed a similar behavior to each other in comparison to 200 and 300µm although the bridging was tolerating higher pressures in case of the 400 µm than 500 µm. One can observe a substantial reduction in maximum pressure and average peak pressure when shifting from 300 µm slot opening to 400 µm. Although the change in opening size is only 100 µm, the change in collapse pressure is far remarkably higher than in case of 300 µm and 400 µm.

3.4.1.2 Particle additive- LC-lube 8,49 ppb

As the concentration of the LC Lube was lowered, there have been observed certain changes in the pressure behavior. The test with the 300 µm slot opening was not longer showing the highest collapse pressures. During the pressure build up process, the pressure was behaving in a similar way as in the case of 250 µm slot opening. Later on, when the bridging materials are sinking towards the slot opening, the 300 µm test shows a higher maximum pressure and a higher average peak pressure. In the case when there is double as little LC Lube material in the system, the D50 rule is not longer showing the same result and the LCM is functioning better in the narrower fracture opening.

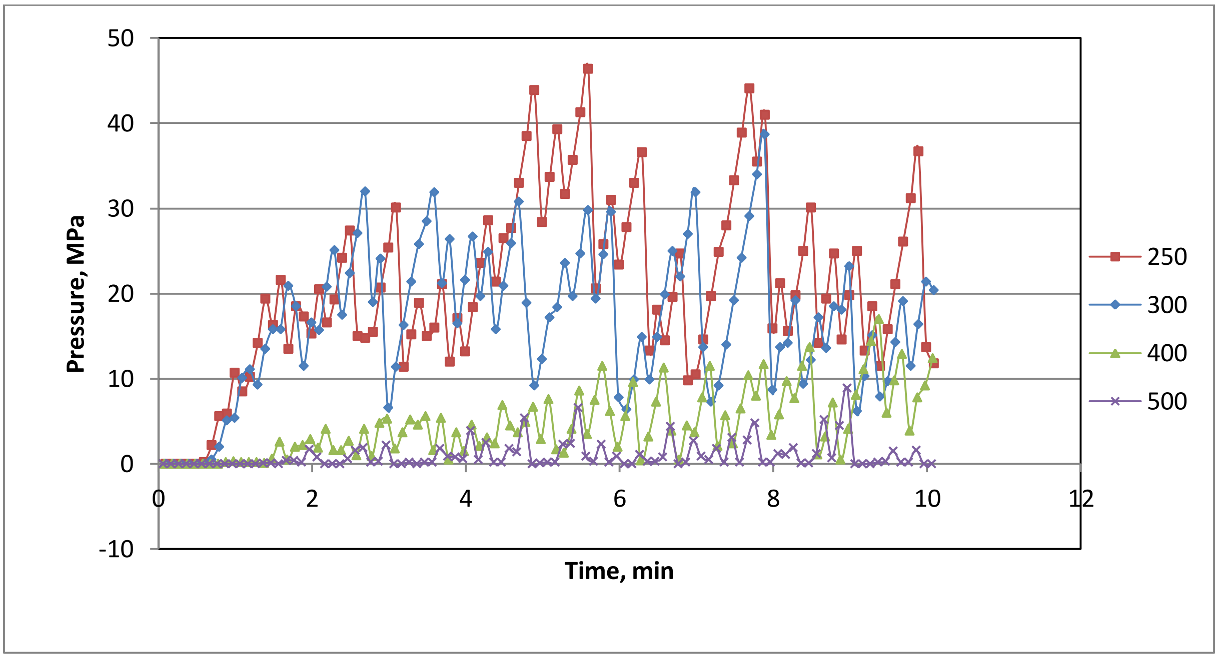


Figure 9: 80/20 OBM + 8,49 ppb LC-Lube

In the case of the 400 µm and 500 µm one can observe that the number of bridges is close to the test with a higher concentration of LCM, but the average peak pressure and maximum pressure is getting higher in case of the 400 µm slot opening. It may be also observed that the pressure build up in case of 400 µm and 500 µm develops slower when the concentration is lowered.

3.4.2 Test with 60/40 OBM

3.4.1.1 Particle additive- LC-Lube 16.85 ppb

16,85 lb/bbl LCM concentration.

During the test with 60/40 oil based mud, the 300 µm slot opening became completely plugged after 10 minutes at a maximum pressure of 60 MPa.

It is remarkable that in the case of the 60/40 OBM testing, the pressure buildup has occurred slower in the case of 250 and 300 µm slots than it has been observed in the case of the 80/20 oil based mud. The high peaks and a maximum pressure were achieved earlier by the 250 µm slot opening test than in the case of 300 µm. However, the 300 µm bridging peaks developing less intense, led to a perfect bridging at a maximum pressure, which again points out that the D50 PSD choice gives good results when it comes to plugging the fracture.

As opposed to the corresponding 80/20 OBM test, the pressure in case of 250 µm opening was developing faster than in 300 µm, but still the plugging result turned out to be better in case of 300 µm.

The difference between the 400 µm and 500 µm slot opening pressure variation is less pronounced in the 60/40 OBM with 16,85 lb/bbl of lost circulation materials than in the 80/20 corresponding experiment. Although more bridges occurred with 400 µm slot, there are quite high peaks generated with the 500 µm slot, being higher than the average pressure in 400 µm slot. The difference in the average pressure is still substantial when the slot opening is enlarged from 300 µm to 400 µm. For the largest openings in the 60/40, 16,85 lb/bbl experiment, the pressure holds more even.

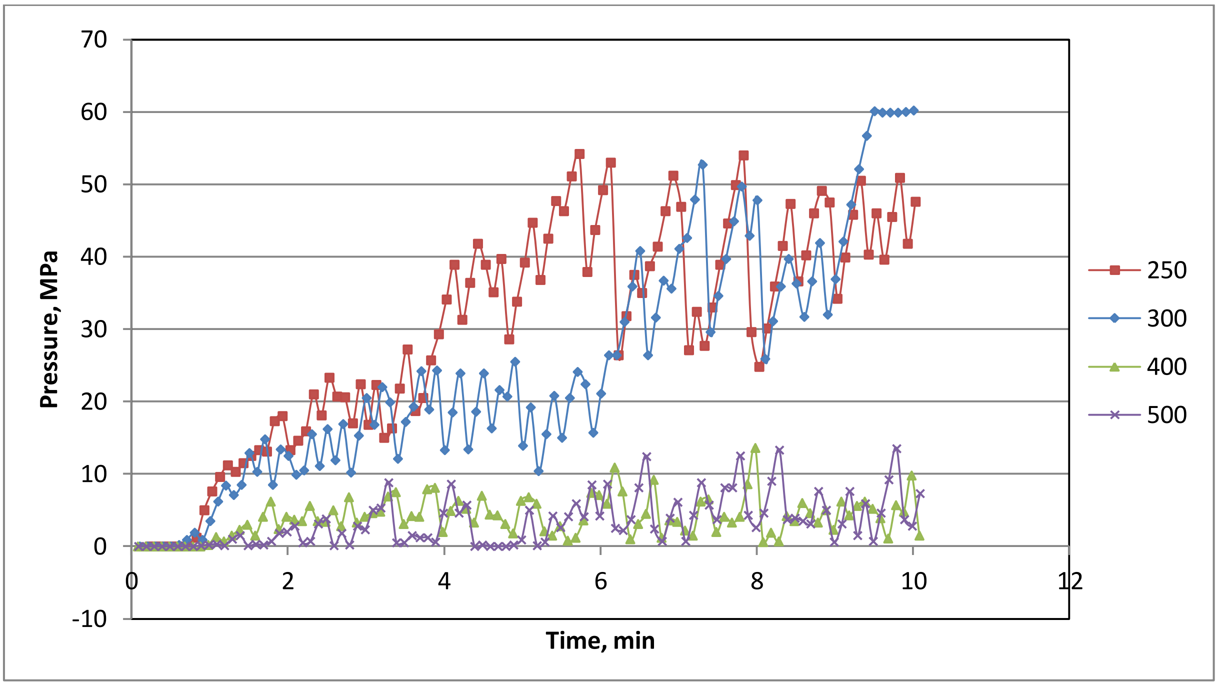


Figure 10: 60/40 OBM 16,85 ppb LC-Lube

3.4.1.1 Particle additive- LC-Lube 8.49 ppb

8,49 lb/bbl LCM concentration.

After reducing the concentration of LC Lube to 8,49 lb/bbl, the pressure build-up with the 250 and 300 µm slots became more escalating in the beginning of the experiment. During the first 10 minutes of the test, the pressure variation with 200 and 300 µm had a higher amplitude than in the case with higher concentration with 300 µm forming higher peak pressures than the 250µm slot opening. In the case of 8,49 lb/bbl LCM concentration, there haven't been any permanent bridging in the course of the experiment, and the maximum peak with 300 µm reached up to 46 MPa.

Pressure variation with 400 and 500 µm also behaved in a slightly different manner: bridging with 400 µm became more active with bridges tolerating higher pressures than in the case of 16,85 lb/bbl concentration, whereas the bridging with 500 µm became less frequent, with pressure going down to atmospheric with no bridging at all.

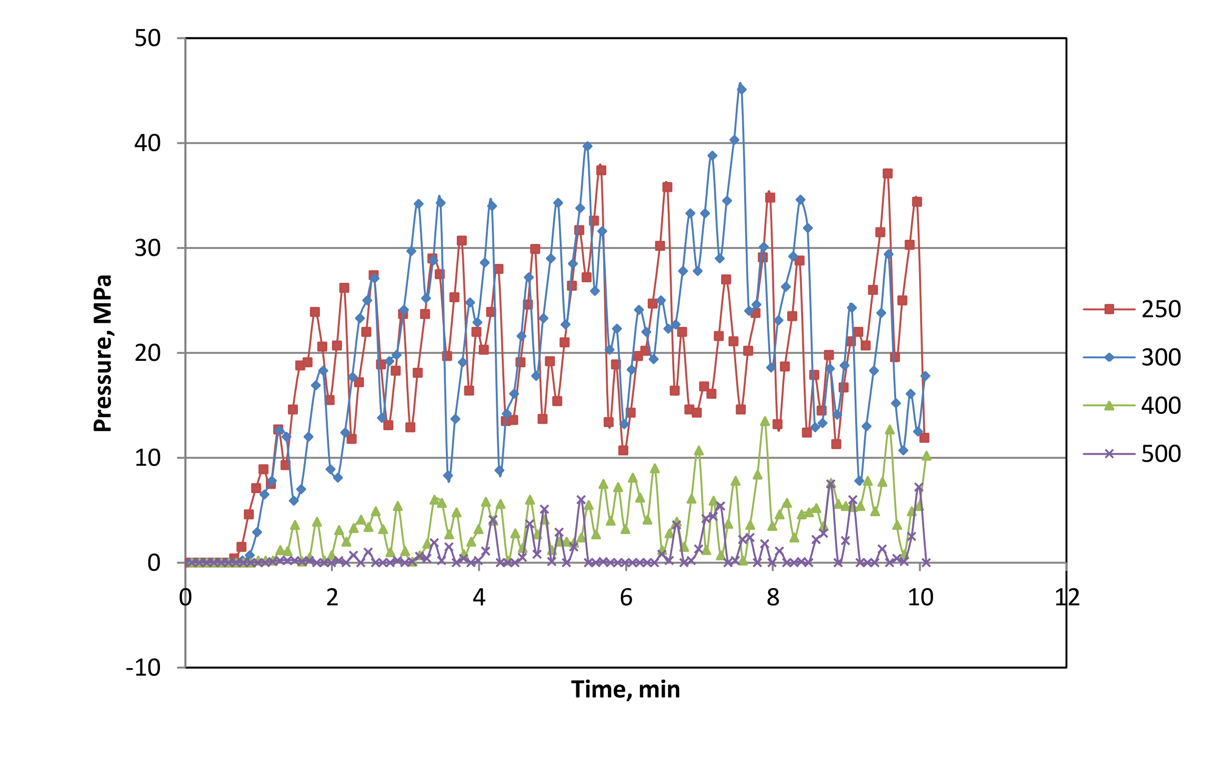


Figure 11: 60/40 OBM + 8,49 ppb LC-Lube

3.4.3 Comparisons of tests with 60/40 and 80/20 experimental results

It is important to observe how the bridging occurs and pressure varies in two different drilling fluids with the same slot opening and the same concentration of the lost circulation materials.

