COMPREHENSIVE APPROACH TO TORQUE AND LOST CIRCULATION PROBLEMS IN GEOTHERMAL WELLS IN TERMS OF DRILLING FLUID

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COMPREHENSIVE APPROACH TO TORQUE AND LOST CIRCULATION PROBLEMS IN GEOTHERMAL WELLS IN TERMS OF DRILLING FLUID

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ABSTRACT

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Drilling in a lost circulation zone has long been a challenge in geothermal wells due to its strong potential for high torque and wellbore instability. Excessive torque and friction values cause overpull, pipe stuck and severe problems ending up with losing the well in some cases. High temperature-high pressure (HTHP) drilling fluids design; which minimize loss rates and friction values, is critical for the success of these challenging drilling practices.

Known fact is that, oil/synthetic based drilling fluids have the best lubricity performance. However, application of these drilling fluid systems is limited because of high cost and environmental constraints. At this point, water-based drilling fluid compositions with high lubricity performance, HTHP resistance and high loss zone plugging performance, are investigated.

In this study, HTHP drilling fluid system; frequently used in Turkey and worldwide, is selected for the experiments. Several chemical commercial lubricants are added in this fluid system to find the compositions for the highest lubricity performance closest to oil/synthetic based drilling fluid systems. Also, considering the formation characteristics and drilling limitations; best fluid compositions are formulated to plug

the potential seepage and partial loss zones and reduce the differential-sticking tendency by using proper lost circulation materials.

Results reveal that lubricity and pore plugging characteristics of the selected compositions are highly innovative and noteworthy to be used in field applications for geothermal drilling industry.

Keywords: Drilling Fluid, Geothermal, Lost Circulation, Lubricity, HTHP, Torque

ÖZ

JEOTERMAL KUYULARDA YAŞANAN BURU VE KAÇAK PROBLEMLERİNİN SONDAJ SIVISI YÖNÜNDEN İNCELENMESİ

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Jeotermal kuyu sondajlarında yaşanan çamur kaçağı; kuyu stabilitesi problemleri, yüksek buru ve sürtünme değerlerine neden olmakta, sondaj dizisinin ağırlık almasına, takım sıkışmalarına ve bazı durumlarda ise kuyunun terk edilmesine varan sorunlara yol açmaktadır. Bu sorunları en aza indirmek için çamur kaçağını kapatmaya yönelik çamur kompozisyonları ile; etkin kayganlaştırma performansı, yüksek sıcaklık ve yüksek basınç (YSYB) dayanımı olan sondaj sıvısı kompozisyonları kullanılmalıdır.

Bilinen en yüksek kayganlaştırma performansını, petrol/sentetik bazlı sondaj sıvıları sağlamaktadır. Ancak hem ekonomik açıdan hem de çevresel nedenlerden dolayı bu sondaj sıvısı sistemlerinin kullanımı kısıtlanmaktadır. Bu noktada, kayganlaştırma performansı yüksek, YSYB koşullarına dayanıklı ve kaçaklı formasyonlarda etkin su bazlı sondaj sıvısı kompozisyonlarının bulunması araştırılmıştır.

Bu çalışma kapsamında, Türkiye ve Dünya'da jeotermal sondajlarda kullanılmakta olan yüksek performanslı YSYB sondaj sıvısı üzerine çeşitli kimyasal ticari kayganlaştırıcılar eklenerek, petrol/sentetik bazlı sondaj sıvısı sistemlerine en yakın kayganlaştırma performansını sağlayan kompozisyonlar belirlenmiştir. Yaşanacak olası tedrici ve kısmi çamur kaçaklarını kapatmak ve basınç farkından dolayı oluşan dizi sıkışması olasılığını en aza indirmek amacıyla uygun kaçak malzemeleri

kullanılmış, formasyon özellikleri ve sondaj sınırlamaları da göz önüne alınarak yeni ve geçerli formülasyonlar oluşturulmuştur.

Sonuçlar, seçilen kompozisyonların kayganlaştırma ve gözenek tıkama özelliklerinin, jeotermal sondaj endüstrisi saha uygulamalarında kullanılması için oldukça yenilikçi ve dikkate değer olduğunu göstermektedir.

Anahtar Kelimeler: Sondaj Sıvısı, Jeotermal, Kaçak, Kayganlaştırma, YSYB, Buru

To My Father

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ABBREVIATIONS

API	American Petroleum Institute
RPM	Rotation Per Minute
HTHP	High Temperature High Pressure
ppb or lb/bbl	Pound Per Barrel
ppg or lb/gal	Pound Per Gallon
mg/lt	Miligrams Per Liter
in-lb	Inch-Pound
PPA	Permeability Plugging Apparatus
PPT	Permeability Plugging Test
PSD	Particle Size Distribution
PV	Plastic Viscosity
YP	Yield Point
MW	Mud Weight

CHAPTER 1

INTRODUCTION

The problem of lost circulation and high torque is apparent in the early history of the drilling industry and is magnified considerably when drilling deep geothermal wells. The industry spends excessive time and money to minimize circulation losses, high torque and the negative effects it comes up with, such as stuck pipe, non-productive rig time and frequently, the abandonment of high cost wells. Furthermore, lost circulation has even been blamed for decreased production in that loss zones resulted in failure to secure production tests, while the plugging of production zones has led to decrease productivity (Bruton et al., 2001). Best drilling fluid compositions are formulated to minimize these problems that will mitigate potential wellbore instability which is a function of how rock reacts to stress redistribution while drilling due to stress anisotropy, ends up with cavings, pack-offs and hole cleaning issues caused by high torque and lost circulation. (Hamid et al, 2018)

Highest lubricity performance is achieved by synthetic/oil-based drilling fluids yielding less torque and drag. However, use of these drilling fluid systems is not preferred due to environmental and economic constraints. Water-based muds are environmental friendly and cheaper compared to synthetic/oil-based drilling fluids. (Ismail et al, 2015).

Within the scope of this thesis, high temperature / high pressure (HTHP) resistant water-based drilling fluid formulations have been investigated. High lubricity performance and effective plugging ability in seepage and partial lost circulation zones are intended.

In the initial phase of the study, high temperature and high pressure resistant drilling fluid is formulated. Calcium carbonate with three different particle size distributions

(PSD) and concentrations are added to base drilling fluid. Concentrations of calcium carbonates are selected as 10, 30 and 50 ppb; considering formation characteristics, reservoir contamination concern and drilling limitations.

Ceramic discs with pore sizes of 20, 50, 120 and 150 microns are used to represent different formation characteristics where seepage and partial losses are expected. In the upper intervals of geothermal wells where severe and total losses are not present, seepage and partial losses can occur. Seepage losses, take the form of whole mud loss at a rate lower than ~10 bbl/hr where partial losses represent for 10 to 100 bbl/hr. These losses are commonly incorporated with loss of whole mud into the pore network system where filter cake has not yet formed. These loss rates are a function of the rock permeability and the overbalance. (Cook et al, 2011)

The plugging performances of these drilling fluids are evaluated using the *FANN Permeability Plugging Apparatus*. Tests are conducted at 300 ^{0}F under 1000 psi over pressure. The fluid loss values of 7.5 minutes and 30 minutes are recorded for each formulated drilling fluid.

Two different types of environmental friendly lubricants are added to the mud compositions in different concentrations (1%, 2%, 3% by volume), which exhibited the best plugging performance. Lubricity tests are performed using *OFITE Lubricity Tester* which represents the drill string in the borehole.

As a result of these experiments, drilling fluids compositions with the best plugging and lubricity performance are tested and analyzed for physical (density, rheology, LTLP/HTHP Filter Loss and cheesing potential) and chemical (pH, Calcium ion, Chloride ion) fluid properties.

In addition to these experiments, drilling fluid compositions with the best plugging and lubrication performance; are contaminated with barite, NaCl, gypsum and lime separately and their effects on drilling fluid properties are investigated.

Moreover, repeatability tests are performed and presented to researchers.

CHAPTER 2

LITERATURE REVIEW

Quigley et al. (1990) used a device called “wellbore friction simulator” to measure the torque between drill string and wellbore in high-angle wells (45-90’). For the experiment, only unweighted lignosulfonate drilling fluid is used with/without lubricant and lubricity performances are evaluated. Tyldsley et al. (1979), investigated the effects of a vegetable oil-based lubricant on torque values and drilling fluid properties in directional wells in North Sea. This environmentally friendly, non-toxic lubricant has been successful in North Sea at high temperatures and has shown positive results when added 3% by volume to the drilling fluid. This lubricant reduces the torque by 30%, at exceeding 10,000 ft of drilling depth. Moreover, it has been observed that this lubricant increases the yield point value, decreases the API fluid loss value of the lignosulfonate mud system used in North Sea. *In this study, tests are conducted at HTHP conditions resistant drilling fluid system which is widely used in geothermal drilling industry.*

Schamp et al. (2006), have studied the torque reduction techniques to decrease the torque values experienced in directional and extended-reach wells in Chayvo field, Russia. Using full-scale test device (Figure 2.1), various methods have been tried to decrease the torque values in wells reaching 9-11 km in length. Torque values have been reduced between 5% and 15% with liquid lubricants even in deepest wells. Positive effect on lubricity is observed when liquid lubricants are added to the drilling fluid at 2-6%. Over 6%, no positive effect on lubricity is observed.

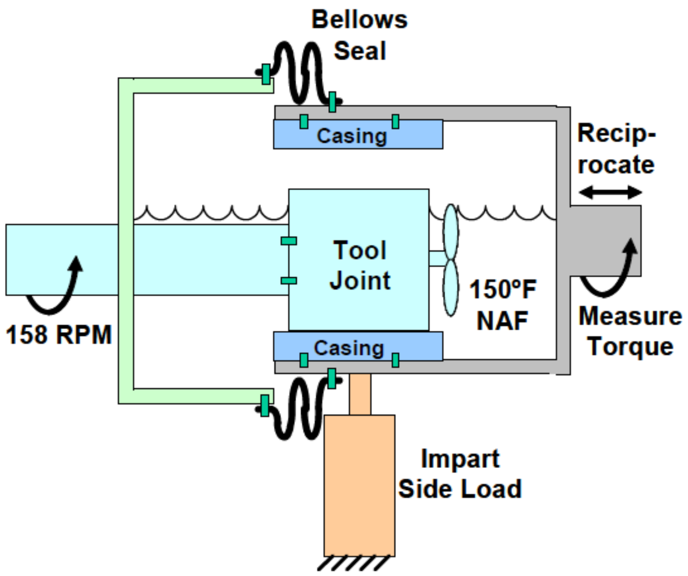

Figure 2.1. Schematic of Full-scale Lubricity Testing Device (Schamp et al, 2006)

Quigley et al. (1989), have compared the lubricity performance of drilling fluids with weighted compositions including the composition of different types of lubricants. As a result of this study, it has been observed that some lubricants are only effective in decreasing the friction values between the drill string and the wellbore tested in the laboratory. Yet, some lubricants have also been shown to assist in increasing wellbore stability and the quality of mud cake, reducing bit balling, as well as reducing the torque values. *In this study, best fluid compositions with chemical commercial lubricants and different sized lost circulation materials are determined.*

Due to environmental constraints, Argillier et al. (1996), have measured the performance of an ester-based lubricant in water-based drilling fluids with different formulations. This lubricant does not adversely affect rheology of drilling fluids and even has played a positive role in reducing fluid loss values. It is observed that the best lubricity performance occurs when 3% of the lubricant is added to the drilling fluids. *In this thesis, both ester-based and tall oil-based environmental friendly lubricants have been compared.*

Foxenberg et al. (2008); have observed the effect of a new environmentally sensitive lubricant in reducing friction and formation compatibility by field studies. The most important feature of this lubricant (PLC - class of phospholipid compounds) has been shown to be that it is completely soluble in well completion fluids, including high-density Calcium Bromide ($CaBr_2$) (Figure.2.2). In addition, Whitfill et al. (2003) have studied lost circulation pill compositions on oil-based drilling fluid systems and have focused on drilling fluid compositions that would prevent lost circulation. *However, in both papers, no studies have been carried out on the water-based mud systems used in the geothermal drilling industry.*

Figure 2.2. Lubricants shown in 14.2-lb/gal after 3 hr at 215°F. Lube C has been used for many years in reservoir drilling fluids. Typical concentration for PLC is 0.6 vol % (Foxenberg et al, 2008)

Skalle et al. (1999), presents *Modified Lubricity Tester* (Figure 2.3) which is modified with a cam setup to measure coefficient of friction values of muds containing particles. Particles like drill cuttings and barite, influence the friction values of the drilling fluid. Large beads have been used to reduce coefficient of friction. However, they are filtered out in SCE (solids control equipment). In order to avoid this situation; authors have studied smaller polymer microbeads which are going to pass unhindered. These beads decrease the coefficient of friction values in water-based drilling fluids around

40 %. *In this study; environmental friendly, liquid drilling fluid lubricants are used and tested with lubricity tester which is worldwide reliable with liquid lubricants.*

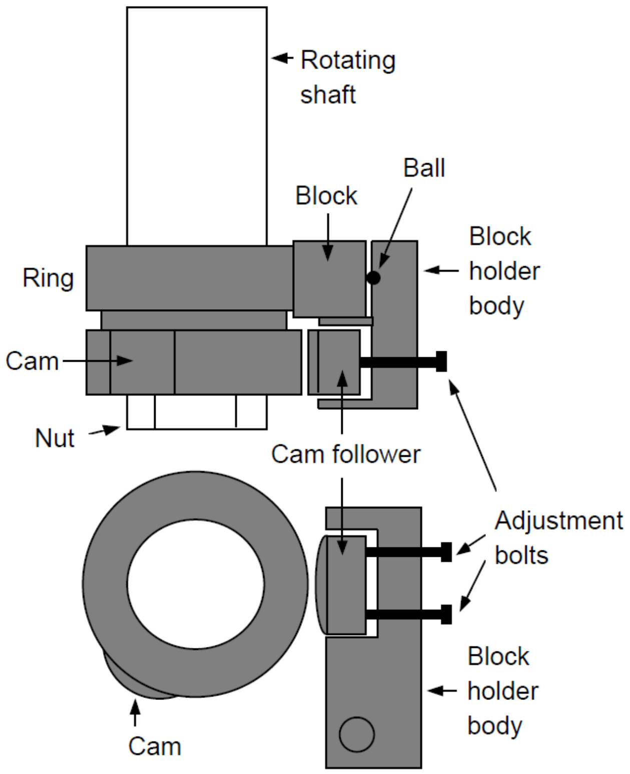

Figure 2.3. Modified lubricity tester. cross-sectional view at the bottom and side view at the top. (Skalle et al, 1999)

Reid et al. (1999), focus on differential sticking problem which has a vital impact on well costs and efficiency of drilling. The mechanisms of this problem are studied, using test results from laboratory data and literature information to research the phenomenon, especially on the ones which relate to fluid properties and composition. Moreover, a differential sticking test conducted with *stickance tester* is presented, along with laboratory application and well site study for the prevention of differential sticking.

Before field application, the equipment is used to study the relationship of sticking behavior to the drilling fluid composition and formulation of water, polymer, and oil-based drilling fluid.

Effect of fluid type, cake thickness parameter, filtration time, and also effect of lubricant are studied; as many studies have shown that the addition of lubricants to oil based and water based drilling fluids will decrease the risk of differential sticking problem and, should sticking still comes out, decrease the force needed to free the stuck drill pipe.

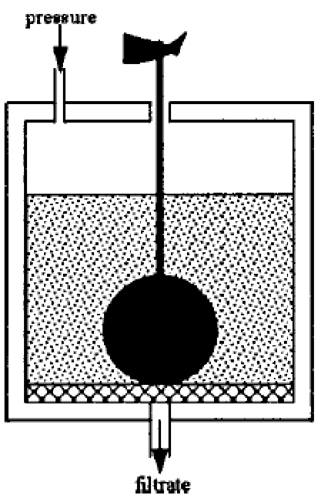

Figure 2.4. Stickance Tester. (Reid et al, 1999)

Isambourg et al. (1999), emphasizes the lubricity effect on well cost which is becoming more vital, due to activity increase in extended reach and deviated wells through depleted reservoirs. Mud properties play an important role in this field of application. Differential sticking problem may involve several mechanisms such as borehole instability, wellbore cleaning deficiency and differential pressure. A better understanding of proper evaluation of the lubricity performance of different mud systems and the mechanism of differential sticking, under simulated down hole conditions, is becoming more serious.

