A PERFORMANCE ANALYSIS OF DIFFERENT TYPES OF LIQUID LUBRICANTS IN WEIGHTED AND UNWEIGHTED WATER BASED DRILLING FLUID BY DIFFERENTIAL STICKING TESTER PARALLEL WITH LUBRICITY TESTER

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ABSTRACT

A PERFORMANCE ANALYSIS OF DIFFERENT TYPES OF LIQUID LUBRICANTS IN WEIGHTED AND UNWEIGHTED WATER BASED DRILLING FLUID BY DIFFERENTIAL STICKING TESTER PARALLEL WITH LUBRICITY TESTER

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Differential sticking is among the most important factor that could affect the well cost and the drilling efficiency. It occurs at the presence of overbalance pressure between mud column of the well and permeable formation. In this circumstance, the differential pressure acting on a drill string makes the drill string to stick on the well bore. Especially in directional and extended-reach wells drilling, high torque, drag and differential sticking become increasingly important issues compared to the vertical wells.

Contact between steel and mud cake produce more friction especially when using water based mud compared to oil or synthetic based mud. To decrease or avoid this friction, one must add lubricants in drilling fluids In this study the performance of three different types of commercial liquid lubricants (soya based natural oil derivative, propylene glycol derivative and ethanol based liquid commercial lubricants) in weighted lignosulfonate mud, which consists barite as weighing agent and unweighted water based lignosulfonate mud were investigated. Experimental study utilized differential sticking tester, lubricity tester and API filter press to study the effectiveness of liquid lubricants.

The concentrations of 2% and 3% lubricant by volume were studied and their performance was observed. According to differential sticking test result, soya based natural oil derivative lubricant has the best performance and gave 26% reduction in sticking coefficient at 2% concentration and 36% at 3% concentration compared to base mud. In addition, Propylene glycol derivative lubricant displayed 13% reduction at 2% concentration and 19% reduction at 3% concentration. Besides these, ethanol based lubricant displayed 23% reduction at 2% concentration and 33% at 3% concentration.

Considering the lubricity test results, the performance of lubricants at 2% and 3% did not show a difference. An effective reduction of lubricity coefficient was observed in soya based natural oil derivative lubricant with an average reduction of 75% compared to the base mud. Propylene glycol derivative lubricant showed 30% reduction and ethanol based derivative lubricant displayed 23% reduction in lubricity coefficient compared to the base mud. Furthermore, soya based natural oil lubricant performed the lowest fluid loss and thin mud cake thickness compared to base mud and exhibited better performance compared to propylene glycol and ethanol derivative lubricants.

Keywords: differential sticking coefficient, lubricity coefficient, mud, lubricant, cake

ÖZ

FARKLI TİPTEKİ SIVI KAYGANLAŞTIRICILARIN PERFORMANSININ YÜKSEK VE DÜŞÜK YOĞUNLUKLU SU BAZLI ÇAMURDA LUBRICITY TESTER'A PARALEL OLARAK DİFERANSİYEL YAPIŞMA CİHAZINDA BELİRLENMESİ

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Dizi yapışması, sondaj verimliliğini ve kuyu maliyetini etkileyen en önemli unsurlar arasında yer alır. Kuyudaki çamur sütunu ile geçirgen formasyon arasında aşırı basınç farkı olması durumunda meydana gelir. Bu durumda, diziye etkiyen basınç farkı dizinin kuyu cidarına yapışmasına neden olur. Özellikle yönlü, yatay açılımlı kuyuların sondajında, yüksek tork, sürtünme ve dizi yapışması dik kazılan kuyuların sondajına göre daha da fazla önem arz etmektedir.

Çelik ile çamur keki arasında oluşan sürtünme özellikle su bazlı çamurlarda diğer petrol ya da sentetik bazlı çamurlara göre daha fazladır. Bu sürtünmeyi azaltmak ya da önlemek için yapılacak işlemlerden birisi çamura kayganlaştırıcılar ilave etmektir. Bu çalışmada, üç farklı tipteki ticari sıvı kayganlaştırıcıların performansları (soya bazlı doğal yağ türevi, polipropilen glikol türevi ve etanol bazlı ticari sıvı kayganlaştırıcılar) barit gibi ağırlaştırıcı materyal içeren yüksek yoğunluklu su bazlı lignosülfonat çamuru ile düşük yoğunluklu lignosülfonat çamurunda araştırılmıştır. Deneysel çalışmada, sıvı kayganlaştırıcıların verimliliğini araştırmak için dizi yapışma cihazı, lubricity tester ve API filter press cihazı kullanılmıştır.

Kayganlaştırıcıların hacimce %2 ve %3 konsantrasyonları çalışılmış ve performansları gözlemlenmiştir. Dizi yapışma cihazına göre, soya bazlı doğal kayganlaştırıcı en iyi performans sergileyerek, baz çamurla kıyaslandığında yapışma katsayısında %2 konsantrasyonda %26 ve %3 konsantrasyonda %36'lık bir azalma göstermiştir. Buna ilaveten, polipropilen glikol türevi kayganlaştırıcı %2 oranında %13 azalma ve %3 oranında %19 azalma göstermiştir. Bunların yanında etanol bazlı kayganlaştırıcı %2 konsantrasyonunda %23 azalma ve %3 konsantrasyonunda ise %33 azalma göstermiştir.

Lubricity test cihazı sonuçları dikkate alındığında %2 ile %3 kayganlaştırıcı kullanımı arasında pek bir fark gözlenmemiştir. Kayganlaştırıcı katsayısında en verimli düşüş baz çamura göre ortalama %75'lik azalma ile soya bazlı doğal yağ türevi kayganlaştırıcıda gözlemlenmiştir. Baz çamura göre, polipropilen glikol türevi kayganlaştırıcı, kayganlık katsayısında %30 azalma, etanol bazlı kayganlaştırıcı ise % 23 azalma göstermiştir. Ayrıca, soya bazlı doğal yağ türevi kayganlaştırıcı, baz çamura göre en düşük su kaybı ve en ince çamur kekini sağlamış ve polipropilen glikol ve etanol türevi kayganlaştırıcılara göre en iyi performansı sergilemiştir.

Anahtar kelimeler: Dizi yapışma katsayısı, kayganlaştırıcılık katsayısı, çamur, kayganlaştırıcı, kek

To my daughter

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NOMENCLATURE

API	American Petroleum Institute
CFL	Chrome Free Lignosulfonate
CMC	Carboxyl Methyl Cellulose
DST	Differential Sticking Tester
HGS	High Gravity Solid
HPHT	High Pressure High Temperature
LGS	Low Gravity Solid
LT	Lubricity Tester
OCMA	Oil Company Material Association
ppb	pounds per barrel
ppm	parts per million
Psi	Pounds per Square Inch
PV	Plastic Viscosity, cP
RPM	Revolution per Minute
TP	Turkish Petroleum Corporation
YP	Yield Point, lbs/100 ft^2
K_{sc}	Bulk Sticking Coefficient
MBC	Methylene Blue Capacity, ppb

CHAPTER 1

INTRODUCTION

1.1. General

The drill string sticking is one of a major nonproductive cost issue in drilling industry. This drilling problem can be divided into two categories; mechanical sticking and differential sticking. Mechanical sticking can occur if the formation pressure of the well exceeds the pressure of the mud column in the well resulting the drill string sticking. However, differential sticking can occur if the pressure of the mud column in the well exceeds the formation pressure of the well while drilling in depleted or permeable formations. The evidence of differential sticking is that the drill pipe cannot rotate or move up and down but mud circulation is still possible, which is opposite to form of a mechanical sticking. The occurrence probability of these incidents varies with type of the well and drilled formation characteristics (Reid et. al., 2000)

In directional or extended reach well drillings, the drill string is exposed to higher frictional forces than vertical wells. Besides this, the probabilities that increase the frictional forces during drilling still remains on both type of the wells because of several factors such as; inadequate hole cleaning, dog legs, key seats, wash outs. All these factors produce extra frictional forces that cause over pulls during tripping out, reduce drilling productive time, increase differential sticking tendency especially during connections when there is no circulation. In addition to this, in an inclined well, when the string is not in motion, the drill string at the inclined portion of the well could lie on the wall of the well bore and penetrate the cake produced by drilling fluid. As time elapses, the filtrate of the mud cake will continue to invade into the formation and decrease mud cake pore pressure. In this case, the drill string imbedded into mud cake is exposed to mud cake pore pressure while the rest of the drill string is exposed to mud pressure. This pressure difference that generated by the reduction of mud cake pore pressure let the drill string stick into the mud cake (Isambourg et. al., 1999).

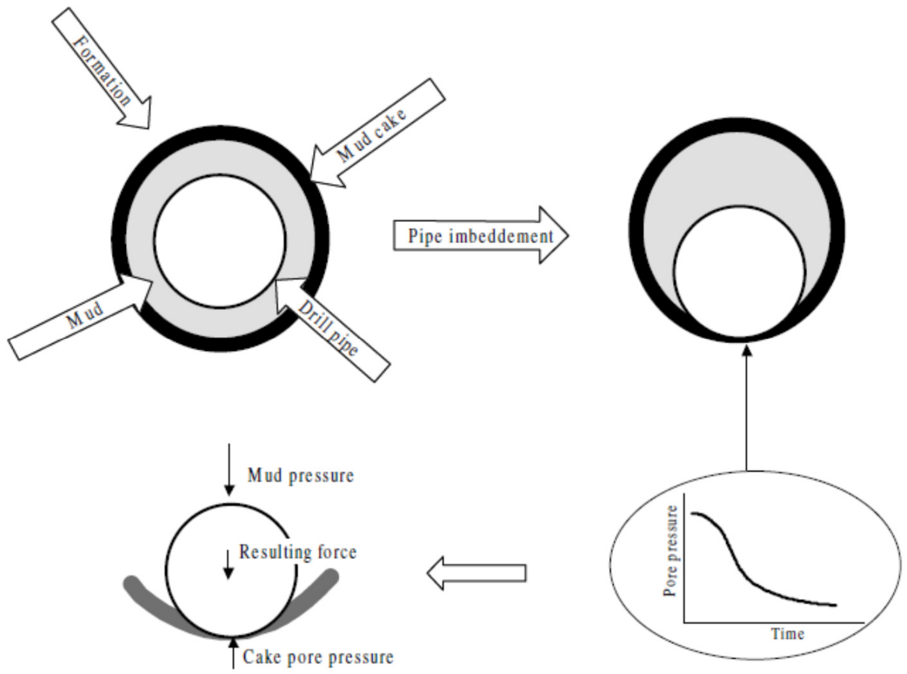

Figure 1.1. Differential Sticking Principle (Isambourg et. al., 1999)

Solutions for reducing frictional forces is a completely different phenomena. For example, increasing the mud density would be useful for hole cleaning and hole stability, on the other hand decreasing mud density could be a solution for differential pipe sticking (Isambourg et. al., 1999). For that reason, the best way to reduce frictional forces is adding lubricants into the mud circulation system to reduce the downhole frictional forces.

Lubricants can be divided into two categories; solid and liquid lubricants. Solid lubricants act like ball bearings generating rolling effect that interfere with the contact area without bonding them (Growcock et. al., 1998), Shamp et. al., 2006). As they do not bond, their performance are independent from the mud type. However, liquid lubricants form a film layer between drill string and the outer surface like formation, casing, wellbore etc. This layer coating the surface roughness protects the drill string from the high compressional forces reducing the effects of torque, drag and sticking (Growcock et. al., 1998).

In this experimental study, three types of liquid lubricants; soya based natural oil derivative, propylene glycol derivative and ethanol based liquid commercial lubricants were chosen to evaluate their performance in water based lignosulfonate mud. The reasons for choosing water based lignosulfonate mud are its cost effective prices and low inhibition properties. Since it is a low cost drilling fluid, this mud is widely used in petroleum industry. Besides this, lignosulfonate mud is a disperse drilling fluid system that can be easily affected by temperature, low gravity solids (LGS) content and chemical reactants. In addition, this mud is not good enough to overcome torque, drag and pipe sticking problems that causes from high friction forces during drilling due to its low lubricity performance.

Lignosulfonate water based drilling fluid system contains bentonite as base additive, NaOH as pH organizer, CMC as fluid loss additive and chrome-free lignosulfonate as a thinner. In this study, certain amount of API OCMA clay is also added into the system in order to simulate drilled solids. Barite is used as a weighting chemical in the mud. However, since barite can be thought as a solid lubricant, its effectiveness on lubricant performance is also examined. Effect of these low and high gravity solids on lubricity and differential sticking are both evaluated. Mud samples are aged at 150º F for 16 hours with roller oven test equipment in order to simulate field conditions.

Throughout the study modified differential sticking tester is used to determine differential sticking coefficient of the mud. The performance of liquid lubricants with the different concentrations of lignosulfonate mud is measured in lbf-in in this test to determine differential sticking coefficient between mud cake and metal surface. Besides this, same test components are used in lubricity tester to determine lubricity coefficient between metal and metal surfaces. API Filter Press test is also carried out to determine effects of lubricants on mud cake thickness and quality. During this test API fluid loss of the samples are measured to examine the differential sticking potential. Methylene blue capacity test is carried out to determine the reactive clays of the mud. Mud density is measured to observe the foaming effect of the lubricant addition. Effects of lubricants on mud rheology such as; plastic viscosity (PV), yield point (YP) and gel strengths are also tested.

CHAPTER 2

LITERATURE REVIEW

2.1. Overview of Pipe Sticking

Pipe sticking is one of the most important drilling disaster that increases non-productive time and as a result drilling costs. Pipe stuck can be divided into two groups; mechanical and differential pipe stuck. Mechanical stuck occurs due to physical restrictions in wellbore like inadequate hole cleaning, key seats, casing failures, drilling assembly failure etc. Differential sticking is described as a drill string failure caused by the differential pressure forces of overbalanced mud column let the drill string stuck into the mud cake generated in permeable formation. Differ from the mechanical sticking, differential sticking is occurred during connections or when the pipe is not moved. In addition to this, limited amount of drill string up and down and rotary freedom can be observed in mechanical sticking, on the other hand no pipe movement but full circulation still exists in differential sticking (Simon et. al., 2005).

If the drill string becomes stuck, all precautions should be taken immediately in order to free the drill string because the possibility of freeing the pipe reduces with time (Simon et. al., 2005). Furthermore, there are some parameters also taken into consideration to reduce the risk of pipe sticking such as; mud density, solid content of the mud, types of fluid, fluid formulation, filtrate volume, cake thickness and lubricity (Simon et. al., 2005, Reid et. al., 2000).

2.2. Previous Studies

In 2005, it is stated that stuck occurs if the drag forces exceeds the power of the rig and as the time elapses on the situation is getting worse due to mud cake built up around drill pipe and increases the contact area and as a result increases the pull out force. This phenomena can be explained in equation 2.1 (Simon et. al., 2005)

$$F = \mathrm{A} \times \left(P_h - P_f\right) \times f \qquad (2.1)$$

where:

F = Force to pull drill string free, kN

A = Filter (Mud) cake contact area, m^2

P_h = Hydrostatic pressure, Pa

P_f = Formation pressure, Pa

f = Friction coefficient

Simon et. al., carried out differential sticking tests at the laboratory with Ofite Differential Sticking Test Equipment according to API RP 13B in 2005. They used polymer and lignosulfonate muds in their research with a fixed barite content. They tested these samples with different drilling fluid lubricants at an amount of 2% by volume, in lignosulfonate mud. They found that filtrate volume decreases with increasing solid content but at the same time cake thickness increases. They also discovered that lubricant added samples decreases the cake thickness. They conducted same test procedures for polymer mud and noted the similar results for polymer mud but the results were much better compared to lignosulfonate mud.

Amorim, et. al., used differential sticking tester as shown in Figure 2.1 and lubricity tester in order to evaluate the behavior of biodegradable lubricants in water based mud. They used eighteen different formulations of bentonite clay, lubricants and polymers. They also examined the effect of lubricants on cake thickness (2011).

Figure 2.1. Differential Sticking Tester and a Plate (Amorim et. al., 2011)

The lubricants that were used in the test composed of modified vegetable oil based, which is soluble in water, ester-ethanol based and blend of vegetable oils that are insoluble in water. Tests were conducted by 1% and 2% by volume of lubricants. They found that lubricants can coat metallic surfaces, diminishes the interaction between steel and mud cake and reducing filtrate volume and mud filter cake plasticity and thickness. They concluded that, the presence of biodegradable lubricants reduces the coefficients both in differential sticking tester and lubricity tester and there is a direct correlation between each test equipment in terms of the coefficients. However, increasing the lubricant concentration in lubricity tester was found unnecessary. The best values were found in ester-ethanol based lubricants with a concentration of 2% by volume in differential sticking test. Besides these, the addition of lubricants did not compromise rheological behaviors of the drilling fluids. The results of the study show that there exist considerable reduction in frictional forces and risk of sticking problems by the use of biodegradable lubricants (Amorim et. al., 2011).

Hunter and Adams studied differential sticking mechanisms with the same laboratory equipment in Figure 2.1 (1978). Tests were conducted with 40 different mud samples including; lime, gypsum, spud, salt saturated mud and mostly lignosulfonate.

The aim of the tests were to find the type of mud system that has the best lubricity characteristics and study the effect of lubricants and drilled solids on sticking. Tests were also conducted at the rig site. The benefit of differential sticking tester was emphasized for gaining accurate comparative usable information between the samples. Low sticking tendency of inhibitive mud system was noted. The importance of thin mud cake and addition of lubricant to reduce the sticking tendency was found. It was observed that an increase on barite and drilled solids content in the mud increases the friction coefficient and possibility of sticking tendency. (Hunter and Adams, 1978).

Watson and Panesar studied on differential sticking considering the effect of solid content, lubricants, mud type and fluid loss on friction. It was found that high solids content increases the sticking tendency and decreases the effectiveness of the lubricants. Furthermore, they emphasized low fluid loss was good for reducing sticking tendency but not enough, to make an accurate results stickance tester should be run (1991).

Reid, et. al., used another kind of stickance tester shown in Figure 2.2. Tests were conducted with high pressure/high temperature fluid loss cell including a metal sphere that allows it to contact with mud cake being produced during filtration. The cell was pressurized with a fixed value of 500 psi throughout the test. As the filtration continues under static conditions, more mud cake was built up on filter paper and around sphere. By using torque wrench, the force needed to free the sphere was measured with definite time intervals. The slope of time and torque values gives the stickance tendency of the mud in (mNm / $sec.^{3/4}$). (2000).

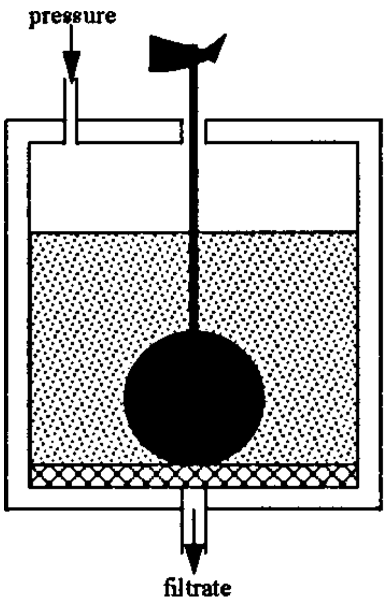

Figure 2.2. Schematic diagram of the Stickance tester (Reid et. al., 2000)

Effect of mud type, fluid loss, mud cake thickness, lubricants, solids content of the mud on differential sticking tendency were evaluated in this investigation. Effect of lubricants on rheological properties were monitored. Effects of mud type on stickance is shown in Figure 2.3.

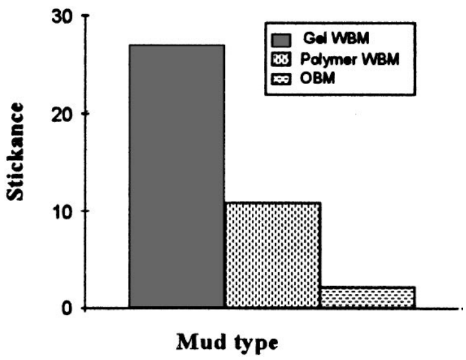

Figure 2.3. Stickance values of different mud types (Reid et. al., 2000)

Laboratory studies indicated that removing low gravity solids from the mud, decreasing fluid loss amount and adding lubricants reduces the sticking tendency. Figure 2.4 displays the effect of various type of lubricants on stickance (Reid et. al., 2000).

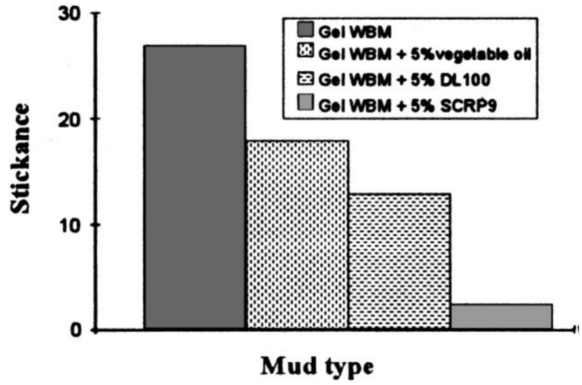

Figure 2.4. Effect of lubricants on stickance (Reid et. al., 2000)

In addition to this, lubricants effect reducing fluid loss and as a result sticking tendency were studied. The results are shown in Figure 2.5. However, it was mentioned that both lubricants reduced the fluid loss, but this does not correlate with the relative effectiveness of reducing the sticking potential (Reid et. al., 2000).

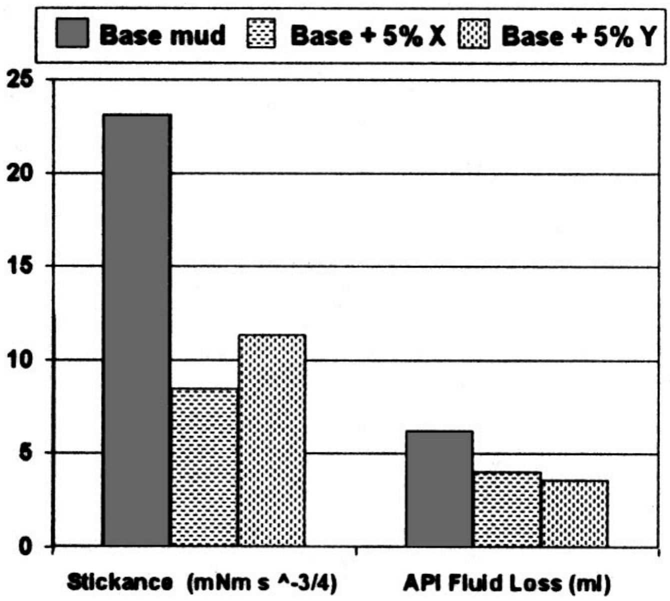

Figure 2.5. Effect of lubricants additions on WBM (Reid et. al., 2000)

The effect of differential pressure on the release torque considering the waiting time was examined in this study by using gel water based mud. According to Figure 2.6 it was found that torque needed to free a stuck object increases with differential pressure, thus increasing the risk of differential sticking. Same manner was acceptable both water and oil based muds even though they have a low stickance sensitivity (Reid et. al., 2000).

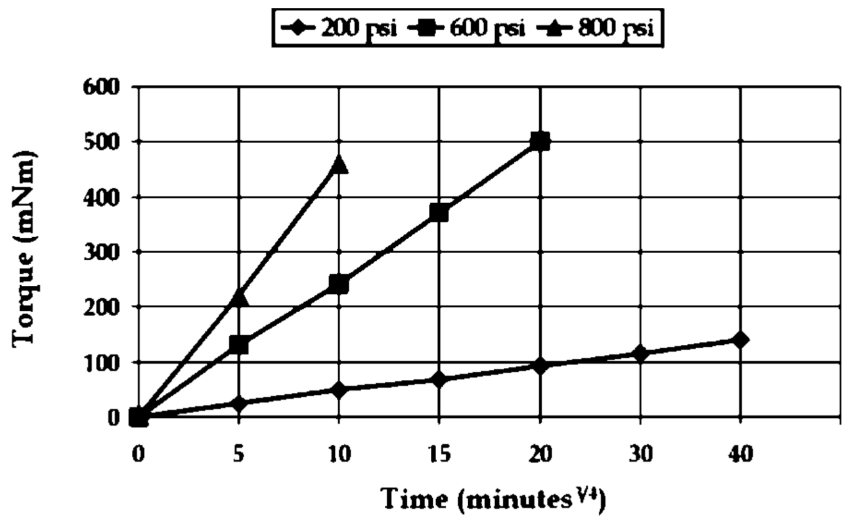

Figure 2.6. Effect of differential pressure on freeing torque for gel WBM (Reid et. al., 2000)

The standard API mud properties show little change after addition of antistickance product. This demonstrates that mud properties can be measured by the drilling fluid engineer at the laboratory or the rig site. Table 2.1 indicates one of the examples produced in this investigation.