3.4.3.1 Comparisons of the 60/40 and 80/20 at 250microns

16,85 lb/bbl LCM concentration.

In the beginning of the test with 16, 85 lb/bbl of LCM, the pressure build up with 60/40 OBM escalated faster than in the case of 80/20. After reaching the average pressure of 40 MPa, it was observed that 80/20 and 60/40 having a similar pressure amplitude, but with 60/40 OBM reaching a higher average peak pressure on the maximum level of 55 MPa.

After 15 minutes of the test, the pressures in both mud systems started to sink reaching the average of 30 MPa. After 22 minutes the slot in the test with 80/20 OBM was plugged at a pressure of 50 MPa. The test with 60/40 OBM was conducted with a higher maximum pressure.

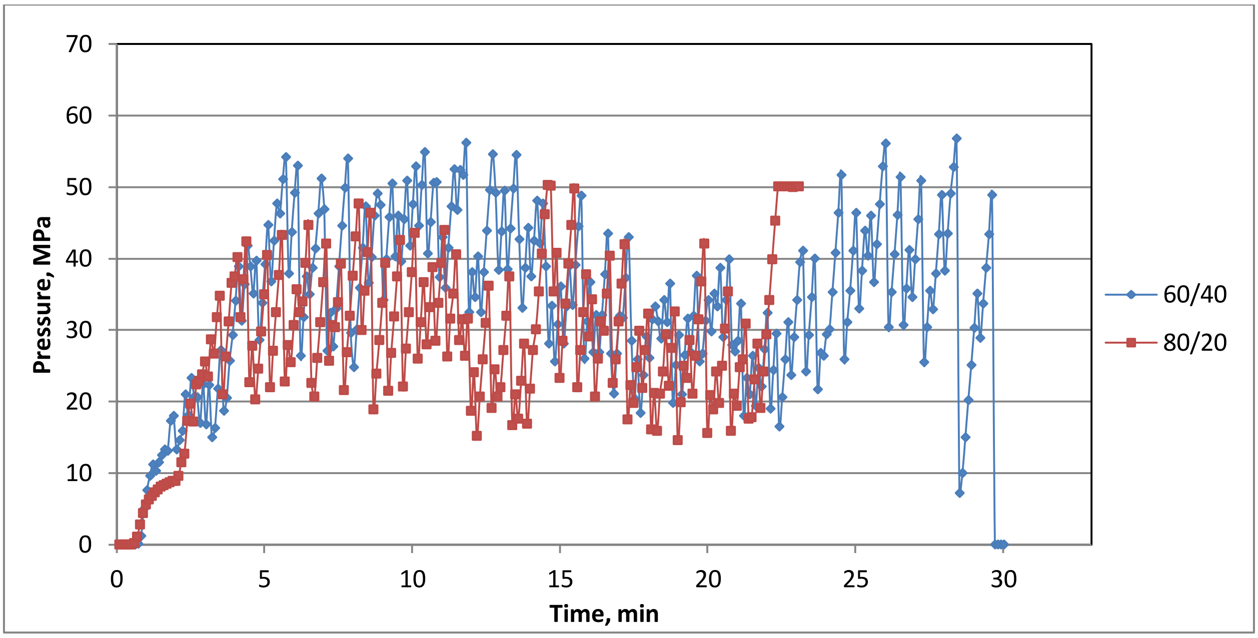


Figure 12: 250µm slot opening, 16,85 ppb LC-Lube

8,49 lb/bbl LCM concentration.

In the test with less bridging material, a more even result of the pressure variation was observed. As is seen from the graph, 60/40 OBM is showing a higher level of the peak bridging pressures especially in the end of the experiment, when more particles are approaching the slot opening. However, during the first 8 minutes of the test, bridging with 80/20 OBM showed the highest peaks reaching for around 45 MPa. The pressure build-up in the beginning of the test was almost similar for the two mud systems.

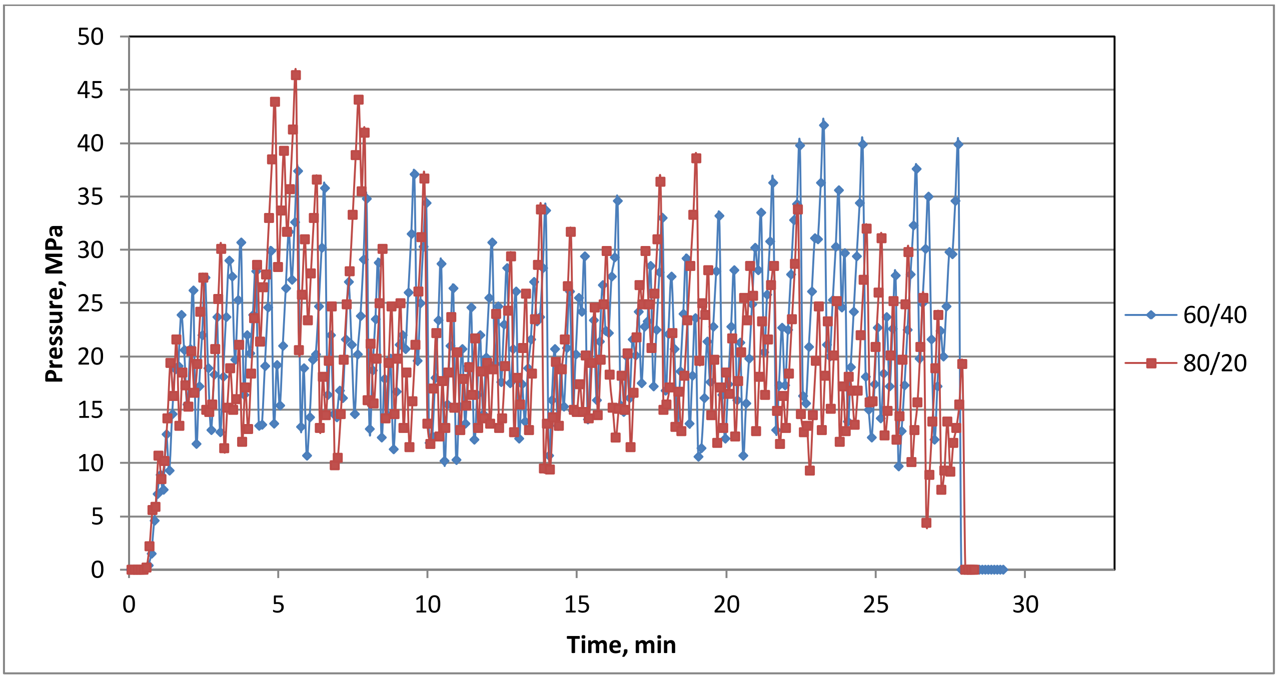


Figure 13: 250 µm slot opening, 8,49 ppb LC-Lube

3.4.3.2 Comparisons of the 60/40 and 80/20 at 300microns

LC-Lube 16,85 ppb

After 10 minutes of the experiment with the 60/40 oil based mud, the 300 µm slot opening became completely plugged with the maximum pressure of 60 MPa. As is seen from the figure, the pressure development in 60/40 OBM was not as steep as in case of the 80/20 OBM. Right from the beginning the bridge was formed with a collapse pressure of 30 MPa in case of 80/20 OBM, and then approaching 57 MPa after first 5 minutes of the experiment, after that, the average pressure in the cell became around 35 MPa gradually going down with time. The bridging with 80/20 OBM occurs at relatively high pressures of 45-50 MPa throughout the experiment.

The pressure in the test with 60/40 OBM escalated gradually, first, forming the bridges at a pressure of 25 MPa, and after 7 minutes going up with the peak pressure of 50 MPa and right after that plugging the 300 µm slot at the highest allowed pressure of 60 MPa, showing validity of the D50 rule in the particle size distribution.

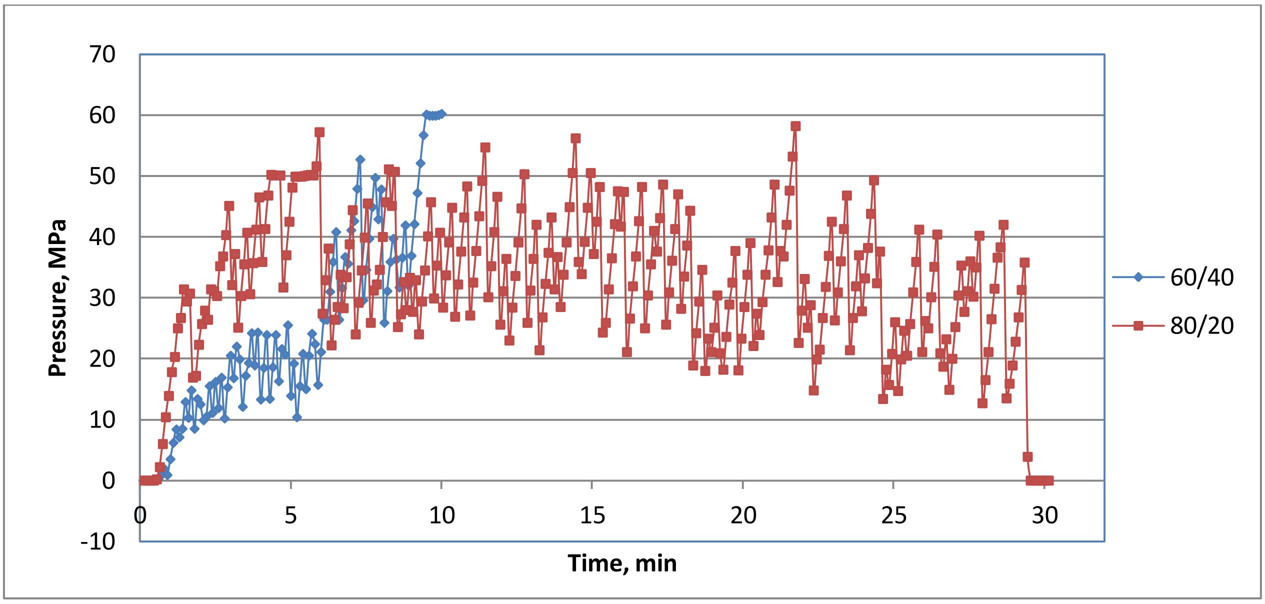


Figure 14: 300µm slot opening, 16,85 ppb LC-Lube

LC-Lube 8,49 ppb

With the LCM volume reduction, the 300µm slot opening is no longer plugged by the 60/40 oil based mud. In the beginning of the test, the pressure in 80/20 mud is increasing more rapidly again, but the difference is not so big in comparison with 60/40. During the test, the frequency and the amplitude of the bridging looks similar for the both mud systems, but it is still seen, that the peaks formed in 60/40 OBM are higher during the most of the time. The only instance, when the 80/20 mud shows a higher peak pressure is during the minute 22 when the peak pressure reaches up to 50 MPa. When the concentration of LC Lube is reduced, the difference in the plugging performance of the mud systems used is reduced.