Fully automated device allows reproducible and accurate measurements of friction between drilling fluid filter cake and metal. That further monitors the filter cake permeability variation and pore pressure, corresponding forces and sticking time. The purpose of this equipment is to help to understand the variation of pore pressure inside the drilling fluids filter cake and corporated forces under differential pressure, and so to appraise the performance of lubricants and spotting fluids. (Isambourg et al, 1999)

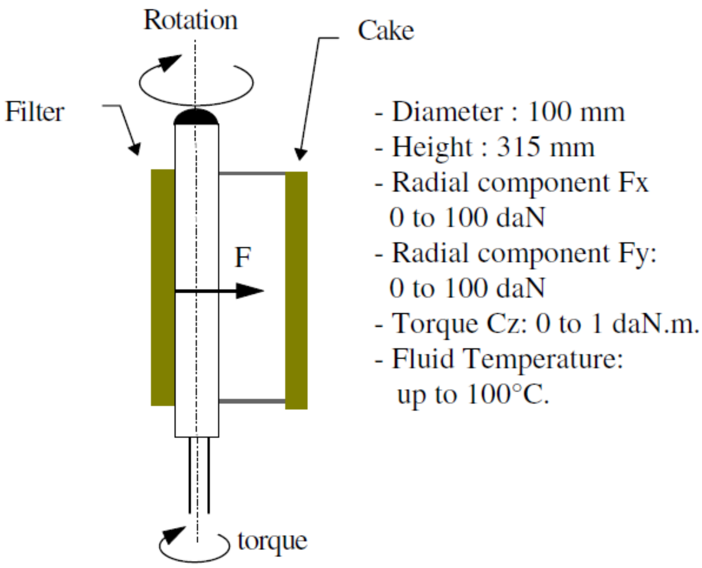

Figure 2.5. Figure and Specifications of Lubricity Captor (Isambourg et al, 1999)

Growcock et al. (1999) have investigated the lubricity potentials of major lubricants for water-based drilling fluids. Bentonite water based, polymer based and lignosulfonate based drilling fluids are used, and lubricity potential of lubricants are compared by calculating the friction coefficients. As a result of this study, none of the lubricants are found to be efficient in lignosulfonate based drilling fluid. Knox et al. (2005) have conducted performance analysis of lubricants added to well completion fluids, low solids water-based drilling fluids, and salt-based reservoir drill-in fluids using Lubricity Unit (Figure 2.6). *In this study, various amounts of lubricants are added on HTHP drilling fluid which is properly designed for geothermal drilling applications. Compositions giving the highest lubrication performance are presented.*

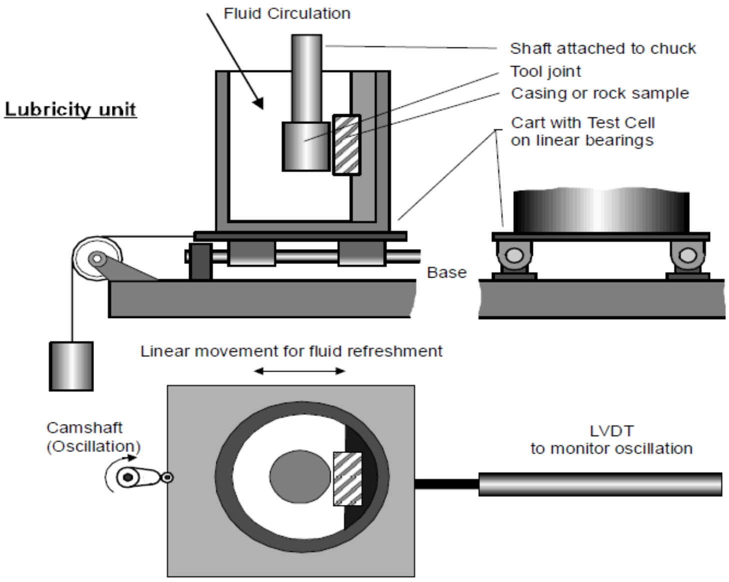

Figure 2.6. Lubricity Unit (Knox et al, 2005)

Bauer et al. (2005) have studied the design of silicate-based lost circulation pill to minimize the loss of time caused by serious lost circulation problems in geothermal wells. Temperature resistance and compatibility of this pill is investigated. However, its effect on lubrication has not been emphasized. Suyan et al. (2007) have studied cross-linked polymers as lost circulation pills. It has been observed that non-acid soluble cross-linked lost circulation pills (stiff rubbery gel) perform better than conventional lost circulation pills in total lost zones. *In this study fluids are formulated to inhibit seepage and partial losses*. Qureshi et al. (2008) have studied and succeeded in lost circulation pill applications using fiber lost circulation material on Potassium Format (HCOOK) reservoir drilling fluids. *In this study, acid-soluble and sized* *calcium carbonate ($CaCO_3$) types are added as a lost circulation material on specially designed drilling fluid for geothermal drilling.*

Figure 2.7. Stiff Rubbery Gel After Complete Gelation (Suyan et al, 2007)

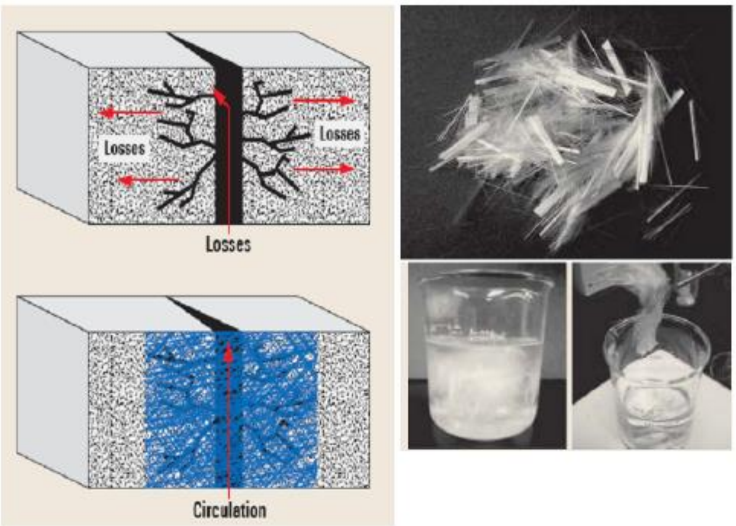

Figure 2.8. A4 Advanced Engineered Fibers (Qureshi et al, 2008)

Sanders et al. (2003), point to oil/synthetic base mud losses as expected to be one of the most tough challenges faced in drilling of the deep water Gulf of Mexico well. In *The Lost Circulation Assessment and Planning* process, planners focused on using polymer based cross-linked pills (PCPs), as an LCM. Cross-linking is described as two polymer chains link, by a grouping like cross linking agent, that links or spans two chains. PCP has been formulated as a blend of cross-linking agents, high molecular weight cross linking polymers and fibrous LCMs for severe-total losses in vugular zones or large natural fractures (Sanders et al, 2003). When activated with temperature and time PCP produces a soft to medium strength, spongy and ductile set gel. (Figure 2.9) *In this thesis, various particle sized and concentrated -acid soluble-calcium carbonates are used as conventional LCMs for plugging seepage and partial losses.*

Figure 2.9. PCP (Sanders et al, 2003)

Tare et al. (2001) call attention to mud gains and losses which are occasionally a problem in deep water drilling operations where the gap between the fracture gradient and the pore pressure is narrow, also, same problem arises when drilling extended reach wells where the problem can come up at higher angles; drilling though formations with high geothermal gradients. The range of mud losses and gains varies from 25 bbls to over 350 bbls of mud leading to notable pit gains and losses. Since these problems arise from the fracture initiation, that will not go on to propagate, mitigation steps are going to be the same as those for problems of lost circulation in general. Although these problems are relative to both oil base and water base muds, oil base fluids are more prone to lost circulation (Delhommer et al, 1987). The solid dependency of density on pressure and temperature, makes the non-aqueous mud more compressible than the water-based mud, which afterwards ends up in a narrower mud density margin and easy occurrence of lost circulation (Zhong et al, 2018). Moreover, there is not any difference between non aqueous mud and water-based mud for the pressure needed to initiate hydraulic fracturing of the formation (Onyia, 1991). Yet, there seems a considerable difference after the fractures are formed (Feng et al, 2017). For water based mud, filter cake is formed instantly caused by a higher spurt fluid loss, which is followed by a higher loss of filtration, that ends up with the formation of thicker filter cakes, allowing to develop bridges that prevent further fracture propagation and shielding the fracture tip from the maximum wellbore pressure. (Power et al, 2003)

Authors have concluded that practical solutions to gain and loss problems can be achieved with the help of the pre-treatment of the mud with properly sized and type of LCMs. By adding proper sized LCMs in sweeps, subsequent treatment of the mud should be applied most efficiently (Tare et al, 2001). *In this thesis, LCM types and concentrations are developed to be compatible with the HTHP mud system to be added continuously while drilling, as well as pumping as a sweep pill.*

Verret et al. (2000), studied on one of the widely used lost circulation material; micronized cellulose fibers, that is generally used for seepage loss control worldwide in most type of drilling muds. However, use of these lost circulation materials has been restricted in reservoir intervals because of their general lack of acid solubility. This paper details experimental study of the rapid sealing characteristic of low concentrations of cellulose fibers, the non-damaging aspect of fiber celluloses in gravel pack or screened completions, the alkaline solubilization of fiber celluloses in a screen completions or simulated gravel pack, and ends up with a discussion of the factors involved in using unconventional alkaline removal solutions versus conventional acids (Verret et al, 2000). *As explained in this thesis, calcium carbonates with different particle size distributions, are currently the most widely used additive in completion, drill-in and workover fluids for seepage and partial losses in reservoir intervals. The primary reason for that is acid solubility of calcium carbonates where filter cakes from those systems are mostly removed by follow-up acid treatments.*

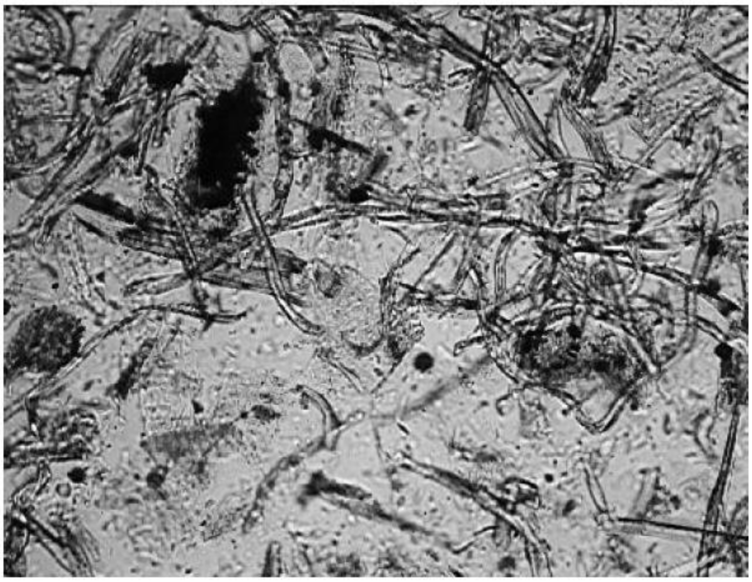

Figure 2.10. Micronized Cellulose Fibers Used in Test Data. Typical 20 micron diameter with lengths of 2 to 200 microns. (Verret et al, 2000)

Khalifeh et al. (2019) states that on occasion the mud hydraulic pressure exceeds the fracture pressure and mud is lost to the formation. In standard testing procedures like

API Recommended Practice 13-1 or 13-2, only a 100 psi or 500 psi differential pressure is required in the pressure cell for lost circulation material performance tests. It is shown that this pressure is by far too low to give any meaningful data for lost circulation material quality and performance although different types of additives for lost circulation are used to plug such losses. *In this study, 1000 psi pressure is applied in permeability plugging test to simulate seepage and partial losses.*

Ettehadi and Altun (2017), investigated the plugging potential of sepiolite drilling fluid over high permeable zones at HTHP conditions (27 to 204 ^{0}C and 2070 or 6895 kPa). 10-90 μm permeable ceramic plates are used to simulate formation characteristics. As a result of the study, sepiolite clay water base mud including $CaCO_3$ has good performance on plugging loss zones at HTHP conditions. Altun et al (2014), also emphasize that sepiolite based drilling fluids formulated in their study, provide very good rheological and filtration properties at temperatures up to 204 °C and under 2070 kPa pressure.

Dick et al. (2000), investigate optimizing bridging particles selection for producing reservoirs in terms of reservoir muds. Authors explain that first move towards composing a non-damaging and minimally invading fluid is to develop suitable particle-size distribution where *Ideal Packing Theory (IPT)* is applied. Ideal packing can be described as full extent of particle size distribution required to seal all voids but fractures, including these created by bridging materials effectively. This subsequent layering of bridging materials results in a less invading and tighter filter cake. In the process of forming a good seal, initial step is to describe the possibility of a worst case based on the largest dominant fracture width or size of the porous media. If porous media aperture size data is not available, permeability data of the formation can be used. Moreover, by taking the square root of the permeability (in mD), median pore size can be estimated from this permeability data. This pore size value should be a rough guide to the median or average size of the pores, known as the D50 which can be extrapolated to estimate the widest pore size where the particle size distribution is optimized based on the expected pore size distribution of the formation. Vickers et al.

(2006), further developed this modification who claims that D90 should be similar to maximum pore throat diameter of the formation. They put requirements for particle size distributions and the pore opening size combinations as reviewed by Kumar et al. (2010). Whitfill (2008) has studied practical approach to the Vickers' method. He suggested that D50 has to be equal to the formation anticipated maximum opening, as the maximum pore opening is not known. On the other hand, for this objective, *Abrams' Rule* has been used. This rule presents that; the median particle size of the bridging material ought to be equal to or slightly greater than one-third (1/3) of the median pore size of the formation. Moreover, concentration of the lost circulation material should be at least 5% by volume of the solids in the mud. (Abrams, 1977). Besides, Luo and Luo (1992), presented a new approach where minimum in depth penetration is achieved when the median particle size of a bridging agent is 1/2 to 2/3 of the median pore size of the target formation, followed by evolving a Shielding Temporary Bridging Technique (STBT). It is presented that the lost circulation materials should be composed of smaller sized rigid particles, relatively larger sized particles as the bridging material, and some deformable particles as the packing materials. It has been presented in this approach that rigid bridging material concentration should be at least 30 kg/m^3 (~3% by volume.) (Jienian, 2001).

Controlling severe to total losses can present significant challenges in naturally fractured formations (Savari et al., 2019). To represent fractured formations, Jeennakorn et al. (2017) used slotted discs. They studied the effects of fluid loss on sealing capability; however, no correlation has been found between the average fluid loss and thickness in slow injection tests. In these tests or the slot wall angle, it has been found that rates of the fluid loss are higher in presence of higher differential pressure. Alsaba et al. (2016a), on the other hand, used similar slotted disks where they have studied application of the sized calcium carbonate, nutshells and graphite as lost circulation materials. The lost circulation material particle size distribution is also vital for the integrity of the seal. To initiate a good seal of the slotted disk, D90 value of being equal or slightly larger than the fracture width is required. Moreover, it is suggested to add very fine particles in the lost circulation material composition to fill the void spaces between the coarser particles, and to produce a seal of less permeable zone and so form better seal integrity.

At some point authors agree with the Vickers' method, but in addition with application of particle shape. Afterwards, optimum particle size distribution selection criteria for a known fracture width, is enhanced by Alsaba et al. (2016b). This approach presents that D50 and D90 should be greater or equal to 30% and 120% of the width of the fracture respectively.

Davidson et al. (2000) deal with lost circulation strategy approaches, gained when drilling in a vugular, highly fractured limestone reservoirs. The reservoir is composed by rocks which have low matrix porosity but has karst related and highly fractured vugular porosity. Vugs and fractures are the main producing and stock tank OOIP (oil originally in place) containing elements. For that reason, the stable plugging of the vugular / fracture porosity is not a good option for curing lost circulation. Attempts to plug the lost circulation zone has not been successful that time and the well is drilled blind with sea water.

Furthermore, loss control strategy is developed based on the loss severity (Fig. 2.11). There is an expectation of total and severe losses in the carbonate zones which is acknowledged that conventional bridging materials will not be efficient in this situation. Below approach against mud loss has been improved:

- The MMS (calcium aluminum silicate) mud;
- Cross linked Polymer Pills;
- Diesel Oil-Bentonite-Cement – Calcium Carbonate pills
- Standard drilling fluid treated with bridging particles;

As a result, authors conclude that fluid loss formulation of the cross-linked polymer, is seen efficient in plugging the loss zones, which have not been cured by the MMS mud (Davidson et al, 2000).

<table>
<tr><th rowspan="2">Type of Losses</th><th rowspan="2">Typical Formations</th><th rowspan="2">Suggested Drilling Fluid (first stage of loss strategy)</th><th colspan="3">Loss Control Strategy</th></tr>
<tr><th>Second Stage</th><th>Third Stage</th><th>Fourth Stage</th></tr>
<tr><td>Seepage</td><td>Porous and permeable formations</td><td>Standard water based or oil based muds</td><td>Particulate LCM pills</td><td>Cross linking polymer pills</td><td>Gunk pills e.g. DOB2C</td></tr>
<tr><td rowspan="2">Partial</td><td>Loose sands and gravel.</td><td rowspan="2">Standard muds treated with bridging materials sized to match pore or fracture size</td><td rowspan="2">Particulate LCM pills</td><td rowspan="2">Cross linking polymer pills</td><td rowspan="2">Gunk pills e.g. DOB2C</td></tr>
<tr><td>Small natural or induced fractures</td></tr>
<tr><td rowspan="2">Severe</td><td>Long sections of loose sands and gravel</td><td>Standard muds treated with bridging materials sized to match pore or fracture size</td><td>Particulate LCM pills</td><td rowspan="2">Cross linking polymer pills</td><td rowspan="2">Gunk pills e.g. DOB2C</td></tr>
<tr><td>Larger natural or induced fractures</td><td>Thixotropic muds</td><td>Allow time for thixotropic mud to gel</td></tr>
</table>

Figure 2.11. Drilling Fluids and Loss Treatments for Different Formations (Davidson et al, 2000)

CHAPTER 3

STATEMENT OF PROBLEM

The goal of this study is to provide a solution-oriented analytical approach to torque and lost circulation problems in geothermal wells; by developing efficient water-based drilling fluid compositions.

Severe drilling risks arise from high torque and lost circulation; should be minimized to ensure wellbore stability. For this reason, HTHP water-based drilling fluid compositions with high lubricity and loss zone plugging performance are investigated. Considering drilling restrictions, environmental constraints, reservoir contamination concern and formation characteristics; proper chemical lubricants and lost circulation materials are designed to overcome major torque and lost circulation problems where seepage and partial losses are present.

Moreover, this study aims to encourage the geothermal drilling industry in Turkey and worldwide, to use the developed drilling fluid compositions with enhanced lubricity and formation plugging performance to improve the success of these challenging drilling practices.

CHAPTER 4

EXPERIMENTAL SET-UP AND PROCEDURE

4.1. Drilling Fluid Selection

For the experiments to be carried out within the scope of the study, field applications are taken into consideration upon deciding on the base drilling fluid composition. After careful examination for the drilling fluid types used in geothermal fields, most proper base fluid formulations are determined.

Considering the limitations for reservoir contamination concern and downhole drilling tool restrictions, various approaches for the selection of lost circulation material are analyzed to determine the proper particle size distributions and concentrations.

Calcium Carbonate ($CaCO_3$) is selected as the additive for lost circulation material. $CaCO_3$ is soluble in acid, so will be dissolved by acidizing operation and minimize any possible reservoir contamination. Particle size distribution of $CaCO_3$ is selected from commercial designs, in accordance with the ceramic disc pore sizes which simulate reservoir characteristics.

Chemical commercial lubricants to be used for enhanced lubricity performance are selected from environmental friendly chemicals that are resistant to high temperature and high pressure conditions.

4.2. Sample Preparation

The compositions of the drilling fluids are shown in Table 4.1. Drilling fluid compositions are prepared using tap water to simulate field conditions. Then, the additives are weighed with the help of precision scales and mixed respectively.

Mixing time is determined as 30 minutes. This time is enough to obtain a homogeneous mixture. Keeping this time longer may result with a change in the particle size of $CaCO_3$, which can affect the particle size distribution in the drilling fluid. For this reason, the mixing time of all drilling fluids prepared is set to be the same.

In this section, mud additives, mixing and aging procedures are summarized.

The following sequence should be followed in preparation of the drilling fluids. The first 8 rows are the mixing procedure of the base drilling fluid, and the 9th row shows mixing of $CaCO_3$ in columns S1-S9 as shown in Table 4.1.

1. Fill the jar with make-up water.
2. Add 10 ppb bentonite slowly with a rate of 5 minutes. Mix 20 minutes.
3. Allow time for the bentonite to yield (16 hours).
4. Add 2 ppb PAC LV slowly with a rate of 5 minutes.
5. Add 1.75 ppb Temperature Stabilizer slowly with a rate of 5 minutes.
6. Add 0.08% HT Thinner slowly with a rate of 2 minutes.
7. Add 3 ppb HT Polymer slowly with a rate of 10 minutes.
8. Add 1.75 ppb XC Polymer slowly with a rate of 10 minutes.
9. Add 10-30-50 ppb $CaCO_3$ slowly with a rate of 5 minutes.