Table 2.1 Mud Properties after addition of Antistickance Product (Reid et. al., 2000)

Property	Base Mud	3% vol Additive A	5% vol Additive A
Weight (lbm/gal)	16.8	16.8	16.8
600 dial reading	97	90	98
300 dial reading	59	60	65
200 dial reading	45	47	52
100 dial reading	31	32	38
6/3	11/10	12/11	18/16
Gels (10 s/10 m)	19/39/46	13/42/56	31/62/96
PV (cP)	36	30	33
YP (lbf/100 ft^2)	23	30	32
HPHT (mL)	11.5	13.0	10
pH (mL)	10.4	10.4	10.3

Annis and Monaghan used another equipment similar with Ofite differential sticking tester to measure the friction between metal and mud cake that is shown in Figure 2.7. The force required to move steel plate and as a result calculating friction between rod and mud cake was done by using hydraulic piston. Tests were conducted with gel water based mud (1961).

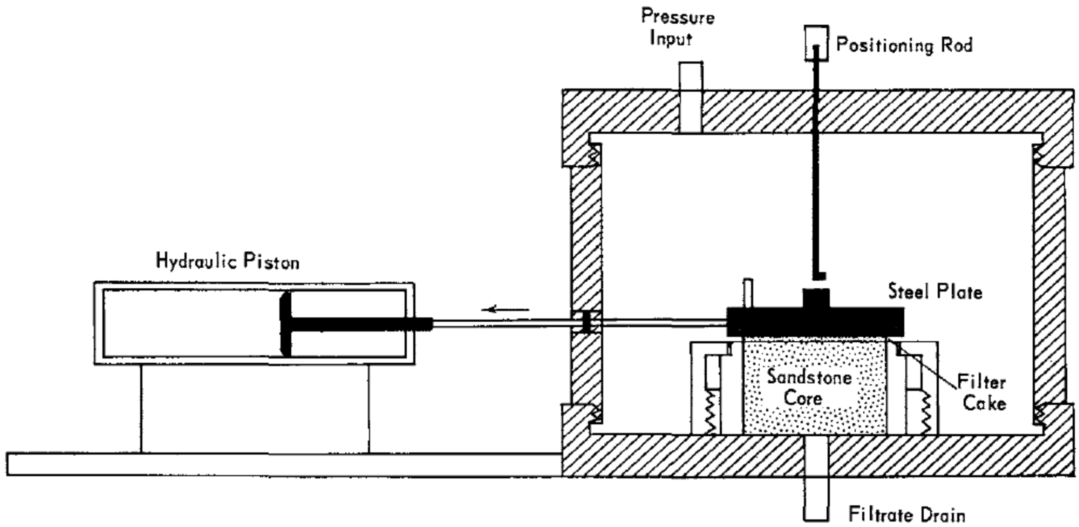

Figure 2.7. Apparatus for Measurement of Sticking Coefficient (Annis and Monaghan, 1961)

According to test results, types of solids present in the mud found important for sticking. The sample slurries contained different amount of bentonite, low yield clays and barite. According to Figure 2.8, sticking coefficient can change with types and amount of solids content in the fluid especially with barite. Increasing barite content increases the sticking coefficient can be seen in Figure 2.9 (Annis and Monaghan, 1961).

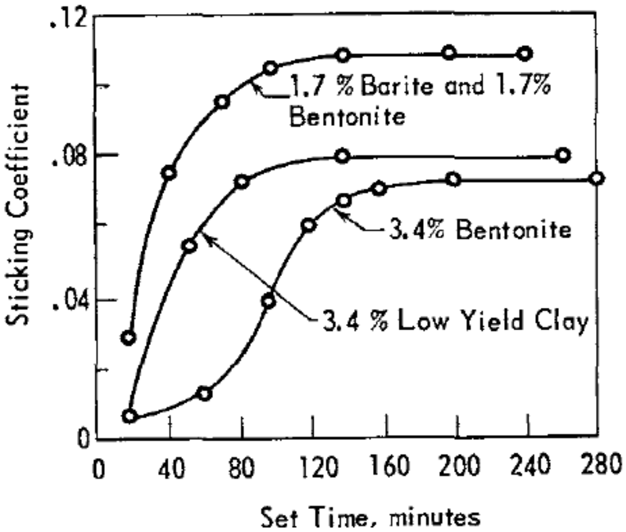

Figure 2.8. Effect of Different Types of Solids on Sticking Coefficient (Annis and Monaghan, 1961)

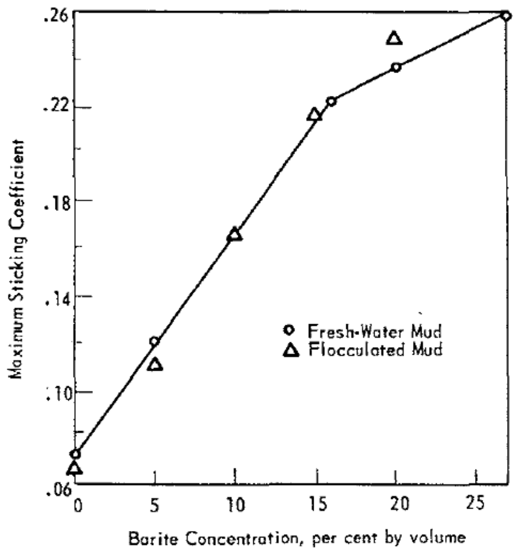

Figure 2.9. Effect of Barite on Sticking Coefficient (Annis and Monaghan, 1961)

Isambourg, et. al., used another equipment to measure the friction between metal and mud cake that is shown in Figure 2.10. The apparatus also measures the mud cake pore pressure and permeability. It is specially designed to allow measurements simulating downhole conditions. The test cell is capable to work up to 100 bars and can be used both water and oil based mud (1999).

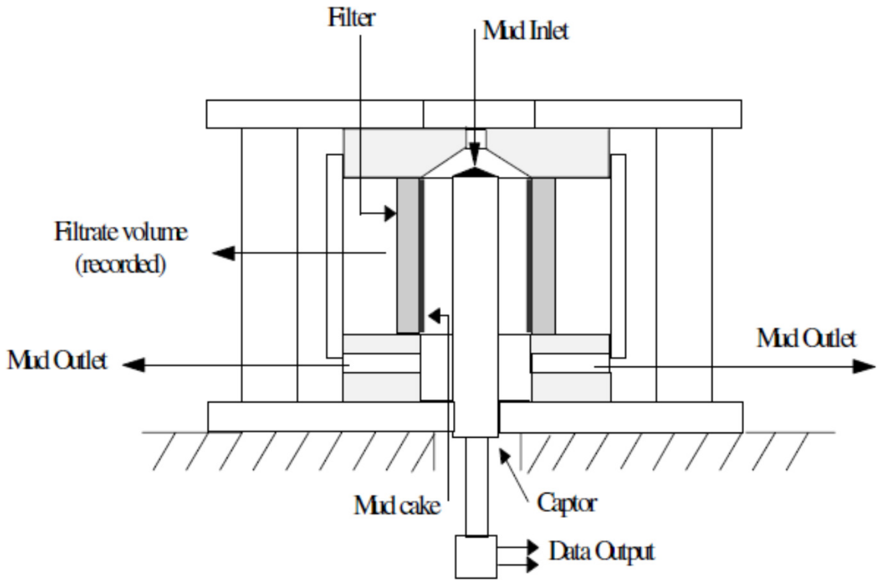

Figure 2.10. Differential Pressure Sticking and Friction Measurement Cell (Isambourg et. al., 1999)

The apparatus is also capable of making both differential sticking and lubricity test. It consists of one rotational cylindrical captor with sensors for measuring lubricity test and one non-rotational cylindrical captor for differential sticking test. As the filtration continues within the porous cylinder during the test, filtrate volume is recorded and mud cake is built. Forces acting on a drill pipe is simulated by captors (Isambourg et. al., 1999).

Effect of solid content and cake thickness were evaluated during this study with four different mud combinations. The study is concluded that mud cake compaction and permeability are more important than mud cake thickness. Besides this, formation permeability less effective on differential sticking. Type and amount of solids affects cake properties and as a result pull out forces to be needed to free drill pipe if stuck occurs (Isambourg et. al., 1999).

Mahto, et. al., studied effect of lubricants on pipe sticking by using self-fabricated stickance tester as shown in Figure 2.11. They thought that if the sticking occurs, lubricant affect the way which the drill string is freed. At the presence of lubricant, pipe can be freed between steel and mud cake, on the other hand with lack of lubricant, pipe can be freed between mud cake and formation. They concluded proper combination of fluid loss additive and lubricants are essential to prevent sticking (2012).

Figure 2.11. Self-Fabricated set up for determination of Sticking Tendency (Mahto et. al., 2012)

Schamp, et. al., were analyzed the performance of over 40 types of lubricants included vegetable oil, fatty acids, alcohols, ester and other chemical groups within seven types of drilling fluids by using Lubricity Tester device. They concluded that almost all lubricants were capable of reducing friction. However, using lubricant in high concentration was found cost effective and unnecessary. In practice using lubricant maximum 3% by volume is applied generally. The results are shown in Figure 2.12 (2012).

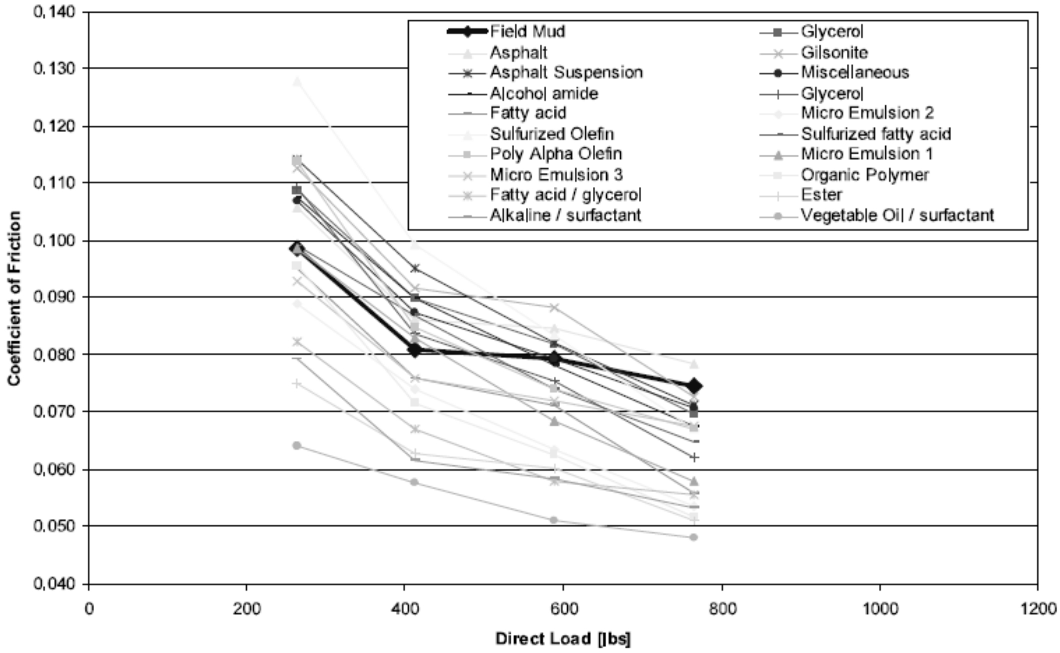

Figure 2.12. Liquid Lubricant Testing Results (Mahto et. al., 2012)

CHAPTER 3

STATEMENT OF THE PROBLEM

Torque and drag is the major drilling problems that can cause drill string sticking phenomena especially during drilling in directional and extended reach wells. This results with loss of time and money even total loss of the well because of stuck pipe. One can tackle this problem by using synthetic or oil base mud while drilling this type of difficult formations. However, as the environmental concerns have been getting an important and integrated issue in the oil industry, and considering the cost effectiveness of the mud systems, adding liquid lubricants into water based mud systems is being considered as an effective alternative to approach the problem.

In this study, performance of three types of commercial liquid lubricants; soya based natural oil derivative, propylene glycol derivative and ethanol based lubricants will be evaluated in weighted and unweighted lignosulfonate water based mud, which are mainly used by Turkish Petroleum Corporation (TP) in oil field operations. Throughout the study, differential sticking tester will be used to analyze the performance of liquid lubricants and to simulate formation and drill string interaction at laboratory conditions. In addition, lubricity tester will also be used to compare the results with differential sticking tester within the context of metal-metal contact, which simulates the interactions between drill string and casing at laboratory conditions. Besides this, API Filter press tests will be carried out to evaluate the effect of filtration and cake thickness on differential sticking. Finally, influence of lubricant addition on mud properties and effect of low gravity solid (LGS) and high gravity solid (HGS) contamination on lubricant performance will also be examined.

CHAPTER 4

EXPERIMENTAL STUDY

4.1. Materials

4.1.1. Lignosulfonate Mud Additives

Analyzing the effect of lubricants in water based mud considering their performance on differential sticking, lubricity, fluid loss and mud cake thickness, lignosulfonate mud is chosen. The base composition of lignosulfonate are prepared by using tap (fresh) water, caustic soda, bentonite, CMC and CFL. Samples containing with different amount of OCMA clay and barite are also tested to evaluate the performance of the lubricants. Composition of the base mud is shown in Table 4.1.

Table 4.1 Base Mud Composition and Sample Preparation of Lignosulfonate Mud

Additives	Concentration	Sample Preparation
Tap Water	1 bbl	350 cc
Caustic Soda	0.5 ppb	0.5 gr
Bentonite	20 ppb	20 gr
CFL	1 ppb	1 gr
CMC	1.5 ppb	1.5 gr

In all phase of this experimental study, tap water was used to prepare the samples. Sodium hydroxide or another name Caustic soda is a pH adjuster that is used to increase pH of the mud as needed. Bentonite is the main chemical additive of fresh water based drilling fluid that is primarily used to control mud rheology and mud fluid loss properties. It is very important for the mud to have suitable amount of bentonite to create a good quality, firm and impermeable mud cake around the wellbore. The quality of the mud cake plays an important role for pipe sticking and formation damage. Bentonite to be used in lignosulfonate water based mud must conform API Spec 13A part 4 (2010).

CMC (carboxyl Methyl Cellulose) is used as a secondary fluid loss control agent with bentonite in lignosulfonate water based drilling fluid. CMC is a cellulosic based anionic polymer that is generally used 1-3 ppb concentrations in the mud. CMC to be used in lignosulfonate water based mud must conform API Spec 13A part 9 (2010).

CFL (Chrome Free Lignosulfonate) is an organic based chrome free lignosulfonate additive that is used as a thinner in water based dispersed lignosulfonate mud. Secondary effect of the CFL is to reduce fluid loss content of the mud to create a firm mud cake. General concentration of the CFL is between 2 and 4 ppb in the mud.

Barium Sulfate or Barite is used as a weighting agent in all types of drilling fluids. The specific gravity of barite is 4.2.

API standard OCMA Clay, which is not a commercial chemical product, is composed of swelling, smectite types of clay minerals that is used to simulate drilled solids of the mud in laboratory conditions.

4.1.2. Lubricant

Lubricants are liquid chemical additives that are added directly to the system to decrease the friction forces between drill string and formation or casing. Lubricants also help to create a good quality of mud cake decreasing the risk of pipe sticking. Three types of lubricants; soya based natural oil derivative, propylene glycol derivative and ethanol based liquid commercial lubricants are used in this study to evaluate their performance in different types of lignosulfonate mud samples. In this study, lubricant samples are shortly named as Lube-B, Lube-C and Lube-D respectively as illustrated in Table 4.2

Table 4.2 Sample Lubricants Used in the Study

Lubricant	Lubricant Content
Lube-B	Soya based natural oil derivative
Lube-C	Propylene glycol derivative
Lube-D	Ethanol based derivative

4.2. Experimental Procedures

4.2.1. Sample Preparation

All laboratory tests are held on Drilling Fluid Laboratory of Drilling Technology Department at Turkish Petroleum (TP) Research Center. Test's first-end test stages are simulated the real time field operations of TP. At the beginning of each test, additives of each mud samples are weighted with an accuracy of 0.01 g.

Figure 4.1. Multimixer

As the first step of sample preparation, bentonite is added into 350 ml tap water and continuously stirred in multimixer (Sterling, 2003) (Figure 4.1) for 4 hours to pre-hydrate the bentonite before adding all other additives. After 4 hours mixing, base additives; caustic soda, CFL, CMC are added every 5 minutes respectively. OCMA clay, barite and lubricant are also added if necessary. Each mud sample is mixed in multimixer 20 minutes after adding all additives.

Figure 4.2. Ageing Cell

Mud samples then filled into the ageing cell (Ofite Instruments, 2009) which is shown in Figure 4.2 and cells are put into insulated and constant temperature controlled Roller Oven (Fann Instruments, 2009) (Figure 4.3) and rolled at 150°F for 16 hours in order to simulate the field conditions. After rolling the mud samples, samples are allowed to cool down at room temperature. All samples are again mixed with Multimixer for 5 minutes before testing.

Figure 4.3. Roller Oven

4.2.2. Differential Sticking Test

Differential sticking is one of the major nonproductive time period in drilling technology. A stuck pipe during drilling will result some economic losses even the loss of the well. Among other methods of pipe-stuck prevention methods the use of lubricants in drilling fluid finds an important place. The performance of lubricants on differential sticking at laboratory conditions is determined by differential sticking tester (Figure 4.4) (Ofite Instruments, 2014). Differential Sticking Tester shown in Figure 4.4 was modified to be able to apply the same force on the test plate for all sample to read the applied torque digitally. Modified Differential Sticking Tester is shown in Figure 4.5.

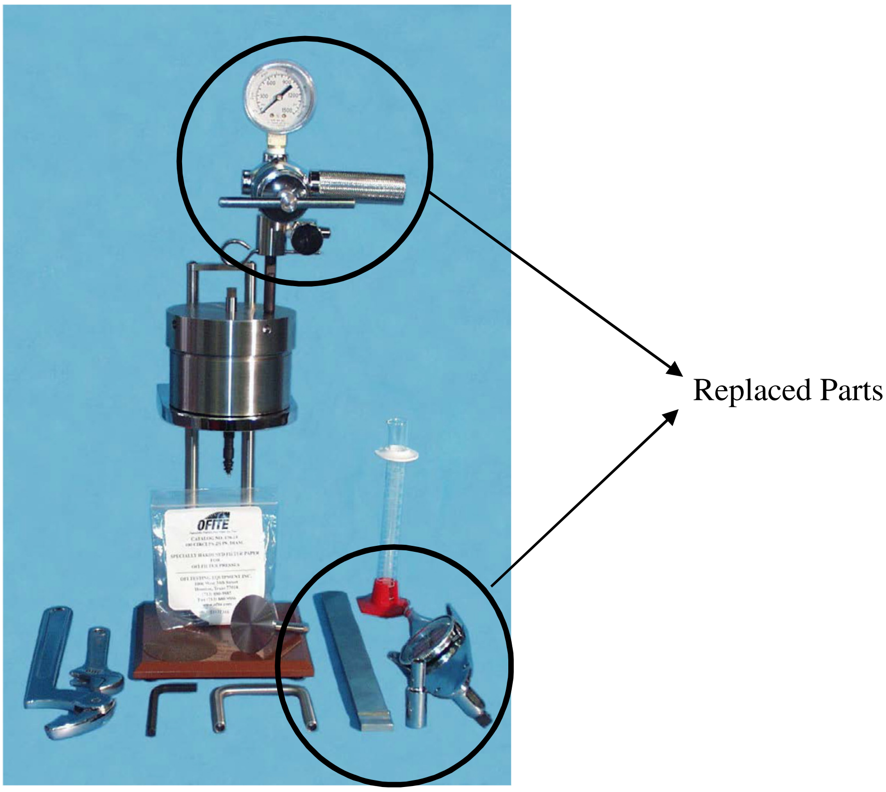

Figure 4.4. Differential Sticking Tester (Ofite Instruments, 2014).

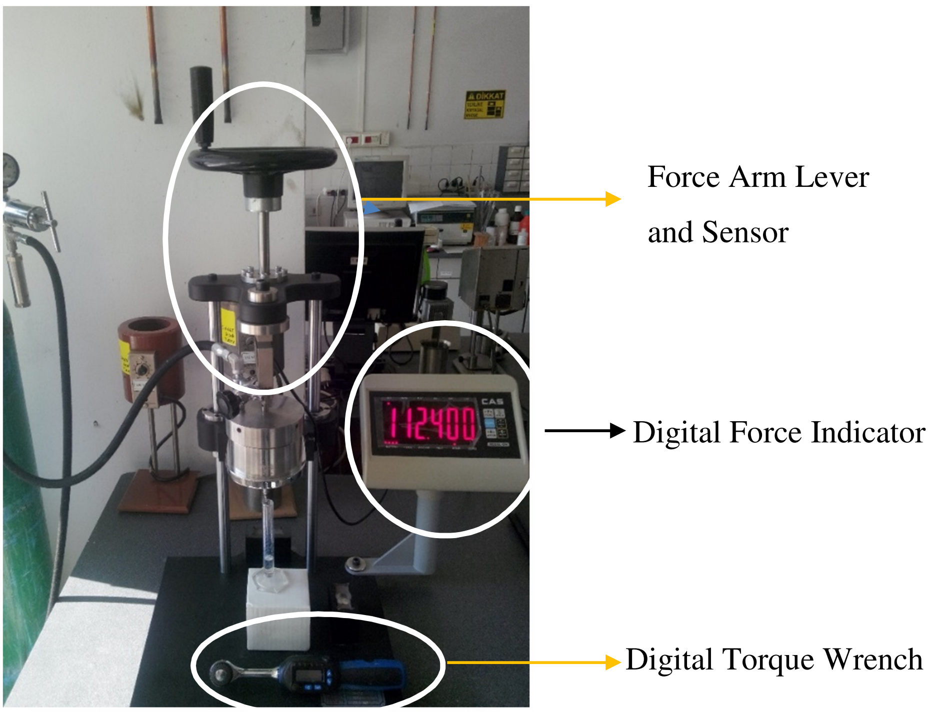

Figure 4.5. Modified Differential Sticking Tester

Modified Differential Sticking Tester is composed of one digital force indicator in kg, test cell with related parts, digital torque wrench and pressurized nitrogen tube. The test cell can be divided into two parts, namely inner cap and top cap. Test steps are detailed below.

- Place the Inner cap of the cell which includes a screen inside on to stand frame.
- Prepare the test cell with related parts at the beginning of the test in the correct order as shown in Figure 4.6
- According to Figure 4.6 firstly put filter paper onto screen at the inner cap and continue with the following parts respectively and tighten with retainer wrench
- Fill the test cell with prepared sample to the scribed line

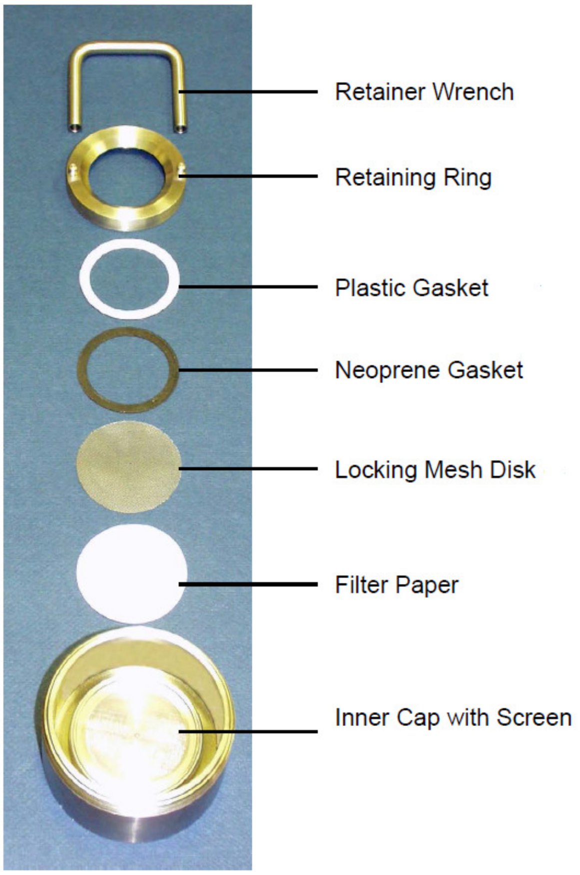

Figure 4.6. Inner cap of the test cell with related parts (Ofite Instruments, 2014).

