AN EXPERIMENTAL STUDY ON USAGE OF HOLLOW GLASS SPHERES (HGS) FOR REDUCING MUD DENSITY IN LOW PRESSURE RESERVOIRS AND LOST CIRCULATION ZONES

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

T.ÇAĞRI ARI

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
PETROLEUM AND NATURAL GAS ENGINEERING

APRIL 2014

Approval of the thesis:

AN EXPERIMENTAL STUDY ON USAGE OF HOLLOW GLASS SPHERES (HGS) FOR REDUCING MUD DENSITY IN LOW PRESSURE RESERVOIRS AND LOST CIRCULATION ZONES

submitted by **T.ÇAĞRI ARI** in partial fulfillment of the requirements for the degree of **Master of Science in Petroleum and Natural Gas Engineering Middle East Technical University** by,

Prof. Dr. Canan Özgen _____________________
Dean, Graduate School of **Natural and Applied Sciences**

Prof. Dr. Mahmut Parlaktuna _____________________
Head of Department, **Petroleum and Natural Gas Engineering**

Prof. Dr. Serhat Akın _____________________
Supervisor, **Petroleum and Natural Gas Engineering Dept., METU**

Examining Committee Members:

Prof. Dr. Mahmut Parlaktuna _____________________
Petroleum and Natural Gas Engineering Dept., METU

Prof. Dr. Serhat Akın _____________________
Petroleum and Natural Gas Engineering Dept., METU

Prof. Dr. Nurkan Karahanoğlu _____________________
Geological Engineering Dept., METU

Dr. Reha Özel _____________________
TPAO Research Center

Selçuk Erkekol, M.Sc. _____________________
TPAO Research Center

Date: 11.04.2014

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Last name: T.Çağrı ARI

Signature:

ABSTRACT

AN EXPERIMENTAL STUDY ON USAGE OF HOLLOW GLASS SPHERES (HGS) FOR REDUCING MUD DENSITY IN LOW PRESSURE RESERVOIRS AND LOST CIRCULATION ZONES

T.Çağrı ARI
M.Sc., Petroleum and Natural Gas Engineering Department
Supervisor: Prof. Dr. Serhat AKIN

April 2014, 85 pages

Drilling fluid is a fluid mixture that is used in oil and gas drilling operations. Generating hydrostatic pressure, carrying cuttings to the surface and maintaining wellbore stability is essential for a drilling fluid with its other important functions. For low pressure reservoirs, hydrostatic pressure that drilling fluid generated should be low. To achieve that, drilling fluid density should be lowered. However, use of drilling fluids with higher density than required could cause partial or complete loss of drilling fluid into the formation which may cause serious problems. To obtain lower mud densities, methods such as air/dust drilling can be used or oil based muds can be preffered. But for enviromental reasons and cost issues, Hollow Glass Spheres (HGS) is a serious alternative. This study aims to find proper HGS type with a convenient composition in a water based mud.

In this study, HGS is used to obtain a density as low as 6.88 ppg which is needed to balance the formation pressure in a low pressure reservoir. Among HGSs with different pressure resistance, HGS5000 and HGS8000X are tested because of the maximum pressure to be encountered in the well is lower than 5000 psi. HGS is selected based on its improved mud properties such as fluid loss, rheological properties, filter cake quality, pH and gelation. After selecting the proper HGS type, laboratory tests are conducted with different water based fluid systems such as KCl-Polymer mud, Polymer based mud and Flo-Pro mud with different concentrations of HGS.

Polymer based mud with HGS at rating of 5000 psi showed the best performance in cuttings carrying capacity which can be interpretted from rheological properties. Polymer based mud with HGS5000 has the lowest fluid loss value by optimizing $CaCO_3$ concentration and has the best filter cake qualities: thin and impermeable. Gelation and pH values of the selected drilling fluid are observed. Polymer optimization for the selected drilling fluid with selected HGS is conducted and particle size analysis is also in the content of this study.