Table 4.1. *HTHP Water-Based Drilling Fluids Compositions*

	DRILLING FLUIDS									
Additives	**Base**	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**
Bentonite, ppb	10	10	10	10	10	10	10	10	10	10
PAC LV, ppb	2	2	2	2	2	2	2	2	2	2
XC Polymer, ppb	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75
Temp. Stab., ppb	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75
HT Thinner, %	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
HT Polymer, ppb	3	3	3	3	3	3	3	3	3	3
$CaCO_3$ A, ppb		10	30	50						
$CaCO_3$ B, ppb					10	30	50			
$CaCO_3$ C, ppb								10	30	50

As shown in Table 4.1, $CaCO_3$ is added to the base drilling fluid with three different particle size distributions (Figure 4.1 – 4.3). D10, D50, D90 and D97 values are also presented in Table 4.2. $CaCO_3$ concentrations are determined as 10 ppb, 30 ppb and 50 ppb for each particle size. It has been presented in various studies that minimum bridging agent concentration should be minimum 30 kg/m^3 (~10 ppb) (Abrams, 1977), 50 kg/m^3 (~18 ppb) (Jienian, 2001), and 30 ppb as per Vickers method (Vickers, 2006).

On the other hand, there are limitations for concentrations and particle sizes of LCM while drilling with directional downhole tools. LCM’s can be detrimental to these equipment as they tend to congregate in large clumps and pack off quickly when used in high concentrations over ~50 ppb.

Besides, limiting the amount of lost circulation bridging materials, provides good advantages as the rheological parameters can be kept in desired specifications, which is also beneficial to reduce ECD and prevent the possibility of lost circulation in low fractured gradient or depleted reservoirs. Moreover, thinner mud cake is achieved with lower solids content, which is good for enhanced wellbore stability. (Jienian and Wenqiang, 2006; Wenqiang and Jienian, 2007)

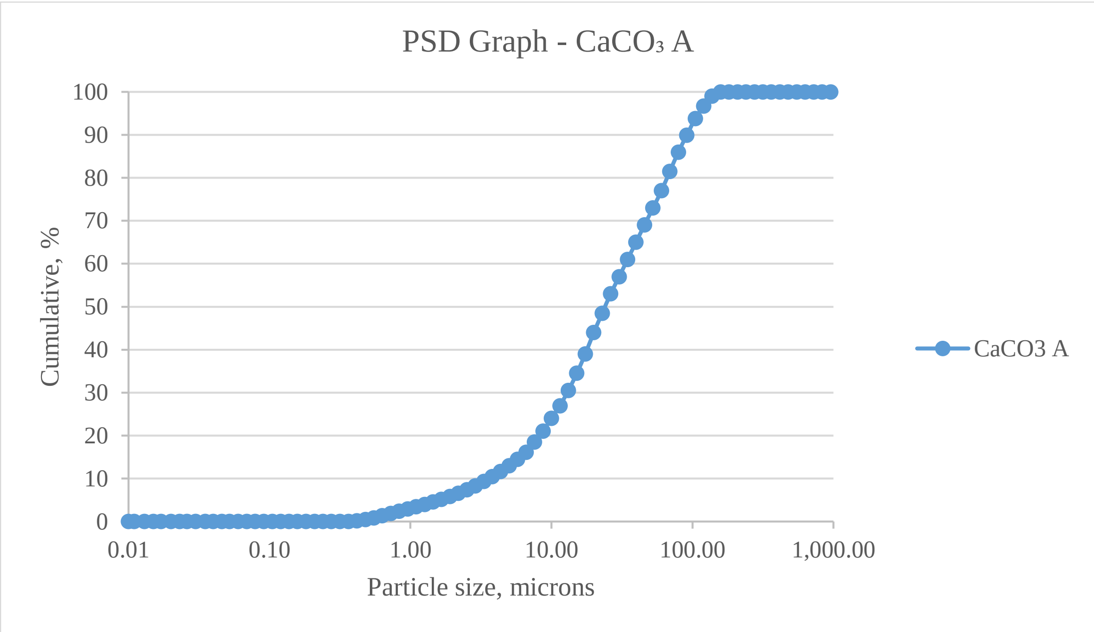

Figure 4.1. $CaCO_3$ A PSD Analysis

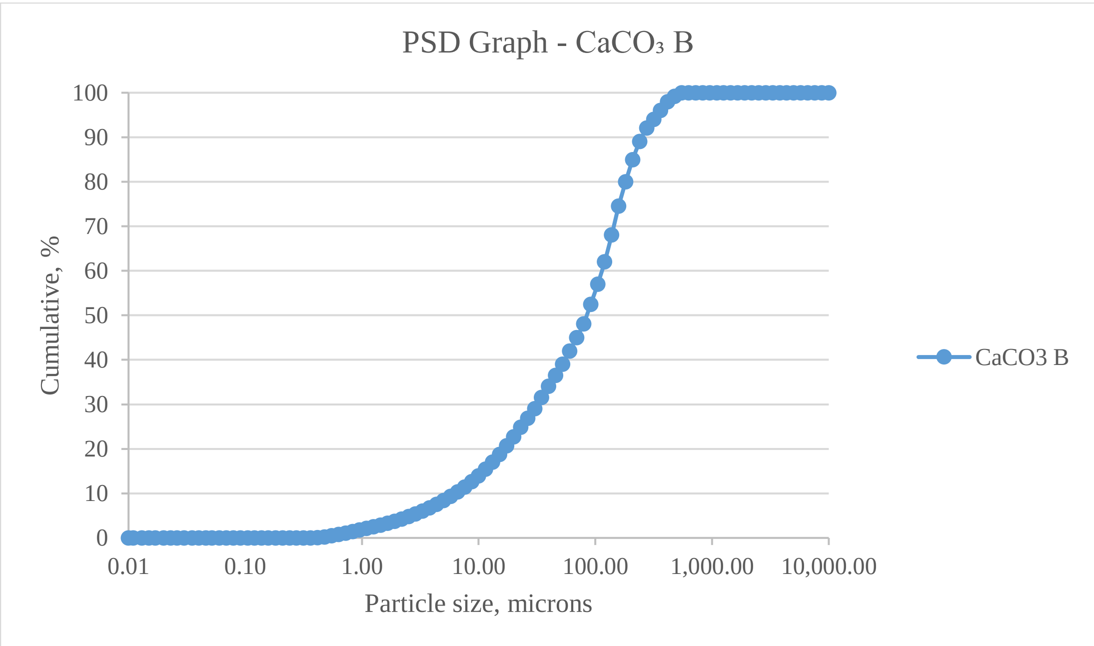

Figure 4.2. $CaCO_3$ B PSD Analysis

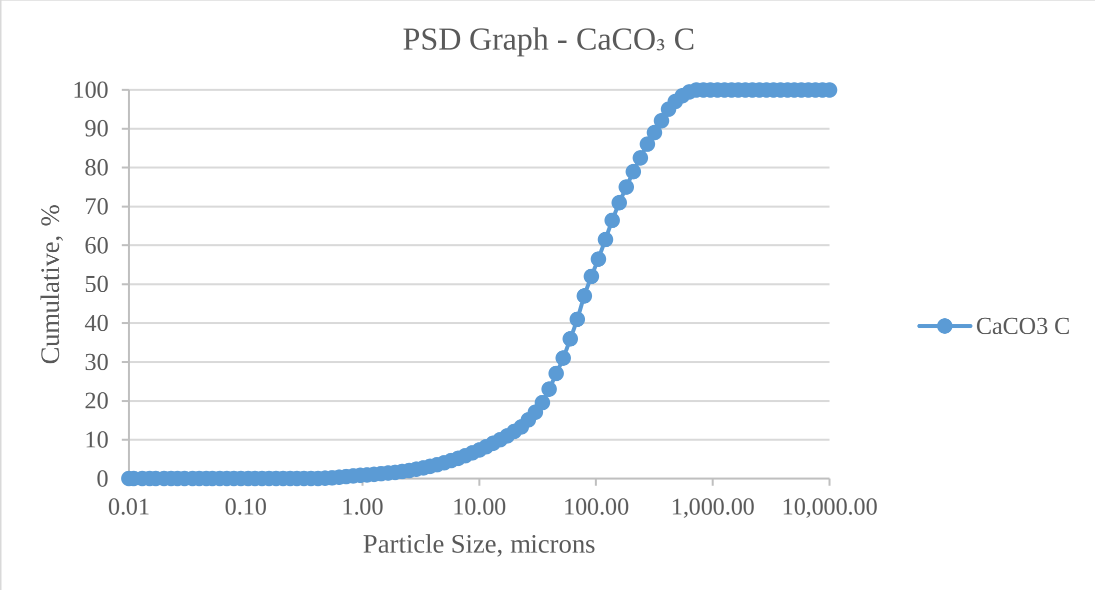

Figure 4.3. $CaCO_3$ C PSD Analysis

Table 4.2. *PSD Analysis of $CaCO_3$ A-B-C*

	$CaCO_3$ A	$CaCO_3$ B	$CaCO_3$ C
D10	3.61	6.34	15.15
D50	24.03	84.60	86.86
D90	91.51	251.30	331.24
D97	122.48	390.11	487.40

After permeability plugging analysis of these compositions are conducted, two different chemical commercial lubricants with concentrations of 1%, 2% and 3%, are added to the drilling fluid compositions with the best plugging performance. Lubricity performance of these compositions are tested after all.

Drilling fluids are placed in *OFITE Aging Cells* with 100 psi given backpressure to prevent evaporation at high temperatures according to API RP-13B (Table 4.3) Aging cells are placed in *FANN Roller Oven* and aged for 16 hours at 300 ^{0}F (149 ^{0}C) to simulate the well conditions.

Table 4.3. *Backpressure Settings at Various Test Temperatures*

Test Temperature		Absolute Water Vapor Pressure		Minimum Backpressure	
ºC	ºF	kPa	psi	kPa	psi
100	212	101	14,7	690	100
120	250	207	30	690	100
150	300	462	67	690	100

After aging for 16 hours, drilling fluids are mixed in multimixer for 5 minutes to ensure that samples are homogenous.

4.2.1. Drilling Fluids Additives

In this section, descriptions and functions of the drilling fluids additives are explained. All additives are received from GEOS Drilling Fluids Co.

4.2.1.1. Non-Treated Bentonite

Non-treated bentonite is a type of clay used as a filtration reducer and viscosifier in water-based mud systems which meets API-13A Standard. Non-treated bentonite builds a thin and impermeable filter cake which enhance fluid loss control. Efficiency of this additive decreases in muds containing high calcium ion (>240 mg/l) and chloride ion (>10,000 mg/l) (GEOS, 2018). In case high calcium ion environment is expected, drilling fluid should be pretreated with soda ash to precipitate calcium ions. As per API-13A Standard, API LTLP fluid loss value is specified as standard for drilling grade bentonite to be below 12.5 ml/30 min.

4.2.1.2. HT Polymer

HT Polymer is a synthetic polymer designed for reducing fluid loss in high temperature and high-salinity environments. HT Polymer performs well up to 475^{0}F. HT Polymer inhibits hydratable and sloughing shale and helps maintain the integrity of cuttings, has a calcium tolerance in excess of 100,000 mg/l. This additive is non-fermenting and may be used in environmentally sensitive areas.

4.2.1.3. Temperature Stabilizer

Temperature stabilizer is an alkaline metal oxide temperature stabilizer and buffers pH in the region 9.5 to 10 and hence improves the temperature stability of polymers, cellulose derivatives and biopolymers. Temperature stabilizer also improves the fluid rheology at high temperature and contributes to HTHP filtration control.

4.2.1.4. HT Deflocculant

HT Deflocculant is a specially designed copolymer, used in high temperature environments in water base muds.

4.2.1.5. Caustic Soda

Caustic Soda (high purity Sodium Hydroxide - NaOH) is being used for pH and alkalinity control in water base muds.

4.2.1.6. PAC-LV

PAC LV, low molecular weight polyanionic cellulose, is used for filtration control in water-based muds. PAC LV controls the filtration with minimum effect on rheology. Moreover, this chemical inhibits hydration and dispersion of water sensitive clays and so helps to wellbore stability. The concentration of treatment levels varies depending on the formulation of the drilling fluid, amount of solids to be drilled, and as hole condition dictates. As the polymers are continuously depleted by adsorption, it is important to compensate the loss by adding enough additional polymers (API RP 13-1, 2009).

4.2.1.7. XC Polymer

XC Polymer, a high molecular weight biopolymer (xanthan gum), is being used as a viscosifier in water base drilling muds. This additive improves hole cleaning and suspension ability of the fluids by modifying rheological parameters. The concentration of the treatment levels depends on the on the desired rheology and suspension characteristics (API RP 13-1, 2009).

4.2.1.8. Calcium Carbonate

Calcium Carbonate is an acid soluble weighting, bridging and lost circulation material used for density control, filtration and lost circulation in all types of muds. By acidizing, proper clean-up is achieved due to the acid soluble nature of this additive.

4.2.1.9. Barite

Barite (barium sulphate - $BaSO_4$) is utilized as a weighting material to increase the density in all types of muds. This additive can be used to increase mud density up to 21 ppg, which also leads to formation pressure control and stability of the borehole by optimizing hydrostatic pressure against unstable formations to keep from sloughing. (API RP 13-1, 2009).

4.2.1.10. Soda Ash (Na_2CO_3)

Soda Ash is a sodium carbonate (Na_2CO_3), used to treat calcium contamination in water-based muds to treat the excess calcium ion in make-up water and while drilling anhydrite and gypsum formations. Typical treatments range from 0.25-2 ppb, depending on the calcium contamination. 1 lb of soda ash removes the calcium from 1.283 lb calcium sulfate (Mi-Swaco, 1998).

4.2.1.11. Sodium Bicarbonate ($NaHCO_3$)

Sodium Bicarbonate ($NaHCO_3$) is utilized to treat cement contamination by decreasing the soluble calcium ions and pH in cement contaminated water-based muds. Treatment levels of sodium bicarbonate typically range from 0.5-2 ppb depending on contamination level and fluid chemistry. (AMC, 2017)

4.2.1.12. Lime ($Ca(OH)_2$)

Lime ($Ca(OH)_2$) is a calcium hydroxide which is highly efficient in removing bicarbonate and carbonate contamination from water-based muds. Removing carbonates from a low-pH drilling fluid involves adding lime. (Garrett, R.L., 1978). For treatment of carbonate contamination in high pH systems, lime is not being used due to its low solubility in this high pH environment.

4.2.1.13. Gypsum ($CaSO_4$)

Gypsum ($CaSO_4$) is calcium sulphate which is used to treat carbonate contamination in high pH environments. Gypsum is used for treatment of carbonate contamination in low pH fluids. (GEOS, 2016).

4.2.1.14. Defoamer

Defoamer is a liquid foam breaker that is used to prevent foaming in all water base muds and all viscosified brine-base workover and completion fluids to prevent foaming during mixing or circulating operations. The level of treatment is 0.05 to 0.1 liters/bbl. Defoamer can be added directly to active system. (GEOS, 2017).

4.2.1.15. Lubricant

Lubricant is an environmentally friendly liquid additive which can be used in all types of water-based drilling fluid systems. This chemical prevents differential sticking and decreases drag and torque problems. Furthermore, lubricant decreases the bit and BHA balling potential, and is thermally stable at temperatures up to 350 °F.

4.3. Water-Based Mud Testing

API RP-13B-1 Standard is employed throughout the experiments (API RP 13B-1, 2017).

4.3.1. Density

FANN Mud Balance is used to measure the density of the drilling muds which is generally referred to as mud weight. (FANN Instruments, 2016). Density or mud weight means weight per unit volume and is measured by weighing the mud. The density of mud can be stated as a density in ppg, ppcf or Specific Gravity (SG), a hydrostatic pressure gradient in lb/in^2 per 1,000 ft of vertical depth.

$$1\ lb/gal = 0{,}119826\ g/cm^3 = 119{,}826\ kg/m^3 = 7{,}480519\ lb/ft^3 \tag{1}$$

4.3.2. Viscosity and Gel Strength

Viscosity and gel strength are two important parameters in drilling fluid to optimize hole cleaning which needs to be monitored continuously during drilling operations.

FANN Viscometer Model 35SA which is a “direct-indicating viscometer” is utilized for evaluation of yield point (YP), plastic viscosity (PV) and gel strength (FANN Instruments, 2018). Viscosity is an evaluation of the shear stress by a given shear rate. For these types of viscometers, equipment constants are adjusted so that PV and YP are achieved by utilizing the readings from speeds of 600 and 300 RPM for the rotor sleeve (FANN Instruments, 2018). Gel strength of the drilling fluid indicates how quickly the structure of mud prevents or reduces the settling of solid particles (Tehrani, 2007). Please see APPENDIX A for the procedures for PVi YP and gel strength measurements.

Below formulations are used for determining Plastic Viscosity (PV) and Yield Point (YP)

$$PV\ (cp) = \theta_{600} - \theta_{300} \tag{2}$$

$$YP\ (lb/100ft^2) = \theta_{300} - YP \tag{3}$$

4.3.3. Fluid Loss

In this section, low pressure and low temperature and high pressure and high temperature fluid loss analysis are conducted for the filtration analysis using the standard API Filter Press for low pressure/low temperature, HTHP Filter Press for high pressure and high temperature.

4.3.3.1. LTLP Fluid Loss

For the evaluation of fluid loss and filter cake properties of the mud; *FANN Series 300 LTLP Filter Press* is utilized. Rate of the filtration is the fluid filter loss evaluated in milliliters (ml) at ambient temperature and 100 psi through a special filter paper for 30 minutes. Wall-building characteristics are demonstrated by the consistency and thickness of the filter cake deposited on specially hardened filter paper after 30 mins (FANN Instruments, 2014).

4.3.3.2. HTHP Fluid Loss

HTHP fluid loss values of muds are measured by *OFITE High Temperature High Pressure (HTHP) Filter Press* under selected pressures and temperatures. To simulate the downhole characteristics, evaluation of muds under HTHP conditions is highly important. Mud properties have to be monitored under high pressures and temperatures as behavior of fluid loss and filter cake characteristics of different formations. (OFITE Instruments, 2019).

HTHP Fluid Loss Tests are conducted under 500 psi net pressure and 300 ^{o}F temperature.

4.3.4. pH

The pH of the mud systems is evaluated after 16 hours of aging in a roller oven. To measure the pH of the mud, a calibrated electronic pH Meter is used. pH value below 10.5 are recommended to control physical properties of the drilling fluid (Annis et al, 1996).