- Insert the torque plate through the hole in the top cap of the cell shown in Figure 4.7. Be careful that the face of the torque plate must face towards inside of the top cap.
- Screw the top cap onto inner cap and tightened with wrench

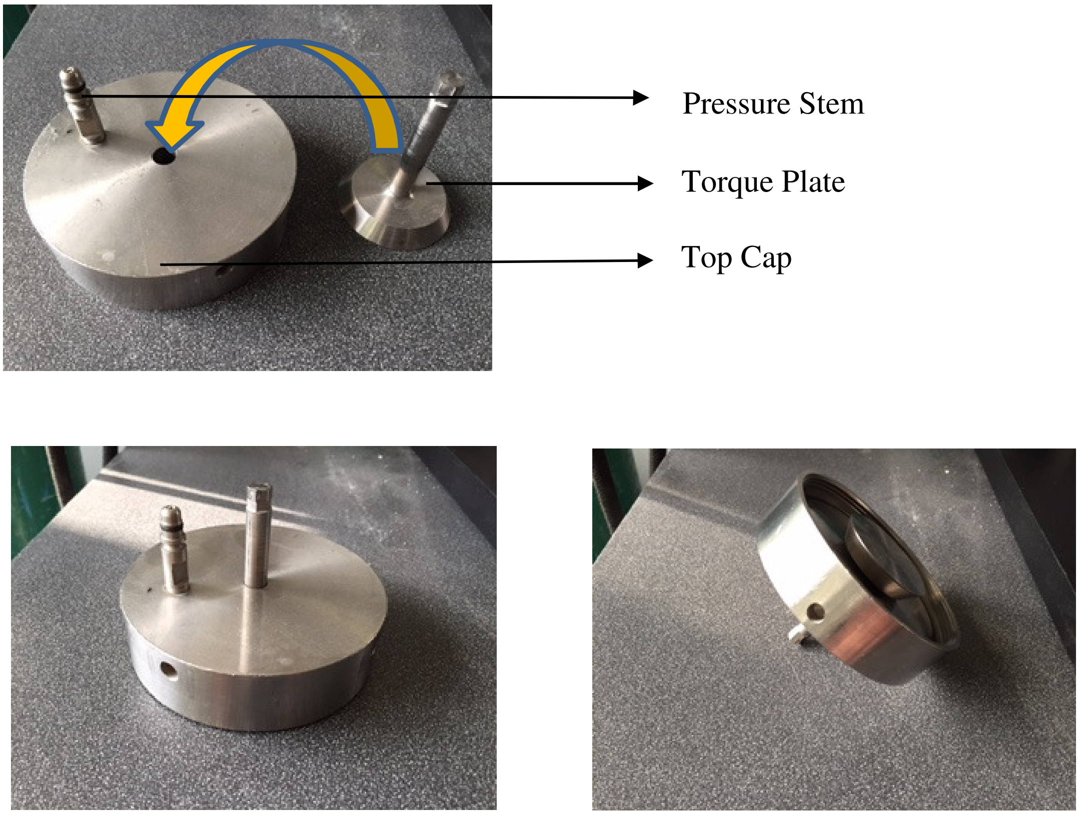

Figure 4.7. Top cap of the test cell with torque plate

- Apply standard pressure of 477.5 psi into cell body for ten minutes from nitrogen tube through pressure stem located at the top cell.
- Apply a 110 kg ± 5 kg of an additional force for ten minutes onto torque plate by turning the force arm lever on the stand in order to let the torque plate stick on the mud cake generated by filtration.
- Check the applied force on the digital screen, which is attached at the stand frame for overloading

- After ten minutes, release the force on the torque plate by turning the force arm lever
- Disconnect the force arm lever from the tip of the torque plate
- Attach the digital torque wrench to the tip of the torque plate
- Measure the torque readings by rotating the torque plate in any direction with wrench.
- Repeat the measurements at seven times allowing the 30 seconds between each reading.
- Release the pressure from the test cell body, dump the mud and clean the test equipment
- Repeat the test procedure described above for 3 times by using the same mud and use the average of all 3 tests to calculate Bulk Sticking Coefficient.

Bulk Sticking Coefficient (K_{sc}) is the ratio of the force necessary to initiate sliding of the plate (F_s) to the normal force on the plate (F_n) (Ofite Instruments, 2014).

$$K_{sc} = F_s / F_n \tag{4.1}$$

The sliding force (F_s) shown in equation 4.2 is the function of average torque readings in inch pounds (T_u). This equation is only used where the radius of the torque plate (r) is 1 inch.

$$F_s = 1.5 \text{ x } T_u \tag{4.2}$$

The normal force (F_n) is calculated by multiplying the area by the differential pressure. Since applied pressure during the test is 477.5 psi.

$$F_n = 477.5 \text{ x } \Pi \text{ x } r^2 = 1{,}500 \text{ x } r^2 \tag{4.3}$$

The Bulk Sticking Coefficient (K_{sc}) is then calculated by using equation 4.3.

$$K_{sc} = 0.001 \text{ x } T_u \tag{4.4}$$

4.2.3. Lubricity Test

Lubricity Tester is another lubricity performance tester used for the analyzing the performance of the drilling fluid lubricants in unweighted and weighted lignosulfonate mud throughout this study. Different from the differential sticking tester, lubricity tester is designed to simulate the lubricant performance at metal-metal contact area considering the rotation of the drill string around casing or borehole wall.

Lubricity Tester shown in Figure 4.8 is used to evaluate the performance of the lubricants at laboratory conditions (Ofite Instruments, 2009). Lubricity tester is composed of three main components. These are test ring, test block and torque wrench.

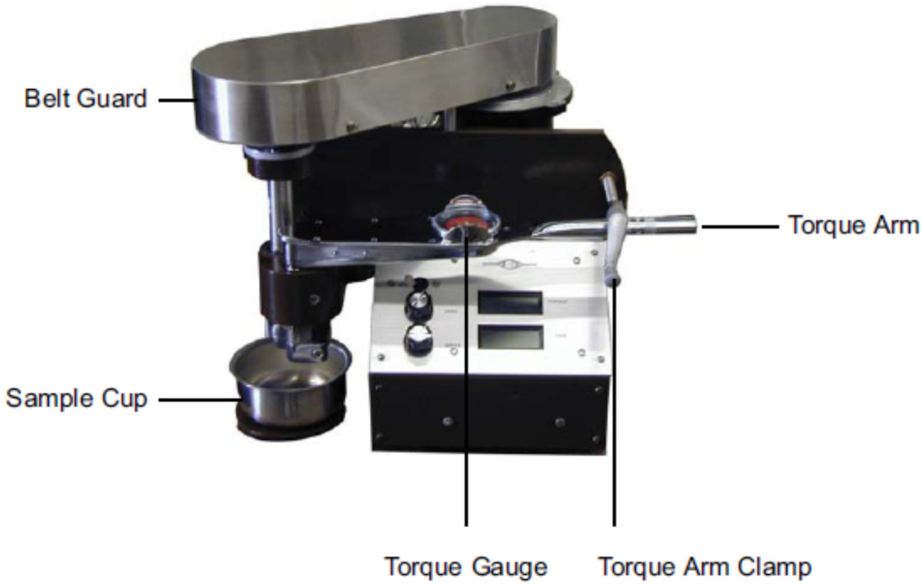

Figure 4.8. Lubricity Tester (Ofite Instruments, 2009).

The basic steps for measuring the lubricity coefficient by lubricity tester are as follows;

- Clean and dry the lubricity tester and its related components such as ring, block, retainer nut and sample cup with acetone. Test ring, block and other related parts are illustrated in Figure 4.9 and 4.10.
- Be sure that all equipment that are exposed to mud sample must be cleaned and dried at the beginning of the test in order to remove any lubricant contaminations coming from previous tests.

Figure 4.9. Lubricity Tester test ring with related parts (Ofite Instruments, 2009).

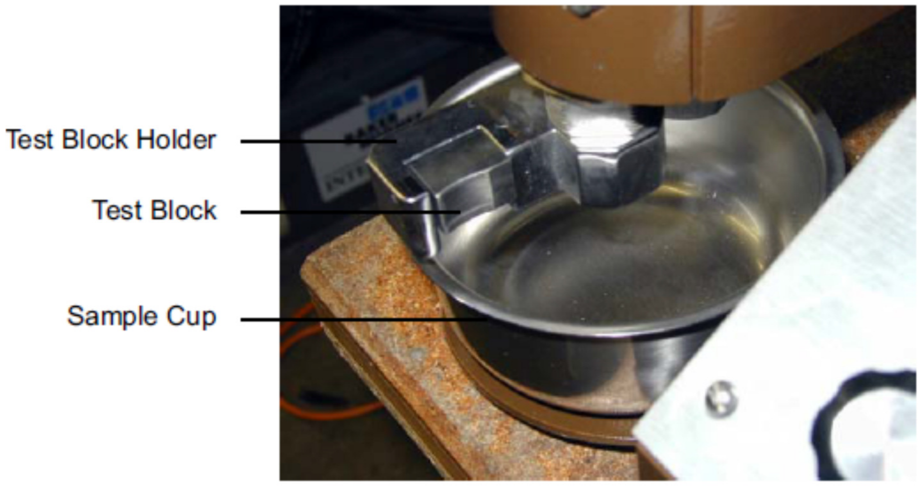

Figure 4.10. Lubricity Tester Test Block and Sample Cup (Ofite Instruments, 2014)

- Connect the test ring to the main shaft by retainer nut shown in Figure 4.9
- Place the test block into the test block holder as illustrated in Figure 4.10.
- Run lubricity tester for 15 minutes in any rpm speed in order to warm-up the machine prior to test.
- Adjust the rotation speed to 60 rpm by using rotation speed control knob and the torque to 0 by using torque knob, and continue to run the machine 5 minutes with these parameters.
- Fill the sample cup approximately 260-280 cc deionized water to determine the correction factor and raise the sample cup with cup stand till the test ring and block are fully submerged into deionized water.
- Position the torque arm by torque arm clamp and tighten till the torque gauge reads 150 inch-pounds.
- Check the rotation speed again and set the rpm at 60 if required.
- Run the machine for 5 minutes and record the torque at the end of 5 minutes.

Torque reading must be between 34±2, otherwise correction factor process must be repeated till the torque is read between 34±2. Correction factor is calculated by this torque reading using equation 4.5.

$$CF = \tau_{\text{distilled water}} / \tau_{\text{reading from tester}} \qquad (4.5)$$

where, CF is correction factor, and $\tau_{\text{distilled water}}$ is taken standard 34 in-lbs. for this machine. At the end of correction factor process, continue testing with mud sample described below.

- Retighten the torque arm, lower the cup stand and discard the fluid
- Clean and dry test block, ring and sample cup again with acetone.
- Mix the drilling fluid (mud) to be tested for 2 minutes by mixer prior to test
- Pour the drilling fluid to the sample cup

- Place the sample cup to the cup stand and raise it till the test ring and block are fully submerged into drilling fluid.
- Adjust the rotation speed to 60 rpm by using rotation speed control knob and the torque to 0 by using torque knob, and continue to run the machine 5 minutes with these parameters.
- Position the torque arm by torque arm clamp and tighten till the torque gauge reads 150 inch-pounds.
- Check the rotation speed and set the rpm at 60 if required.
- Run the machine for 5 minutes and record the torque ($\tau_{reading}$) at the end of 5 minutes.
- Release the torque arm and clean the machine and related parts.

By using this torque reading ($\tau_{reading}$), lubricity coefficient is calculated in the equation 4.6.

$$\text{Lubricity Coefficient} = (\tau_{reading}/100) \text{ x CF} \quad (4.6)$$

4.2.4. Fluid Loss and Mud Cake Thickness Test

Fluid loss and cake thickness play an important role on differential sticking and lubricity. Low permeable and thin mud cake is the desired cake in drilling fluid properties. To determine the filtration (fluid loss) and mud cake thickness, American Petroleum Institute (API) standard Low pressure/low temperature test is run by using 6 unit API Filter Press (Figure 4.11) (Fann Instruments, 2009). During the test, each mud sample is tested twice to determine fluid loss and cake thickness of the samples.

Figure 4.11. 6 Unit API Filter Press

The basic test steps for conducting a filtration test are as follows;

- Place 60 mesh screen in the base cup of the cell
- Put filter paper and neoprene gasket on 60 mesh screen respectively before assembling the cell body
- Pour the mud sample into the cell by leaving approximately 13 mm from top of the cell
- Set the test cell into the frame and tighten with T-Screw
- Place the graduated cylinder under the cell drain to measure the filtration.
- Close the relief valve and adjust the pressure 100 ± 5 psi and allow to start filtration for 30 minutes.
- Report the volume of fluid in the graduated cylinder in milliliters at the end of the process. Since each sample is tested twice, average measurement is taken into consideration.
- Close the pressure valve, release the pressure from the cell by relief valve
- Remove the cell the frame, discard the mud

- Disassemble the cell, remove the neoprene gasket and save the filter paper with a minimum disturbance of the mud cake (ANSI/API Recommended Practice 13B-1, 2009). A sample filtrate cake is shown in Figure 4.12.

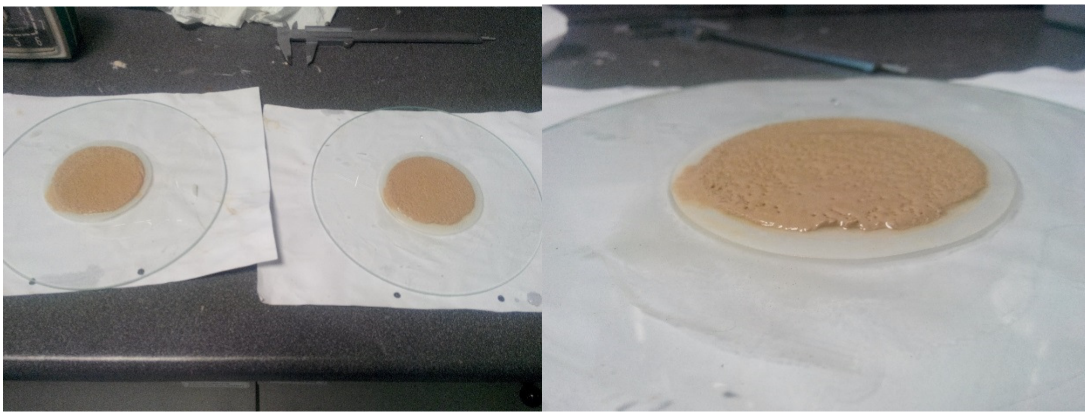

Figure 4.12. Filtrate (Mud) Cake

To determine the effect of the lubricants on mud cake thickness, the filtrate cake on the filter paper generated by the filtration is washed with a gentle stream of water where the filter paper is kept with an angle of 45°. The mud cake is measured from 5 different points of the cake with caliper gage shown in Figure 4.13 and 4.14. Average of readings is recorded in millimeter.

Figure 4.13. Caliper Gage

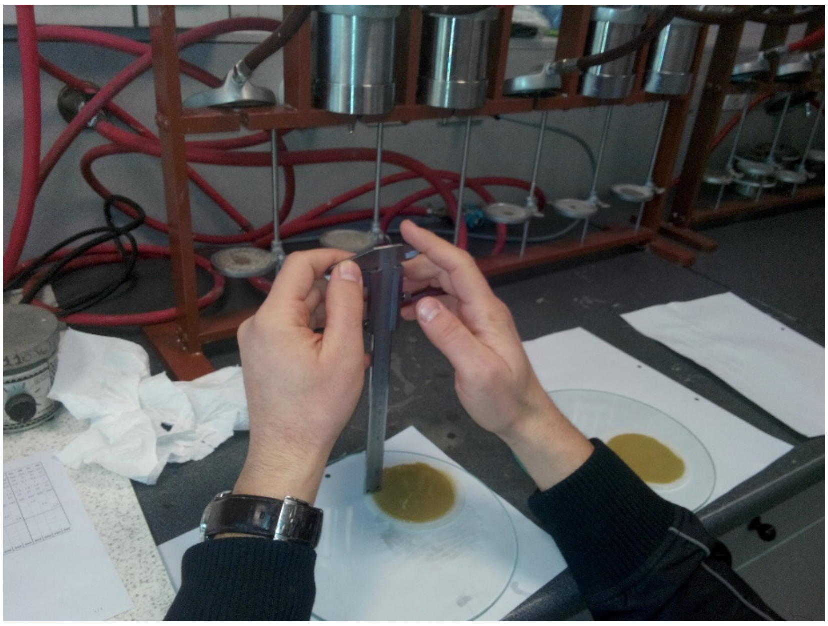

Figure 4.14. Filtrate (Mud) Cake Thickness Measurement

4.2.5. Mud Analysis

4.2.5.1. Rheological Properties

Determining the effect of lubricant on rheological properties viscometer is used for testing (Figure 4.15). This viscometer is capable to measure the direct readings in six different speed ranges from 3 to 600 rpm, which can be used to calculate the Plastic Viscosity (PV), Yield Point (YP) and gel strengths. The principle of the machine depends on rotating the outer cylinder with a known velocity around a bob and measure the test fluid viscosity rely on the gap that created between cylinder and the bob. The friction created in this gap is transferred to a spring by the bob and as a result rheological properties are measured (Fann Instruments, 2008).

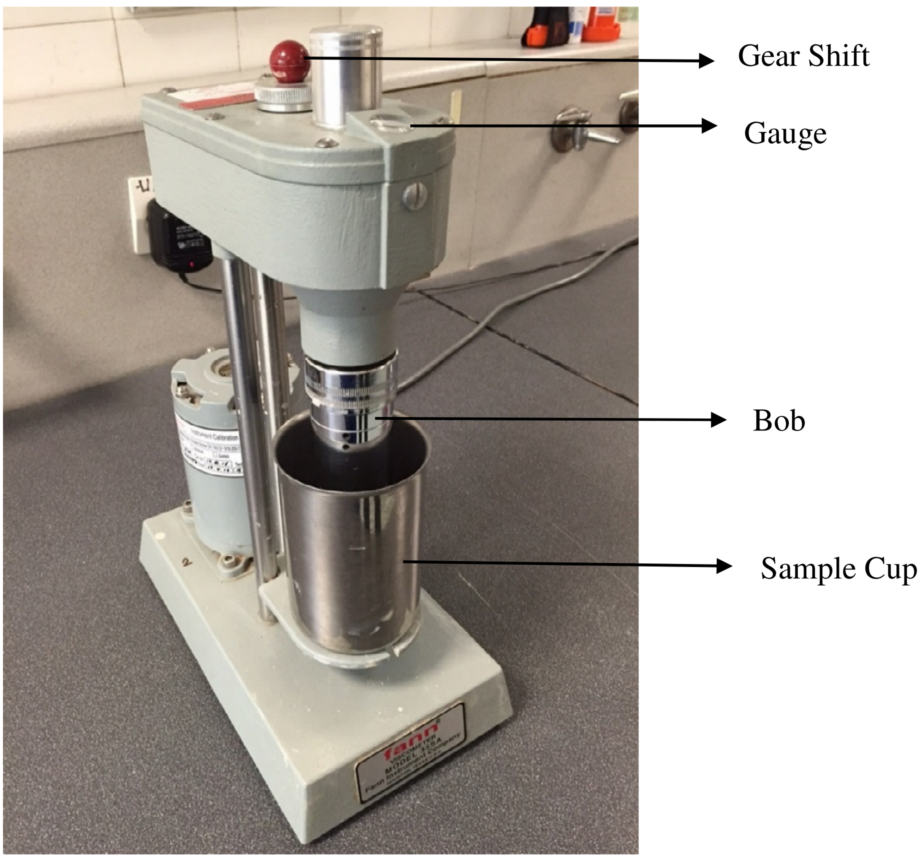

Figure 4.15 Viscometer

The steps of viscometer readings are listed below,

- Pour the drilling fluid into the sample cup
- Raise the sample cup with cup holder till the scribed line at the bob
- Adjust the machine gear shift knob to 600 rpm
- Run the machine and rotate for 1 minute until steady state reading from the gauge is recorded
- Repeat the same procedure for 300 rpm reading

Plastic viscosity and yield point can be calculated from 600 and 300 rpm readings shown in equation 4.7 and 4.8.

$$PV,\ cp = \Theta_{600} - \Theta_{300} \tag{4.7}$$

$$YP,\ lbf/100\ ft^2 = \Theta_{300} - PV \tag{4.8}$$

Measurement of the gel strengths is described below,

- Rotate the sleeve at 600 rpm for 1 minute same as PV and YP determination.
- Stop the machine and adjust the gear shift to 3 rpm
- Wait 10 sec. to measure the gel strength at 10 sec.
- Run the machine again and record the maximum dial reading from the gauge

Same procedure is followed for 10 min. and 30 min. gel strengths by changing the waiting time.

Gel Strength @ 10 sec. = Max dial reading of the gauge at 3 rpm (4.9)

Gel Strength @ 10 min. = Max dial reading of the gauge at 3 rpm (4.10)

Gel Strength @ 30 min. = Max dial reading of the gauge at 3 rpm (4.11)

4.2.5.2. Mud Density Measurement

Examining the lubricants' foam forming potential on mud density measurement, mud balance shown in Figure 4.16 is used for measuring the density of the drilling fluid. The measurement procedure of mud balance is listed below,

- Set the mud balance base support onto a flat place in order to get an accurate measurement
- Dry and clean mud balance
- Fill the mud balance cup with the drilling fluid to be tested
- Close the mud balance top cap by rotating gently till it is seated onto balance cup in order to remove any trapped gas or air affecting the accurate reading
- Observe the mud is expelled through the hole in the top cap
- Close the hole at the top cap by finger and wash the mud balance and dry
- Place the mud balance onto the beam at the base support
- Balance the mud balance by moving the rider alongside of the scale

Measurements are taken in pounds per cubic feet (ppcf) in this study (ANSI/API Recommended Practice 13B-1, 2009).

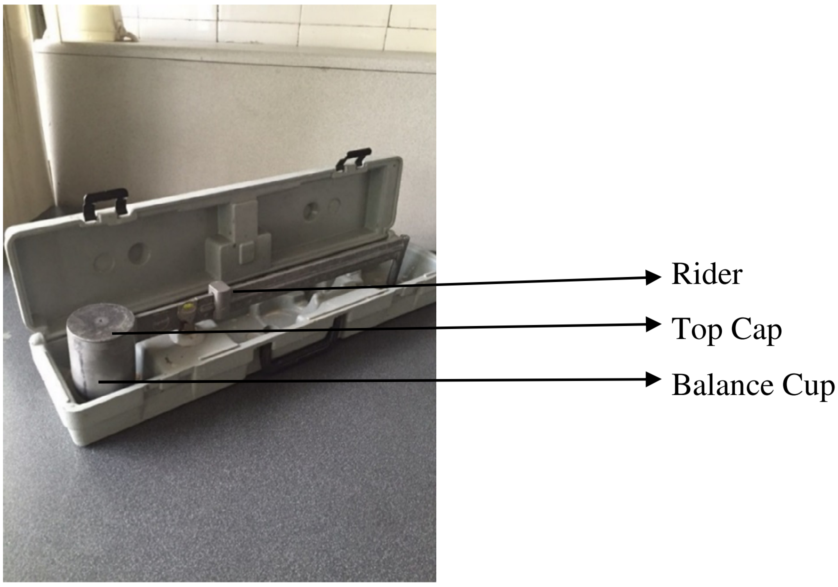

Figure 4.16 Mud Balance

4.2.5.3. Methylene Blue Capacity (MBC) Determination

Determining the reactive clays (bentonite or drilled solids) in drilling fluid, methylene blue test is conducted. The steps of methylene blue capacity determination are listed below,

- Take 2 ml of drilling fluid sample by syringe and put it into an erlenmeyer.
- Add 15 ml of 3% hydrogen peroxide and 0.5 ml of 5N sulfuric acid into erlenmeyer to remove organic materials like CMC and CFL effecting the results
- Add 10 ml of distilled water into erlenmeyer
- Boil the erlenmeyer for 10 minute
- Fill the erlenmeyer to 50 ml with distilled water after boiling
- Add 0.5 ml methylene blue solution by pipette and stir the sample for 30 sec.
- Take a drop from the sample by the dropper and place it onto a filter paper in order to see greenish-blue ring surrounding the dyed solids.
- If not, add another 0.5 ml of methylene blue into the erlenmeyer and repeat the same procedure until to see the greenish-blue ring surrounding the dyed solids.

When the titration reaches the end point, amount of methylene blue consumption is recorded and methylene blue capacity of the sample is calculated in pounds per barrel (ppb) by using the equation 4.12. (M-I Swaco Drilling Fluids, 1998)

$$\text{MBC (ppb)} = (\text{cm}^3 \text{ of methylene blue / cm}^3 \text{ of mud}) \times 5 \qquad (4.12)$$

CHAPTER 5

RESULTS AND DISCUSSION

Experimental procedures for the laboratory tests to analyze the performance of drilling fluid lubricants in weighted and unweighted water based lignosulfonate muds are already described in Chapter 4. Thirty different tests having different mud compositions were run and the list of tests is given in Table 5.1. How to prepare test samples depends on the test matrix at Table 5.1 are given at Table 5.2. Those tests are grouped in 8 different groups where only one parameter is changed while the other mud properties are kept constant. It is important to mention that tests 2A, 5A and 6A are listed twice in Table 5.1 and named as 7A, 8A and 9A, respectively. Throughout the tests, 2% and 3% lubricant concentrations by volume are tested similar with Dogan's article "Performance Analysis of Drilling Fluid Liquid Lubricants" (Dogan et. al., 2009). Percentages above 3% are not tested as it is not recommended by the supplier and not cost effective. Tests with differential sticking tester where run three times for each mud composition to check the repeatability of the tests. The maximum difference of each differential sticking test from the arithmetic average of three repeats is found to be 5.6 %.