Keywords: Drilling fluid, drilling, hollow glass spheres (HGS), glass bubble, drilling mud, low density drill-in fluids (LDDIF), low weight drilling fluids (LWDF)

ÖZ

CAM KÜRECİKLER KULLANILARAK, DÜŞÜK BASINÇLI REZERVUARLARDA VE KAÇAKLI ZONLARDA ÇAMUR YOĞUNLUĞUNUN DÜŞÜRÜLMESİ İLE İLGİLİ DENEYSEL ÇALIŞMA

T.Çağrı ARI
Yüksek Lisans, Petrol ve Doğal Gaz Mühendisliği Bölümü
Tez Yöneticisi: Prof. Dr. Serhat AKIN

Nisan 2014, 85 sayfa

Sondaj sıvısı, petrol ve doğal gaz sondajlarında kullanılan bir akışkandır. Hidrostatik basınç oluşturmak, kesintilerin yüzeye taşınması ve kuyu stabilitesinin sağlanması sondaj sıvısının önemli özelliklerinden bazılarıdır. Düşük basınçlı rezervuarlarda, sondaj sıvısının oluşturduğu hidrostatik basınç düşük olmalıdır. Bu koşulu sağlamak için sondaj sıvısının yoğunluğu düşük olmalıdır. Gerekenden fazla yoğunluk, sondaj sıvısının formasyona tedrici ya da tam olarak kaçmasıyla ciddi sorunlar oluşturabilir. Düşük çamur yoğunlukları elde etmek için havalı sondaj ya da petrol bazlı çamur tercih edilebilir. Fakat çevresel sınırlamalar ve maliyet kısıtlamaları nedenleriyle cam kürecikler (HGS) ciddi bir alternatif oluşturmaktadır. Bu çalışmada uygun HGS'ler kullanılarak su bazlı çamurlarda uygun kompozisyonu oluşturmak amaçlanmıştır.

Bu çalışmada cam kürecikler kullanılarak, düşük basınçlı bir rezervuarda kullanılmak üzere 6.88 ppg sondaj sıvısı yoğunluğuna ulaşmak hedeflenmiştir. Farklı basınç dayanımları olan cam kürecikler arasından HGS5000 ve HGS8000X test edilmiştir, bunun nedeni kuyuda karşılaşılması beklenen basıncın 5000 psi'dan düşük olmasıdır. Cam küreciklerin seçimi; çamur özelliklerine; örnek olarak: Sıvı kaybı, reolojik özellikler, çamur keki kalitesi, pH ve jelleşme değerlerine olan etkileri karşılaştırılarak yapılmıştır. Uygun HGS seçildikten sonra, farklı su bazlı çamurlarda

(KCl-Polimer çamuru, Polimer bazlı çamur ve Flo-Pro çamuru) laboratuar testleri farklı oranlarda HGS kullanılarak yapılmıştır.

Polimer bazlı çamurda 5000 psi dayanımlı HGS, kesintilerin taşınma kapasitesi bakımından (reolojik özelliklerden yorumlanarak) en yüksek performansı göstermiştir. HGS5000 eklenmiş polimer bazlı çamur; $CaCO_3$ optimizasyonu sayesinde, sıvı kaybı değeri bakımından en düşük değeri vermiş ve en iyi filtrat keki özelliklerini sağlamıştır: ince ve geçirimsiz. Seçilen sondaj sıvısındaki jelleşme ve pH değerleri gözlemlenmiştir. Seçilen sondaj sıvısı için polimer optimizasyonu ve tanecik boyut analizi de bu çalışmanın içeriğine dahildir.

Anahtar kelimeler: Sondaj sıvısı, sondaj, cam kürecikler (HGS), sondaj çamuru, düşük ağırlıklı rezervuar sıvıları (LDDIF), düşük ağırlıklı sondaj sıvıları (LWDF)

To my family

ACKNOWLEDGEMENTS

I would like to thank my supervisor Prof. Dr. Serhat Akın for his guidance, advice and providing me an environment where I can improve my ideas.

I want to thank Selçuk Erkekol, Reha Özel and my colleagues in Turkish Petroleum Corporation Research Center for their support and assistance throughout the study. I would like to thank 3M Company for providing the chemicals for the laboratory tests.

I would also like to thank my parents and my sister for their love and confidence in me, my dearest Cansu Afşar for her invaluable support throughout the study.

At last but not the least my closest friends; Mehmet Can Pakdil, Fatih Özgür Sunar, Aslı Arı, Gizem Koral, Görkem Türkili, İsmail Aydın, Ufuk Kılıçaslan, Atalay Çalışan and Serkan Kılıç for never letting me down throughout my life.