4.3.5. Chloride Ion Content

Chloride ion content is measured to evaluate the possible contaminations for drilling fluids. The fluid filtrate sample is titrated with a standardized silver nitrate ($AgNO_3$) solution, using an indicator (potassium chromate) to determine the chloride ion content of the mud sample.

$$[Cl-]\ (mg/lt)\ =\ 1000\ \times V_{sn}\ /\ V_f \tag{4}$$

V_{sn}: $Volume\ of$ 0.01 $Silver\ Nitrate\ (ml)$

V_f: $Filtrate\ Volume\ (ml)$

4.3.6. Calcium Ion Content

Calcium ion content of the drilling fluid is measured to determine the dissolved calcium ions which indicates calcium ion contamination. Calcium ions in a fluid filtrate are evaluated using calcium indicator, EDTA solution and NaOH solution.

$$Calcium\ Ion\ (mg/lt) = 400 * V_{EDTA}/V_f \quad (5)$$

V_{EDTA}: $EDTA\ Volume\ (ml)$

Vf: $Filtrate\ Volume\ (ml)$

$EDTA\ Solution$: $(CAS\ No: 6381-92-6)\ 0{,}01\ mol/lt$;

$Calcium\ Buffer\ Solution$: $1\frac{mol}{lt}\ NaOH\ (CAS\ No: 1310-73-2)$

$$Calcium\ Indicator: Calver\ ®\ II5\ or\ C20H11N2Na3O11S3\ (CAS\ No: 63451-35-4)$$

4.4. Permeability Plugging Test

Down hole static filtration is evaluated by *FANN Permeability Plugging Apparatus (PPA)* which is designed as a high temperature and high pressure equipment. The PPA operates at pressures and temperatures that simulate well conditions. This instrument is ideal for predicting how a mud can form a good and permeable filter cake to seal off under pressure and depleted zones (FANN Instruments, 2016).

A ceramic filter disc is employed by PPA, which is available in wide range of porosities. These discs simulate the formation characteristics with a filter porosity that closely match the actual formation being drilled and allow for testing under increased pressures and back-pressures. (FANN Instruments, 2016).

20-50-120-150-micron filter disc are used in this study. PPA and permeability plugging measurement procedures are presented in APPENDIX B.

Calculations after getting the filtrate values for 7.5 min and 30 min are shown below.

$$Total\ Fluid\ Loss, ml = 2 \times\ V_{f_{30}} \tag{6}$$

$$Static\ Filtration\ Rate, ml/min^{1/2} = \frac{2 \times (V_{f_{30}} - V_{f_{7,5}})}{2{,}739} \tag{7}$$

$$Spurt\ Loss, ml = 2 \times \left(V_{f_{7,5}} - \left(V_{f_{30}} - V_{f_{7,5}}\right)\right) \tag{8}$$

$V_{7.5}$: $Filtrate\ Volume\ after\ 7.5\ min\ (ml)$

V_{30}: $Filtrate\ Volume\ after\ 30\ min\ (ml)$

Spurt loss of the fluid is described as the amount of filtrate recovered instantly after the pressure is applied until the fluid flow through the permeable disc ends and gas blows out freely. The presence of drilling fluid in the spurt shows that there is not an instant seal of the drilling fluid when passed through the porous filter disc. In plenty cases, the purpose is to eliminate or minimize the amount of entire drilling fluid in the spurt and 30-min test (FANN Instruments, 2016).

4.5. Lubricity Performance Test

Lubricity test is designed to simulate the rotation of the drill string which scrapes against borehole or casing while drilling. For this purpose, *OFITE Lubricity Tester* is utilized to evaluate the lubricity of muds and hereby to determine suitable type and concentration of the lubricants. (OFITE Instruments, 2015).

OFITE Lubricity Tester and lubricity measurement procedures are presented in APPENDIX-C.

Friction is evaluated as the coefficient of friction (COF). The COF between two solid faces is described as the force perpendicular to the faces or the frictional force of the load. For the equipment, the force needed to slide the ring and the test block surfaces to each other at a given rate, is evaluated by the power needed to turn the test ring shaft at a prescribed rate of RPM (OFITE Instruments, 2015).

Sample cup for the lubricity tester is not compatible to integrate with heating jacket, therefore, it has not been able to maintain a constant temperature reading. It is assumed that the temperature changes in this test are negligible.

$$Correction\ Factor = \frac{34}{Deionized\ Water\ Torque\ Reading} \tag{9}$$

$$Lubricity\ Coefficient = \frac{Torque\ Reading \times Correction\ Factor}{100\ Pounds} \tag{10}$$

CHAPTER 5

RESULTS AND DISCUSSION

In this section, experimental results and observations are given in detail. These include permeability plugging performance analysis, lubricity performance analysis, drilling fluids chemical and physical analysis, effects of drilling fluid properties on lubricity performance, effects of rheology on plugging performance and repeatability tests to ensure the reliability of the experiments.

5.1. Permeability Plugging Performance Analysis

Within the scope of the study, four different porous ceramic discs, (20, 50, 120 and 150 microns) are selected to represent well conditions and simulate formation characteristics. Experiments are carried out using these ceramic discs under 1000 psi pressure and 300 ^{o}F temperature.

All permeability test results carried out within the scope, can be seen in the following tables and figures. PPT fluid loss values of 30 min and 7.5 min are used to calculate *Spurt Loss*, *Total Fluid Loss*, and *Static Filtration Rate,* using the formulas (6-7-8) in *4.4 Permeability Test* section.

As shown in Table 5.1 and Figure 5.1, drilling fluid composition with **30 lb/bbl $CaCO_3$ A**, yield the most efficient composition for permeability plugging test with a **20-micron** porous ceramic disc.

Table 5.1. *Permeability Plugging Tests Results (20-micron)*

Ceramic Filter Disc Pore Throat Size (micron)	*$CaCO_3$ Type*	*$CaCO_3$ Concentration (lb/bbl)*	*PPT Fluid Loss (ml)*		*Spurt Loss (ml)*	*Total Fluid Loss (ml)*	*Static Filtration Rate (ml/dk$^{1/2}$)*
			7.5 min	*30 min*			
20	-	0	37	49	50	98	8.76
20	A	10	10	17	6	34	5.11
20	**A**	**30**	**7**	**14**	**0**	**28**	**5.11**
20	A	50	7.5	15	0	30	5.48
20	B	10	21	27	30	54	4.38
20	B	30	16	22	20	44	4.38
20	B	50	9	15.5	5	31	4.75
20	C	10	19	28	20	56	6.57
20	C	30	15	22	16	44	5.11
20	C	50	13	20	12	40	5.11

As a result of the 30 min permeability plugging analysis, the lowest total fluid loss value is interpreted as the highest plugging potential. It can be seen from Table 5.1 that, even **Base Mud** can have a plugging potential and highest plugging performance is achieved by **$CaCO_3$ A** addition having the best particle size distribution.

Also, low spurt loss indicates for this case is; immediate seal occurs when fluid passed through the filter.

This result also validates the Abrams rule, Vicker's method and Jienian's approach where they suggest the required concentration of bridging material should be minimum 10 to 30 ppb for water-based drilling fluids. (Abrams, 1977; Jienian, 2001; Vicker's et al, 2006). Best composition is achieved by the addition of **30 lb/bbl $CaCO_3$ A.**

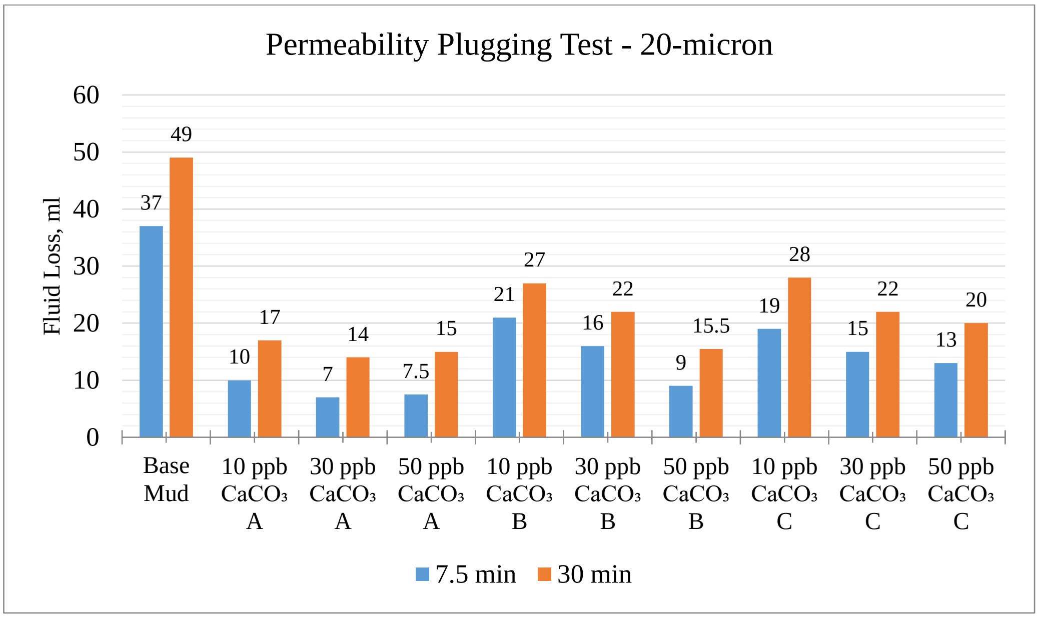

Figure 5.1. Permeability Plugging Test (20-micron)

In permeability plugging test with **50-micron** porous ceramic disc; best results are obtained with the composition containing **50 lb/bbl $CaCO_3$ A.**

Table 5.2. *Permeability Plugging Tests Results (50-micron)*

Ceramic Filter Disc Pore Throat Size (micron)	*$CaCO_3$ Type*	*$CaCO_3$ Concentration (lb/bbl)*	*PPT Fluid Loss (ml)*		*Spurt Loss (ml)*	*Total Fluid Loss (ml)*	*Static Filtration Rate (ml/dk$^{1/2}$)*
			7.5 min	*30 min*			
50	-	0	49	62	72	124	9.49
50	A	10	16	27	10	54	8.03
50	A	30	19	28	20	56	6.57
50	**A**	**50**	**10**	**16**	**8**	**32**	**4.38**
50	B	10	21	26	32	52	3.65
50	B	30	18	24.5	23	49	4.75
50	B	50	11.5	18	10	36	4.75
50	C	10	25	32	36	64	5.11
50	C	30	13.5	20	14	40	4.75
50	C	50	14	21	14	42	5.11

It has been observed from the results shown in Table 5.2 and Figure 5.2, that the total fluid loss values of 30 minutes and spurt loss are lower than the other compositions, indicating good sealing potential.

This result is convenient with the Luo and Luo approach and Abrams rule for the required median particle size of the bridging agent. Abrams rule, Vicker's method and Jienian's approach are also proved for required concentration of the lost circulation materials where they suggest the minimum required concentration should be 10 to 30 ppb for water-based drilling fluids (Abrams, 1977; Luo and Luo, 1992; Jienian, 2001; Vicker's et al, 2006). Best composition is achieved by the addition of **50 lb/bbl $CaCO_3$ A.**

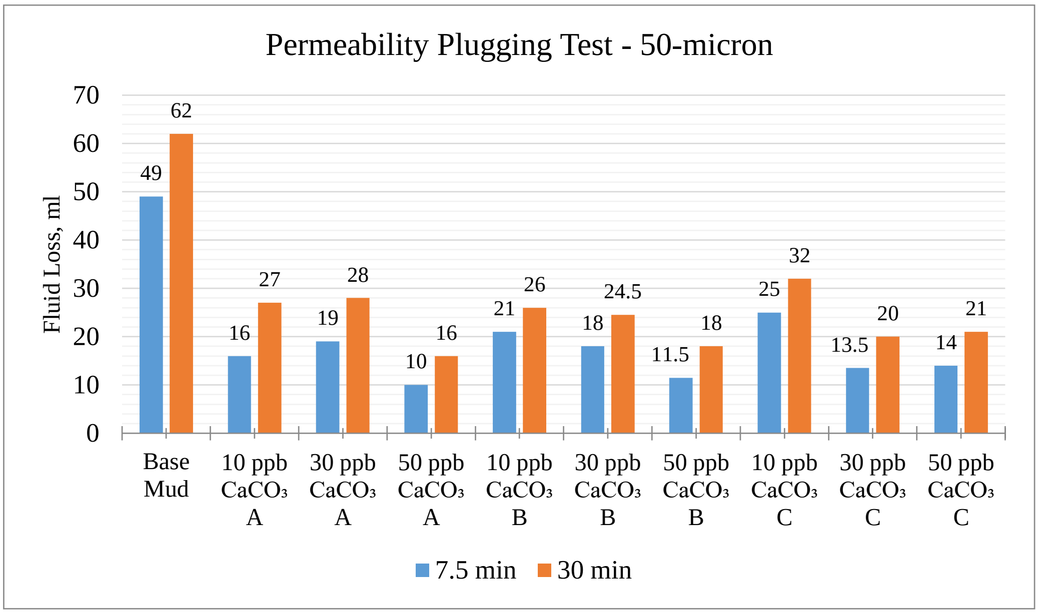

Figure 5.2. Permeability Plugging Test (50-micron)

When the ceramic disc pore size is increased to **120-microns**, most efficient results in permeability plugging tests are obtained by adding **50 lb/bbl $CaCO_3$ C**, to the base drilling fluid (Table 5.3 and Figure 5.3).

This result is convenient with the Luo and Luo approach for the required median particle size of the bridging agent. Abrams rule, Vicker's method and Jienian's approach are also proved for required concentration of the lost circulation materials where they suggest the minimum required concentration should be 10 to 30 ppb for water-based drilling fluids. (Abrams, 1977; Luo and Luo, 1992; Jienian, 2001; Vicker's et al, 2006). Best composition is achieved by the addition of **50 lb/bbl $CaCO_3$ C.**

Table 5.3. *Permeability Plugging Tests Results (120-micron)*

Ceramic Filter Disc Pore Throat Size (micron)	*$CaCO_3$ Type*	*$CaCO_3$ Concentration (lb/bbl)*	*PPT Fluid Loss (ml)*		*Spurt Loss (ml)*	*Total Fluid Loss (ml)*	*Static Filtration Rate (ml/dk$^{1/2}$)*
			7.5 min	*30 min*			
120	-	0	275	275	550	550	0.00
120	A	10	275	275	550	550	0.00
120	A	30	275	275	550	550	0.00
120	A	50	32	39	50	78	5.11
120	B	10	23	30	32	60	5.11
120	B	30	13.5	21	12	42	5.48
120	B	50	16	23	18	46	5.11
120	C	10	29	37	42	74	5.84
120	C	30	14	22	12	44	5.84
120	**C**	**50**	**9.5**	**15**	**8**	**30**	**4.02**

Compared to other compositions; this composition gives the lowest fluid loss value for 30 min. The composition containing **50 lb/bbl $CaCO_3$ C** is interpreted as the highest potential for plugging for a pore size of **120-microns**.

Compositions containing **10 lb/bbl $CaCO_3$ A**, **30 lb/bbl $CaCO_3$ A** and **base mud**; do not even plug the **120-microns** ceramic disc as concentration and median particle size of the bridging material is too low for this ceramic disc (Abrams, 1977; Luo and Luo, 1992).

Also, the purpose is to minimize or eleminate the amount of drilling fluid in the spurt which results with the lowest value in the composition containing **50 lb/bbl $CaCO_3$ C**.

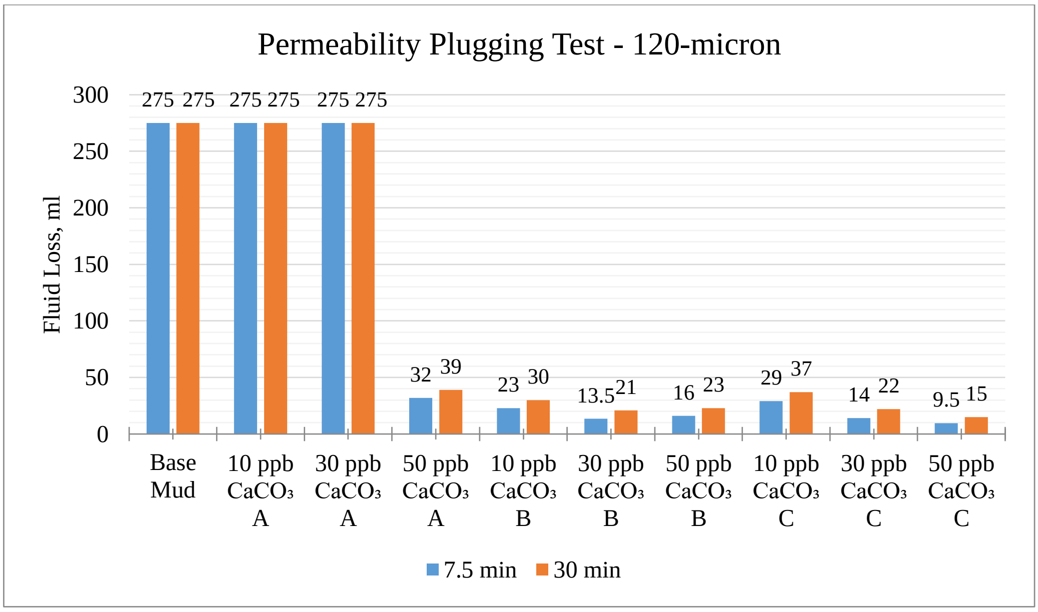

Figure 5.3. Permeability Plugging Test (120-micron)

For the permeability plugging tests with **150-micron** porous ceramic disc shown in Table 5.4, only the composition formed by the addition of **50 lb/bbl $CaCO_3$ B** to the base drilling fluid, could plug the **150-micron** disc.

This result validates the Luo and Luo's approach for the required median particle size of the bridging agent. Abrams rule, Vicker's method and Jienian's approach are also proved for required concentration of the lost circulation materials where they suggest the minimum required concentration should be 10 to 30 ppb for water-based drilling fluids. (Abrams, 1977; Luo and Luo, 1992; Jienian, 2001; Vicker's et al, 2006). Best composition is achieved by the addition of **50 lb/bbl $CaCO_3$ B.**

Table 5.4. *Permeability Plugging Tests Results (150-micron)*

Ceramic Filter Disc Pore Throat Size (micron)	*$CaCO_3$ Type*	*$CaCO_3$ Concentration (lb/bbl)*	*PPT Fluid Loss (ml)*		*Spurt Loss (ml)*	*Total Fluid Loss (ml)*	*Static Filtration Rate (ml/dk$^{1/2}$)*
			7.5 min	*30 min*			
150	-	0	275	275	550	550	0.00
150	A	10	275	275	550	550	0.00
150	A	30	275	275	550	550	0.00
150	A	50	275	275	550	550	0.00
150	B	10	275	275	550	550	0.00
150	B	30	275	275	550	550	0.00
<u>150</u>	**<u>B</u>**	**<u>50</u>**	**<u>22</u>**	**<u>30</u>**	**<u>28</u>**	**<u>60</u>**	**<u>5.84</u>**
150	C	10	275	275	550	550	0.00
150	C	30	275	275	550	550	0.00
150	C	50	275	275	550	550	0.00

Further studies with different concentrations and particle sized LCMs should be studied to optimize the plugging porous media larger than **150-micron**.