Results of the experimental study are discussed for each group of tests separately in the following sub-sections. Section 5.1 discusses the results of Modified Differential Sticking Tester, which is used to evaluate the performance of drilling fluid lubricants considering metal-mud cake contact. In addition, same mud samples are also tested by using lubricity tester to compare the test results regarding metal-metal contact, which is discussed in Section 5.2. Effect of lubricants on fluid loss and mud cake which was performed by using API Filter press test equipment is also discussed in Section 5.3.

Table 5.1 Concentration of Test Matrix

Test No	Base Mud	Ocma Clay, ppb	Barite, ppb	Lube-B, vol.%	Lube-C, vol.%	Lube-D, vol.%
1A	1 bbl	-	-	-	-	-
1B		-	-	2	-	-
1C		-	-	-	2	-
1D		-	-	-	-	2
2A		25	-	-	-	-
2B		25	-	2	-	-
2C		25	-	-	2	-
2D		25	-	-	-	2
3A		50	-	-	-	-
3B		50	-	2	-	-
3C		50	-	-	2	-
3D		50	-	-	-	2
4A		25	50	-	-	-
5A		25	150	-	-	-
5B		25	150	2	-	-
5C		25	150	-	2	-
5D		25	150	-	-	2
6A		25	300	-	-	-
6B		25	300	2	-	-
6C		25	300	-	2	-
6D		25	300	-	-	2
7A (2A)		25	-	-	-	-
7B		25	-	3	-	-
7C		25	-	-	3	-
7D		25	-	-	-	3
8A (5A)		25	150	-	-	-
8B		25	150	3	-	-
8C		25	150	-	3	-
8D		25	150	-	-	3
9A (6A)		25	300	-	-	-
9B		25	300	3	-	-
9C		25	300	-	3	-
9D		25	300	-	-	3

Table 5.2 Sample Preparation of Test Matrix

Test No	Base Mud	Ocma Clay, gr	Barite, gr	Lube-B, cc	Lube-C, cc	Lube-D, cc
1A	350 cc	-	-	-	-	-
1B		-	-	7.5	-	-
1C		-	-	-	7.5	-
1D		-	-	-	-	7.5
2A		25	-	-	-	-
2B		25	-	7.5	-	-
2C		25	-	-	7.5	-
2D		25	-	-	-	7.5
3A		50	-	-	-	-
3B		50	-	7.5	-	-
3C		50	-	-	7.5	-
3D		50	-	-	-	7.5
4A		25	50	-	-	-
5A		25	150	-	-	-
5B		25	150	7.5	-	-
5C		25	150	-	7.5	-
5D		25	150	-	-	7.5
6A		25	300	-	-	-
6B		25	300	7.5	-	-
6C		25	300	-	7.5	-
6D		25	300	-	-	7.5
7A (2A)		25	-	-	-	-
7B		25	-	10.5	-	-
7C		25	-	-	10.5	-
7D		25	-	-	-	10.5
8A (5A)		25	150	-	-	-
8B		25	150	10.5	-	-
8C		25	150	-	10.5	-
8D		25	150	-	-	10.5
9A (6A)		25	300	-	-	-
9B		25	300	10.5	-	-
9C		25	300	-	10.5	-
9D		25	300	-	-	10.5

5.1. Differential Sticking Tester (DST) Performance Analysis

Modified differential sticking tester is used to calculate the bulk sticking coefficient and determine the performance of Lube B, Lube C and Lube D in weighted and unweighted lignosulfonate mud. OCMA clay is added into the base mud in order to simulate drilled solids. Barite is used as a weighting agent, which acts like a solid lubricant. The percentage of lubricant additions are taken as volumetric concentration. Base mud composition is shown in Table 4.1.

5.1.1. DST Performance Analysis - Barite vs 2% Lubricants

The performance of lignosulfonate mud including 2% by volume lubricants is shown in Figure 5.1 with increasing barite concentration. It can be seen that Lube-B indicates the lowest bulk sticking coefficient in weighted and unweighted lignosulfonate mud. Detailed results are shown in Appendix A.

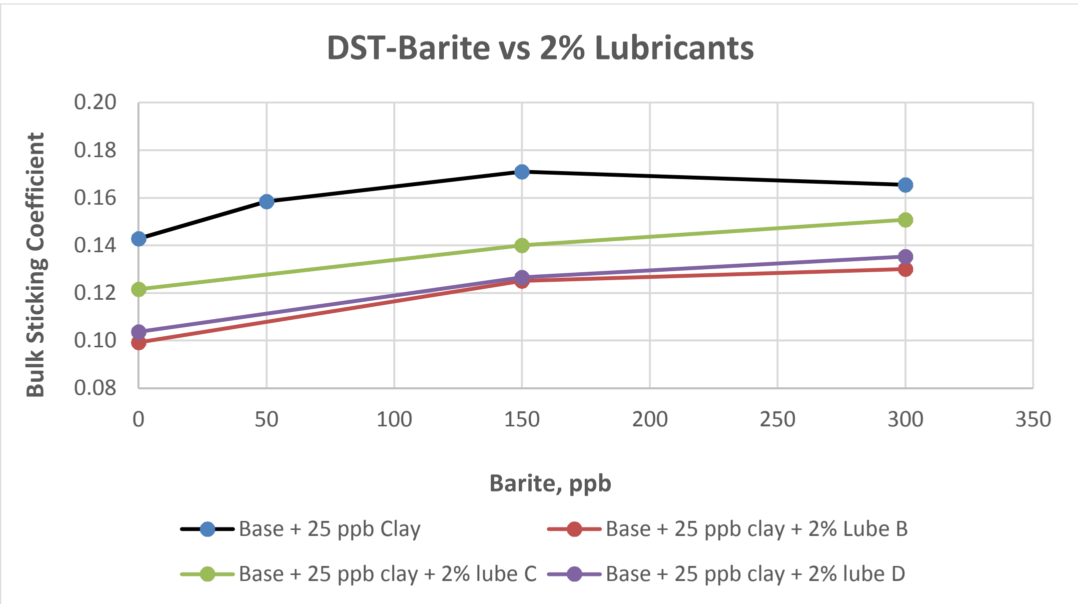

Figure 5.1. DST Performance Analysis – Barite vs 2% Lubricants

As shown in Figure 5.1, bulk sticking coefficients have low measurements in all samples that contain 2% lubricants, compared to samples without lubricant, as expected. Bulk sticking coefficient increases with increasing barite concentration up to 150 ppb at the lubricant free sample; however, it starts to decrease slightly when barite concentration is continued to increase up to 300 ppb. It can be said that, barite act like ball bearings generating rolling effect in high concentration, resulting a decrease in the coefficient value.

Bulk sticking coefficient of the sample contains 2% Lube-C increases with increasing barite concentration, but it tends to decrease when barite concentration is continued to increase up to 300 ppb. Sample contains 2% Lube-D acts similar coefficient behavior with increasing barite concentration like sample contains 2% Lube-C, however more effective compare to Lube-C. The lowest bulk sticking coefficient values are measured at the sample contains 2% Lube-B compare to Lube-C and Lube-D. In addition, Lube-B gives almost similar performance after 150 ppb barite concentration.

5.1.2. DST Performance Analysis - Barite vs 3% Lubricants

The performance 3% lubricants added lignosulfonate mud with increasing barite concentration is shown in Figure 5.2. All lubricants have low measurement values compare to 2% lubricant concentrations. Detailed results are shown in Appendix A.

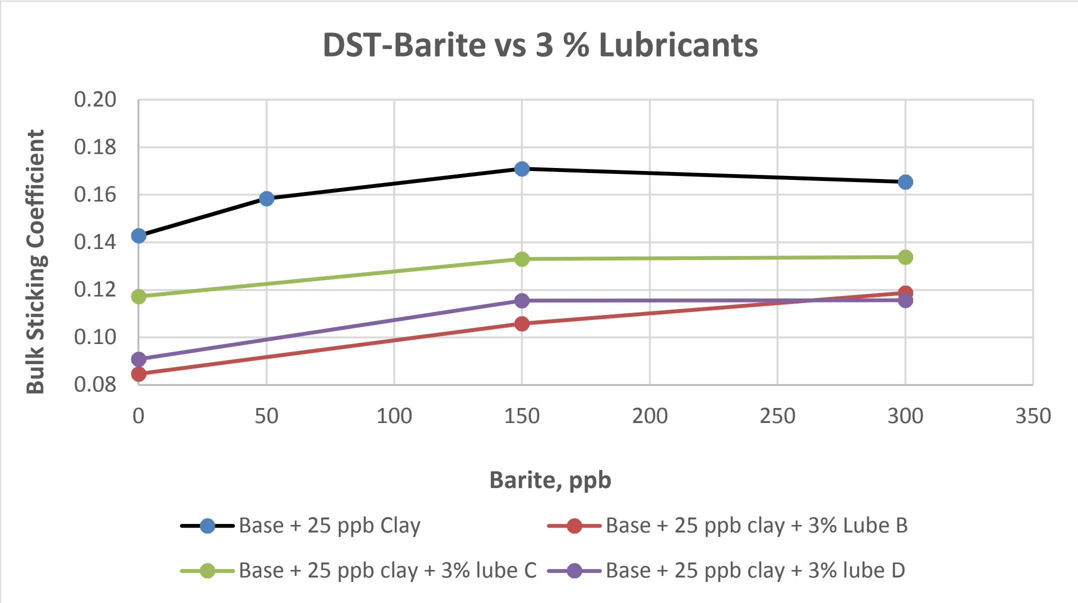

Figure 5.2. DST Performance Analysis – Barite vs 3% Lubricants

As shown in Figure 5.2, bulk sticking coefficients have low measurements in all samples that contain 3% lubricants as expected. Bulk sticking coefficient increases with increasing barite concentration up to 150 ppb at the lubricant free sample; however, Lube-C and Lube-D reach their plato value above 150 ppb barite concentration. Yet, bulk sticking coefficient measurement of Lube-B does not show the same trend after 150 ppb barite concentration like Lube-C and Lube-D.

5.1.3. DST Performance Analysis - Barite vs 2-3% Lubricant-B

The performance of 2% and 3% Lube-B added lignosulfonate mud with increasing barite concentration is shown in Figure 5.3. 3% Lube-B has low measurement values compared to 2% concentration. Detailed results are shown in Appendix A.

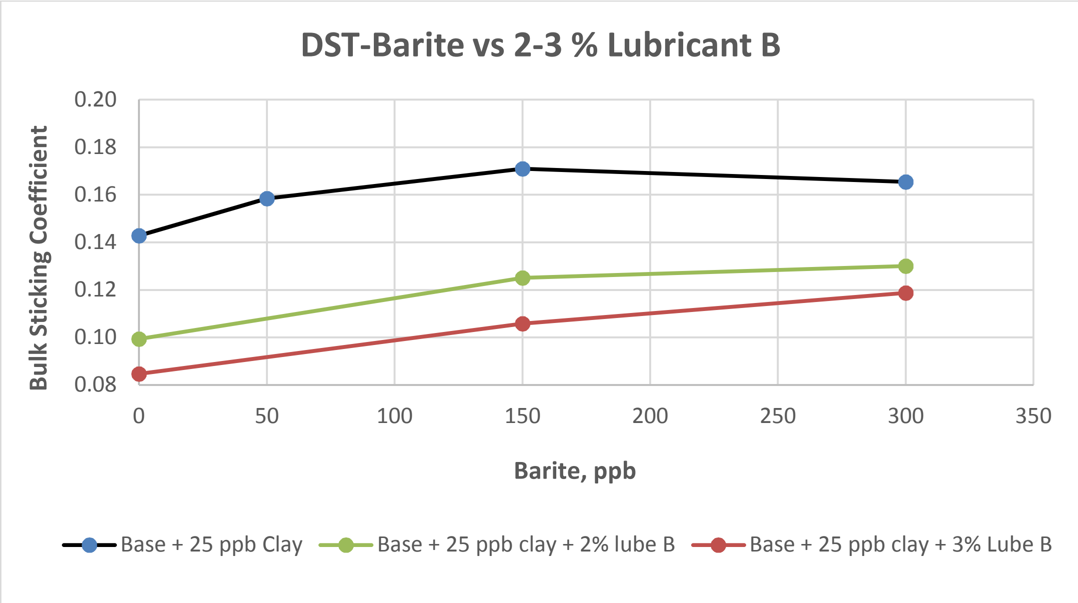

Figure 5.3. DST Performance Analysis – Barite vs 2% and 3% Lube-B

It can be seen in Figure 5.3 that sticking coefficient of 3% concentration of Lube-B has low measurements values compared to 2% concentration of Lube-B even if barite concentration is increased. However, coefficient of 2% Lube-B remains almost stable after 150 ppb barite concentration and tends to reach its plato value. The same trend is not seen in 3% concentration of Lube-B. Coefficient value is getting closer at 300 ppb barite concentration.

5.1.4. DST Performance Analysis - Barite vs 2-3% Lubricant-C

The performance of 2% and 3% Lube-C added lignosulfonate mud with increasing barite concentration is shown in Figure 5.4. Volumetric concentration of 3% Lube-C has low measurement values compared to the 2% concentration. Detailed results are shown in Appendix A.

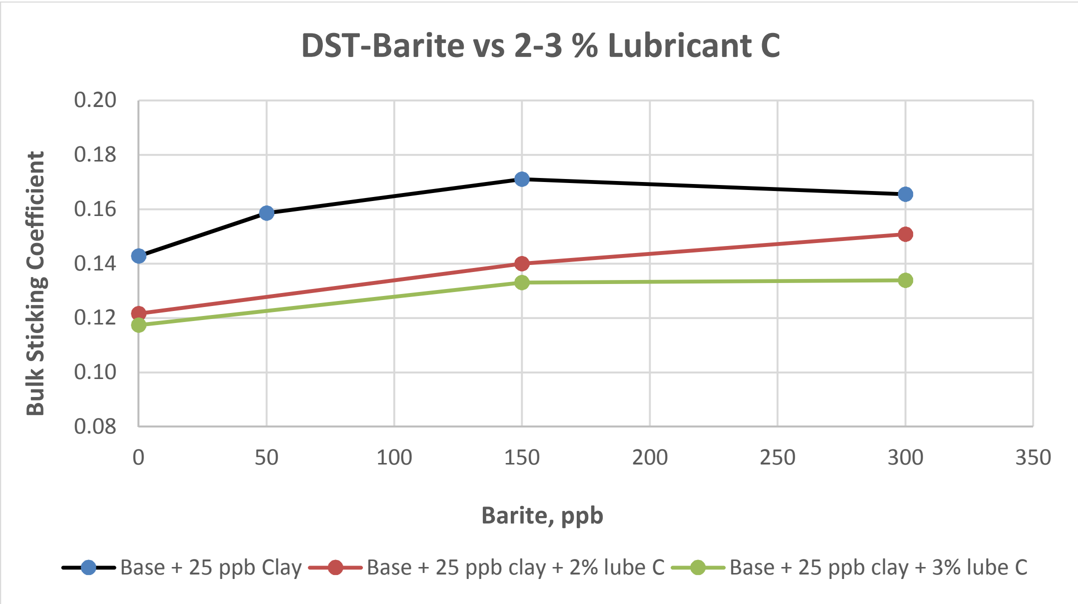

Figure 5.4. DST Performance Analysis – Barite vs 2% and 3% Lube-C

It can be seen in Figure 5.4 that sticking coefficient of 3% concentration of Lube-C has low measurements values compared to 2% concentration of Lube-C even if barite concentration is increased. However, coefficient of 3% Lube-C remains stable after 150 ppb barite concentration and reaches its plato value. The same trend is not seen in 2% concentration of Lube-C. Coefficient value is getting closer at 150 ppb barite concentration, but 3% Lube-C is more effective than 2% Lube-C at 300 ppb barite concentration.

5.1.5. DST Performance Analysis - Barite vs 2-3% Lubricant-D

The performance of 2% and 3% Lube-D added lignosulfonate mud with increasing barite concentration is shown in Figure 5.5. 3% Lube-D has low measurement values compared to 2% concentration. Detailed results are shown in Appendix A.

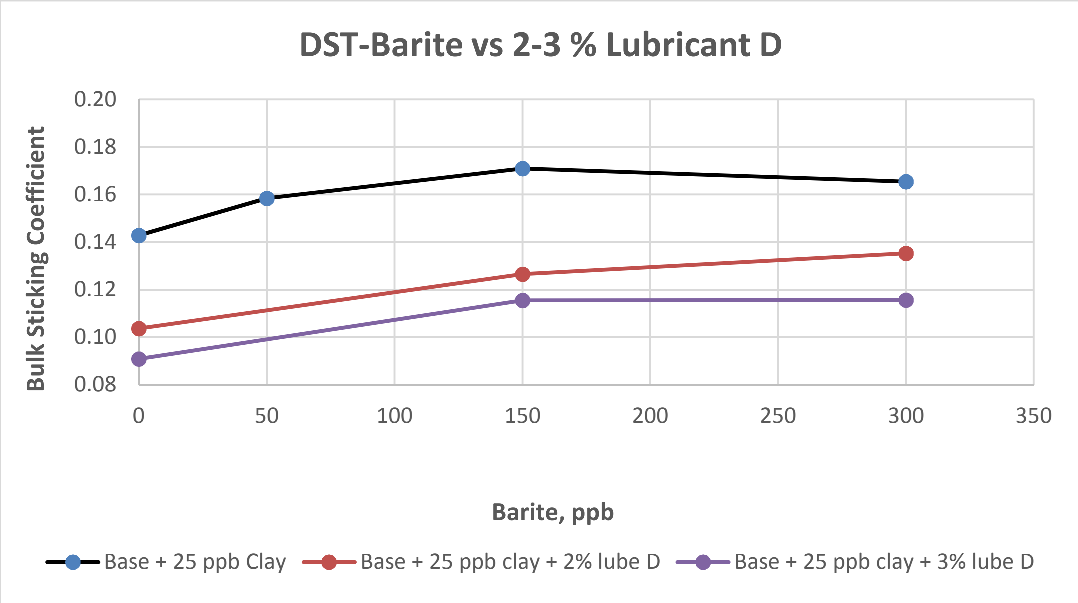

Figure 5.5. DST Performance Analysis – Barite vs 2% and 3% Lube-D

As shown in Figure 5.5 that sticking coefficient of 3% concentration of Lube-D has low measurements values compared to 2% concentration of Lube-D with an increasing barite concentration. However, coefficient of 3% Lube-D remains stable after 150 ppb barite concentration and reaches its plato value. The same trend is not seen in 2% concentration of Lube-D. Difference of coefficient values between 2% and 3% Lube-D is similar until 150 ppb barite concentration. But, difference is getting higher after 150 ppb barite concentration. 3% Lube-D is more effective than 2% Lube-D at 300 ppb barite concentration.

5.1.6. DST Performance Analysis – OCMA Clay vs 2% Lubricants

Effect of an increase of OCMA clay concentration, which is a disperse solid in 2% lubricant added lignosulfonate mud is shown in Figure 5.6. OCMA clay is used to simulate drilled solids in the mud. It can be seen that Lube-B indicates the lowest bulk sticking coefficient value in lignosulfonate mud. Detailed results are shown in Appendix A.

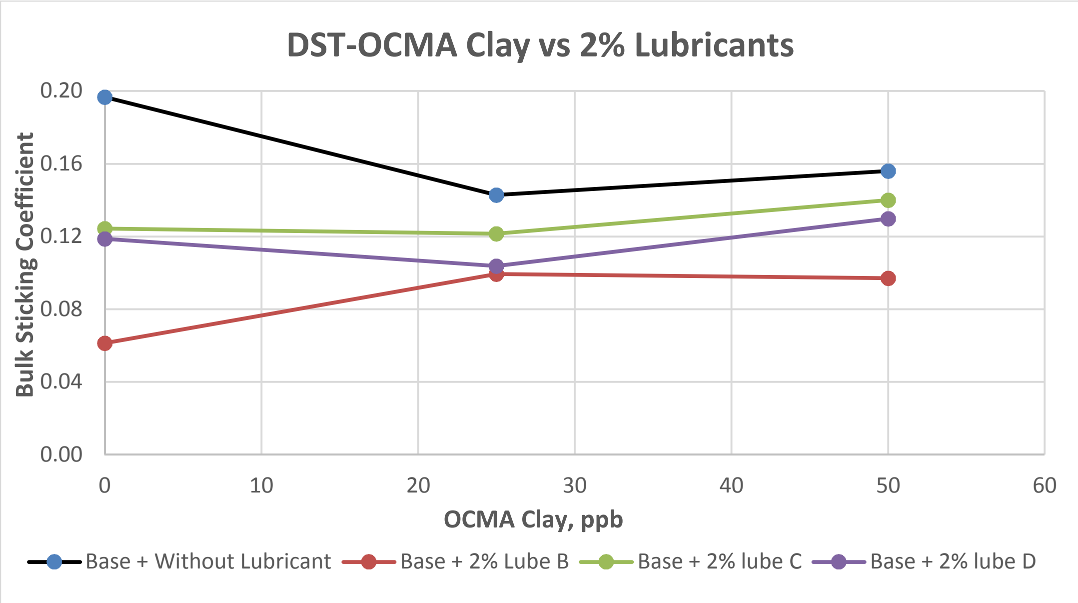

Figure 5.6. DST Performance Analysis – OCMA Clay vs 2% Lubricants

According to Figure 5.6, it can be said that increasing of OCMA clay up to 25 ppb in lubricant free base mud helps to reduce sticking coefficient due to its lubricity properties. After that keeping to increase the concentration of OCMA clay, decreases mud cake quality and mud cake pore pressure and as a result generate an increase in sticking coefficient.

Lube-C is not affected with the increase of OCMA clay up to 25 ppb, but effectiveness of Lube-C decreases after 25 ppb. Lube-D is observed a similar behavior like lubricant free base mud, but more effective than Lube-C. Lube-B acts an optimum performance rather than Lube-C and Lube-D. However, Lube-B surprisingly loses its effectiveness up to 25 ppb OCMA clay concentration but more effective in high concentration of OCMA clay compared to Lube-C and Lube-D.

5.1.7. DST Performance Analysis – OCMA clay & Barite vs Time

This performance analysis has been conducted to examine the effect of time on DST torque readings. As described earlier in experimental study in Chapter 4, bulk sticking coefficient is calculated by average of seven torque readings allowing 30 seconds between each readings. This step is repeated 3 times and average torque reading is calculated and coefficient is found.

In this part, average torque reading of first readings of three mud sample is calculated, this step is carried out for the next six readings of each sample and average torque readings are calculated. Detailed results are shown in Appendix A. Effect of time on OCMA clay and barite is shown in Figure 5.7.

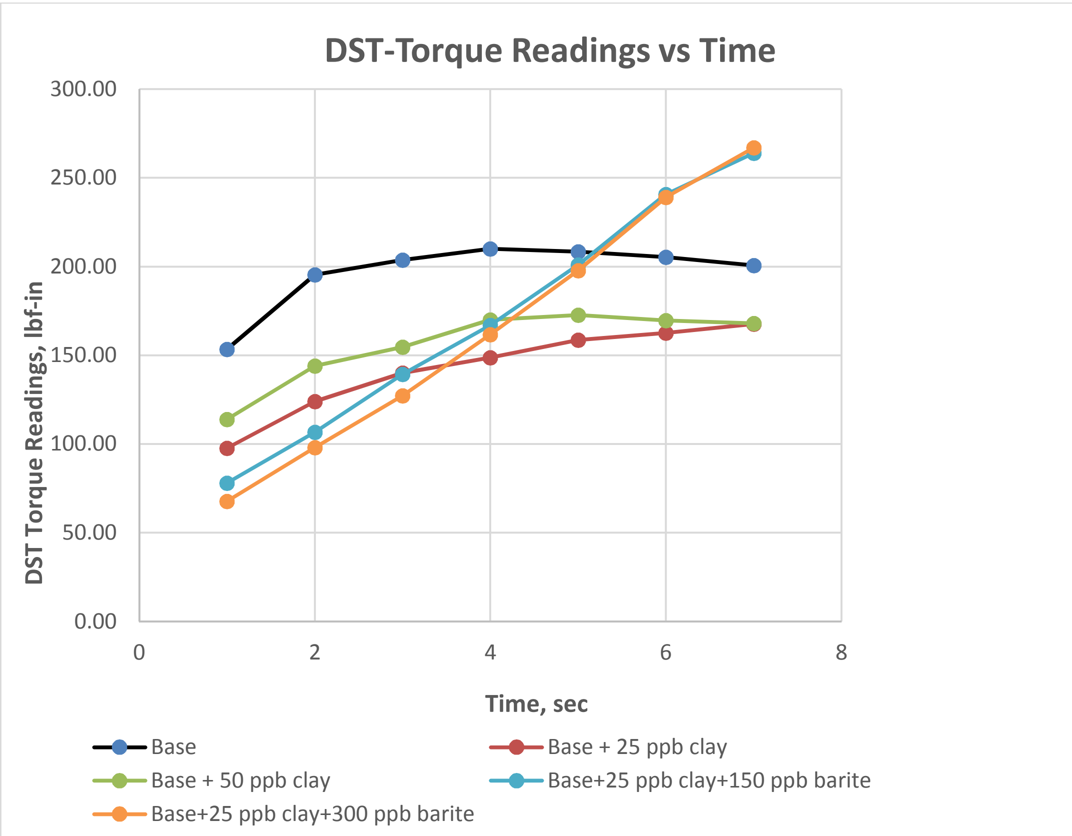

Figure 5.7. DST Performance Analysis – OCMA clay and Barite vs Time

As shown in Figure 5.7, lubricant free mud sample hasn’t got a very big difference between 2nd (60 sec.) and 7th (210 sec.) readings. Base mud+50 ppb OCMA clay and base mud+25 ppb OCMA clay display the similar trend like lubricant free mud sample. Torque readings of these two clay added samples are lower than base mud due to lubrication of disperse clay content. Torque readings of 50 ppb OCMA clay added sample is generally higher than 25 ppb added sample, because of excessive disperse clay contamination. In addition to this, torque readings of barite added samples are getting increase with increasing time. This circumstance indicates the importance of time on weighted mud if differential sticking occurs.