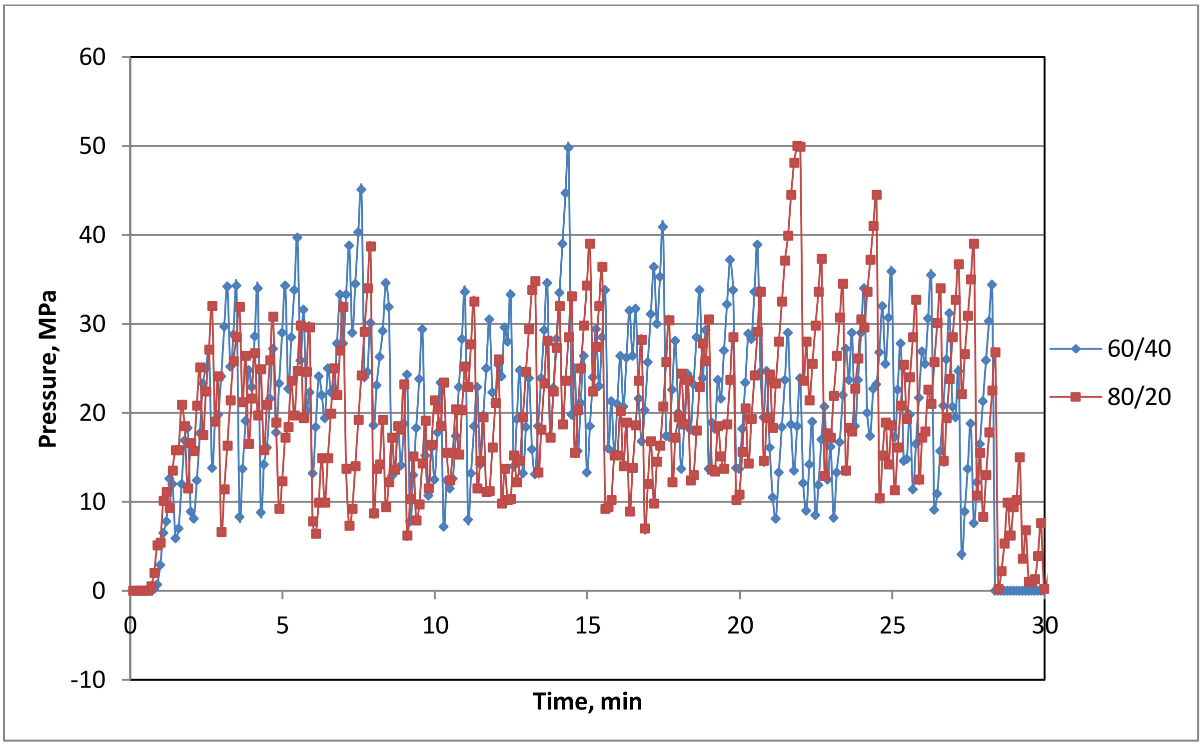


Figure 15: 300µm slot opening with 8,49 ppb LC-Lube concentration

3.4.3.3 Comparisons of the 60/40 and 80/20 at 400 microns

400 µm corresponds to the D70 of the particle size distribution, 70 per cent of the particle mass is less in size than 400 µm.

LC-Lube 16,85 ppb

When the slot opening width was increased to 400 microns, the test with 80/20 oil based mud showed an overall higher pressure throughout the whole time. Peak pressures and the amplitude with 80/20 was dominating, only during the period of time from 18 to 21 minute, the bridging collapse pressure in 60/40 OBM started to escalate to a higher level than with 80/20 OBM. It should also be noted that it took longer time for 60/40 OBM to empty the pressure vessel, which may also be caused by the lower pressure peaks during the experiment.

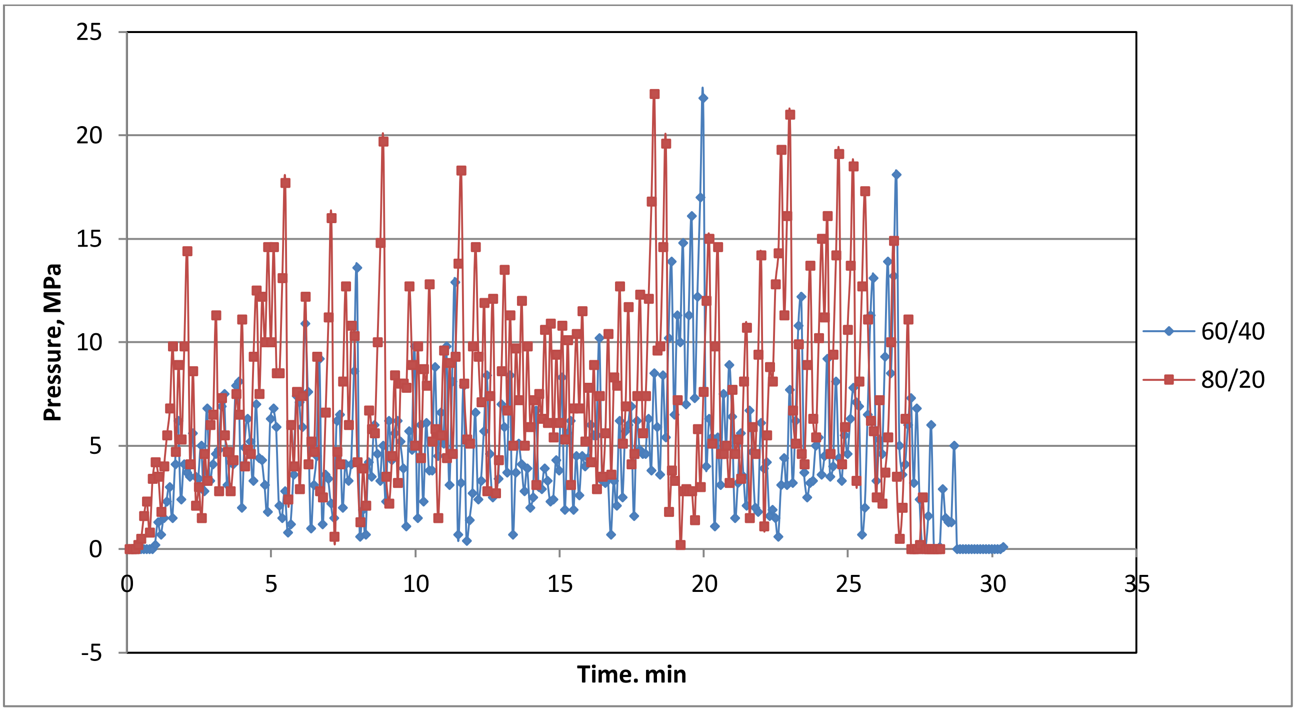


Figure 16: 400 µm slot opening, 16,85 ppb LC-Lube

LC-Lube 8,49 ppb

As the concentration of lost circulation materials became double as little, the shape of pressure graphs of both mud systems became significantly different throughout the experiment. In both cases, the escalation in the beginning became more gradual showing a similar behavior within the first 5 minutes of the test. Afterwards, 80/20 system started to show a higher collapse peaks in comparison with the 60/40 OBM with a higher amplitude of the pressure variation. The overall picture became that the 80/20 OBM has formed more bridges tolerating higher pressure, whereas the 60/40 OBM forms high peaks during the two small periods at minute 14 and minute 25. The average peak pressure in this test wa 18 – 20 MPa.

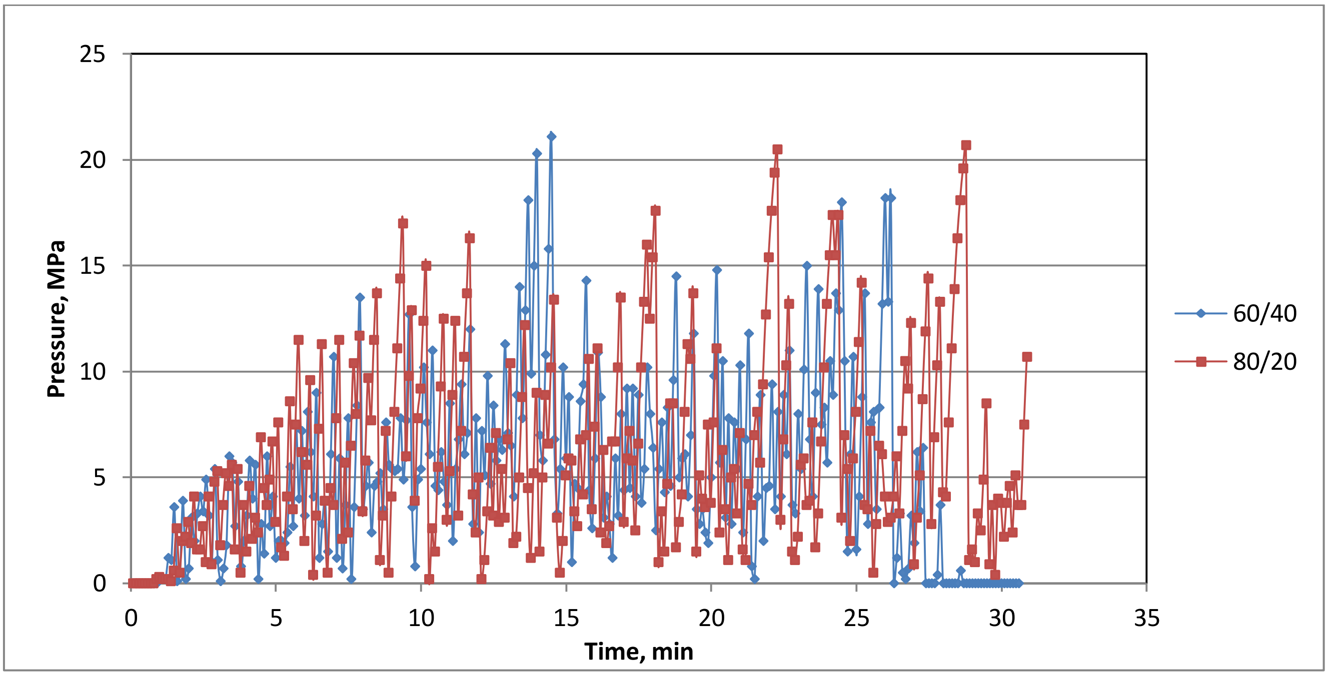


Figure 17: 400µm slot opening, 8,49 ppb LC-Lube

3.4.3.4Comparisons of the 60/40 and 80/20 at 500 microns

According to the Particle Size Distribution, D90 of the particles is approximately 500 µm, that is 10 mass percents of particles are bigger than 500 µm.