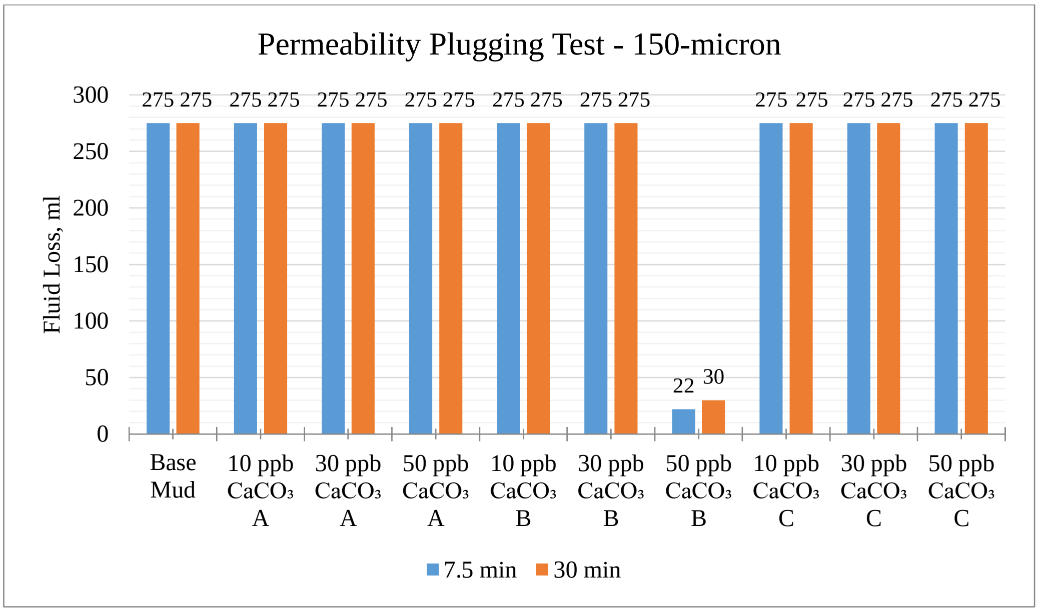

Figure 5.4. Permeability Plugging Test (150-micron)

5.1.1. Drilling Fluid Compositions with Best Plugging Performance

Drilling fluid compositions with best plugging performance in the above-mentioned experiments are summarized in Table 5.5. These identified compositions are then used for lubricity tests.

Table 5.5. *Drilling Fluid Compositions with Best Plugging Performance*

Pore Throat Size (micron)	*Drilling Fluids Composition*
20	Base Mud + 30 lb/bbl $CaCO_3$ A
50	Base Mud + 50 lb/bbl $CaCO_3$ A
120	Base Mud + 50 lb/bbl $CaCO_3$ C
150	Base Mud + 50 lb/bbl $CaCO_3$ B

5.2. Lubricity Performance Analysis

OFITE Lubricity Tester is used for the lubricity performance analysis. Test results obtained from this equipment and the *Lubricity Coefficients* are calculated by using the formulas (9-10) shared in *4.5 Lubricity Performance Test* section.

The frequently used lubricants in water based drilling fluids are; oils, graphite, soaps and surfactants which are primarily petroleum derived products, even though they might come from alike sources, like tar stands and oil shales (Skalle, 2011; Gunstone et al., 2007; Li et al., 2015).

Together with the novel developments in the drilling industry, interest in greener lubricants derived from organic sources have been growing up. It is confirmed by numerous studies that petroleum based lubricants are slow in degradation and detrimental to environment and health of human (Getliff and James, 1996; Neff et al., 2000). Hereof, biodegradable and environmental friendly lubricants are found to be convenient alternatives (Addy et al., 1984; Mueller et al., 2004a; Campanella et al., 2010; Darley et al., 2011; Atabani et al., 2013). Biolubricant is the generic term for renewable and biodegradable type of lubricants (Bart et al., 2012).

For lubricity performance analysis, two types of biodegradable and environmental friendly chemical commercial type of lubricants (tall oil and ester based), are added to water-based drilling fluid. Properties of the lubricants can be seen below in Table 5.6.

Tall oil; which is also called tallol or “liquid rosin”, is obtained as a by-product of the Kraft pulping process of manufacture of wood pulp while pulping mainly conifer trees (Norlin, 2002). Tall oil, a viscous odorous liquid, colored black-yellow, is a by-product mixture of fatty acids (30-60 %), resin acids (40-60 %), and unsaponifiables (5-10 %) reproduced from the softwood extractives (Bajpai, 2018).

Esters are the reaction products of acids or their derivatives with alcohols (Rizvi, 2009). Esters, used as chemical type of lubricants in drilling mud, are reproduced from polyhydric alcohols, that contains more than one hydroxyl group. (Kania et al, 2015).

That attraction between positively charged metal surfaces and ester molecules is generated by the polarity of esters, which promotes the lubricating potential of esters. (Rudnick, 2005; Amorim et al., 2011).

Furthermore, it is believed that esters create stronger lubricious film than synthetic hydrocarbons (Nie, 2012). Besides, esters provide good lubricity performance even at 180°C temperature (Rudnick, 2005).

Table 5.6. *Properties of Lubricants*

Sample Name	*Properties*
LUBE-1	Tall oil Based
LUBE-2	Ester Based

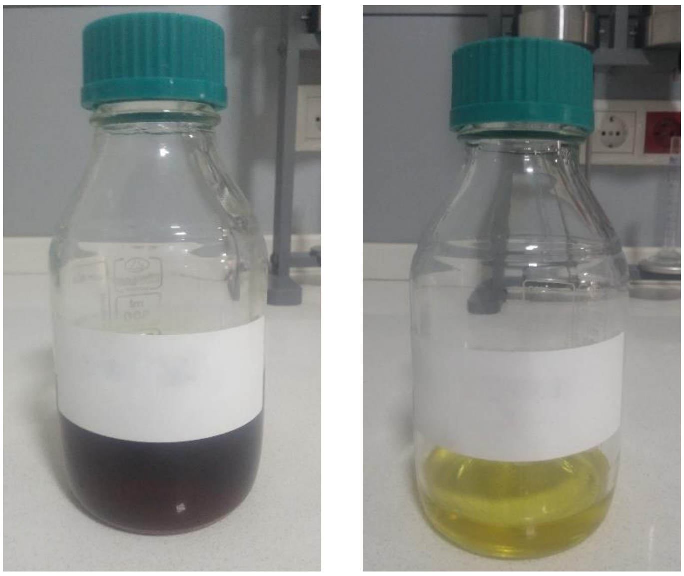

Figure 5.5. Tall oil Based (Left) and Ester Based (Right) Lubricants

Lescure et al. (2013) states that very small amount of lubricants is enough to provide adequate lubricity for water based drilling fluids. Even, 1% of lubricant can decrease the torque by 20%, while the average optimum concentration of lubricant is not over 3% (Mueller et al., 2004a; Amorim et al., 2011; Mueller et al., 2004b; Patel et al., 2013).

Tall oil based; **LUBE-1** and ester-based **LUBE-2**; are added to base drilling fluid; 1%, 2% and 3% by volume.

5.2.1. Drilling Fluid Lubricity Analysis with 30 lb/bbl $CaCO_3$ A

Best plugging potential for **20-micron** ceramic disk is obtained by the base fluid formulation containing **30 lb/bbl $CaCO_3$ A**. **LUBE-1** and **LUBE-2** are added separately to this composition with **1-2-3%** by volume and best lubricity performances are examined. The lubricity coefficients calculated using the *OFITE Lubricity Tester*, are shown in Figure 5.6.

As shown in Figure 5.6 and Table 5.7, increasing the amount of **LUBE-1** up to **2%**, has a positive effect on the lubrication performance of the mud. Lubricity performance tends to decrease at **3%** by volume. For that reason, adding **LUBE-1** higher than **2%,** is not recommended.

Increasing **LUBE-2** concentration, has a positive effect on the lubrication performance of the mud, up to **3%** by volume (Figure 5.6 and Table 5.7).

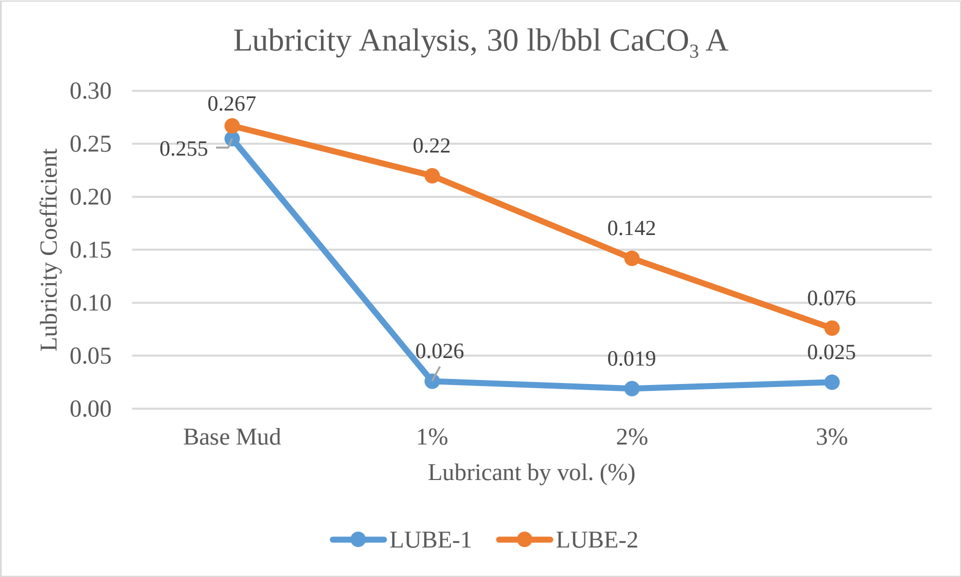

Figure 5.6. Lubricity Performance Analysis, 30 lb/bbl $CaCO_3$ A

Table 5.7. *Lubricity Test Results, 30 lb/bbl $CaCO_3$ A*

	Sample						
	1	*2*	*3*	*4*	*5*	*6*	*7*
Bentonite (ppb)	10	10	10	10	10	10	10
PAC LV (ppb)	2	2	2	2	2	2	2
XC Polymer (ppb)	1.75	1.75	1.75	1.75	1.75	1.75	1.75
Temp. Stab. (ppb)	1.75	1.75	1.75	1.75	1.75	1.75	1.75
HT Thinner (%)	0.08	0.08	0.08	0.08	0.08	0.08	0.08
HT Polymer (ppb)	3	3	3	3	3	3	3
$CaCO_3$ A (ppb)	**30**	**30**	**30**	**30**	**30**	**30**	**30**
LUBE-1 (%)		**1%**	**2%**	**3%**			
LUBE-2 (%)					**1%**	**2%**	**3%**
Mixing Time (min)				*30*			
Roller Oven				*300^{o}F @ 16 hr*			
Test Temperature (^{o}F)				*120*			
Test Time (min)	5	5	5	5	5	5	5
Rot/min	60	60	60	60	60	60	60
Applied Torque (in-lb)	150	150	150	150	150	150	150
Measured Torque	26.2	2.7	2.0	2.6	22.1	14.2	7.6
Calibration Torque	35.0	35.0	35.0	35.0	34.1	34.1	34.1
Correction Factor	0.971	0.971	0.971	0.971	0.997	0.997	0.997
Lubricity Coefficient	0.255	0.026	**0.019**	0.025	0.220	0.142	0.076

It is clearly observed that lubricity performance of **LUBE-1** is much higher than **LUBE-2** when compared to each other.

Best lubricity performance is obtained from the formulation containing **2% LUBE-1**.

When compared to base mud; lubricity coefficient is decreased by **92%** with the addition of **2% LUBE-1.**

5.2.2. Drilling Fluid Lubricity Analysis with 50 lb/bbl $CaCO_3$ A

LUBE-1 and **LUBE-2** are added separately with concentrations of **1-2-3%** on the drilling fluids containing **50 lb/bbl $CaCO_3$ A**. This composition is chosen as the best plugging potential for **50-micron** ceramic disc. The lubricity coefficients calculated using the OFITE Lubricity Tester are shown in Figure 5.7.

As shown in Figure 5.7 and Table 5.8, increasing **LUBE-1** concentration to **2%** has a positive effect on lubrication performance, while further increase in the amount of **LUBE-1** decreased the performance of lubricity. Therefore, increasing **LUBE-1** concentration over **2%** is not recommended.

On the other hand, increasing **LUBE-2** concentration by **3%**, has a positive effect on the lubricity performance of the mud (Figure 5.7 and Table 5.8).

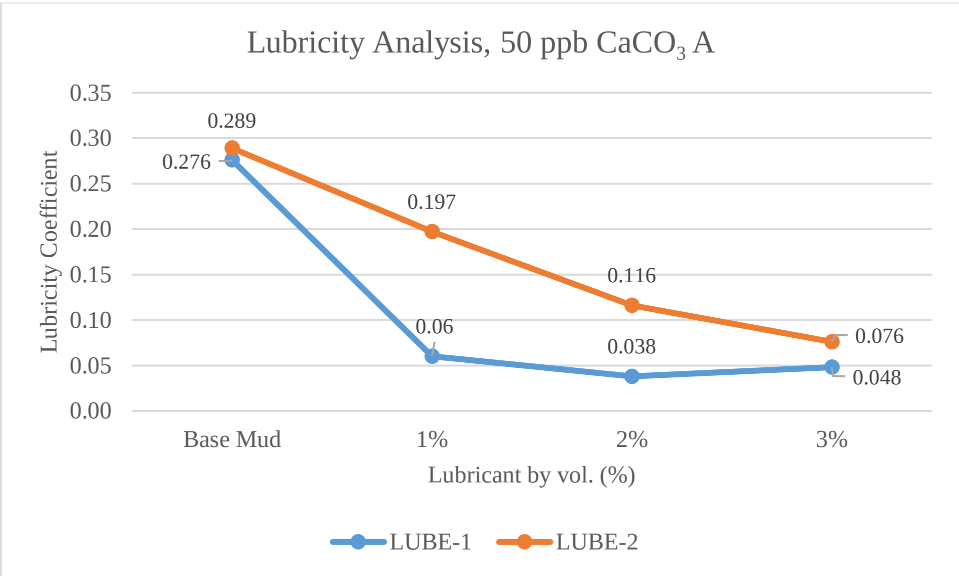

Figure 5.7. Lubricity Performance Analysis, 50 lb/bbl $CaCO_3$ A

Table 5.8. *Lubricity Test Results, 50 lb/bbl $CaCO_3$ A*

	Sample						
	1	*2*	*3*	*4*	*5*	*6*	*7*
Bentonite (ppb)	10	10	10	10	10	10	10
PAC LV (ppb)	2	2	2	2	2	2	2
XC Polymer (ppb)	1.75	1.75	1.75	1.75	1.75	1.75	1.75
Temp. Stab. (ppb)	1.75	1.75	1.75	1.75	1.75	1.75	1.75
HT Thinner (%)	0.08	0.08	0.08	0.08	0.08	0.08	0.08
HT Polymer (ppb)	3	3	3	3	3	3	3
$CaCO_3$ A (ppb)	**50**	**50**	**50**	**50**	**50**	**50**	**50**
LUBE-1 (%)		**1%**	**2%**	**3%**			
LUBE-2 (%)					**1%**	**2%**	**3%**
Mixing Time (min)				*30*			
Roller Oven				*300 ^oF @ 16 hr*			
Test Temperature (^oF)				*120*			
Test Time (min)	5	5	5	5	5	5	5
Rot/min	60	60	60	60	60	60	60
Applied Torque (in-lb)	150	150	150	150	150	150	150
Measured Torque	29.0	6.3	4.0	5.0	19.5	11.5	7.5
Calibration Torque	35.7	35.7	35.7	35.7	33.7	33.7	33.7
Correction Factor	0.952	0.952	0.952	0.952	1.009	1.009	1.009
Lubricity Coefficient	0.276	0.060	**0.038**	0.048	0.197	0.116	0.076

When **LUBE-1** and **LUBE-2** lubricants are compared to each other, lubricity performance of **LUBE-1** is much higher than that of **LUBE-2**.

For this experiment group, highest lubrication performance is obtained from the composition with **2% LUBE-1**.

When compared to base mud; lubricity coefficient is decreased by **86%** with the addition of **2% LUBE-1.**

5.2.3. Drilling Fluid Lubricity Analysis with 50 lb/bbl $CaCO_3$ C

LUBE-1 and **LUBE-2** are added separately **1-2-3%** by volume on the drilling fluids containing **50 lb/bbl $CaCO_3$ C**. This composition is chosen as the best plugging potential for **120-micron** ceramic disc. The lubricity coefficients calculated using the *OFITE Lubricity Tester* are shown in Figure 5.8.

Unlike previous experiments, adding **LUBE-1** up to **3%**, has a positive effect on the lubricity performance of the mud. (Figure 5.8 and Table 5.9).

Addition of **LUBE-2** up to **3%**, increases the lubricity performance of the fluid as like **LUBE-1**. (Figure 5.8 and Table 5.9).

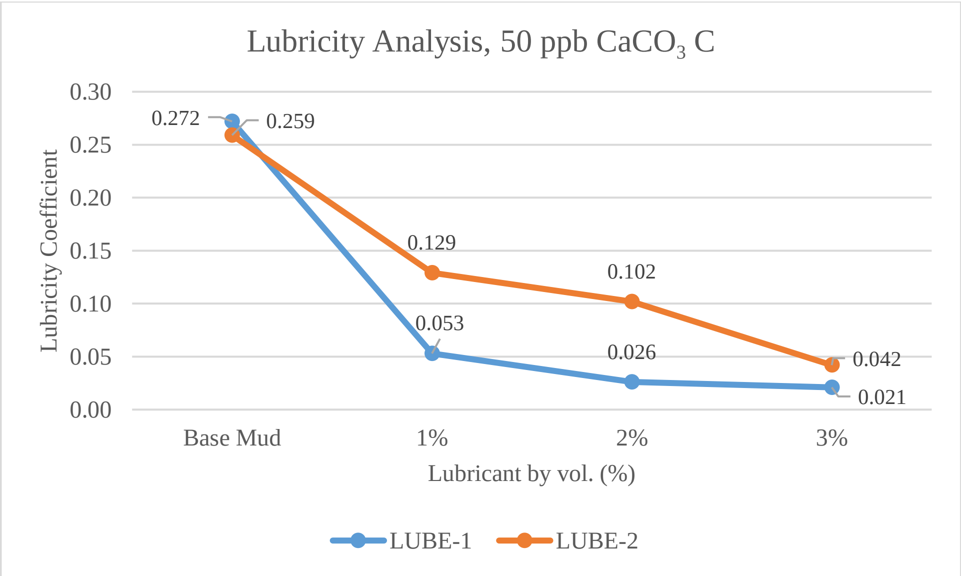

Figure 5.8. Lubricity Performance Analysis, 50 lb/bbl $CaCO_3$ C

Table 5.9. *Lubricity Test Results, 50 lb/bbl $CaCO_3$ C*

	Sample						
	1	*2*	*3*	*4*	*5*	*6*	*7*
Bentonite (ppb)	10	10	10	10	10	10	10
PAC LV (ppb)	2	2	2	2	2	2	2
XC Polymer (ppb)	1.75	1.75	1.75	1.75	1.75	1.75	1.75
Temp. Stab. (ppb)	1.75	1.75	1.75	1.75	1.75	1.75	1.75
HT Thinner (%)	0.08	0.08	0.08	0.08	0.08	0.08	0.08
HT Polymer (ppb)	3	3	3	3	3	3	3
$CaCO_3$ C (ppb)	**50**	**50**	**50**	**50**	**50**	**50**	**50**
LUBE-1 (%)		**1%**	**2%**	**3%**			
LUBE-2 (%)					**1%**	**2%**	**3%**
Mixing Time (min)				*30*			
Roller Oven				*300 ^{o}F @ 16 hr*			
Test Temperature (^{o}F)				*120*			
Test Time (min)	5	5	5	5	5	5	5
Rot/min	60	60	60	60	60	60	60
Applied Torque (in-lb)	150	150	150	150	150	150	150
Measured Torque	27.4	5.3	2.6	2.1	12.5	9.9	4.1
Calibration Torque	34.2	34.2	34.2	34.2	33	33	33
Correction Factor	0.994	0.994	0.994	0.994	1.030	1.030	1.030
Lubricity Coefficient	0.272	0.053	0.026	**0.021**	0.129	0.102	0.042

However, the performance of **LUBE-1** is much higher when compared to **LUBE-2**

Although, both lubricants yield the best results at **3%**, the formulation giving the highest lubricity performance is determined with **3% LUBE-1** composition as seen in Figure 5.8 and Table 5.9.