5.2. Lubricity Tester (LT) Performance Analysis

Lubricity tester is used to calculate the lubricity coefficient in metal to metal contact, and to evaluate the performance of Lube B, Lube C and Lube D parallel with differential sticking tester in weighted and unweighted lignosulfonate mud. Same mud samples are used for measuring the lubricity coefficient.

5.2.1. LT Performance Analysis - Barite vs 2% Lubricants

The performance of 2% lubricants added lignosulfonate mud with increasing barite concentration is shown in Figure 5.8. It can be seen that Lube-B indicates the lowest lubricity coefficient in weighted and unweighted lignosulfonate mud. Detailed results are shown in Appendix A.

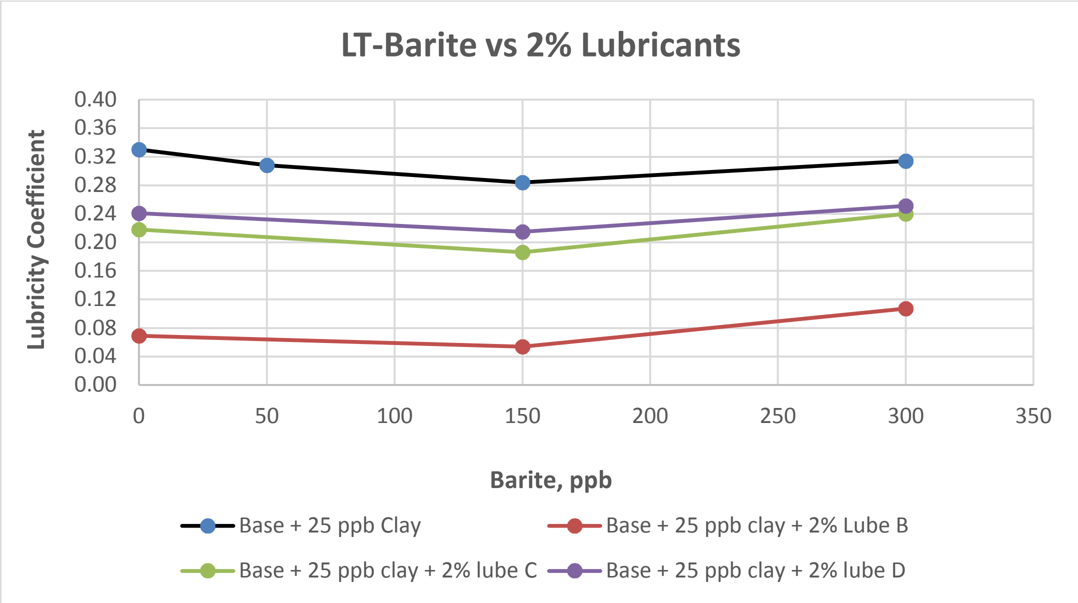

Figure 5.8. LT Performance Analysis – Barite vs 2% Lubricants

As shown in Figure 5.8, lubricity coefficients have low measurements in all samples that contain 2% lubricants as expected. Unlike differential sticking tester, lubricity coefficient decreases with increasing barite concentration up to 150 ppb at the lubricant free sample. However, it starts to increase slightly when barite concentration is continued to increase up to 300 ppb. It can be explained that, barite acts like ball bearings generating rolling effect until 150 ppb, but after that creates a torque in high concentration of barite mud sample in metal-metal contact.

The effect of increase of barite, which is a non-dispersed solid in 2% Lube-B, Lube-C and Lube-D added water based lignosulfonate mud displays the same trend like lubricant free sample. Besides this, optimum lubricity coefficient can be observed from Lube-B added sample.

5.2.2. LT Performance Analysis - Barite vs 3% Lubricants

The performance of 3% lubricants added lignosulfonate mud with increasing barite concentration is shown in Figure 5.9. It can be seen that Lube-B indicates the lowest lubricity coefficient in weighted and unweighted lignosulfonate mud. Detailed results are shown in Appendix A.

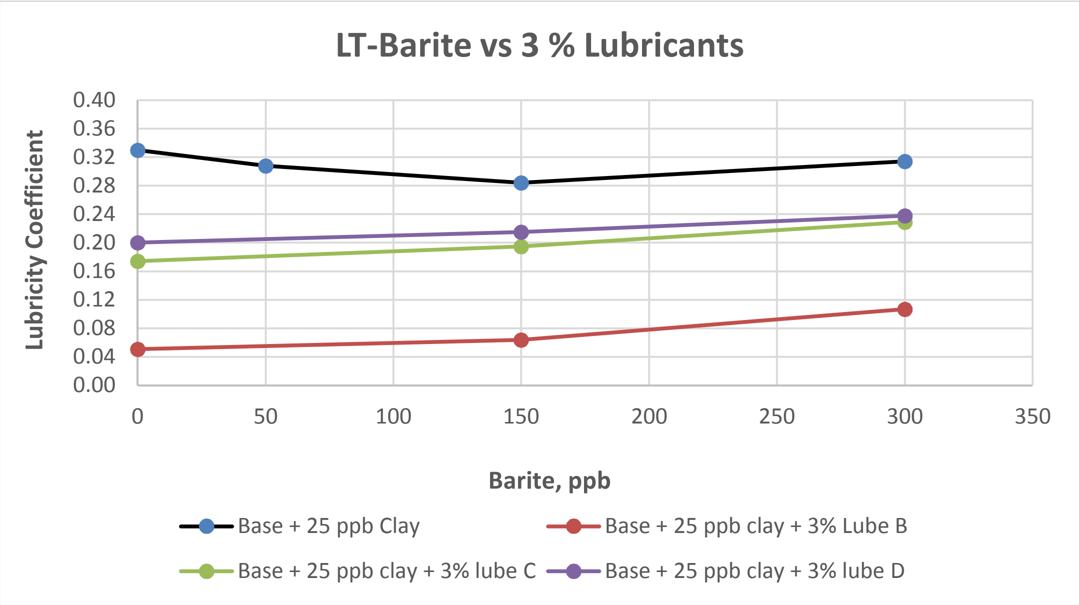

Figure 5.9. LT Performance Analysis – Barite vs 3% Lubricants

According to Figure 5.9, 3% lubricant added mud samples are only effective in unweighted mud samples compared with the 2% lubricant added samples. The performance of 3% lubricants added lignosulfonate mud samples are similar with 2% added samples with increasing barite concentration, which means increasing lube concentration up to 3% is insignificant in metal-metal contact.

5.2.3. LT Performance Analysis - Barite vs 2-3% Lubricant-B

The performance of 2% and 3% Lube-B added lignosulfonate mud on lubricity coefficient with increasing barite concentration is shown in Figure 5.10. It can be observed that, an increase of Lube-B from 2% to 3% by volume is slightly effective in unweighted mud sample. However, it is more effective in any case of barite concentration compared to lubricant free base mud sample. Detailed results are shown in Appendix A.

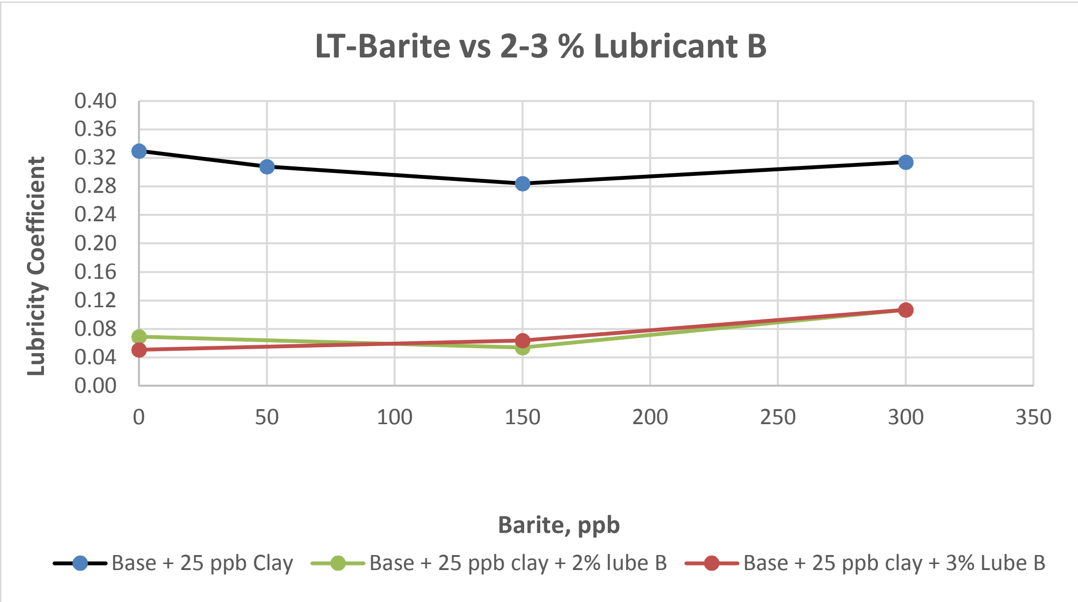

Figure 5.10. LT Performance Analysis – Barite vs 2% and 3% Lube-B

5.2.4. LT Performance Analysis - Barite vs 2-3% Lubricant-C

The performance of 2% and 3% Lube-C added lignosulfonate mud with increasing barite concentration is shown in Figure 5.11. It can be seen that, an increase of Lube-C from 2% to 3% by volume is more effective in an unweighted mud sample. However, it's effectiveness on lubricity coefficient is getting similar with increasing barite concentration. Increasing Lube-C concentration is ineffective after 150 ppb barite concentration. Lube-C is less effective compared to Lube-B. Detailed results are shown in Appendix A.

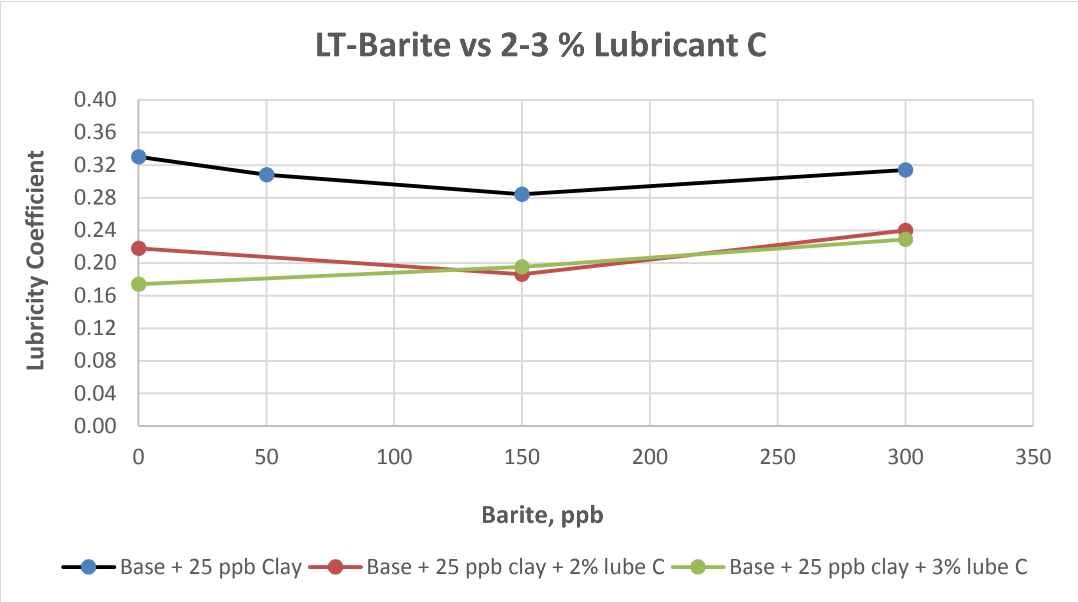

Figure 5.11. LT Performance Analysis – Barite vs 2% and 3% Lube-C

5.2.5. LT Performance Analysis - Barite vs 2-3% Lubricant-D

The performance of 2% and 3% Lube-D added lignosulfonate mud with increasing barite concentration is shown in Figure 5.12. Lube-D has performed a similar trend like Lube-B and Lube-C. It is more effective in unweighted mud sample but getting lose its performance with increasing barite concentration. In addition to this, Lube-D has performed the worst measurement values compared to Lube-B and Lube-C. Detailed results are shown in Appendix A.

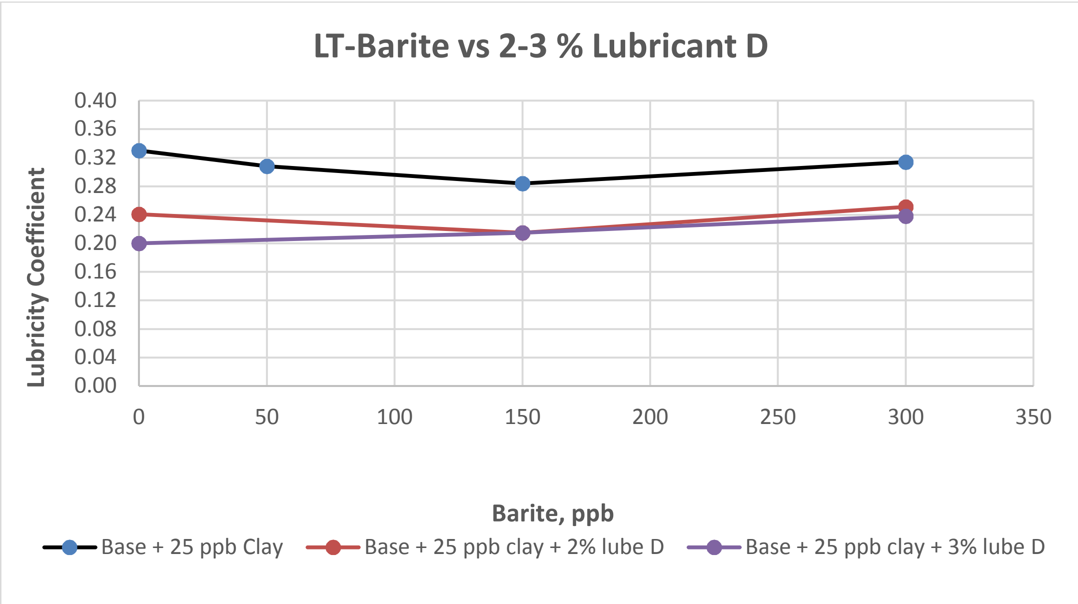

Figure 5.12. LT Performance Analysis – Barite vs 2% and 3% Lube-D

5.3. Fluid Loss and Mud Cake Thickness Analysis

API Filter Press test equipment is used to evaluate the drilling fluid lubricants on fluid loss and mud cake thickness in this part of study. Drilling a well with a low fluid loss (low filtration) and a thin mud cake are the desired properties of drilling fluid properties in drilling industry. In this case, low permeable zone is generated around borehole due to low filtration and as a result mud cake pore pressure is stabilized and prevent possible drilling problems; like drill string stuck, hole instability, etc. Thin mud cake is also important for drilling in order to overcome stuck problems during trips in/out and minimize the contact area so that reduce the friction and torque.

5.3.1. Fluid Loss and Mud Cake Thickness Analysis in Lubricant Free Base Samples with increasing OCMA Clay.

The effect of increasing OCMA clay on lignosulfonate base mud can be seen in Figure 5.13. According to the figure, fluid loss decreases with increasing OCMA clay, on the other hand mud cake thickness increases which is usual but undesirable for mud properties. The effects of lubricants in these kind of circumstances are examined further part of this chapter. Detailed results are shown in Appendix B.

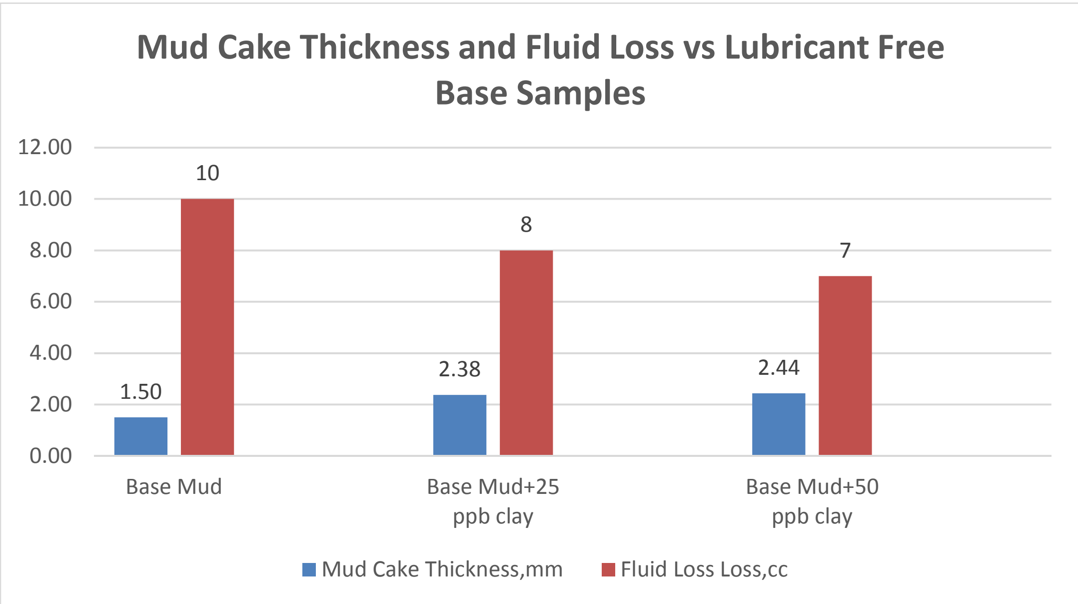

Figure 5.13. Mud Cake Thickness and Fluid Loss Analysis – OCMA Clay vs Lubricant Free Samples**.**

5.3.2. Fluid Loss and Mud Cake Thickness Analysis in 2%Lubricant Base Samples vs with OCMA Clay and Barite Free Sapmles

The performance analysis of lubricants on OCMA clay and barite free samples are evaluated in Figure 5.14. Adding 2% lubricant decreases fluid loss in all lubricant added samples. In addition to this, the more fluid loss reduction is achieved by Lube-B added sample. Moreover, thin mud cake thickness is achieved only in Lube-B added sample rather than other lubricants compared to base mud. Detailed results are shown in Appendix B.

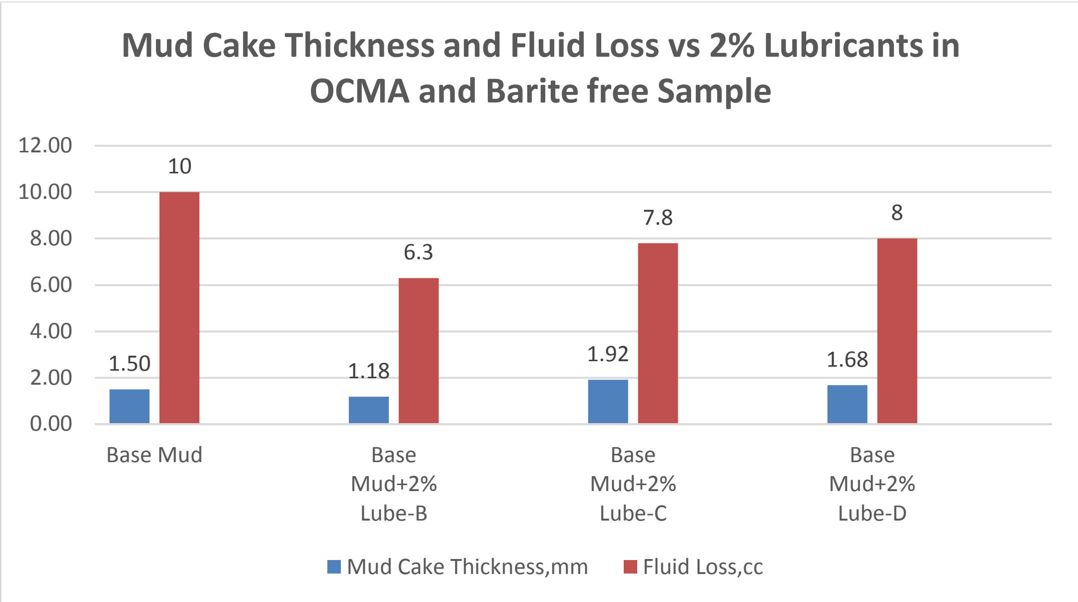

Figure 5.14. Mud Cake Thickness and Fluid Loss Analysis – OCMA Clay vs 2% Lubricant Added Samples**.**

5.3.3. Fluid Loss and Mud Cake Thickness Analysis in 2%Lubricant vs Base Samples with 25 ppb OCMA Clay.

The performance analysis of lubricants on 25 ppb OCMA added samples are shown in Figure 5.15. Adding 2% lubricant decreases Fluid loss slightly in Lube-C and Lube-D added samples, but more fluid loss reduction is observed in Lube-B added sample. Besides this, thin mud cake thickness is achieved only in Lube-B added sample rather than other lubricants compared to base mud. Detailed results are shown in Appendix B.

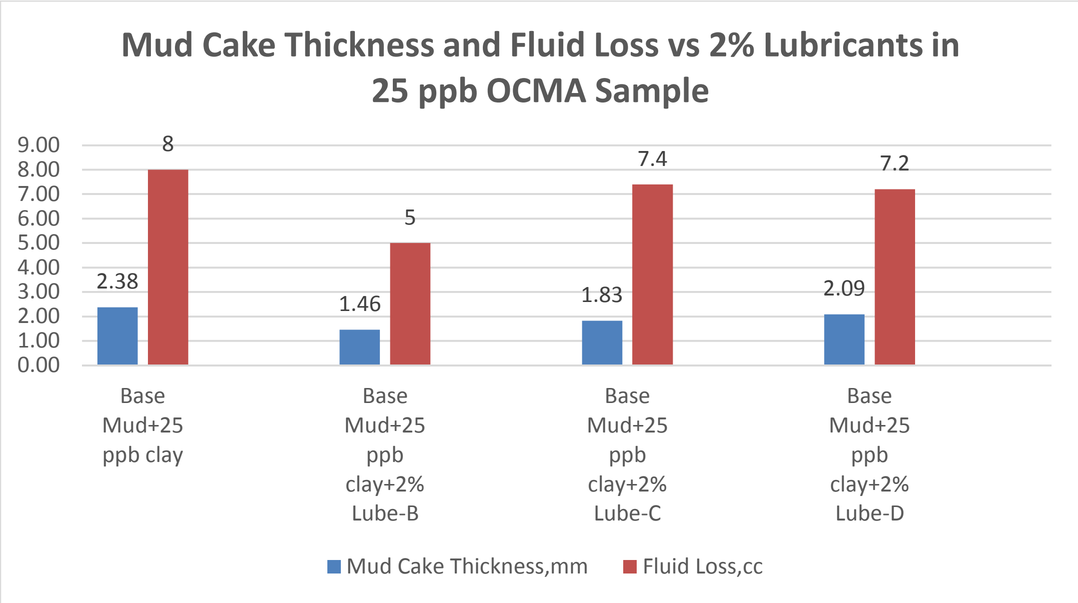

Figure 5.15. Mud Cake Thickness and Fluid Loss Analysis – 25 ppb OCMA Clay vs 2% Lubricant Added Samples.