LC-Lube 16,85 ppb

As the width of the slot opening increases, fewer differences in behavior of the two mud systems are to be observed. During the first ten minutes of the test mud systems behave in a similar way. After 10 minutes the 60/40 OBM starts to form higher peaks reaching to 18 – 20 MPa. Later on the behavior of the pressure becomes similar again, and only in the end of the test, during last 5 minutes, it may be observed that the 60/40 OBM shows a higher average peak pressure during. The highest peak pressure in this test is 20 MPa.

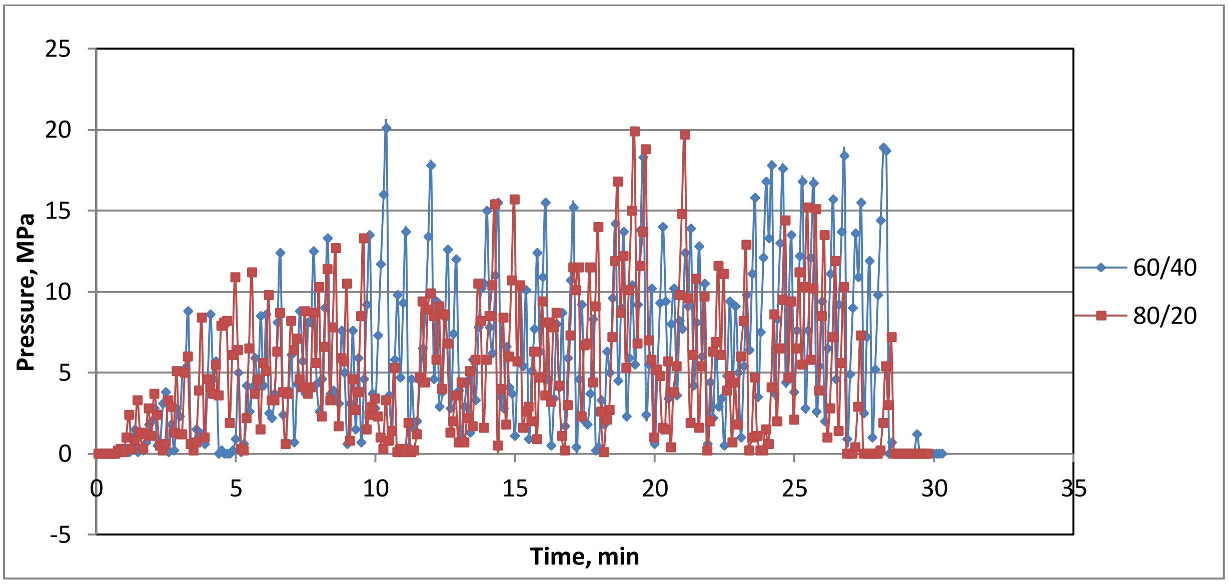


Figure 18: 500µm slot opening, 16,85 ppb LC-Lube

LC-Lube 8,49 ppb

In this test, one can observe that in both mud systems the peaks are becoming less frequent, and the peak pressures are becoming higher with time in the course of the experiment. Still the 80/20 OBM system portrays a slightly better performance when it comes to plugging, making the highest collapse pressure up to 21 MPa in the end of the test. On the other side, at 8,49 ppb concentration and a 500 µm width of the slot opening, the difference in lost circulation particles performance in the two mud systems becomes less pronounced.

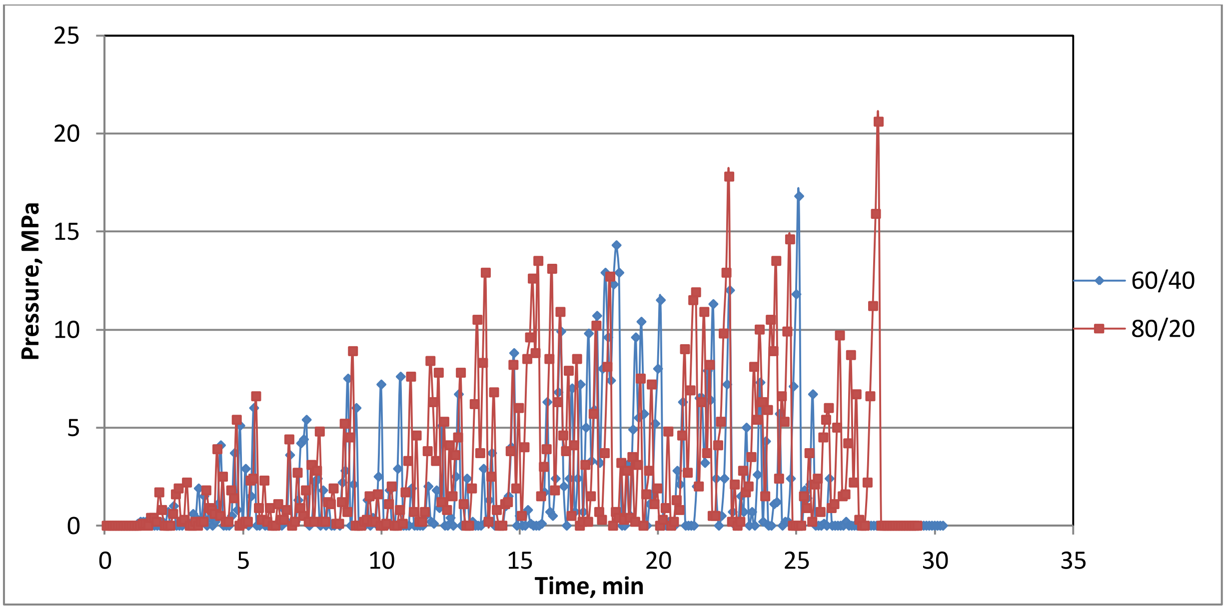


Figure 19: 500µm slot opening, 8,49 ppb LC-Lube

3.4.3.5 Comparisons of the 60/40 and 80/20 at 100 microns without LCM.

One test was performed with no lost circulation particles to observe the performance of mud systems with a narrowest slot opening used in the experiment. It turned out that in this case the maximum pressure and the average peak pressure is higher with the 80/20 OBM system, the highest peak being 50 MPa, the amplitude of the pressure is also higher in case of 80/20 OBM.

In this case the bridging is caused by the particles, which contain in the mud before the LCM addition, which is weighting agent, bentonite in the case of the two mud systems used in the experiment. Although the density of the mud system used is the same, the amount bentonite is different, being slightly higher in 80/20 OBM (1065 g/liter) than in 60/40 OBM (997 g/liter). But this difference is very small, and the test shows that bentonite make more stable bridges in the mud system with a higher oil fraction.

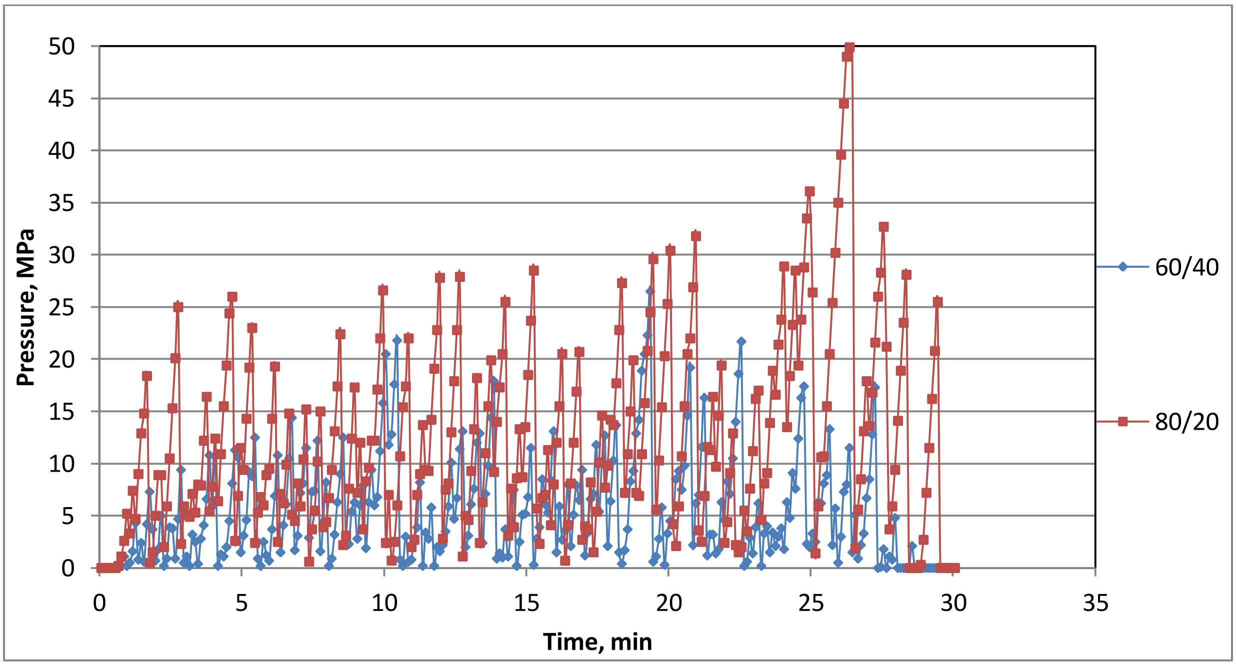


Figure 20: 100µm slot opening, no LCM

4 Analysis of the experimental data and discussion

4.1 Data Analysis Methodologies

The data analysis methodology is based on reference [10]

For the further analysis of the data obtained, it was decided to use the following methodologies to extract more information. Normally, maximum pressure observed has been reported. In addition to traditional parameters, other parameters are used:

1. Maximum Pressure in the cell (P_{max}). This parameter describes the maximum strength of the bridge during the course of the experiment. The difficulty in analyzing this parameter is that the distribution of particles in the drilling mud may be not uniform. During the experiment, however, the mud was mixed thoroughly to make the distribution as even as possible.
2. Average Pressure in the cell (P_{ave}). This parameter refers to the mean pressure value during the experiment.
3. Average Peak Pressure in the cell (P_{peak}). During the experiment, the peak pressure values show the strength of the formed bridges. The particles form bridges more than once during the experiment. The average peak pressure values show the average strength of the bridges and is a reliable measure to analyze the sealing resistance.
4. Total number of bridges (N). This parameter shows the performance of the particles in terms of forming new barriers once the bridge collapses. Number of bridges equals to the number of peaks.

In both mud systems the maximum , average and average peak pressure is increasing from 250 µm to 300 µm slot opening and then substantially decreasing and continued to slightly decrease from 400 µm to 500 µm, the pressure in most cases being higher in 60/40 OBM. The effect of highest pressure in 300 µm can be explained by the fact that D50 of the Particle Size Distribution is very close to 300 µm.