When compared to base mud; lubricity coefficient is decreased by **94%** with the addition of **3% LUBE-1.**

5.2.4. Drilling Fluid Lubricity Analysis with 50 lb/bbl $CaCO_3$ B

LUBE-1 and **LUBE-2** are added separately with concentrations of **1-2-3%** on the drilling fluids containing **50 lb/bbl $CaCO_3$ B**. This composition is chosen as the best plugging potential for **150-micron** ceramic disc. The lubricity coefficients calculated using the OFITE Lubricity Tester are shown in Figure 5.9.

As seen from Figure 5.9 and Table 5.10, increasing the concentration of **LUBE-1** to **2%**, has a positive effect on the lubricity performance of the drilling fluid. However, decrease in lubricity performance is observed in **3% LUBE-1** concentration. For this reason, adding **LUBE-1** higher than **2%** by volume is not recommended.

Increasing the concentration of **LUBE-2**, has a positive effect on the lubrication performance of the mud up to **3%** by volume (Figure 5.9 and Table 5.10).

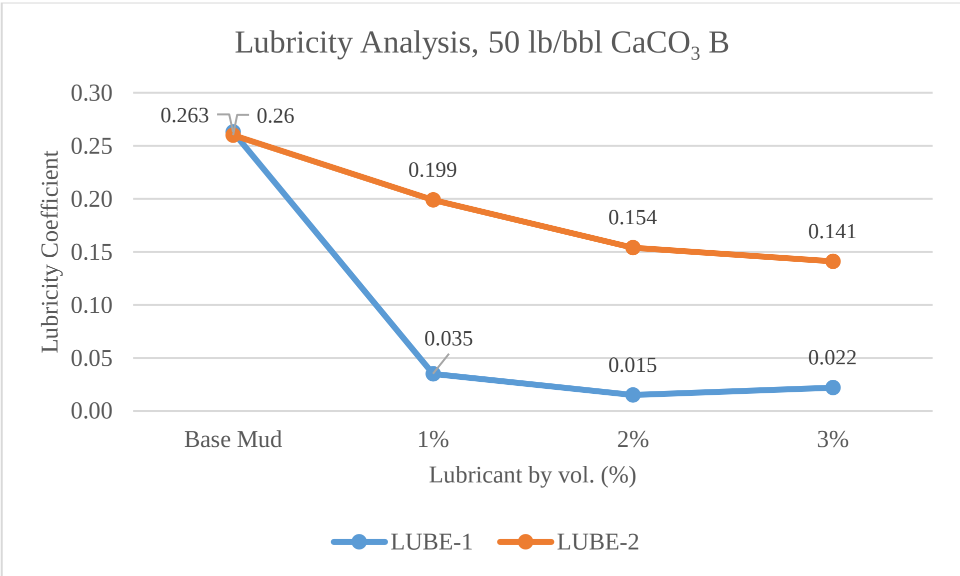

Figure 5.9. Lubricity Performance Analysis, 50 lb/bbl CaCO3 B

Table 5.10. *Lubricity Test Results, 50 lb/bbl $CaCO_3$ B*

	Sample						
	1	*2*	*3*	*4*	*5*	*6*	*7*
Bentonite (ppb)	10	10	10	10	10	10	10
PAC LV (ppb)	2	2	2	2	2	2	2
XC Polymer (ppb)	1.75	1.75	1.75	1.75	1.75	1.75	1.75
Temp. Stab. (ppb)	1.75	1.75	1.75	1.75	1.75	1.75	1.75
HT Thinner (%)	0.08	0.08	0.08	0.08	0.08	0.08	0.08
HT Polymer (ppb)	3	3	3	3	3	3	3
$CaCO_3$ B (ppb)	**50**	**50**	**50**	**50**	**50**	**50**	**50**
LUBE-1 (%)		**1%**	**2%**	**3%**			
LUBE-2 (%)					**1%**	**2%**	**3%**
Mixing Time (min)				*30*			
Roller Oven				*300 °F @ 16 hr*			
Test Temperature (°F)				*120*			
Test Time (min)	5	5	5	5	5	5	5
Rot/min	60	60	60	60	60	60	60
Applied Torque (in-lb)	150	150	150	150	150	150	150
Measured Torque	27.0	3.6	1.5	2.3	20.0	15.4	14.1
Calibration Torque	34.9	34.9	34.9	34.9	34.1	34.1	34.1
Correction Factor	0.974	0.974	0.974	0.974	0.997	0.997	0.997
Lubricity Coefficient	0.263	0.035	**0.015**	0.022	0.199	0.154	0.141

In comparison, performance of **LUBE-1** is much higher than that of **LUBE-2**.

As a result, for drilling fluid lubricity analysis with **50 lb/bbl $CaCO_3$ B**; the formulation giving the highest lubrication performance is determined as the composition containing **2% LUBE-1**.

When compared to base mud; lubricity coefficient is decreased by **92%** with the addition of **2% LUBE-1.**

5.2.5. Foam Forming Potential Analysis

In base muds, foam formation is not observed before and after aging. When lubricant is added, foam is not formed before aging. Yet, there is a traceable amount of breakable foam after aging. It is observed that; when lubricant concentration is increased, the amount of foam also increases.

In order not to affect the lubricity performance tests, a foam breaker is added to the drilling fluids by **‰1** and the foam has been completely broken.

Illustrative examples of ester-based (**LUBE-2**) lubricant added drilling fluids with foam and foam breaker are shown below (Figure 5.10-5.13).

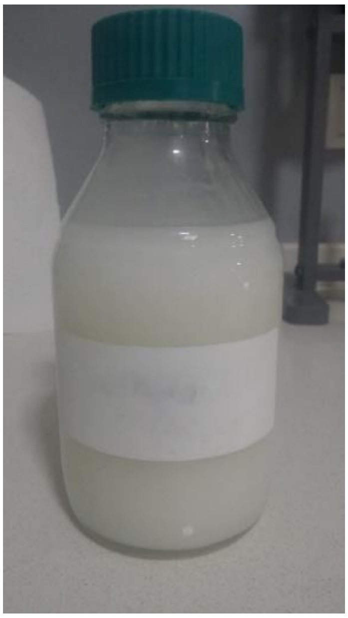

Figure 5.10. Defoamer

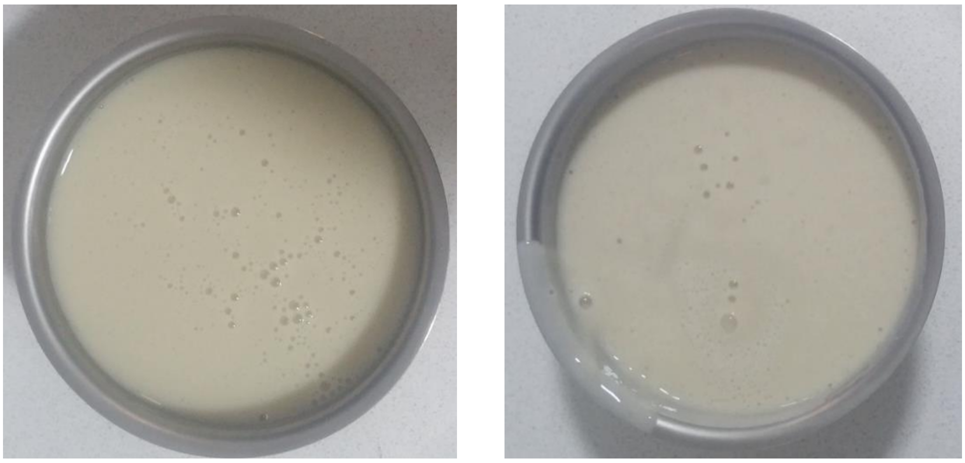

Figure 5.11. Before and After ‰1 Defoamer (%1 LUBE-2)

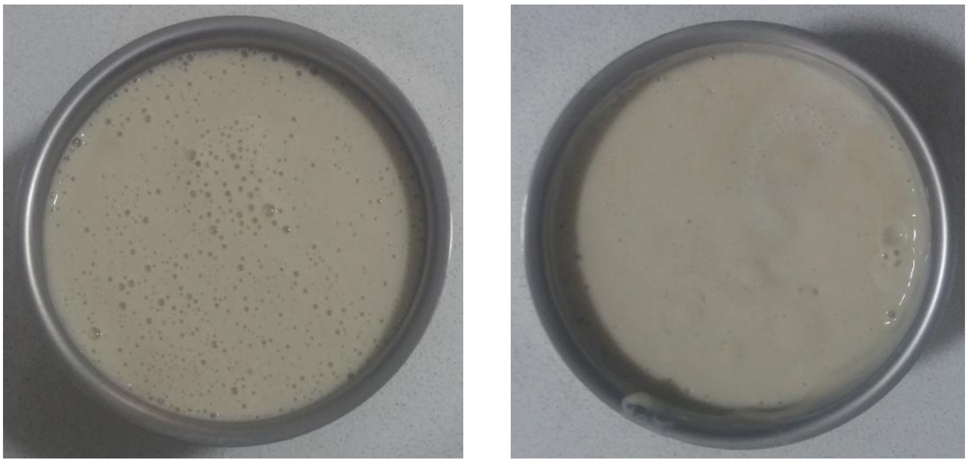

Figure 5.12. Before and After ‰1 Defoamer (2% LUBE-2)

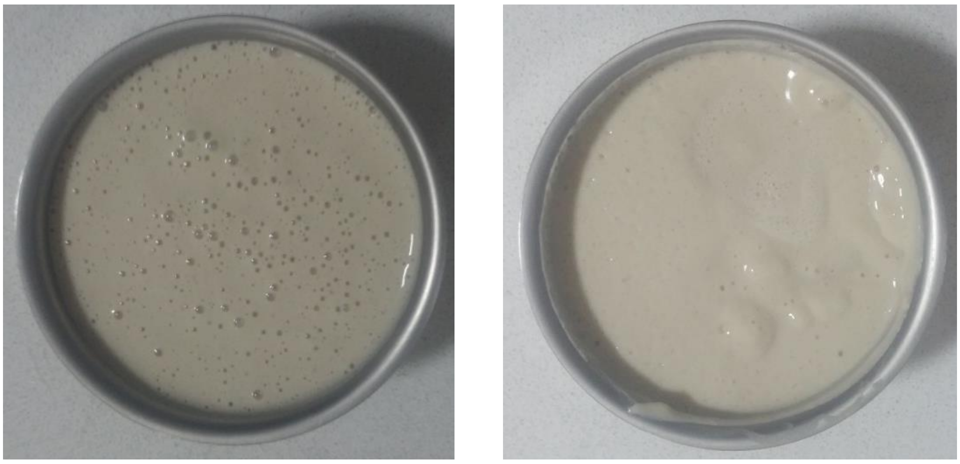

Figure 5.13. Before and After ‰1 Defoamer (3% LUBE-2)

5.2.6. Greasing and Cheesing Analysis

Cheesing or greasing of drilling fluid are not desired physical properties. Reaction between divalent ions and lubricant may result with grease-like precipitate formation. Greasing can be formed with relatively low concentrations of divalent ions depending on the lubricant's nature. On the other hand, cheesing can damage the producing zone (Knox et al, 2005). As effect of greasing and cheesing increases drilling fluid lubricity performance decreases (Shettigar et al, 2015). Cheesing or greasing is not observed in pre- and post-aged drilling fluids with **LUBE-1** and **LUBE-2**.

5.2.7. Drilling Fluid Compositions with Best Plugging and Lubricity Performance

Drilling fluid compositions with the best plugging and lubricity performance in the above-mentioned experiments are summarized in Table 5.11.

Table 5.11. *Drilling Fluid Compositions with Best Plugging and Lubricity Performance*

Pore Throat Size (micron)	*Drilling Fluids Composition*
20	Base Mud + 30 lb/bbl $CaCO_3$ A + 2% LUBE-1
50	Base Mud + 50 lb/bbl $CaCO_3$ A + 2% LUBE-1
120	Base Mud + 50 lb/bbl $CaCO_3$ C + 3% LUBE-1
150	Base Mud + 50 lb/bbl $CaCO_3$ B + 2% LUBE-1

5.3. Drilling Fluids Physical and Chemical Analysis

Physical and chemical drilling fluid tests are performed on the formulations with the highest lubricity potentials providing the most efficient plugging performance for each ceramic disc size.

Mud weight, rheological analysis and fluid loss tests are performed as physical properties. Calcium ion, pH and chloride ions are determined as chemical analysis (Table 5.12). In addition, chemical tests for deionized water used for mud tests and make-up water for drilling fluid preparation are also determined and specified in Table 5.13.

The following sequence should be followed in preparation of drilling fluids.

1. Fill the jar with make-up water.
2. Add 10 ppb bentonite slowly with a rate of 5 minutes. Mix 20 minutes.
3. Allow time for the bentonite to yield (16 hours).
4. Add 2 ppb PAC LV slowly with a rate of 5 minutes.
5. Add 1.75 ppb Temperature Stabilizer slowly with a rate of 5 minutes.
6. Add 0.08% HT Thinner slowly with a rate of 2 minutes.
7. Add 3 ppb HT Polymer slowly with a rate of 10 minutes.
8. Add 1.75 ppb XC Polymer slowly with a rate of 10 minutes.
9. Add 30/50 ppb $CaCO_3$ A/B/C slowly with a rate of 5 minutes.
10. Add 2-3% LUBE-1 slowly with a rate of 2 minutes.

Table 5.12. *Drilling Fluids Physical and Chemical Properties Test Results*

	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
	Base	*(20µ)*	*(20µ)*	*(50µ)*	*(50µ)*	*(120µ)*	*(120µ)*	*(150µ)*	*(150µ)*
Bentonite (ppb)	10	10	10	10	10	10	10	10	10
PAC LV (ppb)	2	2	2	2	2	2	2	2	2
XC Polymer (ppb)	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75
Temp. Stab. (ppb)	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75
HT Thinner (%)	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
HT Polymer (ppb)	3	3	3	3	3	3	3	3	3
$CaCO_3$ A (ppb)	**-**	**30**	**30**	**50**	**50**	**-**	**-**	**-**	**-**
$CaCO_3$ B (ppb)	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**50**	**50**
$CaCO_3$ C (ppb)	**-**	**-**	**-**	**-**	**-**	**50**	**50**	**-**	**-**
LUBE-1 (%)	**-**	**-**	**2%**	**-**	**2%**	**-**	**3%**	**-**	**2%**
Mixing Time (min)					*30 min*				
Roller Oven					*300 °F @ 16 hr*				
Test Temperature (°F)					*120*				
600 rpm	62	79	102	68	114	43	106	46	99
300 rpm	41	50	69	44	77	28	70	31	66
200 rpm	32	38	54	33	61	20	54	21	50
100 rpm	21	23	35	20	40	12	35	15	33
6 rpm	4	4	6	3	7	3	6	3	5
3 rpm	3	2	4	2	5	2	4	2	4
PV	21	29	33	24	37	15	36	15	33
YP	20	21	36	20	40	13	34	16	33
Gels (10 sec/10 min)	3/7	4/8	5/14	3/8	6/18	2/2	4/10	2/4	4/10
API Fluid Loss (cc)	7.6	6.4	5.2	5	4.8	3.7	3.3	4.1	3.9
HTHP Fluid Loss (cc)	26	26	17	22	18	30	26	26	24
MW (ppg)	9.0	9.1	9.1	9.3	9.3	9.3	9.3	9.3	9.3
Ca (mg/lt)	148	148	180	200	160	224	120	200	180
Cl (mg/lt)	480	480	900	1,600	1,500	1,400	1,200	900	1,000
pH	9.2	9	8.3	8.5	7.9	8.5	8.0	8.7	7.8

It is observed that physical and chemical drilling fluid test results are in accordance with the desired drilling fluid physical and chemical properties. Moreover, lubricant addition has not shown remarkable negative effects on physical and chemical properties of the mud. As a positive effect, decrease in the API and HTHP fluid loss values is observed. Furthermore, slight increase in rheology values is within the manageable parameters. These type of drilling fluids can tolerate; *chloride ion* and *calcium ion* values below ~10,000 mg/lt for *chloride ion*, and below ~400 mg/lt for *calcium ion,* where test results reveal within the recommended range (GEOS, 2018).

Table 5.13. *Chemical Properties of Make-up and Deionized Water*

Chemical Properties	*Make-up Water*	*Deionized Water*
Cl (mg/lt)	20	<10
Ca (mg/lt)	25	<10
Total Hardness (mg/lt)	35	<10
pH	7.2	6.8

Make-up water and deionized water analysis results are also within the desired parameters which do not affect drilling fluids performance. Cl, Ca, Total Hardness and pH values are in the range of recommended parameters for a make-up water to mix HTHP water-based drilling fluid.

5.4. Effects of Drilling Fluid Properties on Lubricity Performance

During drilling operations, physical and chemical properties of drilling fluid are affected by external factors such as formation and cement contamination. A contaminant can be any type material (solid, liquid or gas) that has a negative effect on the chemical or physical characteristics of a mud. In order to represent such factors, main drilling fluid composition has been contaminated and the effects of drilling fluid properties on lubricity performance have been investigated. Detailed test results and lubricity analysis can be seen in Tables 5.14-5.17 and Figure 5.14-5.17.