5.3.4. Fluid Loss and Mud Cake Thickness Analysis in 2%Lubricant vs Base Samples with 50 ppb OCMA Clay.

The performance analysis of lubricants on 50 ppb OCMA added samples are shown in Figure 5.16. Adding 2% lubricant decreases fluid loss slightly in Lube-C but lead to effective decrease in Lube-B. On the other hand, Lube-D has almost no effect on fluid loss Mud cake thickness reduction is achieved only in Lube-B. Mud cake thickness is steady the same in Lube-C compared to base mud. Lube-D acts the worst performance when considering mud cake thickness. Mud cake is increased in Lube-D added sample compared to base mud, which is insignificant. Detailed results are shown in Appendix B.

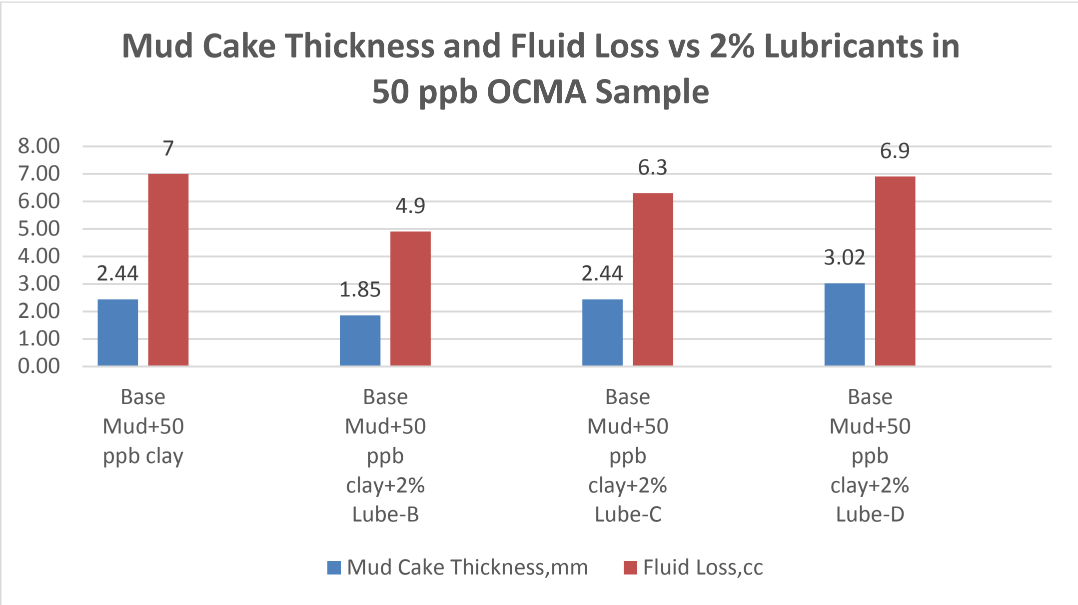

Figure 5.16. Mud Cake Thickness and Fluid Loss Analysis – 50 ppb OCMA Clay vs 2% Lubricant Added Samples.

5.3.5. Fluid Loss and Mud Cake Thickness Analysis in 2%Lubricant vs Base Samples with 25 ppb OCMA Clay and 150 ppb Barite

The performance analysis of lubricants on 25 ppb OCMA and 150 ppb Barite added samples are shown in Figure 5.17. Adding 2% lubricant decreases Fluid loss in all lubricant added samples, but more fluid loss reduction is observed in Lube-B added sample. Lube-B added sample creates a thin mud cake rather than other lubricants compared to base mud. Lube-D added sample has no effect on mud cake thickness. Detailed results are shown in Appendix B.

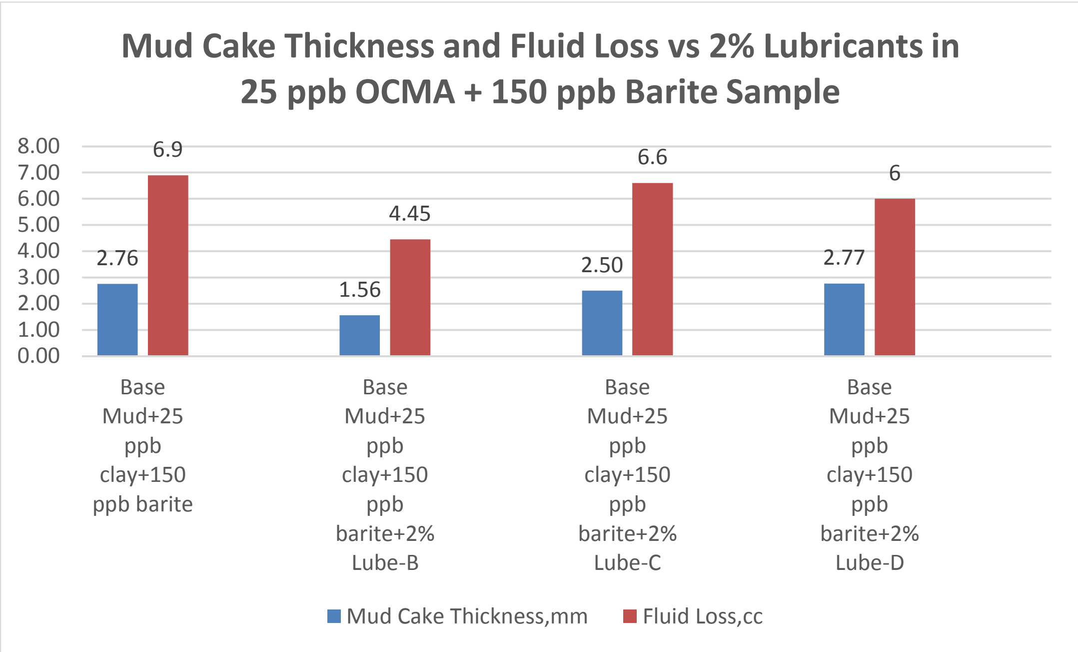

Figure 5.17. Mud Cake Thickness and Fluid Loss Analysis – 25 ppb OCMA Clay and 150 ppb Barite vs 2% Lubricant Added Samples.

5.3.6. Fluid Loss and Mud Cake Thickness Analysis in 2%Lubricant vs Base Samples with 25 ppb OCMA Clay and 300 ppb Barite

The performance analysis of lubricants on 25 ppb OCMA and 300 ppb Barite added samples are shown in Figure 5.18. Adding barite to base mud has an impact for decreasing the fluid loss but at the same time it increases the mud thickness which is undesirable. As seen on Figure 5.18, more fluid loss reduction is observed in Lube-B added sample. Moreover, Lube-B added sample creates a thin mud cake rather than other lubricants compared to base mud. Lube-C and Lube-D added sample has a little effect on fluid loss and their mud cake thicknesses are similar but not very well compared to Lube-B. Detailed results are shown in Appendix B.

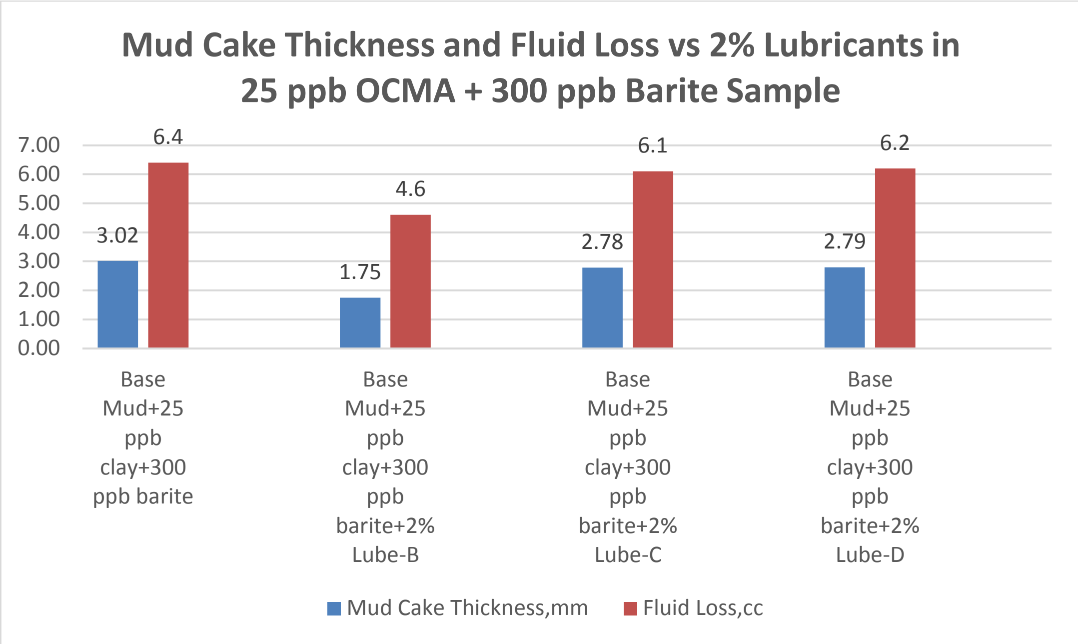

Figure 5.18. Mud Cake Thickness and Fluid Loss Analysis – 25 ppb OCMA Clay and 300 ppb Barite vs 2% Lubricant Added Samples.

5.3.7. Fluid Loss and Mud Cake Thickness Analysis in 3%Lubricant vs Base Samples with 25 ppb OCMA Clay.

The performance analysis of lubricants on 25 ppb OCMA added samples are shown in Figure 5.19. Adding 3% lubricant decreases Fluid loss slightly in Lube-C and Lube-D added samples, but more fluid loss reduction is observed in Lube-B added sample. Besides this, thin mud cake thickness is achieved only in Lube-B added sample rather than other lubricants compared to base mud. LUBE-C and Lube-D has little effect on mud cake thickness. Increasing Lubricant concentration up to 3% is insignificant for LUBE-C and LUBE-D due to an increase on mud cake thickness and low fluid loss reduction fluid. However, increasing lubricant concentration up to 3% for Lube-B indicates a positive effect both in fluid loss and mud cake thickness. Detailed results are shown in Appendix B.

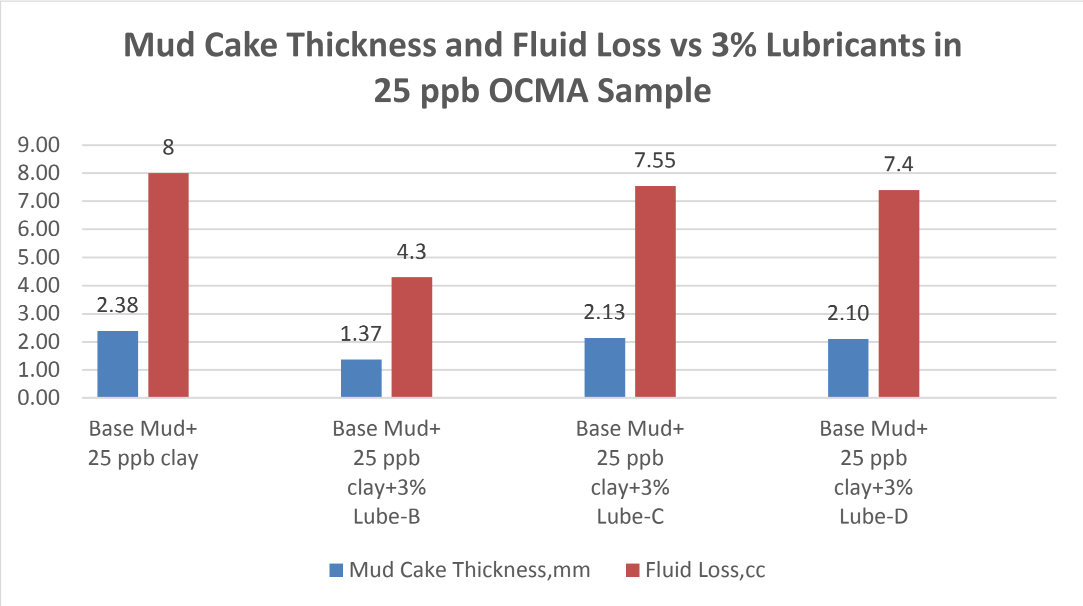

Figure 5.19. Mud Cake Thickness and Fluid Loss Analysis – 25 ppb OCMA Clay vs 3% Lubricant Added Samples.

5.3.8. Fluid Loss and Mud Cake Thickness Analysis in 3%Lubricant vs Base Samples with 25 ppb OCMA Clay and 150 ppb Barite

The performance analysis of lubricants on 25 ppb OCMA and 150 ppb Barite added samples are shown in Figure 5.20. Adding 3% lubricant decreases fluid loss in all lubricant added samples, but more fluid loss reduction is observed in Lube-B added sample. Lube-B added sample creates a thin mud cake rather than other lubricants compared to base mud. Lube-D added sample increases the mud cake thickness and fluid loss compared to 2%. Lube-C has positively affected by concentration increase especially for mud cake thickness. Increasing the concentration for Lube-B has no effect for fluid loss but slightly effective for mud cake thickness. Detailed results are shown in Appendix B.

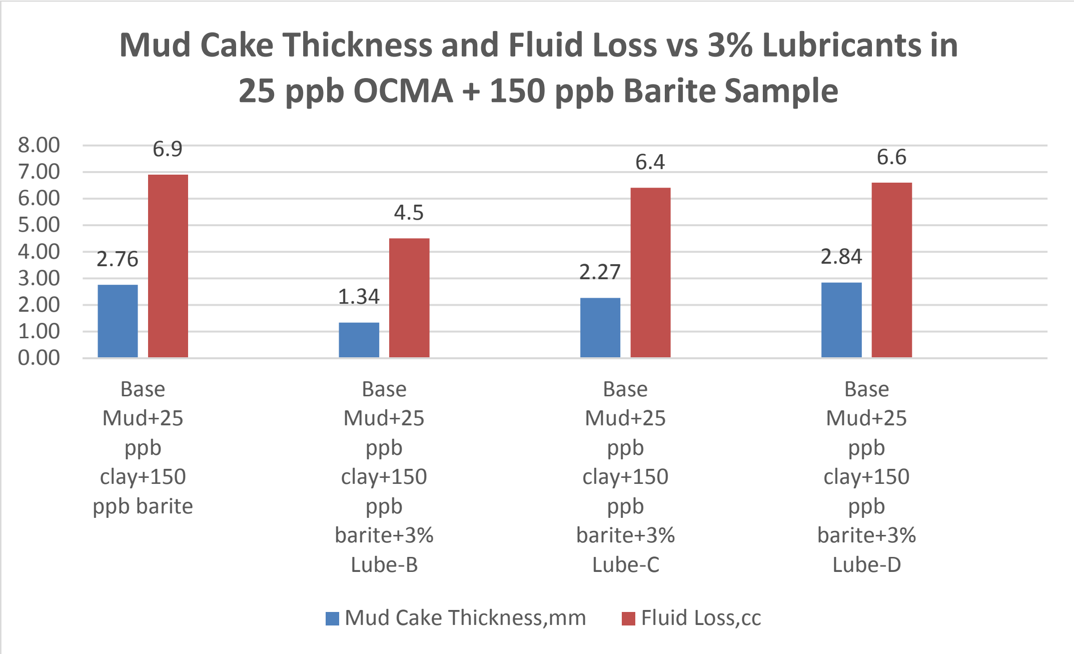

Figure 5.20. Mud Cake Thickness and Fluid Loss Analysis – 25 ppb OCMA Clay and 150 ppb Barite vs 3% Lubricant Added Samples.

5.3.9. Fluid Loss and Mud Cake Thickness Analysis in 3%Lubricant vs Base Samples with 25 ppb OCMA Clay and 300 ppb Barite

The performance analysis of lubricants on 25 ppb OCMA and 300 ppb Barite added samples are shown in Figure 5.21. Adding barite to mud samples has an impact for decreasing the fluid loss but at the same time it increases the mud cake thickness and reducing the mud cake pore pressure which is undesirable. As seen on Figure 5.21, more fluid loss reduction is observed in Lube-B added sample. Moreover, Lube-B added sample creates a thin mud cake rather than other lubricants compared to base mud. On the other hand, increasing the lubricant concentration up to 3% is insignificant for all lubricant added samples if compared with 2% lubricant added ones. Detailed results are shown in Appendix B.

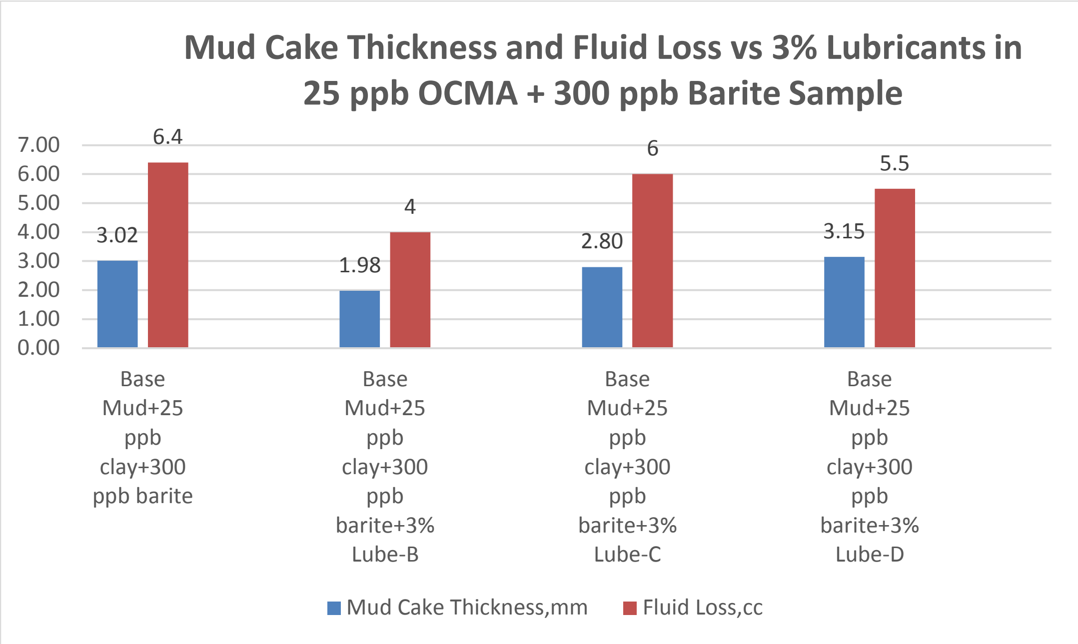

Figure 5.21. Mud Cake Thickness and Fluid Loss Analysis – 25 ppb OCMA Clay and 300 ppb Barite vs 3% Lubricant Added Samples.

5.4. Effect of lubricants on other Mud Properties

Effect of lubricants on other mud properties are also tested to have absolute decision for analyses. As described in Chapter 4, rheological properties; like plastic viscosity (PV), yield point (YP) and 10 sec/10 min/30 min gel strengths of the drilling fluids are tested. Methylene Blue Capacity (MBC) tests are carried out to clarify and observe the clay increases in the samples. Mud density measurements is also carried out to see the effect of lubricants on mud density.

5.4.1. Rheological Analysis

Effect of clay and barite on rheological properties with lubricant free or lubricant added samples are also evaluated in this study. It can be clearly observed that increasing OCMA clay concentration in any type of sample mud resulting an increase in plastic viscosity (PV), yield point (YP) and gel strengths. In addition to this, an increase in barite concentration causes an increase especially in PV. Furthermore, considering the each group of mud samples, no significant change is observed on rheological properties compared to the base mud of each group.

Table 5.3 Rheological Properties of the Mud Samples

	PV	YP	Gel, 10 sec	Gel, 10 min	Gel 30 min
1A	19	11	3	4	4
1B	14	8	3	3	4
1C	22	17	4	4	4
1D	20	17	2	2	2
2A	26	19	4	6	6
2B	26	30	6	8	9
2C	33	31	3	4	4
2D	33	37	3	4	4
3A	47	35	9	13	15
3B	44	56	4	6	8
3C	50	47	5	8	11
3D	49	53	6	8	11
4A	31	41	7	10	13
5A	40	35	8	13	14
5B	40	42	8	9	10
5C	46	31	6	9	11
5D	51	32	6	10	12
6A	63	34	8	14	20
6B	56	63	6	10	12
6C	54	72	7	12	15
6D	55	59	7	12	14
7A (2A)	26	19	4	6	6
7B	24	22	2	2	2
7C	25	21	2	3	3
7D	25	24	2	3	3
8A (5A)	40	35	8	13	14
8B	37	43	4	6	7
8C	43	28	5	8	10
8D	42	39	5	8	11
9A (6A)	63	34	8	14	20
9B	60	59	4	6	8
9C	55	30	5	8	10
9D	50	60	7	13	15

5.4.2. Methylene Blue Capacity (MBC) Analysis

Methylene Blue Capacity test is conducted to determine the reactive clays (bentonite or drilled solids) in drilling fluid. In this study OCMA clay is taken as a drilled solids in sample muds. Bentonite is the main additive of lignosulfonate mud. According to the test results, it is proved that increasing clay content of the sample muds resulting an increase in methylene blue capacity. In other words, it can be said that any increase on reactive clay of the mud samples is confirmed by MBC test along with this study. Detailed results are shown in Appendix A.

5.4.3. Mud Density Analysis

Mud density, can called as mud weight, and of the samples is measured in order to see the effect of lubricant on measuring the mud density due to their foam occurance during mixing. No foam is observed with the addition of lubricant samples during testing which means that mud density is measured precisely. In addition to this, mud density increases with increasing clay or barite content as usual. Detailed results are shown in Appendix A.

CHAPTER 6

CONCLUSIONS

The performance of three different types of commercial drilling fluid lubricants, which are soya based natural oil derivative (Lube-B), propylene glycol derivative (Lube-C) and ethanol based (Lube-D) liquid lubricants, in weighted and unweighted water based lignosulfonate mud were tested in this study and the following conclusions were drawn from the analysis of results:

- The barite concentration of 150 ppb in lubricant free sample in differential sticking test (DST) resulted with 20% increase on bulk sticking coefficient compared to no barite in the mud, however coefficient reduced by 4% at barite concentration of 300 ppb which is attributed to the rolling effect of barite.

- On the other hand, lubricity coefficient decreased by 14% at 150 ppb of barite in the mud compared to no barite case in lubricity test (LT) and it increased by 10% again at 300 ppb of barite case.

- Increasing the clay concentration from 0 ppb to 25 ppb decreased the sticking coefficient by 27%, but an increase to 50 ppb resulted with a 9% increase as a result of excessive dispersed solids in the mud.

- Effect of the time on torque readings in DST is also evaluated. An increase in clay content increases the torque readings around maximum 55% but soon after torque is stabilized. On the other hand, torque readings of barite added samples are getting increase approximately 40% in between each torque readings with increasing time and total of 240% difference is observed. This circumstance indicates the importance of time on weighted mud if differential sticking occurs.

- All 2% lubricant added samples decrease the sticking coefficient value according to DST. Rolling effect of barite is also observed at higher barite concentration (300 ppb). The efficient reduction is observed when Lube-B is added into the mud.

- All 3% lubricant added samples decrease the bulk sticking coefficient value according to DST. Rolling effect of barite is clearly observed for Lube-C and Lube-D added sample at 300 ppb barite concentration. There is no difference in sticking coefficient by using Lube-C and Lube-D between 150 and 300 ppb barite concentration even 3% is used. The efficient reduction is observed when Lube-B is used at 150 ppb barite concentration. However, Lube-B and Lube-D display a similar performance at 300 ppb barite concentration.

- Lube-B shows the optimum effective performance in DST test and gives an average of 26% reduction in sticking coefficient at 2% added samples and 36% reduction at 3% added samples.

- Lube-C with the volume of 2% and 3% concentration have similar behavior until the barite concentration reaches 150 ppb in DST test and only 4% difference is observed between 2% and 3%. Lube-C is more effective at 3% concentration and reduces sticking coefficient 10% more when 150 ppb barite concentration is exceeded compared to 2%. Average reduction is observed around 13% at 2% added samples and 19% at 3% Lube-C added samples.

- Lube-D with the volume of 3% concentration is more effective than the concentration of 2% until the barite concentration reaches 150 ppb in DST test. However, Lube-D is more effective at 3% concentration after 150 ppb barite concentration is exceeded. Average reduction is observed around 23% at 2% added samples and 33% at 3% Lube-D added samples.

- All 2% and 3% lubricant added samples decrease lubricity coefficient value according to lubricity test. Different from DST test, lubricity coefficient is decreases with increasing barite content up to 150 ppb, but then start to increase after 150 ppb. The efficient reduction is observed an average of 75% in Lube-B added samples compared to the base mud both in 2% and 3% concentrations. Average reduction is observed 30% in Lube-C and 23% in Lube-D added sample.

- According to lubricity test results, increasing the lubricant concentration up to 3% is inefficient. The performance of 2% and 3% lubricant added samples are similar in weighted mud. However, 3% lubricant added sample is slightly effective than 2% lubricant added sample considering Lube-C and Lube-D in unweighted mud sample.

- Lube-B performs the lowest fluid loss and thin mud cake properties considering Lube-C and Lube-D compared to base mud both in unweighted and weighted mud samples.

- None of the lubricants have foam forming potential problem that affects the density measurements.

- The standard API mud properties show little change after addition of lubricants and samples can easily be stirred and measured at laboratory conditions.