4.2 Analysis of 16.85 ppb LC Lube additive system

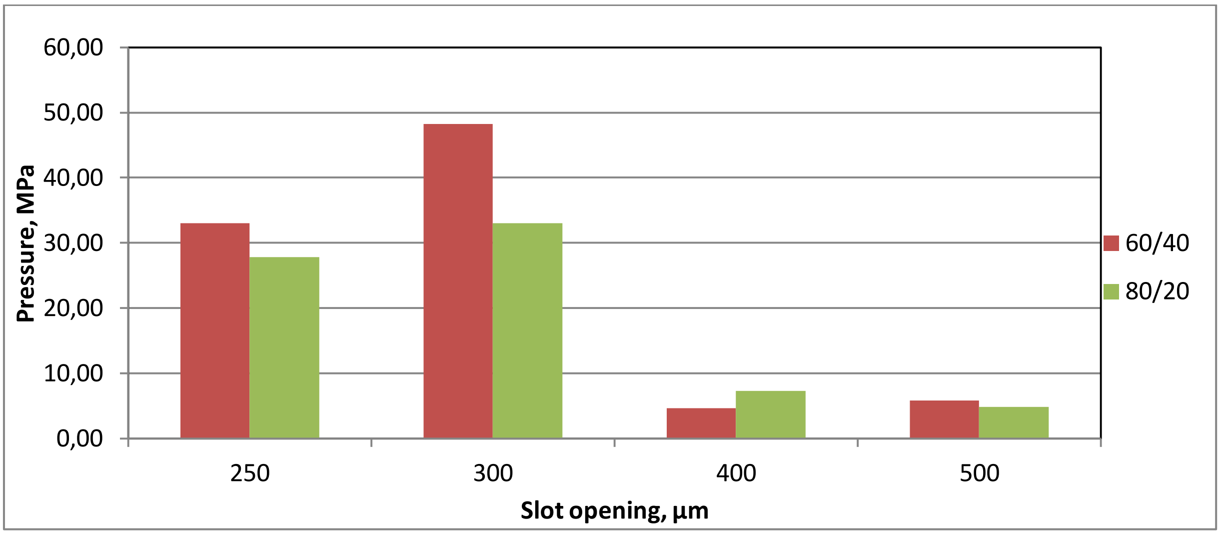


Figure 21: Average pressure with the 16,85 LC-Lube concentration

250 micron

From the comparison of Maximum Pressure, Average pressure, Average Peak pressure and number of peaks, it was observed that in the case of 250µm the bridging is initiated more frequently, tolerating more pressure, and with a higher maximum pressure in the mud with a lower oil water ratio. That is lost circulation will be better controlled with a 60/40 OBM in the case when the fracture will be 250 microns.

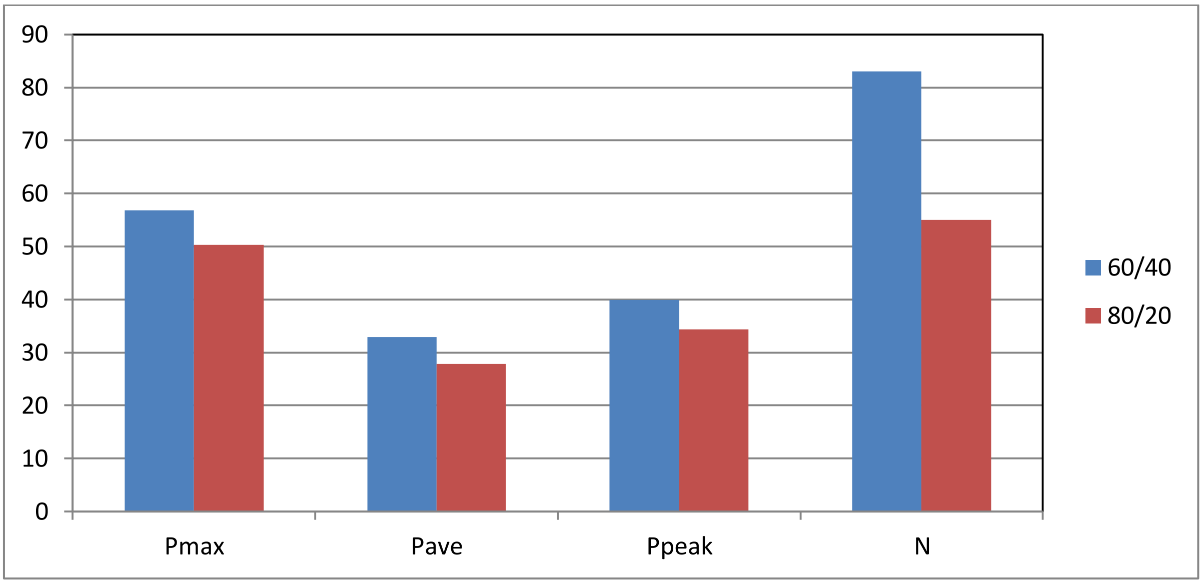


Figure 22: Pressure parameters and number of peaks with 250 µm slot and 16,85 ppb LC-Lube concentration

300 micron

In the case of 300 µm the situation with the experiment became completely different than with the 250 µm. When using the 60/40 OBM the slot opening became perfectly plugged after 10 minutes with a highest allowed pressure of 60 MPa. When plugged, the pressure started to vary from 60 MPa to 60,2 MPa and than 60 again staying perfectly plugged for some time after bridging. When computing the Maximum Pressure, Average Pressure, average Peak pressure and number of peaks, it was assumed that after perfectly plugging the slot opening, the pressure in the cell stays constant and is 60 MPa and the number of peaks and average peak pressure is compared only to the moment of bridging since no peaks are generated after that by the system with the 60/40 OBM. As is seen from the graph, the only variable, which is less in 60/40 OBM is the average peak pressure. The reason for was that the escalation of the pressure happened much faster in 80/20 OBM and bridging at higher pressures started at the early stage of the test. On the other hand in 60/40 OBM the pressure increase was more gradual and resulted in lower average values during the first 10 minutes, after which the slot became perfectly plugged. It is reasonable to predict that if the equipment would allow a higher pressure in the test vessel, the average peak pressure in the 60/40 OBM would be higher. On the other side, perfect plugging happened when the pressure was going from 60 MPa to 60,2 MPa and then back to 60 MPa for some time, that is making some new peaks at a pressure of 60 MPa. With the assumption of peak pressure varying around 60 MPa through the rest of the test, the Ppeak in 60/40 OBM would be reasonably higher. That is why it is reasonable to state that the average peak pressure during the first 10 minutes of the experiment is not representative for the whole 30 minutes experiment.

Judging from the rest of the data, maximum pressure, average pressure, number of peaks and the fact that the system with 60/40 OBM managed to perfectly plug the 300 µm slot opening, one may conclude that the Lost Circulation Materials revealed a better performance in the 60/40 OBM system with the 16,85 lb/bbl concentration of LC Lube.

As is described above, the D50 of the Particle Size Distribution of the LC-Lube is 310 µm which is very close to the slot opening used in this particular test, which makes the both mud systems perform better than in the tests with other slot openings.

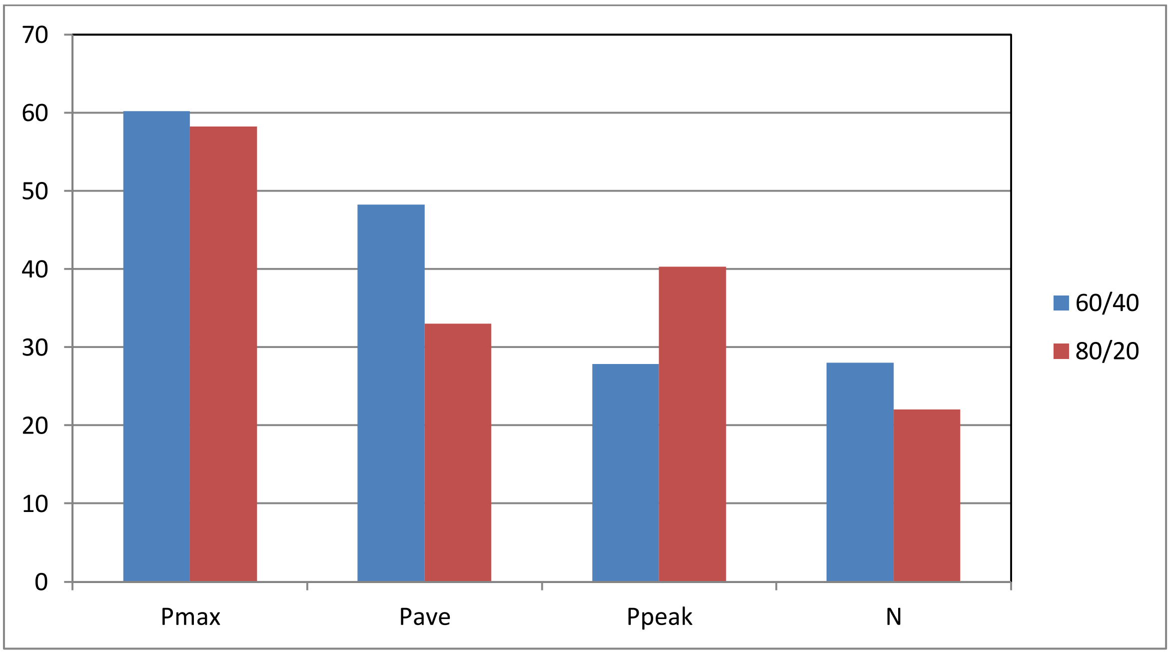


Figure 23: Pressure parameters and number of peaks with 300 µm slot and 16,85 ppb LC-Lube concentration

400 micron

When it comes to the analysis of 400 µm slot opening, the 60/40 mud system reveals a lower average pressure, lower peak pressure, slightly less peaks formed and the maximum pressure is the same in two mud systems. In comparison with the two previous slot openings the pressure values in this case are rather low to provide some information about significant differences between the performances of LCM in the two mud systems. As for the number of bridges formed, this value is almost the same, so is the maximum pressure. It is possible to conclude from the data that the LCM behaves more or less the same in the two mud systems.

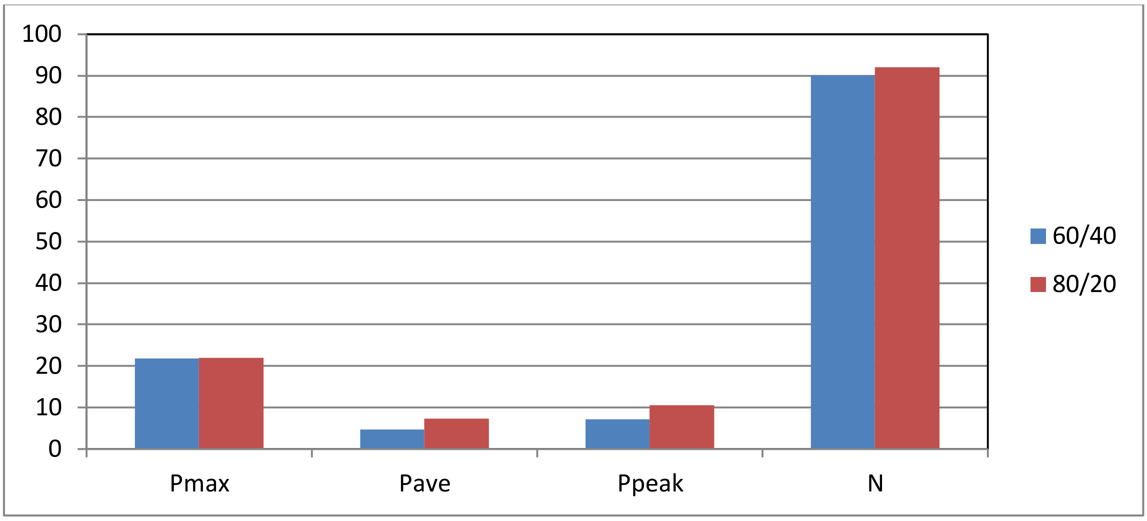


Figure 24: Pressure parameters and number of peaks with 400 µm slot and 16,85 ppb LC-Lube concentration

The same situation occurs in the test with 500 µm, maximum pressure is the same in both systems, the number of peaks slightly differs, whereas average pressure and average peak pressure differs, being insignificantly higher in the 60/40 OBM. It is possible to conclude that in the case of 500 µm slot opening, the lost circulation materials perform in a similar way in the two different mud systems.