The following sequence should be followed in preparation of the drilling fluids shown in Table 5.14. The first 10 rows are the mixing procedure of the drilling fluid sample 1, and the 11th row shows mixing procedure for samples of 2 (11-a), 3 (11-b), 4 (11-c), and 5 (11-d)

1. Fill the jar with make-up water.
2. Add 10 ppb bentonite slowly with a rate of 5 minutes. Mix 20 minutes.
3. Allow time for the bentonite to yield (16 hours).
4. Add 2 ppb PAC LV slowly with a rate of 5 minutes.
5. Add 1.75 ppb Temperature Stabilizer slowly with a rate of 5 minutes.
6. Add 0.08% HT Thinner slowly with a rate of 2 minutes.
7. Add 3 ppb HT Polymer slowly with a rate of 10 minutes.
8. Add 1.75 ppb XC Polymer slowly with a rate of 10 minutes.
9. Add 30 ppb $CaCO_3$ A slowly with a rate of 5 minutes.
10. Add 2% LUBE-1 slowly with a rate of 2 minutes.
11. Follow the sequence as per below additive types.
    - i) Add 125 ppb barite slowly with a rate of 15 minutes.
    - ii) Add 5 ppb NaCl slowly with a rate of 5 minutes.
    - iii) Add 2.5 ppb lime slowly with a rate of 5 minutes.
    - iv) Add 2 ppb gypsum slowly with a rate of 5 minutes.

5.4.1. Effect of Lime ($Ca(OH)_2$)

The possibility of cement drilling is certain on most wells drilled. Drilling wells requires cementing operation after each liner or casing is set (Trotter et al, 2015). The only case under which cement is not considered as a contaminant is, when calcium-base drilling fluids, brines and oil / synthetic based muds are used, or when the cement is cured well enough. The most widely used mud system is bentonitic systems like in this case, where cement can have negative effects on the mud properties. The severity of the cement contamination depends on several factors like the amount of cement drilled, solids concentration and type, and previous chemical treatment.

In order to represent cement contamination of drilling fluids which comes up with casing cementing and lost circulation cement plugs; **2.5 ppb of *lime*** is added to the formulations with highest lubricity performance and best plugging capacity. Calcium ion and pH values of drilling fluids are increased.

It has been observed that lubricity performance of drilling fluids is affected negatively by cement contamination.

5.4.2. Effect of Calcium Ion

There are very few areas worldwide, where gypsum or anhydrite is not encountered while drilling. They are almost identical in chemical composition. Gypsum ($CaSO_4.2H_2O$), with its attached water, has higher solubility than anhydrite ($CaSO_4$). The contamination severity of this chemical depends mostly on the amount of $CaSO_4$ drilled. If only a small amount of contaminant is encountered, that can be tolerated by treating and precipitating the calcium ion. If higher amounts are encountered, mud parameters are going to be out of control.

The calcium ion coming from the formation during drilling, can negatively affect the physical and chemical properties of the mud. **2 ppb *gypsum*** is added to the best compositions to simulate this condition and drilling fluid is exposed to calcium ion contamination.

As a result of this contamination, lubricity performance of the drilling fluid is affected negatively.

5.4.3. Effect of Chloride Ion

During drilling operations, chloride ion increases and affects physical properties negatively when drilling fluid is exposed to high salinity formation fluids and salt formation. NaCl is encountered as the highest frequently drilled salt and is the major constituent of saltwater flows. The primary effect on mud is flocculation of the clays. Rheological parameters and fluid loss tend to be out of control when NaCl is encountered at certain level. The presence of NaCl can be confirmed by the increase in chlorides. The clays dehydrate with enough sodium and time. In doing so, the particle size is reduced due to the decrease in adsorbed water. However, the dehydrated clay particles flocculate, causing uncontrolled physical fluid parameters. The fluid loss will generally tend to get out of control with the amount of salt incorporated into the mud.

To represent chloride contamination, **5 ppb *NaCl*** is added to the most efficient compositions determined, and the chloride ion concentration of the system is increased over 10,000 mg/l.

Lubricity performance of all drilling fluids are negatively affected (Table 5.14-5.17).

5.4.4. Effect of Barite

Density of the drilling fluid is increased in order to minimize the wellbore instability problems and control the hydrostatic pressure. Sonmez et al. (2013) test the influence of drilling fluid density on lubricity performance and conclude that; increasing the density of the base drilling fluid, which also includes OCMA clay to simulate drilled solids, did not change the lubricity performance.

However, the physical properties of the mud (PV, filter cake quality, etc.) may be affected negatively in HTHP conditions. In order to simulate this case, *barite* is added as a weighting material and density is increased up to 11.0 ppg. It has been observed that density increase comes up with a decrease in lubricity performance. (Table 5.14-5.17).

Table 5.14. *Effects of Drilling Fluid Properties on Lubricity Performance (30 ppb $CaCO_3$ A +2 % LUBE-1)*

	1	*2*	*3*	*4*	*5*
Bentonite (ppb)	10	10	10	10	10
PAC LV (ppb)	2	2	2	2	2
XC Polymer (ppb)	1.75	1.75	1.75	1.75	1.75
Temp. Stab. (ppb)	1.75	1.75	1.75	1.75	1.75
HT Thinner (%)	0.08	0.08	0.08	0.08	0.08
HT Polymer (ppb)	3	3	3	3	3
Barite (ppb)		**125**			
NaCl (ppb)			**5**		
Lime (ppb)				**2.5**	
Gypsum (ppb)					**2**
$CaCO_3$ A (ppb)	**30**	**30**	**30**	**30**	**30**
LUBE-1 (%)	**2%**	**2%**	**2%**	**2%**	**2%**
Mixing Time			*30 min*		
Roller Oven			*300 ^oF @ 16 hr*		
Mixing Time – after cont.			*15 min*		
Roller Oven - after cont.			*300 ^oF @ 4 hr*		
600 rpm	102	92	35	65	40
300 rpm	69	57	21	37	22
200 rpm	54	42	15	26	16
100 rpm	35	26	8	16	10
6 rpm	6	4	3	5	3
3 rpm	4	3	2	4	2
PV	33	35	14	28	18
YP	36	22	7	9	4
Gels (10 sec/10 min)	5/14	2/4	2/3	9/35	3/10
API Fluid Loss (cc)	5.2	4.5	5.3	18.4	6.0
MW (ppg)	9.1	11.0	9.1	9.1	9.1

Table 5.14 (cont'd)

	1	*2*	*3*	*4*	*5*
Ca (mg/lt)	180	200	240	420	820
Cl (mg/lt)	900	1500	13000	1300	1200
pH	8.3	8.2	7.8	12.2	7.7
Pm				3.0	
		Lubricity Test			
Test Time (min)	5	5	5	5	5
Rot/min	60	60	60	60	60
Applied Torque (in-lb)	150	150	150	150	150
Measured Torque	2	21.5	19.9	29.6	22.8
Calibration Torque	35.0	34.8	34.8	34.8	34.8
Correction Factor	0.971	0.977	0.977	0.977	0.977
Lubricity Coefficient	0.019	0.210	0.194	0.289	0.223

For *30 ppb CaCO3 A +2 % LUBE-1* case; initial effects of the contaminations come up with uncontrolled viscosity and gel strengths in all cases, and loss of filtration control in the effect of lime case. This is the outcome of an increase in the pH and the adsorption of the calcium ions onto the clay particles, that cause flocculation. As it can be seen in Table 5.14, lubricity coefficient is affected negatively in all cases.

Table 5.15. *Effects of Drilling Fluid Properties on Lubricity Performance (50 ppb $CaCO_3$ A +2 % LUBE-1)*

	1	*2*	*3*	*4*	*5*
Bentonite (ppb)	10	10	10	10	10
PAC LV (ppb)	2	2	2	2	2
XC Polymer (ppb)	1.75	1.75	1.75	1.75	1.75
Temp. Stab. (ppb)	1.75	1.75	1.75	1.75	1.75
HT Thinner (%)	0.08	0.08	0.08	0.08	0.08
HT Polymer (ppb)	3	3	3	3	3
Barite (ppb)		**110**			
NaCl (ppb)			**5**		
Lime (ppb)				**2.5**	
Gypsum (ppb)					**2**
$CaCO_3$ A (ppb)	**50**	**50**	**50**	**50**	**50**
LUBE-1 (%)	**2%**	**2%**	**2%**	**2%**	**2%**
Mixing Time			*30 min*		
Roller Oven			*300 ^oF @ 16 hr*		
Mixing Time – after cont.			*15 min*		
Roller Oven - after cont.			*300 ^oF @ 4 hr*		
600 rpm	114	72	68	52	54
300 rpm	77	44	43	31	35
200 rpm	61	31	33	22	24
100 rpm	40	18	21	13	15
6 rpm	7	3	4	3	3
3 rpm	5	2	2	2	2
PV	37	28	25	21	19
YP	40	16	18	10	16
Gels (10 sec/10 min)	6/18	2/4	3/6	2/14	2/8
API Fluid Loss (cc)	4.8	3.8	4.2	5.4	4.6
MW (ppg)	9.3	11.0	9.3	9.3	9.3
Ca (mg/lt)	160	240	260	360	680
Cl (mg/lt)	1500	1600	11000	1600	1600

Table 5.15 (cont'd)

	1	*2*	*3*	*4*	*5*
pH	7.9	8.3	8.0	10.1	7.7
Pm				2.6	
	Lubricity Test				
Test Time (min)	5	5	5	5	5
Rot/min	60	60	60	60	60
Applied Torque (in-lb)	150	150	150	150	150
Measured Torque	4.0	22.2	20.4	32.8	20.0
Calibration Torque	35.7	35.0	35.0	35.0	35.0
Correction Factor	0.952	0.971	0.971	0.971	0.971
Lubricity Coefficient	0.038	0.216	0.198	0.319	0.194

As shown in Table 5.15; physical and chemical properties are affected by all contaminants. Especially, rheology values get out of control and lubricity performance is decreased in each case.

Table 5.16. *Effects of Drilling Fluid Properties on Lubricity Performance (50 ppb $CaCO_3$ B +2 % LUBE-1)*

	1	*2*	*3*	*4*	*5*
Bentonite (ppb)	10	10	10	10	10
PAC LV (ppb)	2	2	2	2	2
XC Polymer (ppb)	1.75	1.75	1.75	1.75	1.75
Temp. Stab. (ppb)	1.75	1.75	1.75	1.75	1.75
HT Thinner (%)	0.08	0.08	0.08	0.08	0.08
HT Polymer (ppb)	3	3	3	3	3
Barite (ppb)		**110**			
NaCl (ppb)			**5**		
Lime (ppb)				**2.5**	
Gypsum (ppb)					**2**
$CaCO_3$ B (ppb)	**50**	**50**	**50**	**50**	**50**
LUBE-1 (%)	**2%**	**2%**	**2%**	**2%**	**2%**
Mixing Time			*30 min*		
Roller Oven			*300 ^oF @ 16 hr*		
Mixing Time – after cont.			*15 min*		
Roller Oven - after cont.			*300 ^oF @ 4 hr*		
600 rpm	99	76	59	73	58
300 rpm	66	46	36	43	33
200 rpm	50	33	27	30	26
100 rpm	33	20	16	18	16
6 rpm	5	3	3	3	3
3 rpm	4	2	2	2	2
PV	33	30	23	30	25
YP	33	16	13	13	8
Gels (10 sec/10 min)	4/10	3/4	3/4	3/18	3/9
API Fluid Loss (cc)	3.9	3.4	3.8	7.5	4.3
MW (ppg)	9.3	11.0	9.3	9.3	9.3
Ca (mg/lt)	180	200	260	400	800
Cl (mg/lt)	1000	1500	12000	1400	1500

Table 5.16 (cont'd)

	1	*2*	*3*	*4*	*5*
pH	7.8	8.3	7.8	11.5	7.6
Pm				2.8	
	Lubricity Test				
Test Time (min)	5	5	5	5	5
Rot/min	60	60	60	60	60
Applied Torque (in-lb)	150	150	150	150	150
Measured Torque	1.5	19.2	18.3	29.8	21.9
Calibration Torque	34.9	34.8	34.8	34.8	34.8
Correction Factor	0.974	0.977	0.977	0.977	0.977
Lubricity Coefficient	0.015	0.188	0.179	0.291	0.214

The changes in drilling fluids physical properties indicate an unstable fluid system, regardless of which chemical contaminant is present. For the effects of drilling fluid properties on lubricity performance (50 ppb CaCO3 B + 2 % LUBE-1), all contaminants affect lubricity performance negatively (Table 5.16).

Table 5.17. *Effects of Drilling Fluid Properties on Lubricity Performance (50 ppb $CaCO_3$ C +3 % LUBE-1)*

	1	*2*	*3*	*4*	*5*
Bentonite (ppb)	10	10	10	10	10
PAC LV (ppb)	2	2	2	2	2
XC Polymer (ppb)	1.75	1.75	1.75	1.75	1.75
Temp. Stab. (ppb)	1.75	1.75	1.75	1.75	1.75
HT Thinner (%)	0.08	0.08	0.08	0.08	0.08
HT Polymer (ppb)	3	3	3	3	3
Barite (ppb)		**110**			
NaCl (ppb)			**5**		
Lime (ppb)				**2,5**	
Gypsum (ppb)					**2**
$CaCO_3$ C (ppb)	**50**	**50**	**50**	**50**	**50**
LUBE-1 (%)	**3%**	**3%**	**3%**	**3%**	**3%**
Mixing Time			*30 min*		
Roller Oven			*300 ^oF @ 16 hr*		
Mixing Time – after cont.			*15 min*		
Roller Oven - after cont.			*300 ^oF @ 4 hr*		
600 rpm	106	79	43	50	30
300 rpm	70	49	27	31	19
200 rpm	54	34	20	22	16
100 rpm	35	20	12	13	11
6 rpm	6	3	2	2	3
3 rpm	4	2	1	2	3
PV	36	30	16	19	11
YP	34	19	11	12	7
Gels (10 sec/10 min)	4/10	3/4	2/3	3/12	3/13
API Fluid Loss (cc)	3.3	4.5	4.4	3.0	2.8
MW (ppg)	9.3	11.0	9.3	9.3	9.3
Ca (mg/lt)	120	220	200	480	880
Cl (mg/lt)	1200	1400	11700	1500	1400

Table 5.17 (cont'd)

	1	*2*	*3*	*4*	*5*
pH	8.0	8.3	7.9	10.6	7.3
Pm				2.5	
			Lubricity Test		
Test Time (min)	5	5	5	5	5
Rot/min	60	60	60	60	60
Applied Torque (in-lb)	150	150	150	150	150
Measured Torque	2.1	19.7	20.4	24.5	18.2
Calibration Torque	34.2	36.0	36.0	36.0	36.0
Correction Factor	0.994	0.944	0.944	0.944	0.944
Lubricity Coefficient	0.021	0.196	0.203	0.244	0.181

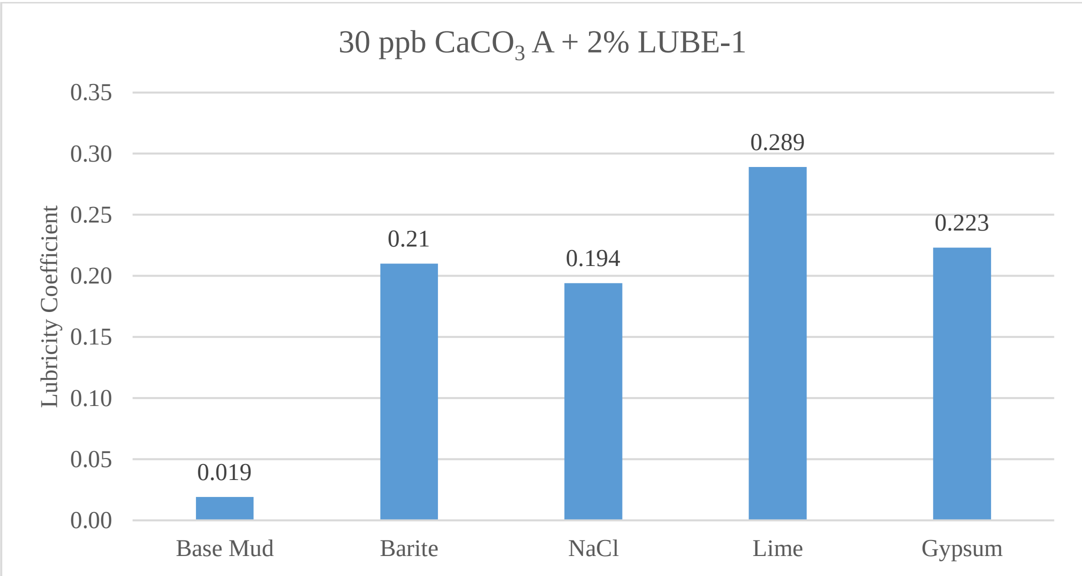

Figure 5.14. Lubricity Coefficient Comparison (30 ppb $CaCO_3$ A + 2% LUBE-1)

For *30 ppb CaCO3 A+ 2% LUBE-1* case; all contaminants affect lubricity performance negatively. Lime worsens the lubricity coefficient more than the other contaminants (Figure 5.14).

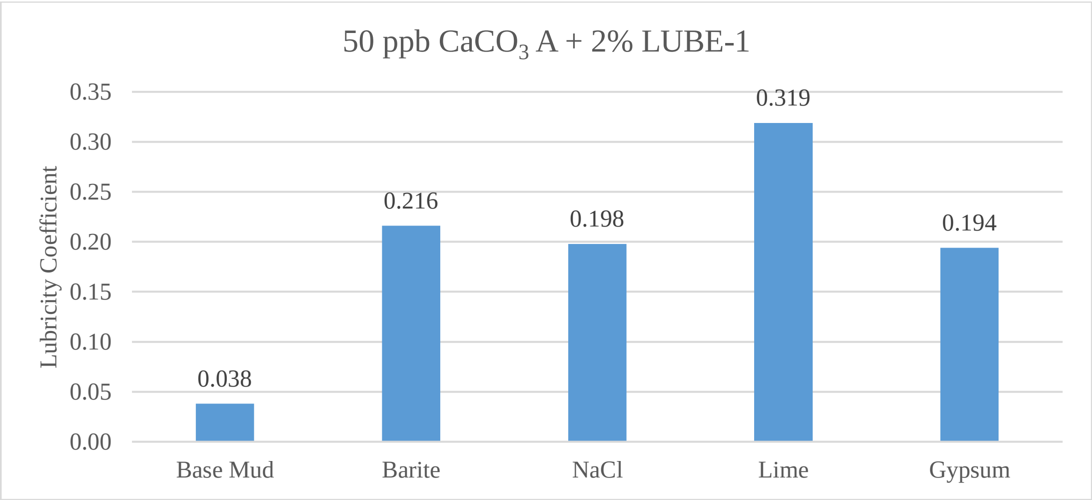

Figure 5.15. Lubricity Coefficient Comparison (50 ppb $CaCO_3$ A + 2% LUBE-1)

From Figure 5.15; it is apparently seen that lubricity is negatively affected by all contaminants. Base mud lubricity is better than all cases including contaminants. Gypsum causes the least negative effect on lubricity comparing the other chemicals.