TABLE OF CONTENTS

LIST OF TABLES

TABLES

LIST OF FIGURES

FIGURES

NOMENCLATURE

ppg……………………………………………………..………….…. pound per gallon

cc…………………………………………………..……………………… minilitre

rpm……………………………………………...……………….. rate per minute

ppb……………………………………………………………….. pound per barrel

µm……………………………………………………………………….. micron

bbl………………………………………………………………………… barrel

cp……………………………………………………………………….. centipoise

psi…………………………………………………………. pounds per square inch

CHAPTER 1

INTRODUCTION

Drilling low pressure reservoirs have always been a difficulty for drilling industry. Low pressured reservoirs with low permeability and depleted zones are hard to drill in terms of technical difficulties and higher costs. The necessity for lightweight drilling fluids emerges for that reason.

The most important function of a drilling fluid is to form hydrostatic pressure to balance formation pressure. However having more hydrostatic pressure than the formation pressure may cause serious problems depending on the formation drilled. The most expected problem would be lost circulation. Lost circulation has always caused the highest mud costs. In addition to mud costs it contributes problems in the well such as wellbore instability, stuck pipe and poor cement jobs. Beside these technical and economical parameters, it may result loss of well control and even blow outs may occur. Especially in Thrace region of Turkey while drilling natural gas storage wells, lost circulation is a common problem. When the circulation is lost, well control can not be done properly. Therefore having lower mud weights is a must.

Drilling low pressure reservoirs with low permeabilities and depleted wells require lower density drilling fluids. Mud densities higher than stated limits could cause partial or total losses of the drilling fluid, increase in drilling costs due to extended drilling time, fracturing the formation and possible formation damage.

Having mud weights lower than pure water (Specific Gravity: 8.33 ppg) may be achieved in limited ways. Air/dust drilling is one of the options. Oil Based Mud (OBM) is another possible option. Adding Hollow Glass Spheres (HGS) to the drilling fluid is a new concept in petroleum industry but a serious alternative for achieving low densities.

HGS is used as a density reducing agent in drilling fluids to have lighter mud weights. The material is stable, incompressible and virtually insoluble in water or oil. It has a high strength to weight ratio which derives survivals in high pressure downhole conditions [1]. HGS's density differs from 0.38 g/cc to 0.42 g/cc depending on its pressure resistance and its particle size changes between 15 µm to 135 µm. These are unicellular hollow spheres that have a composition of Pyrex-like soda-lime-borosilicate glass.

The practice of using HGS to reduce the density of drilling fluids has become more important due to increasing demand for 'hydrostatic pressure management' with high performance low density fluids. [2]

In this study, performances of water based muds at a density of 6.88 ppg with different hollow glass spheres are evaluated in terms of fluid loss, filter cake quality, pH, gelation and rheological properties.

6.88 ppg mud densities are achieved in different water based muds. Since maximum pressure to be encountered in the well is lower than 5000 psi. HGS5000 (5000psi) and HGS8000X (8000psi) are tested with KCl/Polymer, Polymer based and Flo-Pro muds with different HGS concentrations to reduce mud density to target density. After selecting the proper HGS type with the proper water based mud; optimization for polymers, bridging materials and PHPA are conducted in terms of drilling fluid properties. Particle size analysis of the HGS: Dry and wet sieve analyses are conducted. For applications in the field, its storage and mixing methods are also studied.

CHAPTER 2

LITERATURE REVIEW

The main function of a drilling fluid is to control the formation pressure to ensure a safe and successful drilling operation. Mud density should be kept in its optimum value to ensure adequate pressure to obstruct the influx of formation fluids also not going beyond the fracture resistance of formations subjected in open hole. [3] Several terms should be examined to understand the concept of pressure control. Mud window is the term used for the interval between normal pore pressure and overburden pressure of the formation. Hydrostatic pressure should be kept between these two values for a successful drilling operation. In low pressure and depleted reservoirs, formation requires lower hydrostatic pressures. For mud densitites lower than water density, there are limited ways. Adding light weight solids such as Hollow Glass Spheres (HGS) to various type of water based muds is the main content of this study. Other alternative methods such as underbalanced drilling and oil based systems are also examined.

Some important parameters need to be defined for pressure control. These are pressure gradient, hydrostatic pressure, equivalent mud weight, fracture gradient, formation pressure, normal pressure, abnormal pressure zone, subnormal pressure zone and lost circulation.