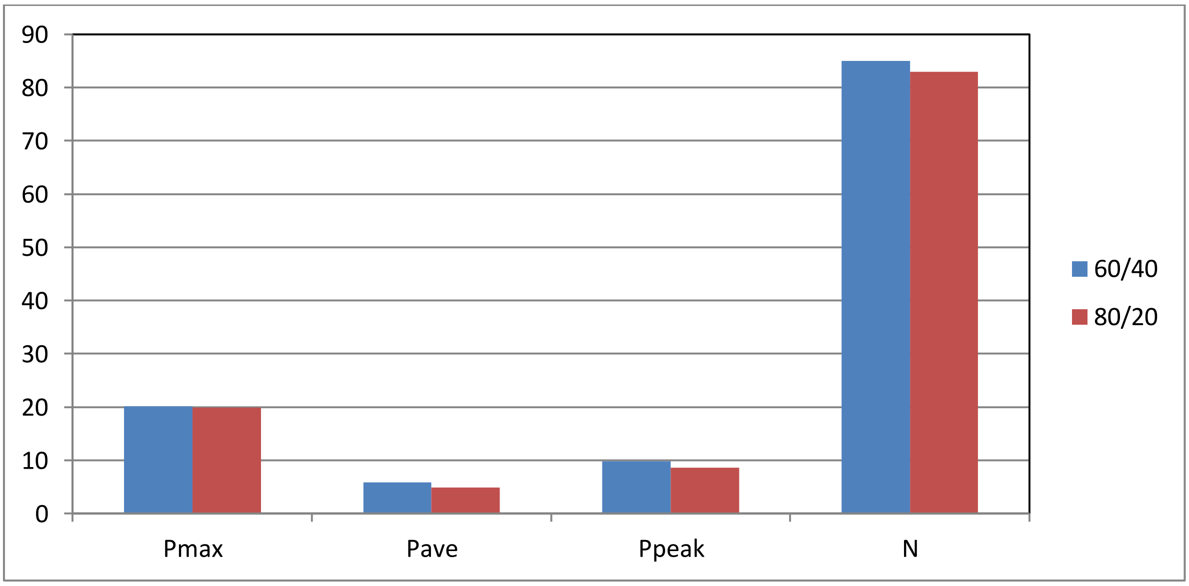


Figure 25: Pressure parameters and number of peaks with 500 µm slot and 16,85 ppb LC-Lube concentration

4.3 Analysis of 8.49 ppb LC Lube additive system

After a careful examination of the tests with a concentration of lost circulation materials of 8,49 ppb, it was observed that the average pressure and average peak pressure during the tests have been higher in the 60/40 OBM in the case of 250 and 300 µm slot openings, and this difference was higher in case of 300 µm slot opening. During the test with 300 µm the number of peaks and the maximum pressure was approximately the same for both oil based systems. One can observe, the bridging is initiated better in the 60/40 OBM but the concentration is not enough to make a lot of difference and the average pressure and average peak pressure is 2-3 MPa higher in case of 60/40 OBM.

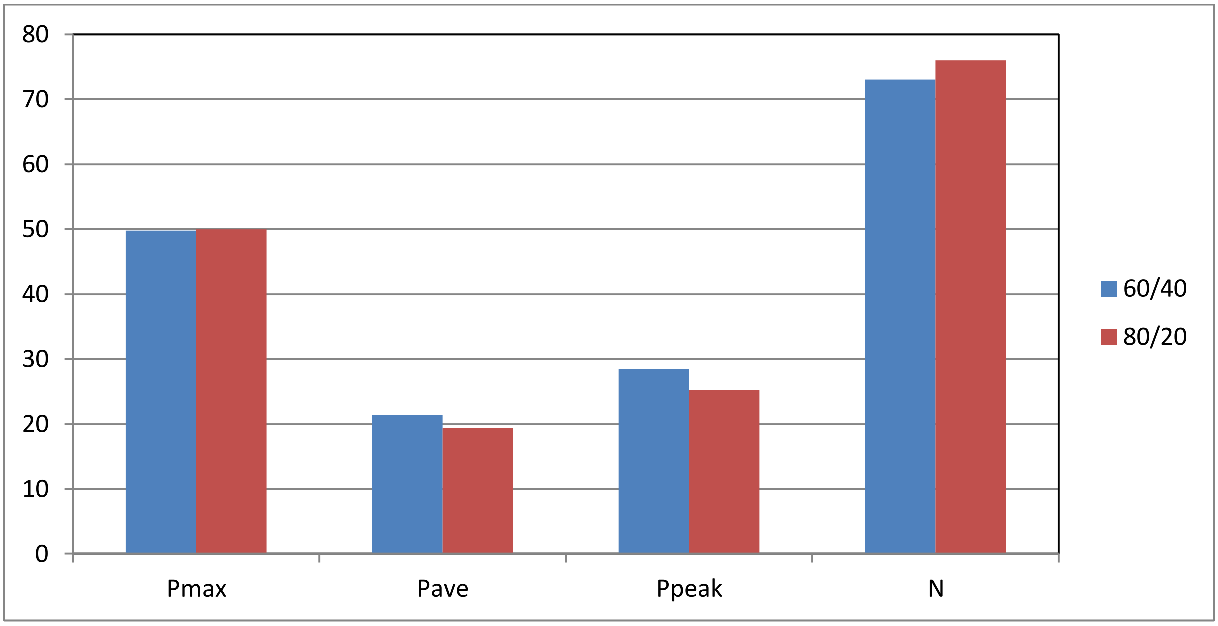


Figure 26: Pressure parameters and number of peaks with 300 µm slot and 8,49 ppb LC-Lube concentration

In the test with 250 µm the maximum pressure and the number of pressure peaks was higher in 80/20, whereas the average pressure and the average peak pressure was higher in 60/40 OBM. In this case it is hard to draw any conclusions from the comparison of the two mud systems.

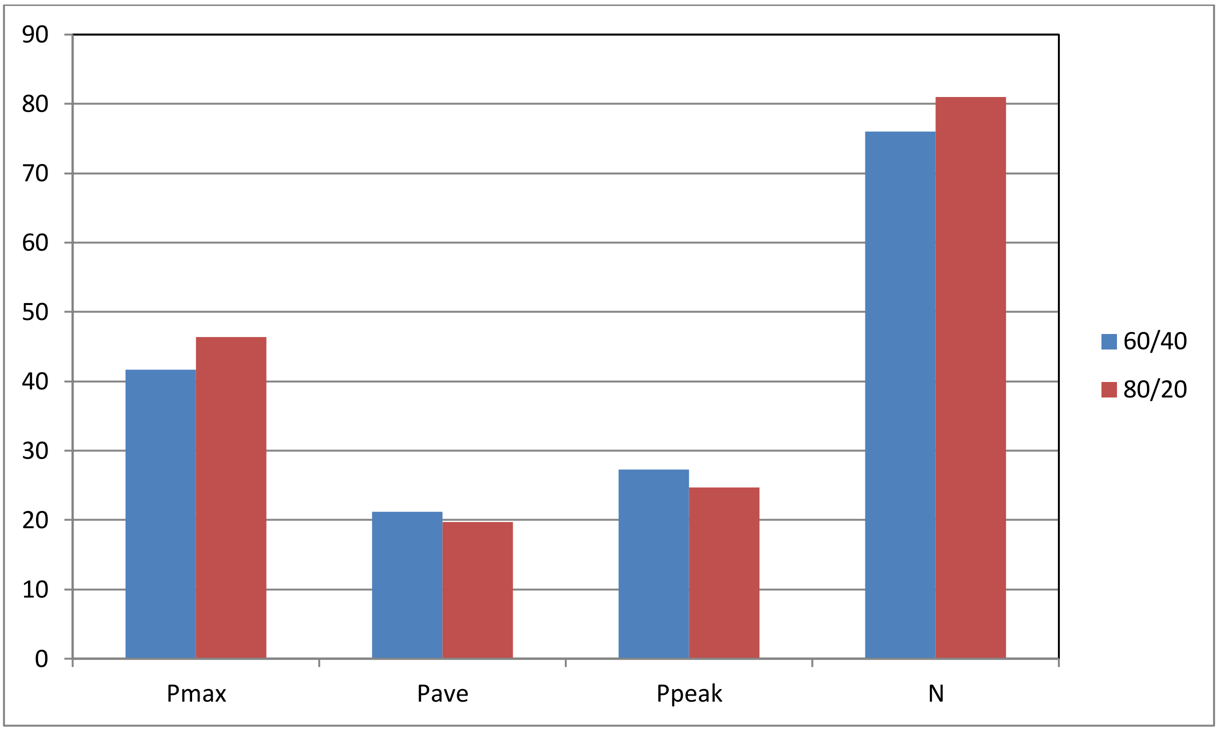


Figure 27: Pressure parameters and number of peaks with 250 µm slot and 8,49 ppb LC-Lube concentration

In case of 400 and 500 µm slots, from the data generated during these two experiments, it is impossible to draw some correlations between the oil water ratio and the performance of bridging particles. The reasons for that are low concentration of LCM and the width of the slot opening which is much higher than the D50 of the Particle Size Distribution.

4.4 Analysis of particle free system at 100 µm slot

The bridging test of the two oil based muds have shown the following results: the maximum pressure, average pressure and average peak pressure are remarkably higher in 80/20 OBM; whereas the number of bridges is higher in 60/40 OBM. The experiment shows that bridging occurs more often in 60/40 OBM, whereas the strength of the bridge is higher in case of the 80/20 OBM when the bridging is accomplished by barite instead of the LC Lube.