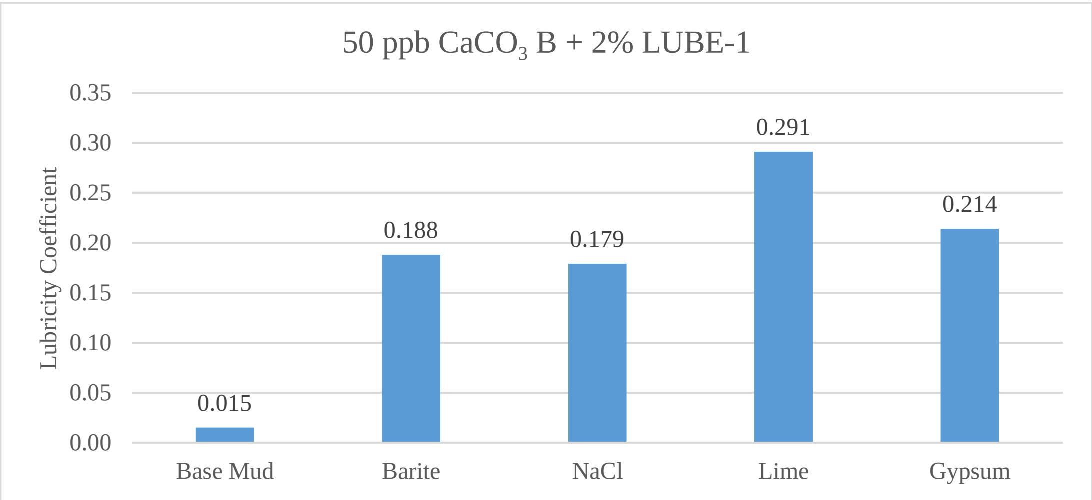

Figure 5.16. Lubricity Coefficient Comparison (50 ppb $CaCO_3$ B + 2% LUBE-1)

For the case of *50 ppb CaCO3 B + 2% LUBE-1* addition; it is obvious that lubricity coefficient is affected most by lime, least by NaCl addition. Upon this, lubricity worsens in every case (Figure 5.16).

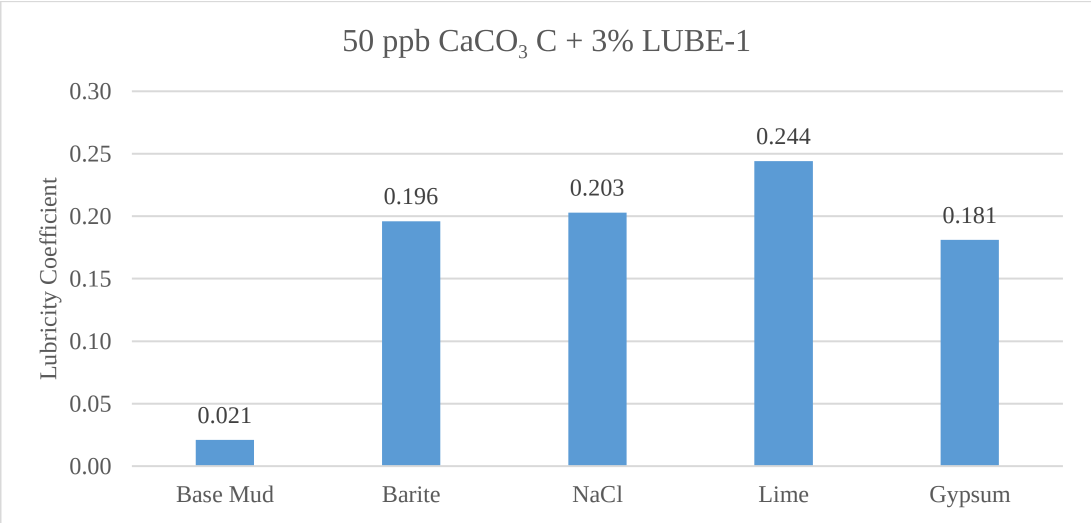

Figure 5.17. Lubricity Coefficient Comparison (50 ppb $CaCO_3$ C + 3% LUBE-1)

For *50 ppb CaCO3 C + 3% LUBE-1* case; lime addition decreases the lubricity performance most. Base mud provides the best lubricity result without any contaminants.

5.5. Effects of Rheology on Plugging Potential

Drilling fluids contaminated with salt, gypsum and lime; indicate lower rheological properties which may affect on plugging potential of the fluid with decreasing suspension characteristics (Table 5.14-5.17).

Erge et al (2020), suggest adjusting yield point value minimum; 20 lb/100 ft^2, for better hole cleaning and to keep wellbore strengthening materials in suspension in geothermal drilling applications. As shown in Table 5.14-5.17, contaminated muds are all below that value which may end up with lower suspension ability and decrease in plugging performance of drilling fluid.

To observe the effects of rheology on plugging potential, permeability plugging ability of drilling fluids contaminated with salt are tested. As shown in Table 5.18, PPA results reveal that, decrease in rheological parameters, ends up with a decrease in the plugging ability of the fluid.

Table 5.18. Effects of Rheology on Plugging Potential

Ceramic Filter Disc Pore Throat Size (micron)	*Mud*	*$CaCO_3$ Type*	*LUBE-1 Conc. (%)*	*$CaCO_3$ Conc. (lb/bbl)*	*PPT Fluid Loss (ml)*		*Spurt Loss (ml)*	*Total Fluid Loss (ml)*	*Static Filtration Rate (ml/dk$^{1/2}$)*
					7.5 min	*30 min*			
20	Base	A	2	30	7	13.5	1	27	4.75
20	w/Salt	A	2	30	11	20	4	40	6.57
50	Base	A	2	50	10	15.5	9	31	4.02
50	w/Salt	A	2	50	13	19	14	38	4.38
120	Base	C	3	50	9	14	8	28	3.65
120	w/Salt	C	3	50	10	16	8	32	4.38
150	Base	B	2	50	21	29	26	58	5.84
150	w/Salt	B	2	50	26	37	30	74	8.03

5.6. Repeatability Tests

Repeatability tests are conducted to ensure the reliability of the experiments and presented for researchers. Repeatability for lubricity tests, permeability plugging tests and physical and chemical properties of drilling fluid tests can be seen in Table 5.18-20.

Table 5.19. *Drilling Fluids Physical and Chemical Properties Repeatability Test Results*

	1 (20µ)	*2 (20µ)*	*3 (50µ)*	*4 (50µ)*	*5 (120µ)*	*6 (120µ)*	*7 (150µ)*	*8 (150µ)*
Bentonite (ppb)	10	10	10	10	10	10	10	10
PAC LV (ppb)	2	2	2	2	2	2	2	2
XC Polymer (ppb)	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75
Temp. Stab. (ppb)	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75
HT Thinner (%)	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
HT Polymer (ppb)	3	3	3	3	3	3	3	3
$CaCO_3$ A (ppb)	**30**	**30**	**50**	**50**	-	-	-	-
$CaCO_3$ B (ppb)	-	-	-	-	-	-	**50**	**50**
$CaCO_3$ C (ppb)	-	-	-	-	**50**	**50**	-	-
Mixing Time (min)				*30 min*				
Roller Oven				*300 °F @ 16 hr*				
Test Temperature (°F)				*120*				
600 rpm	79	75	68	68	43	45	46	48
300 rpm	50	49	44	43	28	30	31	32
200 rpm	38	37	33	33	20	19	21	22
100 rpm	23	25	20	20	12	13	15	16
6 rpm	4	4	3	4	3	3	3	4
3 rpm	2	3	2	3	2	2	2	3
PV	29	26	24	25	15	15	15	16
YP	21	23	20	18	13	15	16	16
Gels (10 sec/10 min)	4/8	4/12	3/8	3/5	2/2	2/3	2/4	3/5
API Fluid Loss (cc)	6.4	6.2	5	5.6	3.7	3.8	4.1	4.0
HTHP Fluid Loss (cc)	26	24	22	24	30	28	26	27
MW (ppg)	9.1	9.2	9.3	9.2	9.3	9.2	9.3	9.2
Ca (mg/lt)	148	160	200	200	224	220	200	210
Cl (mg/lt)	480	500	1600	1500	1400	1300	900	900
pH	9	9	8.5	8.8	8.5	8.9	8.8	9

Drilling fluids physical and chemical tests are repeated to ensure the reliability of the test methods and equipment. No significant changes are observed for rheology measurements, API/HTHP fluid loss, mud weight, pH, and calcium and chloride ion determination.

Table 5.20. *Lubricity Repeatability Test Results*

	1 (20μ)	*2 (20μ)*	*3 (50μ)*	*4 (50μ)*	*5 (120μ)*	*6 (120μ)*	*7 (150μ)*	*8 (150μ)*
Bentonite (ppb)	10	10	10	10	10	10	10	10
PAC LV (ppb)	2	2	2	2	2	2	2	2
XC Polymer (ppb)	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75
Temp. Stab. (ppb)	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75
HT Thinner (%)	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
HT Polymer (ppb)	3	3	3	3	3	3	3	3
$CaCO_3$ A (ppb)	**30**	**30**	**50**	**50**	**-**	**-**	**-**	**-**
$CaCO_3$ B (ppb)	**-**	**-**	**-**	**-**	**-**	**-**	**50**	**50**
$CaCO_3$ C (ppb)	**-**	**-**	**-**	**-**	**50**	**50**	**-**	**-**
Mixing Time (min)	*30 min*							
Roller Oven	*300 ^oF @ 16 hr*							
Test Temperature (^oF)	*120*							
Lubricity Test								
Test Time (min)	5	5	5	5	5	5	5	5
Rot/min	60	60	60	60	60	60	60	60
Applied Torque (in-lb)	150	150	150	150	150	150	150	150
Measured Torque	26.2	26.8	29.0	28.6	27.4	25.1	27.0	26.1
Calibration Torque	0.971	0.997	0.952	1.009	0.994	1.030	0.974	0.997
Correction Factor	35.0	34.1	35.7	33.7	34.2	33.0	34.9	34.1
Lubricity Coefficient	0.255	0.267	0.276	0.289	0.272	0.259	0.263	0.260

To confirm the *Lubricity Test* and equipment reliability; best compositions for all different sized ceramic filter discs are repeated for lubricity analysis and have observed that no significant change for lubricity coefficients is occurred.

Table 5.21. *Permeability Plugging Repeatability Test Results*

Ceramic Filter Disc Pore Throat Size (micron)	*$CaCO_3$ Type*	*$CaCO_3$ Concentration (lb/bbl)*	*PPT Fluid Loss (ml)*		*Spurt Loss (ml)*	*Total Fluid Loss (ml)*	*Static Filtration Rate ($ml/dk^{1/2}$)*
			7.5 min	*30 min*			
20	A	10	8	16	0	32	5.84
20	A	10	10	17	6	34	5.11
20	A	30	9	16	4	32	5.11
20	A	30	7	14	0	28	5.11
20	A	50	10	17	6	34	5.11
20	A	50	7.5	15	0	30	5.48
50	A	10	16	27	10	54	8.03
50	A	10	18	29	14	58	8.03
50	A	30	19	28	20	56	6.57
50	A	30	16	27	10	54	8.03
50	A	50	10	16	8	32	4.38
50	A	50	11	17	10	34	4.38
120	A	50	32	39	50	78	5.11
120	A	50	34	41	54	82	5.11
120	C	10	29	37	42	74	5.84
120	C	10	31	39	46	78	5.84
120	C	30	14	22	12	44	5.84
120	C	30	15	24	12	48	6.57
120	C	50	9.5	15	8	30	4.02
120	C	50	9	15	6	30	4.38
150	B	10	275	275	550	550	0.00
150	B	10	275	275	550	550	0.00
150	B	30	275	275	550	550	0.00
150	B	30	275	275	550	550	0.00
150	B	50	22	30	28	60	5.84
150	B	50	24	31	34	62	5.11

To ensure the reliability of *Permeability Plugging Apparatus* and test method, 20-50-120-150 micron ceramic discs are tested for all $CaCO_3$ concentrations and have seen only negligible differences in PPT test results which do not affect outcome and evaluation.

CHAPTER 6

CONCLUSION

In this study, geothermal drilling fluids are analyzed to achieve the best formulation plugging the seepage and partial lost circulation zones in HTHP conditions. Moreover, highest lubricity performances are determined with the addition of lubricants to these drilling fluid compositions. Over and above, chemical and physical fluid properties are tested. In addition to all these tests, fluid formulations with the best plugging and lubricity performance; are treated with NaCl, gypsum, lime and barite and tested for lubricity performance analysis.

For permeability plugging analysis with *FANN Permeability Plugging Apparatus*;

- Highest plugging performance is achieved by adding 30 ppb of $CaCO_3$ A to base drilling fluid for 20-micron porous ceramic disc.
- Highest plugging performance is achieved by adding 50 ppb of $CaCO_3$ A to base drilling fluid for 50-micron porous ceramic disc.
- Highest plugging performance is achieved by adding 50 ppb of $CaCO_3$ C to base drilling fluid for 120-micron porous ceramic disc.
- Highest plugging performance is achieved by adding 50 ppb of $CaCO_3$ B to base drilling fluid for 150-micron porous ceramic disc.

For lubricity performance analysis with *OFITE Lubricity Tester;*

- Highest lubricity performance is achieved when 2% LUBE-1 is added to the best drilling fluid composition containing 30 ppb $CaCO_3$ A for 20-micron porous ceramic disc. Lubricity coefficient is decreased by 92%.
- Highest lubricity performance is achieved when 2% LUBE-1 is added to the best drilling fluid composition containing 50 ppb $CaCO_3$ A for 50-micron porous ceramic disc. Lubricity coefficient is decreased by 86%.

- Highest lubricity performance is achieved when 3% LUBE-1 is added to the best drilling fluid composition containing 50 ppb $CaCO_3$ C for 120-micron porous ceramic disc. Lubricity coefficient decreased by 94%.
- Highest lubricity performance is achieved when 2% LUBE-1 is added to the best drilling fluid composition containing 50 ppb $CaCO_3$ B for 150-micron porous ceramic disc. Lubricity coefficient decreased by 92%.
- Best lubricity performance has been observed in fluid compositions containing LUBE-1.
- Lubricity performance of LUBE-1 is higher than LUBE-2 for all compositions.
- Both lubricants have formed breakable foam after aging.
- Lubricant additions do not lead to cheesing or greasing.

For chemical and physical drilling fluid analysis;

- Physical and chemical test results of compositions that give the best plugging and lubricity performance; are within the recommended values for geothermal drilling applications.
- Addition of lubricant has increased rheological properties slightly but remained between manageable values.
- Addition of lubricant has led to a decrease in API fluid loss values; as a positive impact.
- Addition of lubricant has led to a decrease in HTHP fluid loss values; as a positive impact.

For effects of drilling fluid properties on lubrication performance;

- High salinity affects the physical properties of the fluid and lubricity performance negatively.
- Gypsum increases the amount of calcium ion in the fluid. Rheological properties and lubricity performance are adversely affected.
- Lime increases pH and calcium ion concentration in the fluid and affects the lubricity performance and physical properties negatively.

- Increasing the fluid density with barite causes an increase in the PV value of the drilling fluid and has a negative effect on the lubricity coefficient.

For effects of rheological parameters on plugging performance;

- Drilling fluids contaminated with salt, indicate insufficient rheological properties which reduce the plugging potential of the fluid with decreasing suspension characteristics.

CHAPTER 7

RECOMMENDATIONS

- In this study, only calcium carbonate is used as lost circulation material because of the acid-soluble nature of the additive. Other LCMs like cellulose fiber, mica and blend of nutshell, may be helpful for some specific applications where reservoir contamination is not a concern.
- Ceramic filter disc pore sizes are selected as *20-50-120-150 microns* to simulate seepage and partial losses while drilling geothermal wells. Disc pore sizes may be widened over 150 microns to simulate large fractures and severe losses. LCM concentrations and particle size distributions should also be optimized to plug these openings.
- Two commonly used and water-based mud compatible type of lubricants are used to test friction values in lubricity tests. Following the developments in lubricants industry, enhanced type of lubricants may be used, and concentrations may be optimized to keep the fluid more cost effective.
- *Permeability Plugging Analysis* are carried out at 300 ^{0}F and 1000 psi over pressure to simulate conventional formation characteristics. The effect of temperature and pressure may be studied to increase the area of application.

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APPENDICES

A. PROCEDURE FOR RHEOLOGICAL MEASUREMENTS

The procedure for PV and YP measurement is shown as below;

1. Put the fluid sample in a container and adjust the rotor sleeve to the scribed line.
2. Rotate at 600 rpm, wait for the dial reading until it reaches to a steady value. Read the dial reading at 600 rpm.
3. Change to 300 rpm and wait for the dial reading until it reaches to a steady value. Read the dial reading for 300 rpm.
4. Report the temperature of the sample.

The procedure used for measuring gel strength is as follows:

1. Mix the sample at 600 rpm.
2. Adjust the gear shift knob to the 3 rpm position, after that turn the motor to OFF position.
3. Wait for 10 seconds.
4. Set the motor to ON position at low speed.
5. Record the dial when the gel breaks as noted by a peak dial reading.

B. PROCEDURE FOR PERMEABILITY PLUGGING MEASUREMENTS

The PPA (See Fig. B-1) utilizes a conventional HTHP Heating Jacket to simulate reservoir temperature. Fluid filtrate is collected from the top cell of this equipment, whereas pressure is given from the bottom of the cell. This set-up helps to prevent solid particles not to settle during static test where settling is not expected normally in a well. Hydraulic pressure is applied to the mud sample through a piston in the cell. Maximum limits for test pressure and test temperature are 5,000 psi and 500°F, respectively, whereas the maximum backpressure is 750 psi. Carbon dioxide (CO_2) is utilized as a pressurizing source to provide the backpressure (FANN Instruments, 2016).

Figure B-1. Permeability Plugging Apparatus (FANN Instruments, 2016)

C. PROCEDURE FOR LUBRICITY MEASUREMENTS

OFITE Lubricity Tester (See Fig. C-1) evaluates mud resistance of different lubricants. The standard lubricity coefficient test is conducted for 5 minutes at 60 rpm with 150 in-lb of force (the equivalent of approximately 600 psi pressure of the intermediate fluid) is applied to two hardened steel faces, a stationary block and rotating ring. Prior to test, lubricity tester should be run for 15 min to zero the torque reading (OFITE Instruments, 2015).

Figure C-1. Lubricity Tester (OFITE Instruments, 2015)

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FOREIGN LANGUAGES

Advanced English

PUBLICATIONS

1. Ahmet Sonmez, M. Versan Kok, Reha Ozel, “Performance Analysis of Drilling Fluid Liquid Lubricants” Journal of Petroleum Science and Engineering, June, 27, 2013. 108 (2013) 64-73

HOBBIES

Music, Poetry, Travelling