CHAPTER 7

RECOMMENDATIONS

Recommendations of this investigation for further studies are as follows;

- Because only barite is used as a solid lubricant for analyzing the performance of lubricants in lignosulfonate mud, calcium carbonate and graphite could be used for further studies as a solid lubricant.

- Performance analyses are carried out only for lignosulfonate mud in this investigation. The performance of lubricants in different types of KCl-Polymer mud could be examined.

- Tests are conducted in fresh water base mud. Salty or salt saturated mud systems could be used for evaluating the performance lubricants.

- Rheological measurements are conducted at room temperature and samples are aged only at 150 °F temperature prior to measurement. So, different temperature values will be better to use to observe the effectiveness of them.

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APPENDIX A

TEST RESULTS OF DIFFERENTIAL STICKING TESTER AND LUBRICITY TESTER

Table A.1: Test results of 2% Lubricants in OCMA clay and Barite free Samples via DST and LT

	1A				1B				1C				1D			
Tap water, cc	350				350				350				350			
API Test Calibration Bentonite, ppb	20				20				20				20			
Mixing, min	15				15				15				15			
Aging @ Room temperature, hr	4				4				4				4			
Caustic, ppb	0,5				0,5				0,5				0,5			
Chrome free Lignosulfonate, ppb	1				1				1				1			
CMC-Lv, ppb	1,5				1,5				1,5				1,5			
OCMA Bentonite (Clay), ppb	0				0				0				0			
API Test Calibration Barite, ppb	0				0				0				0			
Lube-B, % vol.					2,0											
Lube-C, % vol.									2,0							
Lube-D, % vol.													2,0			
Mixing, min.	20				20				20				20			
Aging, hr	16				16				16				16			
Aging Temperature, F	150				150				150				150			
Viscosity Measurement Temperature, F	80				80				80				80			
Viscosity, 600 rpm reading	49				36				61				57			
Viscosty, 300 rpm reading	30				22				39				37			
PV, cp	**19**				**14**				**22**				**20**			
YP, lb/100 ft2	**11**				**8**				**17**				**17**			
Jel, 10sec./ 10min./ 30min.	3	4	4		3	3	4		4	4	4		2	2	2	
Mud Density, lb/cuft	65,00				65,00				65,00				65,00			
Lubricity Tester Test time, min	5				5				5				5			
RPM	60				60				60				60			
Lubricity Tester Applied Torque (in-lb)	150				150				150				150			
Lubricity Tester Test Temperature, F	80				80				80				80			
Lubricity Tester Measured Torque, 0 min	36,8				13,2				30,7				30,3			
Lubricity Tester Measured Torque, 5 min	40,1				7,8				21,2				19,9			
Calibration Torque Reading	33,5				34,1				33,7				34,3			
Correction Factor	1,015				0,997				1,009				0,991			
Mud Lubricity Coefficient	**0,407**				**0,078**				**0,214**				**0,197**			
MBT, lb/bbl	20,0				20,0				20,0				20,0			
DST Testi Pressure, psi	475,0				475,0				475,0				475,0			
Waiting Time prior to disc sticking, min	10				10				10				10			
Disc sticking weight, kg	110				110				110				110			
Disc sticking weight, min	10,0				10,0				10,0				10,0			
Wating time in each torque reading, sec	30,0				30,0				30,0				30,0			
1. measurement, 30 sec.	148,0	158,0	154,0	153,3	69,0	36,0	50,0	51,7	92,0	104,0	104,0	100,0	104,0	96,0	106,0	102,0
2. measurement, 60 sec.	198,0	197,0	191,0	195,3	65,0	55,0	58,0	59,3	135,0	148,0	144,0	142,3	146,0	135,0	132,0	137,7
3. measurement, 90 sec.	207,0	204,0	200,0	203,7	62,0	57,0	63,0	60,7	132,0	142,0	141,0	138,3	142,0	129,0	131,0	134,0
4. measurement, 120 sec.	210,0	211,0	209,0	210,0	63,0	61,0	66,0	63,3	126,0	130,0	131,0	129,0	129,0	118,0	125,0	124,0
5. measurement, 150 sec.	207,0	210,0	208,0	208,3	58,0	63,0	69,0	63,3	123,0	126,0	127,0	125,3	119,0	115,0	118,0	117,3
6. measurement, 180 sec.	203,0	208,0	205,0	205,3	62,0	66,0	70,0	66,0	115,0	122,0	123,0	120,0	117,0	106,0	111,0	111,3
7. measurement, 210 sec.	201,0	201,0	200,0	200,7	58,0	71,0	68,0	65,7	113,0	114,0	119,0	115,3	108,0	101,0	104,0	104,3
Average Torque Reaing, lbf-in	196,3	198,4	195,3		62,4	58,4	63,4		119,4	126,6	127,0		123,6	114,3	118,1	
Total Average Torque Reading, lbf-in	196,7				61,4				124,3				118,7			
DST Bulk Sticking Coefficient	**0,197**				**0,061**				**0,124**				**0,119**			
Arithmetical Mistake Tolerance, %	0,2	0,9	0,7		1,6	4,9	3,3		3,9	1,8	2,1		4,1	3,7	0,4	

Table A.2: Test results of 2% Lubricants in 25 ppb OCMA clay and Barite free Samples via DST and LT

	2A				2B				2C				2D			
Tap water, cc	350				350				350				350			
API Test Calibration Bentonite, ppb	20				20				20				20			
Mixing, min	15				15				15				15			
Aging @ Room temperature, hr	4				4				4				4			
Caustic, ppb	0,5				0,5				0,5				0,5			
Chrome free Lignosulfonate, ppb	1				1				1				1			
CMC-Lv, ppb	1,5				1,5				1,5				1,5			
OCMA Bentonite (Clay), ppb	25				25				25				25			
API Test Calibration Barite, ppb	0				0				0				0			
Lube-B, % vol.					2,0											
Lube-C, % vol.									2,0							
Lube-D, % vol.													2,0			
Mixing, min.	20				20				20				20			
Aging, hr	16				16				16				16			
Aging Temperature, F	150				150				150				150			
Viscosity Measurement Temperature, F	80				80				80				80			
Viscosity, 600 rpm reading	71				82				97				103			
Viscosty, 300 rpm reading	45				56				64				70			
PV, cp	**26**				**26**				**33**				**33**			
YP, lb/100 ft2	**19**				**30**				**31**				**37**			
Jel, 10sec./ 10min./ 30min.	4	6	6		6	8	9		3	4	4		3	4	4	
Mud Density, lb/cuft	67,50				67,50				67,50				67,50			
Lubricity Tester Test time, min	5				5				5				5			
RPM	60				60				60				60			
Lubricity Tester Applied Torque (in-lb)	150				150				150				150			
Lubricity Tester Test Temperature, F	80				80				80				80			
Lubricity Tester Measured Torque, 0 min	30,7				13,1				30,6				31,5			
Lubricity Tester Measured Torque, 5 min	31,5				6,6				22,2				24,5			
Calibration Torque Reading	32,5				33,4				34,6				34,6			
Correction Factor	1,046				1,018				0,983				0,983			
Mud Lubricity Coefficient	**0,330**				**0,067**				**0,218**				**0,241**			
MBT, lb/bbl	23,75				23,75				23,75				23,75			
DST Testi Pressure, psi	475,0				475,0				475,0				475,0			
Waiting Time prior to disc sticking, min	10				10				10				10			
Disc sticking weight, kg	110				110				110				110			
Disc sticking weight, min	10,0				10,0				10,0				10,0			
Wating time in each torque reading, sec	30,0				30,0				30,0				30,0			
1. measurement, 30 sec.	103,0	92,0	98,0	97,7	97,0	88,0	90,0	91,7	101,0	81,0	93,0	91,7	88,0	81,0	91,0	86,7
2. measurement, 60 sec.	129,0	118,0	125,0	124,0	106,0	99,0	98,0	101,0	111,0	104,0	107,0	107,3	109,0	98,0	102,0	103,0
3. measurement, 90 sec.	142,0	138,0	140,0	140,0	108,0	103,0	101,0	104,0	125,0	121,0	120,0	122,0	107,0	102,0	105,0	104,7
4. measurement, 120 sec.	150,0	144,0	152,0	148,7	105,0	105,0	102,0	104,0	130,0	126,0	129,0	128,3	110,0	110,0	107,0	109,0
5. measurement, 150 sec.	160,0	156,0	160,0	158,7	105,0	101,0	98,0	101,3	132,0	130,0	130,0	130,7	109,0	105,0	106,0	106,7
6. measurement, 180 sec.	162,0	160,0	166,0	162,7	100,0	97,0	95,0	97,3	140,0	138,0	136,0	138,0	112,0	106,0	106,0	108,0
7. measurement, 210 sec.	170,0	165,0	168,0	167,7	96,0	97,0	94,0	95,7	139,0	129,0	132,0	133,3	109,0	109,0	106,0	108,0
Average Torque Reaing, lbf-in	145,1	139,0	144,1		102,4	98,6	96,9		125,4	118,4	121,0		106,3	101,6	103,3	
Total Average Torque Reading, lbf-in	142,8				99,3				121,6				103,7			
DST Bulk Sticking Coefficient	**0,143**				**0,099**				**0,122**				**0,104**			
Arithmetical Mistake Tolerance, %	1,7	2,6	1,0		3,2	0,7	2,4		3,1	2,6	0,5		2,5	2,1	0,4	

Table A.3: Test results of 2% Lubricants in 50 ppb OCMA clay and Barite free Samples via DST and LT

	3A				3B				3C				3D			
Tap water, cc	350				350				350				350			
API Test Calibration Bentonite, ppb	20				20				20				20			
Mixing, min	15				15				15				15			
Aging @ Room temperature, hr	4				4				4				4			
Caustic, ppb	0,5				0,5				0,5				0,5			
Chrome free Lignosulfonate, ppb	1				1				1				1			
CMC-Lv, ppb	1,5				1,5				1,5				1,5			
OCMA Bentonite (Clay), ppb	50				50				50				50			
API Test Calibration Barite, ppb	0				0				0				0			
Lube-B, % vol.					2,0											
Lube-C, % vol.									2,0							
Lube-D, % vol.													2,0			
Mixing, min.	20				20				20				20			
Aging, hr	16				16				16				16			
Aging Temperature, F	150				150				150				150			
Viscosity Measurement Temperature, F	80				80				80				80			
Viscosity, 600 rpm reading	129				144				147				151			
Viscosty, 300 rpm reading	82				100				97				102			
PV, cp	**47**				**44**				**50**				**49**			
YP, lb/100 ft2	**35**				**56**				**47**				**53**			
Jel, 10sec./ 10min./ 30min.	9	13	15		4	6	8		5	8	11		6	8	11	
Mud Density, lb/cuft	71,00				71,00				71,00				71,00			
Lubricity Tester Test time, min	5				5				5				5			
RPM	60				60				60				60			
Lubricity Tester Applied Torque (in-lb)	150				150				150				150			
Lubricity Tester Test Temperature, F	80				80				80				80			
Lubricity Tester Measured Torque, 0 min	31,0				18,1				24,5				23,6			
Lubricity Tester Measured Torque, 5 min	28,8				6,8				23,6				23,3			
Calibration Torque Reading	33,0				33,6				33,6				33,6			
Correction Factor	1,030				1,012				1,012				1,012			
Mud Lubricity Coefficient	**0,297**				**0,069**				**0,239**				**0,236**			
MBT, lb/bbl	28,75				28,75				28,75				28,75			
DST Testi Pressure, psi	475,0				475,0				475,0				475,0			
Waiting Time prior to disc sticking, min	10				10				10				10			
Disc sticking weight, kg	110				110				110				110			
Disc sticking weight, min	10,0				10,0				10,0				10,0			
Wating time in each torque reading, sec	30,0				30,0				30,0				30,0			
1. measurement, 30 sec.	118,0	111,0	113,0	114,0	86,0	90,0	91,0	89,0	111,0	120,0	110,0	113,7	111,0	110,0	113,0	111,3
2. measurement, 60 sec.	143,0	142,0	147,0	144,0	90,0	96,0	92,0	92,7	138,0	144,0	135,0	139,0	128,0	118,0	122,0	122,7
3. measurement, 90 sec.	153,0	156,0	155,0	154,7	90,0	99,0	94,0	94,3	147,0	144,0	142,0	144,3	132,0	127,0	125,0	128,0
4. measurement, 120 sec.	172,0	168,0	170,0	170,0	96,0	109,0	100,0	101,7	149,0	152,0	145,0	148,7	135,0	133,0	135,0	134,3
5. measurement, 150 sec.	165,0	175,0	178,0	172,7	96,0	109,0	99,0	101,3	151,0	154,0	151,0	152,0	136,0	137,0	133,0	135,3
6. measurement, 180 sec.	158,0	176,0	175,0	169,7	94,0	103,0	98,0	98,3	154,0	160,0	153,0	155,7	145,0	137,0	138,0	140,0
7. measurement, 210 sec.	155,0	176,0	173,0	168,0	96,0	109,0	102,0	102,3	158,0	161,0	155,0	158,0	139,0	135,0	137,0	137,0
Average Torque Reaing, lbf-in	152,0	157,7	158,7		92,6	102,1	96,6		144,0	147,9	141,6		132,3	128,1	129,0	
Total Average Torque Reading, lbf-in	156,1				97,1				144,5				129,8			
DST Bulk Sticking Coefficient	**0,156**				**0,097**				**0,144**				**0,130**			
Arithmetical Mistake Tolerance, %	2,7	1,0	1,6		4,7	5,2	0,5		0,3	2,3	2,0		1,9	1,3	0,6	

Table A.4: Test results of 2% Lubricants in 25 ppb OCMA clay and 150 ppb Barite Samples via DST and LT

	4A				5A				5B				5C				5D			
Tap water, cc	350				350				350				350				350			
API Test Calibration Bentonite, ppb	20				20				20				20				20			
Mixing, min	15				15				15				15				15			
Aging @ Room temperature, hr	4				4				4				4				4			
Caustic, ppb	0,5				0,5				0,5				0,5				0,5			
Chrome free Lignosulfonate, ppb	1				1				1				1				1			
CMC-Lv, ppb	1,5				1,5				1,5				1,5				1,5			
OCMA Bentonite (Clay), ppb	25				25				25				25				25			
API Test Calibration Barite, ppb	50				150				150				150				150			
Lube-B, % vol.									2,0											
Lube-C, % vol.													2,0							
Lube-D, % vol.																	2,0			
Mixing, min.	20				20				20				20				20			
Aging, hr	16				16				16				16				16			
Aging Temperature, F	150				150				150				150				150			
Viscosity Measurement Temperature, F	80				80				80				80				80			
Viscosity, 600 rpm reading	103				115				122				123				134			
Viscosty, 300 rpm reading	72				75				82				77				83			
PV, cp	**31**				**40**				**40**				**46**				**51**			
YP, lb/100 ft2	**41**				**35**				**42**				**31**				**32**			
Jel, 10sec./ 10min./ 30min.	7	10	13		8	13	14		8	9	10		6	9	11		6	10	12	
Mud Density, lb/cuft	74,00				84,00				84,00				84,00				84,00			
Lubricity Tester Test time, min	5				5				5				5				5			
RPM	60				60				60				60				60			
Lubricity Tester Applied Torque (in-lb)	150				150				150				150				150			
Lubricity Tester Test Temperature, F	80				80				80				80				80			
Lubricity Tester Measured Torque, 0 min	43,9				30,5				19,3				24,0				24,7			
Lubricity Tester Measured Torque, 5 min	32,2				27,6				5,4				18,6				21,4			
Calibration Torque Reading	35,6				33,1				33,7				34,0				33,8			
Correction Factor	0,955				1,027				1,009				1,000				1,006			
Mud Lubricity Coefficient	**0,308**				**0,284**				**0,054**				**0,186**				**0,215**			
MBT, lb/bbl	23,75				23,75				23,75				23,75				23,75			
DST Testi Pressure, psi	475,0				475,0				475,0				475,0				475,0			
Waiting Time prior to disc sticking, min	10				10				10				10				10			
Disc sticking weight, kg	110				110				110				110				110			
Disc sticking weight, min	10,0				10,0				10,0				10,0				10,0			
Wating time in each torque reading, sec	30,0				30,0				30,0				30,0				30,0			
1. measurement, 30 sec.	87,0	87,0	88,0	87,3	81,0	75,0	78,0	78,0	76,0	78,0	71,0	75,0	88,0	76,0	79,0	81,0	79,0	83,0	81,0	81,0
2. measurement, 60 sec.	115,0	115,0	119,0	116,3	111,0	100,0	109,0	106,7	98,0	88,0	79,0	88,3	116,0	99,0	103,0	106,0	98,0	90,0	96,0	94,7
3. measurement, 90 sec.	142,0	142,0	140,0	141,3	146,0	132,0	140,0	139,3	120,0	112,0	105,0	112,3	140,0	135,0	127,0	134,0	118,0	111,0	110,0	113,0
4. measurement, 120 sec.	164,0	163,0	166,0	164,3	180,0	165,0	156,0	167,0	140,0	130,0	127,0	132,3	155,0	138,0	143,0	145,3	136,0	123,0	132,0	130,3
5. measurement, 150 sec.	182,0	183,0	180,0	181,7	211,0	198,0	194,0	201,0	154,0	145,0	141,0	146,7	170,0	151,0	162,0	161,0	149,0	137,0	143,0	143,0
6. measurement, 180 sec.	204,0	199,0	201,0	201,3	250,0	238,0	234,0	240,7	164,0	155,0	152,0	157,0	173,0	158,0	178,0	169,7	162,0	150,0	161,0	157,7
7. measurement, 210 sec.	221,0	213,0	218,0	217,3	279,0	259,0	254,0	264,0	171,0	158,0	164,0	164,3	190,0	168,0	190,0	182,7	170,0	158,0	169,0	165,7
Average Torque Reaing, lbf-in	159,3	157,4	158,9		179,7	166,7	166,4		131,9	123,7	119,9		147,4	132,1	140,3		130,3	121,7	127,4	
Total Average Torque Reading, lbf-in	158,5				171,0				125,1				140,0				126,5			
DST Bulk Sticking Coefficient	**0,159**				**0,171**				**0,125**				**0,140**				**0,126**			
Arithmetical Mistake Tolerance, %	0,5	0,7	0,2		5,1	2,5	2,6		5,4	1,1	4,2		5,3	5,6	0,2		3,0	3,8	0,8	

Table A.5: Test results of 2% Lubricants in 25 ppb OCMA clay and 300 ppb Barite Samples via DST and LT

	6A				**6B**				**6C**				**6D**			
Tap water, cc	350				350				350				350			
API Test Calibration Bentonite, ppb	20				20				20				20			
Mixing, min	15				15				15				15			
Aging @ Room temperature, hr	4				4				4				4			
Caustic, ppb	0,5				0,5				0,5				0,5			
Chrome free Lignosulfonate, ppb	1				1				1				1			
CMC-Lv, ppb	1,5				1,5				1,5				1,5			
OCMA Bentonite (Clay), ppb	25				25				25				25			
API Test Calibration Barite, ppb	300				300				300				300			
Lube-B, % vol.					2,0											
Lube-C, % vol.									2,0							
Lube-D, % vol.													2,0			
Mixing, min.	20				20				20				20			
Aging, hr	16				16				16				16			
Aging Temperature, F	150				150				150				150			
Viscosity Measurement Temperature, F	80				80				80				80			
Viscosity, 600 rpm reading	160				175				180				169			
Viscosty, 300 rpm reading	97				119				126				114			
PV, cp	**63**				**56**				**54**				**55**			
YP, lb/100 ft2	**34**				**63**				**72**				**59**			
Jel, 10sec./ 10min./ 30min.	8	14	20		6	10	12		7	12	15		7	12	14	
Mud Density, lb/cuft	96,00				96,00				96,00				96,00			
Lubricity Tester Test time, min	5				5				5				5			
RPM	60				60				60				60			
Lubricity Tester Applied Torque (in-lb)	150,0				150				150				150			
Lubricity Tester Test Temperature, F	80				80				80				80			
Lubricity Tester Measured Torque, 0 min	31,5				13,6				28,5				29,5			
Lubricity Tester Measured Torque, 5 min	30,8				10,3				23,6				24,4			
Calibration Torque Reading	33,4				32,8				33,4				33,1			
Correction Factor	1,018				1,037				1,018				1,027			
Mud Lubricity Coefficient	**0,314**				**0,107**				**0,240**				**0,251**			
MBT, lb/bbl	23,75				23,75				23,75				23,75			
DST Testi Pressure, psi	475,0				475,0				475,0				475,0			
Waiting Time prior to disc sticking, min	10				10				10				10			
Disc sticking weight, kg	110				110				110				110			
Disc sticking weight, min	10,0				10,0				10,0				10,0			
Wating time in each torque reading, sec	30,0				30,0				30,0				30,0			
1. measurement, 30 sec.	70,0	65,0	68,0	67,7	58,0	61,0	60,0	59,7	75,0	80,0	74,0	76,3	67,0	71,0	69,0	69,0
2. measurement, 60 sec.	100,0	95,0	99,0	98,0	92,0	91,0	89,0	90,7	120,0	118,0	121,0	119,7	108,0	103,0	106,0	105,7
3. measurement, 90 sec.	120,0	130,0	132,0	127,3	126,0	115,0	117,0	119,3	145,0	151,0	150,0	148,7	136,0	125,0	132,0	131,0
4. measurement, 120 sec.	157,0	165,0	163,0	161,7	142,0	135,0	138,0	138,3	166,0	161,0	162,0	163,0	147,0	137,0	140,0	141,3
5. measurement, 150 sec.	192,0	201,0	200,0	197,7	155,0	152,0	156,0	154,3	168,0	171,0	170,0	169,7	162,0	150,0	158,0	156,7
6. measurement, 180 sec.	234,0	243,0	240,0	239,0	170,0	163,0	166,0	166,3	181,0	185,0	188,0	184,7	173,0	158,0	165,0	165,3
7. measurement, 210 sec.	259,0	272,0	270,0	267,0	189,0	178,0	179,0	182,0	196,0	191,0	194,0	193,7	183,0	171,0	181,0	178,3
Average Torque Reaing, lbf-in	161,7	167,3	167,4		133,1	127,9	129,3		150,1	151,0	151,3		139,4	130,7	135,9	
Total Average Torque Reading, lbf-in	165,5				130,1				150,8				135,3			
DST Bulk Sticking Coefficient	**0,165**				**0,130**				**0,151**				**0,135**			
Arithmetical Mistake Tolerance, %	2,3	1,1	1,2		2,3	1,7	0,6		0,4	0,1	0,3		3,0	3,4	0,4	

Table A.6: Test results of 3% Lubricants in 25 ppb OCMA clay and Barite Samples via DST and LT

	7A				7B				7C				7D			
Tap water, cc	350				350				350				350			
API Test Calibration Bentonite, ppb	20				20				20				20			
Mixing, min	15				15				15				15			
Aging @ Room temperature, hr	4				4				4				4			
Caustic, ppb	0,5				0,5				0,5				0,5			
Chrome free Lignosulfonate, ppb	1				1				1				1			
CMC-Lv, ppb	1,5				1,5				1,5				1,5			
OCMA Bentonite (Clay), ppb	25				25				25				25			
API Test Calibration Barite, ppb	0				0				0				0			
Lube-B, % vol.					3,0											
Lube-C, % vol.									3,0							
Lube-D, % vol.													3,0			
Mixing, min.	20				20				20				20			
Aging, hr	16				16				16				16			
Aging Temperature, F	150				150				150				150			
Viscosity Measurement Temperature, F	80				80				80				80			
Viscosity, 600 rpm reading	71				70				71				74			
Viscosty, 300 rpm reading	45				46				46				49			
PV, cp	**26**				**24**				**25**				**25**			
YP, lb/100 ft2	**19**				**22**				**21**				**24**			
Jel, 10sec./ 10min./ 30min.	4	6	6		2	2	2		2	3	3		2	3	3	
Mud Density, lb/cuft	67,50				67,50				67,50				67,50			
Lubricity Tester Test time, min	5				5				5				5			
RPM	60				60				60				60			
Lubricity Tester Applied Torque (in-lb)	150,0				150				150				150			
Lubricity Tester Test Temperature, F	80				80				80				80			
Lubricity Tester Measured Torque, 0 min	30,7				14,0				25,2				29,5			
Lubricity Tester Measured Torque, 5 min	31,5				5,1				18,1				21,0			
Calibration Torque Reading	32,5				33,9				35,4				35,7			
Correction Factor	1,046				1,003				0,960				0,952			
Mud Lubricity Coefficient	**0,330**				**0,051**				**0,174**				**0,200**			
MBT, lb/bbl	23,75				23,75				23,75				23,75			
DST Testi Pressure, psi	475,0				475,0				475,0				475,0			
Waiting Time prior to disc sticking, min	10				10				10				10			
Disc sticking weight, kg	110				110				110				110			
Disc sticking weight, min	10,0				10,0				10,0				10,0			
Wating time in each torque reading, sec	30,0				30,0				30,0				30,0			
1. measurement, 30 sec.	103,0	92,0	98,0	97,7	82,0	77,0	81,0	80,0	95,0	85,0	83,0	87,7	85,0	78,0	81,0	81,3
2. measurement, 60 sec.	129,0	118,0	125,0	124,0	85,0	86,0	84,0	85,0	111,0	105,0	109,0	108,3	90,0	87,0	87,0	88,0
3. measurement, 90 sec.	142,0	138,0	140,0	140,0	84,0	88,0	87,0	86,3	117,0	119,0	113,0	116,3	92,0	91,0	93,0	92,0
4. measurement, 120 sec.	150,0	144,0	152,0	148,7	85,0	90,0	88,0	87,7	126,0	121,0	119,0	122,0	89,0	96,0	94,0	93,0
5. measurement, 150 sec.	160,0	156,0	160,0	158,7	81,0	87,0	88,0	85,3	127,0	124,0	123,0	124,7	90,0	97,0	98,0	95,0
6. measurement, 180 sec.	162,0	160,0	166,0	162,7	81,0	88,0	86,0	85,0	135,0	132,0	125,0	130,7	88,0	95,0	95,0	92,7
7. measurement, 210 sec.	170,0	165,0	168,0	167,7	80,0	84,0	87,0	83,7	133,0	133,0	128,0	131,3	92,0	96,0	95,0	94,3
Average Torque Reaing, lbf-in	145,1	139,0	144,1		82,6	85,7	85,9		120,6	117,0	114,3		89,4	91,4	91,9	
Total Average Torque Reading, lbf-in	142,8				84,7				117,3				90,9			
DST Bulk Sticking Coefficient	**0,143**				**0,085**				**0,117**				**0,091**			
Arithmetical Mistake Tolerance, %	1,7	2,6	1,0		2,5	1,2	1,3		2,8	0,2	2,6		1,6	0,6	1,0	