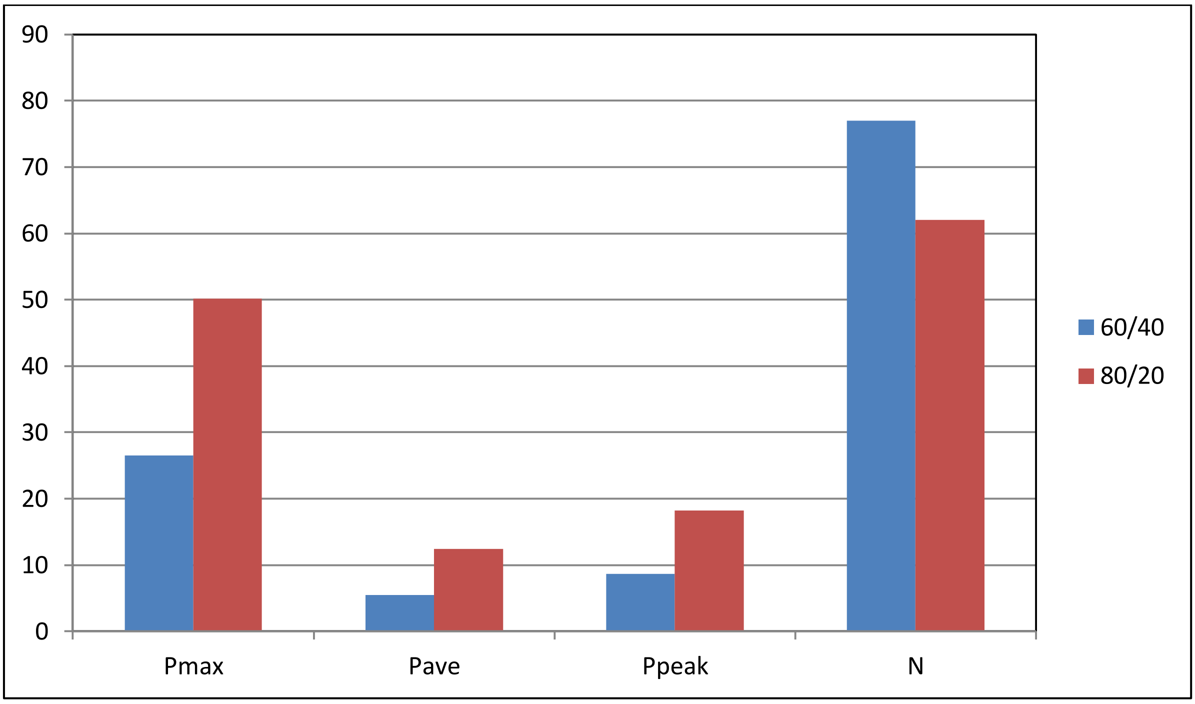


Figure 28: Pressure parameters and number of peaks with 100 µm slot and no LCM

It is rather remarkable, in the case of 100 µm the bridging is accomplished better in the drilling fluid with a higher concentration of oil. The 80/20 OBM system has a lower viscosity than in the case of 60/40 OBM, and thus the friction between the particles is anticipated to be more in the case of 60/40 drilling fluid. More friction between the particles means more effective bridging, whereas the situation with the 100 µm is different.

5 Summary and Conclusions

In this project, the performance of the LC-Lube in the 80/20 and 60/40 oil based systems was compared. After the bridging experiments, the data was analyzed, using the maximum pressure, average pressure, average peak pressure and the number of peaks.

In the figure 29 we may observe the variation in average pressure between the two mud systems when the concentration of LCM was 16,85 ppb. The higher average pressure is generated in 250µm and 300µm slots and the 300µm slot became perfectly plugged during the test with 60/40 OBM. It is seen that the bridging performance in 60/40 is better with this slot widths.

The number of peaks in the test with 60/40 OBM and 250µm and 300µm slots are also higher in the 80/20 OBM. The number of peaks has to do with the resiliency of the material, that is, the ability of the particles to deform without yielding or crushing. This ability is observed to be better in 60/40 OBM with the slot openings mentioned above.

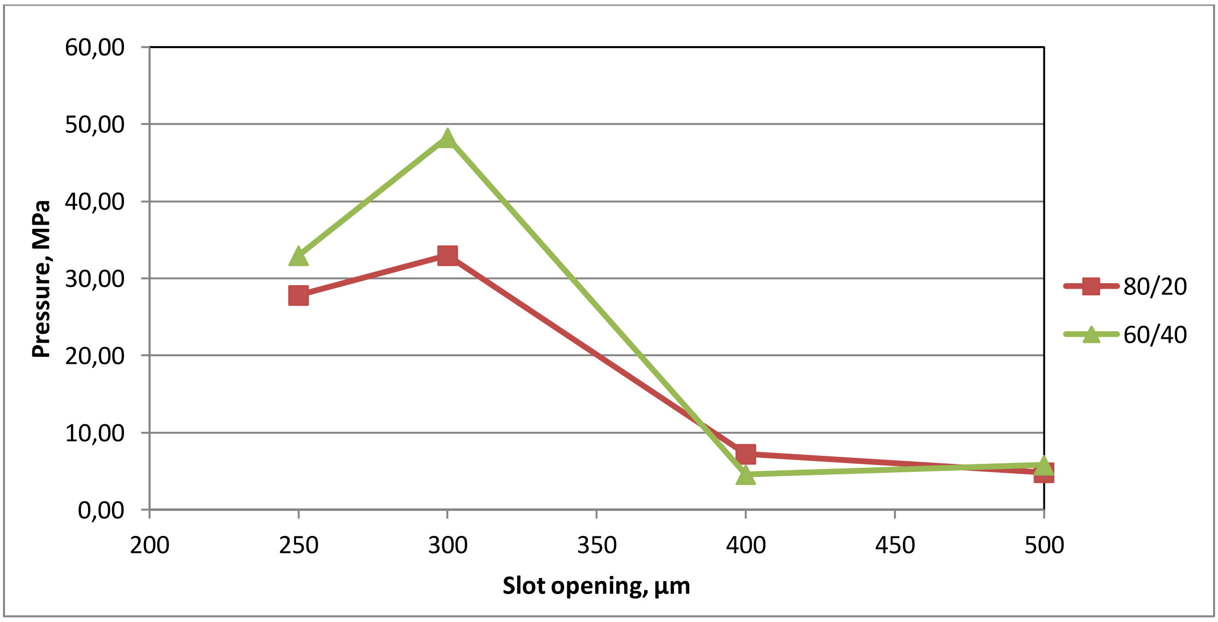


Figure 29: Average pressure in tests with different slot openings, 16,85 ppb LC-Lube

In the case of double as little concentration of LC-Lube, the situation with the average pressure and average peak pressure is repeating. In the figures 30 and 31, it is seen that in the test with 60/40 OBM the pressures are higher in the case of 250 and 300 µm slot openings, whereas when the slot is widened, the difference vanishes. The shape of the graph remains the same even when the concentration is changed.

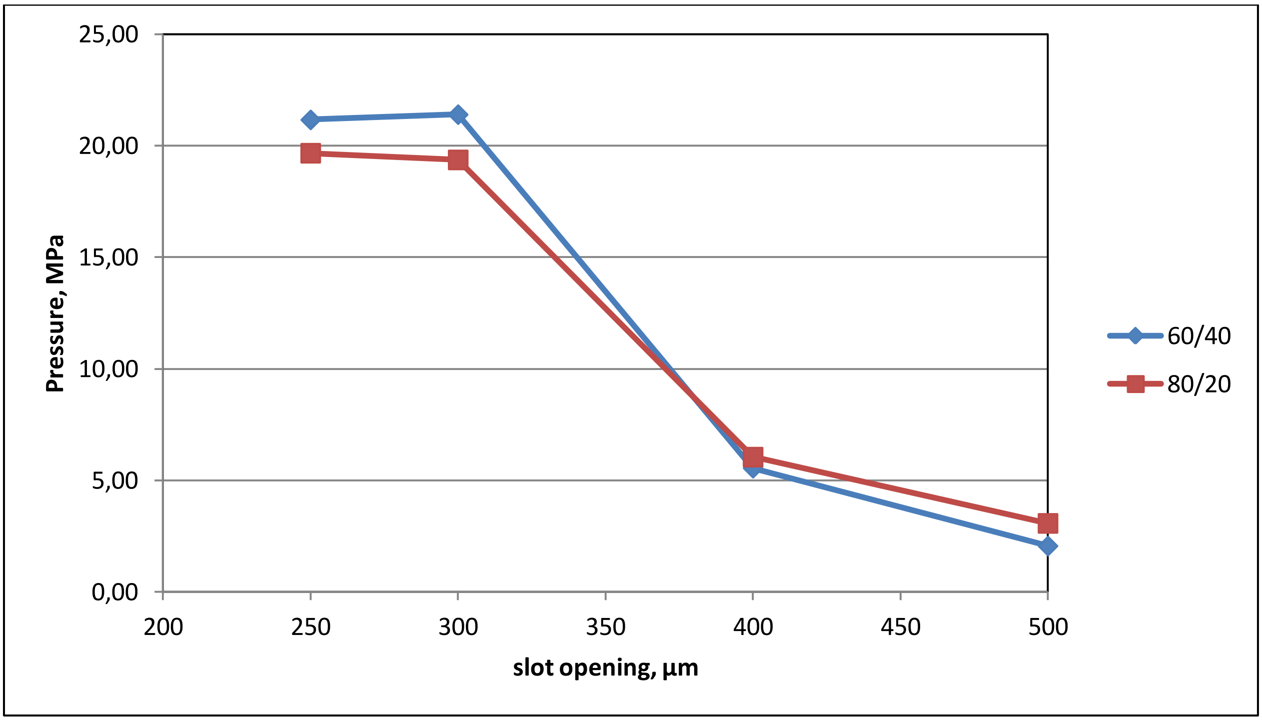


Figure 30: Average pressure in tests with different slot openings, 8,49 ppb LC-Lube

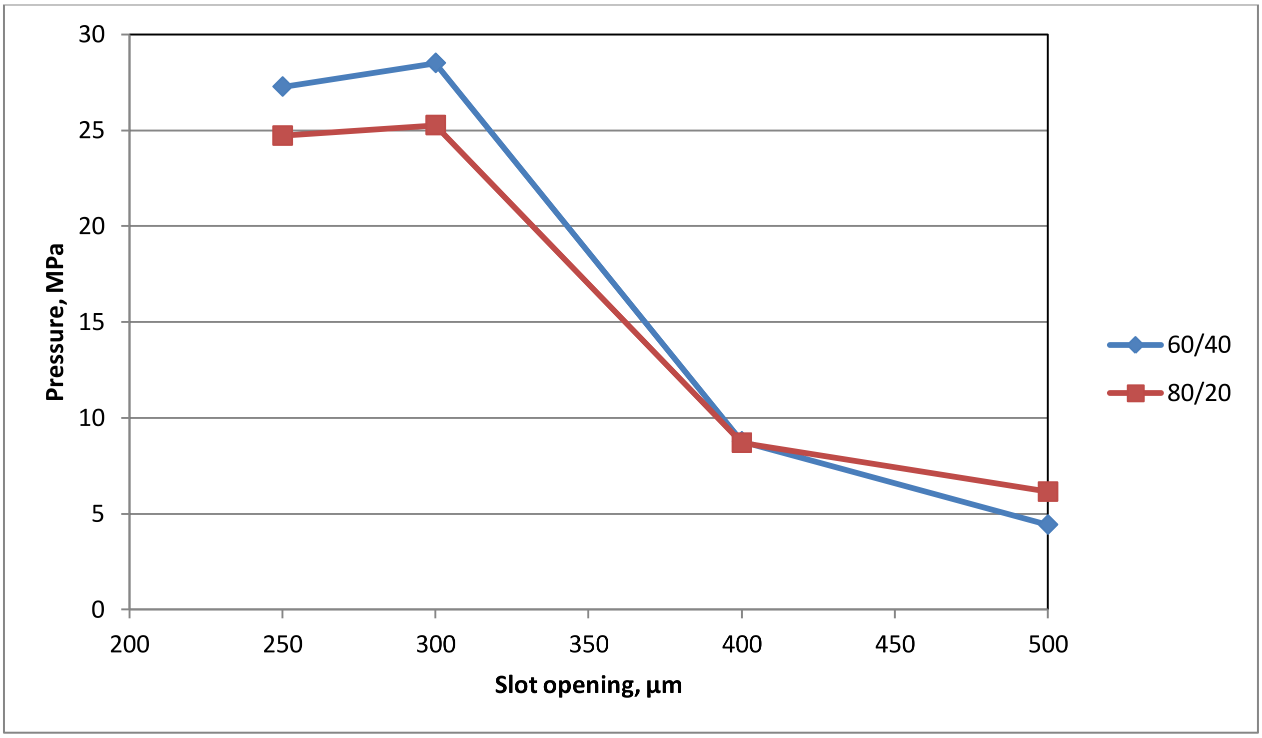


Figure 31: Average Peak Pressure with different slot openings, 8,49 ppb LC-Lube

A summary of the experimental results is the following:

1. As a result, it has been investigated that judging by the maximum pressure, average pressure, average peak pressure and the number of peaks, the performance of LC Lube was best in the tests with 250 µm and 300 µm slot openings with a concentration of 16,85 lb/bbl. In the case of the 300 µm slot, the opening became perfectly plugged. In this case the D50 of the particle size distribution of LC Lube was approximately the same as the slot opening.

2. When the concentration is set double as little, that is 8,49 lb/bbl, the difference in performance between the 60/40 and 80/20 oil based systems becomes less pronounced, and might still be observed in the tests with 250 and 300 µm slot openings where the average test pressure and the average peak pressure is slightly higher in the 60/40 oil based drilling fluid.

3. When the slot opening is made 400 µm and 500 µm, the lost circulation materials in two different systems have fewer differences than in 250 µm and 300 µm slot openings. In the case of 400 µm the bridging occurs slightly better in the 80/20 OBM system, and in the case of 500 µm pressures are higher in 60/40 Oil based system. However, these differences are not so obvious as in the case of 250 and 300 µm slot openings.

4. At 100 µm with no LC Lube present, and having mainly barite in the oil based system, the bridging performance of barite, according to the maximum Pressure, average pressure and average peak pressure, is better in the 80/20 oil based system.

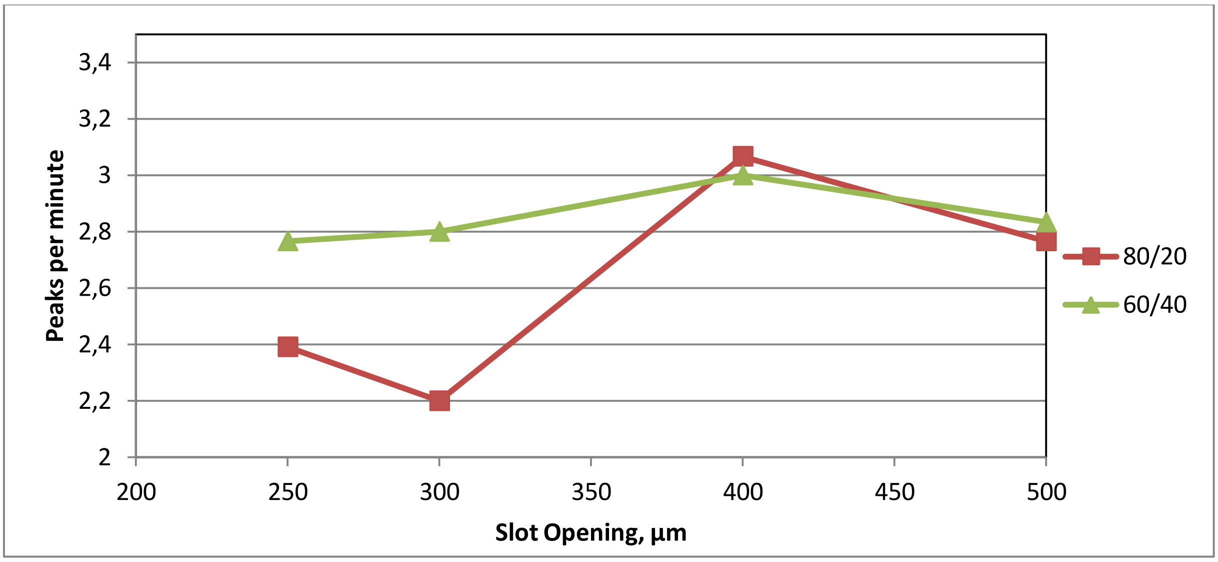
5. Comparing the viscosity of the two mud systems with the lost circulation performance, in the fluid systems, when the slot openings are D50 and D25 of the Particle Size Distribution, it is possible to observe that the higher the viscosity of the drilling mud system, the better is the bridging performance of the LC Lube in the mud system. However, more experiments are needed to describe this correlation.

Reference

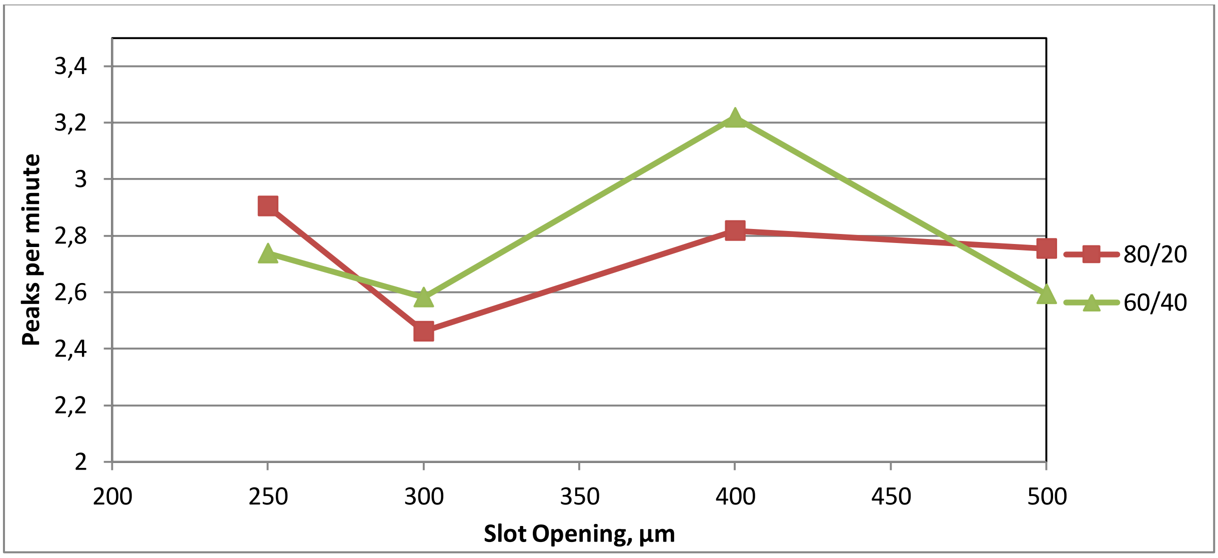
1. New Design Models and Materials Provide Engineered Solutions to Lost Circulation. Donald L. Whitfill, Dale E. Jamison. SPE 101693
2. How to Drill Mature, Depleted Reservoirs Without Downhole Losses Using Engineered Drilling Fluids. Alan Calder, Barry Fitzgerald. SPE 123832
3. Comprehensive Approach to Severe Lost Circulation Problems in Russia. Natalia Collins, Andrei Kharitonov. SPE 135704
4. Novel Rheological Tool to Determine Lost Circulation Materials (LCM) Plugging Performance. Sandeep Kulkarni, Sharath Savari. SPE 150726
5. Wellbore Strengthening: The Less-Studied Properties of Lost-Circulation Materials. Arunesh Kumar, Sharath Savari. SPE 133484
6. Lost Circulation Material Selection, Particle Size Distribution and Fracture Modelling with Fracture Simulation Software. Don Whitfill/Halliburton. IADC/SPE 115039
7. A New Binary LCM System Helped Cure Losses during Cementing while Minimizing Risk of Plugging for Slim Liners. Devesh Bhairsora, Nestor Paton. SPE 150712
8. Improved Lost Circulation Treatment Design and Testing Techniques Minimize Formation Damage. Sharath Savari, Arunesh Kumar. Halliburton. SPE 143603
9. Optimizing in Four Steps Composite Lost-Circulation Pills Without Knowing Loss Zone Width. Slaheddine Kefi, SPE, Jesse C. Lee. Schlumberger. IADC/SPE 133735
10. Experimental and Mechanistic Modeling of Fracture Sealing Resistance with Respect to Fluid and Fracture Properties. Mostafavi, V. and Hareland, G., Belayneh, M., Aadnoy, B.S. ARMA 11-198
11. Lost Circulation Treatments for Naturally Fractured, Vugular, or Cavernous Formations. B.E. Canson, Amoco Production Co. SPE/IADC 13440
12. Drilling Fluids for Wellbore Strengthening. M.S. Aston, M.W. Alberty. BP Exploration. IADC/SPE 87130.
13. Fracture Closure Stress (FCS) and Lost Returns Practices. Fred E. Dupriest, SPE, ExxonMobil. SPE/IADC 92192
14. Lost Circulation. Joseph U. Messenger. Pennwell Publishing Company. Tulsa, Oklahoma. 1981.

15. Drilling and Drilling Fluids. G.V. Chilingarian. Petroleum Engineering Department. University of southern California, Los Angeles. P. Vorabutr. Texas Pacific Oil Company, Inc. Dallas
16. An Analysis and the Control of Lost Circulation. Howard G.C., Scott P.P. Trans. AIME, 1951.
17. Experimental and Analytical Borehole Stability Study. Mesfin Belayneh. Stavanger University College. 2004.
18. Classification of Drilling-Induced Fractures and their Relationship to In-Situ Stress Directions. The Log Analysts (Society of professional Well Log Analysts) 1998.
19. Stability of highly inclined boreholes. B.S. Aadnøy, M.E. Chenvert . SPE Drilling Eng. (1987).
20. Elastoplastic Fracture Model Improves Predictions in Deviated Wells. Bernt Aadnøy, Erik Kårstad, Mesfin Belayneh, SPE, IRIS. SPE110355
21. Mud design to minimize rock impairment due to particle invasion. Abrams, A. JPT (May 1977)
22. Optimizing the selection of Bridging particles for reservoir drilling fluids. Dick M. A., T.J. Heinz. SPE 58793
23. A new methodology that surpasses current bridging theories. Vickers, Stephen;Cowie, Martin.
24. Lost Circulation Material selection, Particle size distribution and fracture modeling with fracture simulation software. Whitfill, Don. IADC/SPE 115039

Appendix A: Number of peaks per minute in two mud systems



Figur 32: Number of Peaks per minute as a function of slot opening, concentration of 16,85 ppb LC-Lube



Figur 33:Number of Peaks per minute as a function of slot opening, concentration of 8,49 ppb LC-Lube