Table A.7: Test results of 3% Lubricants in 25 ppb OCMA clay and 150 ppb Barite Samples via DST and LT

	8A				8B				8C				8D			
Tap water, cc	350				350				350				350			
API Test Calibration Bentonite, ppb	20				20				20				20			
Mixing, min	15				15				15				15			
Aging @ Room temperature, hr	4				4				4				4			
Caustic, ppb	0,5				0,5				0,5				0,5			
Chrome free Lignosulfonate, ppb	1				1				1				1			
CMC-Lv, ppb	1,5				1,5				1,5				1,5			
OCMA Bentonite (Clay), ppb	25				25				25				25			
API Test Calibration Barite, ppb	150				150				150				150			
Lube-B, % vol.					3,0											
Lube-C, % vol.									3,0							
Lube-D, % vol.													3,0			
Mixing, min.	20				20				20				20			
Aging, hr	16				16				16				16			
Aging Temperature, F	150				150				150				150			
Viscosity Measurement Temperature, F	80				80				80				80			
Viscosity, 600 rpm reading	115				117				114				123			
Viscosty, 300 rpm reading	75				80				71				81			
PV, cp	**40**				**37**				**43**				**42**			
YP, lb/100 ft2	**35**				**43**				**28**				**39**			
Jel, 10sec./ 10min./ 30min.	8	13		14	4	6	7		5	8	10		5	8	11	
Mud Density, lb/cuft	84,00				84,00				84,00				84,00			
Lubricity Tester Test time, min	5				5				5				5			
RPM	60				60				60				60			
Lubricity Tester Applied Torque (in-lb)	150,0				150				150				150			
Lubricity Tester Test Temperature, F	80				80,0				80				80			
Lubricity Tester Measured Torque, 0 min	30,5				10,1				24,5				25,4			
Lubricity Tester Measured Torque, 5 min	27,6				6,2				19,2				21,2			
Calibration Torque Reading	33,1				32,9				33,5				33,5			
Correction Factor	1,027				1,033				1,015				1,015			
Mud Lubricity Coefficient	**0,284**				**0,064**				**0,195**				**0,215**			
MBT, lb/bbl	23,75				23,75				23,75				23,75			
DST Testi Pressure, psi	475,0				475,0				475,0				475,0			
Waiting Time prior to disc sticking, min	10				10				10				10			
Disc sticking weight, kg	110				110				110				110			
Disc sticking weight, min	10,0				10,0				10,0				10,0			
Wating time in each torque reading, sec	30,0				30,0				30,0				30,0			
1. measurement, 30 sec.	81,0	75,0	78,0	78,0	68,0	73,0	74,0	71,7	65,0	66,0	69,0	66,7	65,0	58,0	58,0	60,3
2. measurement, 60 sec.	110,0	100,0	109,0	106,3	78,0	88,0	90,0	85,3	91,0	100,0	96,0	95,7	90,0	83,0	84,0	85,7
3. measurement, 90 sec.	146,0	132,0	140,0	139,3	95,0	103,0	104,0	100,7	111,0	125,0	121,0	119,0	112,0	100,0	110,0	107,3
4. measurement, 120 sec.	180,0	165,0	156,0	167,0	100,0	110,0	110,0	106,7	140,0	140,0	135,0	138,3	127,0	121,0	117,0	121,7
5. measurement, 150 sec.	211,0	198,0	194,0	201,0	113,0	122,0	119,0	118,0	152,0	160,0	151,0	154,3	139,0	134,0	124,0	132,3
6. measurement, 180 sec.	250,0	238,0	234,0	240,7	119,0	130,0	128,0	125,7	168,0	175,0	165,0	169,3	149,0	145,0	137,0	143,7
7. measurement, 210 sec.	279,0	259,0	254,0	264,0	128,0	129,0	140,0	132,3	189,0	195,0	180,0	188,0	167,0	155,0	150,0	157,3
Average Torque Reaing, lbf-in	179,6	166,7	166,4		100,1	107,9	109,3		130,9	137,3	131,0		121,3	113,7	111,4	
Total Average Torque Reading, lbf-in	170,9				105,8				133,0				115,5			
DST Bulk Sticking Coefficient	**0,171**				**0,106**				**0,133**				**0,115**			
Arithmetical Mistake Tolerance, %	5,1	2,5	2,6		5,3	2,0	3,3		1,6	3,2	1,5		5,0	1,5	3,5	

Table A.8: Test results of 3% Lubricants in 25 ppb OCMA clay and 300 ppb Barite Samples via DST and LT

	9A				9B				9C				9D			
Tap water, cc	350				350				350				350			
API Test Calibration Bentonite, ppb	20				20				20				20			
Mixing, min	15				15				15				15			
Aging @ Room temperature, hr	4				4				4				4			
Caustic, ppb	0,5				0,5				0,5				0,5			
Chrome free Lignosulfonate, ppb	1				1				1				1			
CMC-Lv, ppb	1,5				1,5				1,5				1,5			
OCMA Bentonite (Clay), ppb	25				25				25				25			
API Test Calibration Barite, ppb	300				300				300				300			
Lube-B, % vol.					3,0											
Lube-C, % vol.									3,0							
Lube-D, % vol.													3,0			
Mixing, min.	20				20				20				20			
Aging, hr	16				16				16				16			
Aging Temperature, F	150				150				150				150			
Viscosity Measurement Temperature, F	80				80				80				80			
Viscosity, 600 rpm reading	160				179				140				160			
Viscosty, 300 rpm reading	97				119				85				110			
PV, cp	**63**				**60**				**55**				**50**			
YP, lb/100 ft2	**34**				**59**				**30**				**60**			
Jel, 10sec./ 10min./ 30min.	8	13	20		4	6	8		5	8	10		7	13	15	
Mud Density, lb/cuft	96,00				96,00				96,00				96,00			
Lubricity Tester Test time, min	5				5				5				5			
RPM	60				60				60				60			
Lubricity Tester Applied Torque (in-lb)	150,0				150				150				150			
Lubricity Tester Test Temperature, F	80,0				80				80				80			
Lubricity Tester Measured Torque, 0 min	31,5				11,0				28,5				25,0			
Lubricity Tester Measured Torque, 5 min	30,8				10,2				22,0				23,1			
Calibration Torque Reading	33,4				32,5				32,7				33,1			
Correction Factor	1,018				1,046				1,040				1,027			
Mud Lubricity Coefficient	**0,314**				**0,107**				**0,229**				**0,237**			
MBT, lb/bbl	23,75				23,75				23,75				23,75			
DST Testi Pressure, psi	475,0				475,0				475,0				475,0			
Waiting Time prior to disc sticking, min	10				10				10				10			
Disc sticking weight, kg	110				110				110				110			
Disc sticking weight, min	10,0				10,0				10,0				10,0			
Wating time in each torque reading, sec	30,0				30,0				30,0				30,0			
1. measurement, 30 sec.	70,0	65,0	68,0	67,7	69,0	59,0	62,0	63,3	57,0	65,0	68,0	63,3	50,0	50,0	64,0	54,7
2. measurement, 60 sec.	100,0	95,0	99,0	98,0	92,0	87,0	90,0	89,7	95,0	101,0	96,0	97,3	86,0	88,0	99,0	91,0
3. measurement, 90 sec.	120,0	130,0	132,0	127,3	112,0	109,0	109,0	110,0	118,0	130,0	125,0	124,3	109,0	111,0	120,0	113,3
4. measurement, 120 sec.	157,0	165,0	163,0	161,7	128,0	120,0	126,0	124,7	143,0	150,0	138,0	143,7	127,0	120,0	125,0	124,0
5. measurement, 150 sec.	192,0	201,0	200,0	197,7	137,0	130,0	138,0	135,0	156,0	166,0	150,0	157,3	137,0	128,0	135,0	133,3
6. measurement, 180 sec.	234,0	243,0	240,0	239,0	146,0	142,0	147,0	145,0	166,0	177,0	160,0	167,7	144,0	135,0	148,0	142,3
7. measurement, 210 sec.	259,0	272,0	270,0	267,0	160,0	159,0	161,0	160,0	180,0	191,0	177,0	182,7	157,0	141,0	156,0	151,3
Average Torque Reaing, lbf-in	161,7	167,3	167,4		120,6	115,1	119,0		130,7	140,0	130,6		115,7	110,4	121,0	
Total Average Torque Reading, lbf-in	165,5				118,2				133,8				115,7			
DST Bulk Sticking Coefficient	**0,165**				**0,118**				**0,134**				**0,116**			
Arithmetical Mistake Tolerance, %	2,3	1,1	1,2		2,0	2,6	0,6		2,3	4,7	2,4		0,0	4,6	4,6	

APPENDIX B

TEST RESULTS OF FLUID LOSS AND MUD CAKE THICKNESS

Table B.1: Test results of 2% Lubricants in OCMA clay and Barite free Samples in terms of Fluid Loss and Mud Cake Thickness

API Filter Press Test	1A		1B		1C		1D	
Tap Water, cc	350		350		350		350	
API Test Calibration Bentonite, ppb	20		20		20		20	
Caustic, ppb	0.5		0,5		0.5		0.5	
Chrome free Lignosulfonate, ppb	1		1		1		1	
CMC-Lv, ppb	1.5		1.5		1.5		1.5	
OCMA Clay, ppb	0		0		0		0	
API Test Calibration Barite, ppb	0		0		0		0	
Lubricant-B, % vol.			2.0					
Lubricant-C, % vol.					2.0			
Lubricant-D, % vol.							2.0	
Mud Cake Thickness, mm 1. Measurement	1.5	1.3	1.0	1.2	1.8	1.9	1.5	1.7
Mud Cake Thickness, mm 2. Measurement	1.3	1.5	1.2	1.3	1.8	2.1	1.7	1.6
Mud Cake Thickness, mm 3. Measurement	1.4	1.6	1.2	1.2	2.0	2.0	1.6	1.8
Mud Cake Thickness, mm 4. Measurement	1.6	1.6	1.1	1.2	1.9	1.9	1.8	1.8
Mud Cake Thickness, mm 5. Measurement	1.7	1.5	1.2	1.2	1.9	1.9	1.7	1.6
Mud Cake Thickness, mm 6. Measurement	1.50	1.50	1.14	1.22	1.88	1.96	1.66	1.70
Average Mud Cake Thickness, mm,	1.50		1.18		1.92		1.68	
API Fluid Loss, cc	9.9	10.1	6.4	6.2	7.8	7.8	7.8	8.2
Average API Fluid Loss, cc	10		6.3		7.8		8	

Table B.2: Test results of 2% Lubricants in 25 ppb OCMA clay and Barite free Samples in terms of Fluid Loss and Mud Cake Thickness

API Filter Press Test	**2A**		**2B**		**2C**		**2D**	
Tap Water, cc	350		350		350		350	
API Test Calibration Bentonite, ppb	20		20		20		20	
Caustic, ppb	0.5		0.5		0,5		0.5	
Chrome free Lignosulfonate, ppb	1		1		1		1	
CMC-Lv, ppb	1.5		1.5		1.5		1.5	
OCMA Clay, ppb	25		25		25		25	
API Test Calibration Barite, ppb	0		0		0		0	
Lubricant-B, % vol.			2.0					
Lubricant-C, % vol.					2.0			
Lubricant-D, % vol.							2.0	
Mud Cake Thickness, mm 1. Measurement	2.1	2.3	1.3	1.5	1.7	2.0	2.0	2.0
Mud Cake Thickness, mm 2. Measurement	2.4	2.5	1.4	1.5	1.9	1.9	2.1	2.1
Mud Cake Thickness, mm 3. Measurement	2.4	2.4	1.3	1.7	1.7	2.0	2.0	2.2
Mud Cake Thickness, mm 4. Measurement	2.4	2.5	1.5	1.6	1.7	1.9	2.0	2.1
Mud Cake Thickness, mm 5. Measurement	2.5	2.3	1.4	1.4	1.7	1.8	2.1	2.3
Mud Cake Thickness, mm 6. Measurement	2.36	2.40	1.38	1.54	1.74	1.92	2.04	2.14
Average Mud Cake Thickness, mm	2.38		1.46		1.83		2.09	
API Fluid Loss, cc	8.1	7.9	4.8	5.2	7.5	7.3	7.3	7.1
Average API Fluid Loss, cc	8		5		7.4		7.2	

Table B.3: Test results of 2% Lubricants in 50 ppb OCMA clay and Barite free Samples in terms of Fluid Loss and Mud Cake Thickness

API Filter Press Test	3A		3B		3C		3D	
Tap Water, cc	350		350		350		350	
API Test Calibration Bentonite, ppb	20		20		20		20	
Caustic, ppb	0.5		0.5		0.5		0.5	
Chrome free Lignosulfonate, ppb	1		1		1		1	
CMC-Lv, ppb	1.5		1.5		1.5		1.5	
OCMA Clay, ppb	50		50		50		50	
API Test Calibration Barite, ppb	0		0		0		0	
Lubricant-B, % vol.			2.0					
Lubricant-C, % vol.					2.0			
Lubricant-D, % vol.							2.0	
Mud Cake Thickness, mm 1. Measurement	2.7	2.4	1.6	2.0	2.4	2.2	3.0	2.8
Mud Cake Thickness, mm 2. Measurement	2.5	2.2	1.6	2.1	2.4	3.0	3.1	3.0
Mud Cake Thickness, mm 3. Measurement	2.7	2.3	1.8	2.1	2.3	2.6	3.2	2.9
Mud Cake Thickness, mm 4. Measurement	2.4	2.3	1.7	1.9	2.5	2.2	3.1	2.9
Mud Cake Thickness, mm 5. Measurement	2.6	2.3	1.8	1.9	2.2	2.6	3.1	3.1
Mud Cake Thickness, mm 6. Measurement	2.58	2.30	1.70	2.00	2.36	2.52	3.10	2.94
Average Mud Cake Thickness, mm	2.44		1.85		2.44		3.02	
API Fluid Loss, cc	7.3	6.7	4.9	4.9	6.5	6.1	6.9	6.9
Average API Fluid Loss, cc	7		4.9		6.3		6.9	

Table B.4: Test results of 2% Lubricants in 25 ppb OCMA clay and 150 ppb Barite Samples in terms of Fluid Loss and Mud Cake Thickness

API Filter Press Test	**5A**		**5B**		**5C**		**5D**	
Tap Water, cc	350		350		350		350	
API Test Calibration Bentonite, ppb	20		20		20		20	
Caustic, ppb	0.5		0.5		0.5		0.5	
Chrome free Lignosulfonate, ppb	1		1		1		1	
CMC-Lv, ppb	1.5		1.5		1.5		1.5	
OCMA Clay, ppb	25		25		25		25	
API Test Calibration Barite, ppb	150		150		150		150	
Lubricant-B, % vol.			2.0					
Lubricant-C, % vol.					2.0			
Lubricant-D, % vol.							2.0	
Mud Cake Thickness, mm 1. Measurement	2.4	2.9	1.6	1.6	2.6	2.4	2.8	2.8
Mud Cake Thickness, mm 2. Measurement	2.6	2.7	1.6	1.6	2.5	2.4	2.7	2.6
Mud Cake Thickness, mm 3. Measurement	2.5	3.0	1.6	1.7	2.7	2.5	3.0	2.5
Mud Cake Thickness, mm 4. Measurement	3.0	3.0	1.4	1.6	2.6	2.3	2.9	2.8
Mud Cake Thickness, mm 5. Measurement	2.5	3.0	1.5	1.4	2.6	2.4	2.8	2.8
Mud Cake Thickness, mm 6. Measurement	2.60	2.92	1.54	1.58	2.60	2.40	2.84	2.70
Average Mud Cake Thickness, mm	2.76		1.56		2.50		2.77	
API Fluid Loss, cc	6.8	7	4.3	4.6	6.7	6.5	5.8	6.2
Average API Fluid Loss, cc	6.9		4.45		6.6		6	

Table B.5: Test results of 2% Lubricants in 25 ppb OCMA clay and 300 ppb Barite Samples in terms of Fluid Loss and Mud Cake Thickness

API Filter Press Test	6A		6B		6C		6D	
Tap Water, cc	350		350		350		350	
API Test Calibration Bentonite, ppb	20		20		20		20	
Caustic, ppb	0.5		0.5		0.5		0.5	
Chrome free Lignosulfonate, ppb	1		1		1		1	
CMC-Lv, ppb	1.5		1.5		1.5		1.5	
OCMA Clay, ppb	25		25		25		25	
API Test Calibration Barite, ppb	300		300		300		300	
Lubricant-B, % vol.			2.0					
Lubricant-C, % vol.					2.0			
Lubricant-D, % vol.							2.0	
Mud Cake Thickness, mm 1. Measurement	3.1	3.1	1.8	1.7	2.9	2.9	2.7	2.6
Mud Cake Thickness, mm 2. Measurement	2.9	3.1	1.6	1.7	2.7	2.5	2.8	2.8
Mud Cake Thickness, mm 3. Measurement	2.9	2.9	2.0	1.9	2.8	2.9	2.8	2.8
Mud Cake Thickness, mm 4. Measurement	3.0	3.1	1.6	1.8	2.8	2.7	2.7	2.8
Mud Cake Thickness, mm 5. Measurement	3.0	3.1	1.7	1.7	2.9	2.7	3.0	2,.9
Mud Cake Thickness, mm 6. Measurement	2.98	3.06	1.74	1.76	2.82	2.74	2.80	2.78
Average Mud Cake Thickness, mm	3.02		1.75		2.78		2.79	
API Fluid Loss, cc	6.3	6.5	4.7	4.5	5.8	6.4	6.1	6.3
Average API Fluid Loss, cc	6.4		4.6		6.1		6.2	

Table B.6: Test results of 3% Lubricants in 25 ppb OCMA clay and Barite free Samples in terms of Fluid Loss and Mud Cake Thickness

API Filter Press Test	**7A**		**7B**		**7C**		**7D**	
Tap Water, cc	350		350		350		350	
API Test Calibration Bentonite, ppb	20		20		20		20	
Caustic, ppb	0.5		0.5		0.5		0.5	
Chrome free Lignosulfonate, ppb	1		1		1		1	
CMC-Lv, ppb	1.5		1.5		1.5		1.5	
OCMA Clay, ppb	25		25		25		25	
API Test Calibration Barite, ppb	0		0		0		0	
Lubricant-B, % vol.			3.0					
Lubricant-C, % vol.					3.0			
Lubricant-D, % vol.							3.0	
Mud Cake Thickness, mm 1. Measurement	2.1	2.3	1.4	1.2	2.0	2.2	2.1	2.1
Mud Cake Thickness, mm 2. Measurement	2.4	2.5	1.4	1.5	2.2	2.1	2.0	2.0
Mud Cake Thickness, mm 3. Measurement	2.4	2.4	1.3	1.5	2.2	2.2	2.2	2.1
Mud Cake Thickness, mm 4. Measurement	2.4	2.5	1.3	1.4	2.0	2.2	2.2	2.1
Mud Cake Thickness, mm 5. Measurement	2.5	2.3	1.4	1.3	2.0	2.2	2.1	2.1
Mud Cake Thickness, mm 6. Measurement	2.36	2.40	1.36	1.38	2.08	2.18	2.12	2.08
Average Mud Cake Thickness, mm	2.38		1.37		2.13		2.10	
API Fluid Loss, cc	8.1	7.9	4.5	4.1	7.6	7.5	7.3	7.5
Average API Fluid Loss, cc	8		4.3		7.55		7.4	

Table B.7: Test results of 3% Lubricants in 25 ppb OCMA clay and 150 ppb Barite Samples in terms of Fluid Loss and Mud Cake Thickness

API Filter Press Test	**8A**		**8B**		**8C**		**8D**	
Tap Water, cc	350		350		350		350	
API Test Calibration Bentonite, ppb	20		20		20		20	
Caustic, ppb	0.5		0.5		0.5		0.5	
Chrome free Lignosulfonate, ppb	1		1		1		1	
CMC-Lv, ppb	1.5		1.5		1.5		1.5	
OCMA Clay, ppb	25		25		25		25	
API Test Calibration Barite, ppb	150		150		150		150	
Lubricant-B, % vol.			3.0					
Lubricant-C, % vol.					3.0			
Lubricant-D, % vol.							3.0	
Mud Cake Thickness, mm 1. Measurement	2.4	2.9	1.3	1.3	2.1	2.4	2.8	2.6
Mud Cake Thickness, mm 2. Measurement	2.6	2.7	1.4	1.4	2.1	2.3	3.0	2.8
Mud Cake Thickness, mm 3. Measurement	2.5	3.0	1.3	1.3	2.3	2.3	2.8	2.8
Mud Cake Thickness, mm 4. Measurement	3.0	3.0	1.4	1.3	2.4	2.3	2.9	2.8
Mud Cake Thickness, mm 5. Measurement	2.5	3.0	1.4	1.3	2.3	2.2	3.0	2.9
Mud Cake Thickness, mm 6. Measurement	2.60	2.92	1.36	1.32	2.24	2.30	2.90	2.78
Average Mud Cake Thickness, mm	2.76		1.34		2.27		2.84	
API Fluid Loss, cc	6.8	7	4.5	4.5	6.3	6.5	6.7	6.5
Average API Fluid Loss, cc	6.9		4.5		6.4		6.6	

Table B.8: Test results of 3% Lubricants in 25 ppb OCMA clay and 300 ppb Barite Samples in terms of Fluid Loss and Mud Cake Thickness

API Filter Press Test	**9A**		**9B**		**9C**		**9D**	
Tap Water, cc	350		350		350		350	
API Test Calibration Bentonite, ppb	20		20		20		20	
Caustic, ppb	0.5		0.5		0.5		0.5	
Chrome free Lignosulfonate, ppb	1		1		1		1	
CMC-Lv, ppb	1.5		1.5		1.5		1.5	
OCMA Clay, ppb	25		25		25		25	
API Test Calibration Barite, ppb	300		300		300		300	
Lubricant-B, %			3.0					
Lubricant-C, %					3.0			
Lubricant-D, %							3.0	
Mud Cake Thickness, mm 1. Measurement	3.1	3.1	2.0	2.0	2.6	2.7	2.8	3.2
Mud Cake Thickness, mm 2. Measurement	2.9	3.1	1.9	2.0	2.8	3.0	2.8	3.3
Mud Cake Thickness, mm 3. Measurement	2.9	2.9	2.0	1.9	2.7	2.8	3.1	3.2
Mud Cake Thickness, mm 4. Measurement	3.0	3.1	1.9	2.0	2.9	2.8	3.1	3.4
Mud Cake Thickness, mm 5. Measurement	3.0	3.1	2.0	2.1	2.9	2.8	3.2	3.4
Mud Cake Thickness, mm 6. Measurement	2.98	3.06	1.96	2.00	2.78	2.82	3.00	3.30
Average Mud Cake Thickness, mm	3.02		1.98		2.80		3.15	
API Fluid Loss, cc	6.3	6.5	4	4	5.9	6.1	5.5	5.5
Average API Fluid Loss, cc	6.4		4		6		5.5	