Pressure Gradient: Pressure gradient is the pressure applied by each foot of fluid.

$$PG = 0.052 \times MW \quad (1)$$

Where;

PG is the pressure gradient in psi/ft

MW is the mud weight in pound per gallon (ppg) [4]

Hydrostatic Pressure: The pressure exerted by the fluid column due to its density and true vertical depth (TVD) of the well is calculated as follows:

Hydrostatic Pressure (P_{HYD}) = 0.052 × MW_1 × TVD (2)

Where;

P_{HYD} is in pound per square inch (psi)

MW_1 is in pound per gallon (ppg),

TVD is in feet. [4]

Equivalent Circulating Mud Weight: Equivalent mud weight on the bottom of the well is calculated as follows:

EMW= Ps/ (0.052 x TVD) + MW_1 (3)

Where;

Ps is the total of hydrostatic pressure, circulating pressure and imposed pressure in pound per square inch, psi

TVD is in feet,

MW_1 is in pound per gallon, ppg. [4]

Fracture Gradient: The pressure needed to cause fractures in a formation at a known depth. If the fracture gradient of an area is unknown, leak-off test can be run to determine the fracture gradient. [4]

Formation Pressure: Formation pressure which is also known as pore pressure is the pressure of the fluid applied in pore spaces of any formation such as water, oil or gas. [4]

Normal Pressure: When the hydrostatic pressure of the drilling fluid column is equal to the density of the original fluid that is present in the geological environment, it is called normal pressure as figured in Figure 2.1. Normal pressures differ from 0.465 psi/ft in Marine basins which is equal to 8.9 ppg; salt water to 0.433 psi/ft equal to 8.33 ppg water in Inland areas. [4]

For a given region then,

If Formation Pressure = Hydrostatic Pressure, the formation pressure is normal.

If Formation Pressure < Hydrostatic Pressure, the formation is underpressured.

If Formation Pressure > Hydrostatic Pressure, the formation is overpressured. [5]

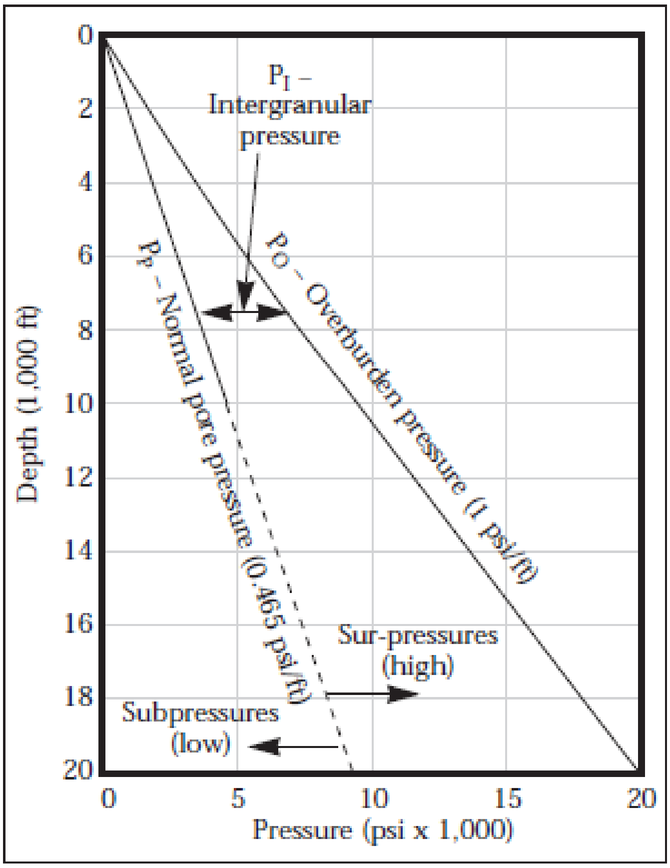

Figure 2. 1: Normal pressure profile [6]

Abnormal Formation Pressure: Abnormal zones are comprised because of particular sealed zones which are impermeable. The fluid is sealed in the formation and with increasing depth, overburden load increases thus formation pressure increases.

Subnormal Formation Pressure: Subnormal pressures are experienced on the zones which have lower pore pressures than the normal hydrostatic pressure. Severe drilling problems may be encountered in drilling subnormal pressure zones. Lost circulation is the most common problem due to pressure differential between the total of hydrostatic pressure, circulating pressure, and imposed pressure and the formation pressure. [4]

Lost Circulation: Lost circulation is the partial or total loss of drilling fluid from the wellbore to the formation. Lost circulation may occur in different formations which are figured in Figure 2.2. It has always been a serious problem for drilling industry. Not only increasing the fluid costs, but also increasing the total costs of drilling. It causes poor cement jobs, poor zonal isolation, increased casing corrosion, wellbore instability and stuck pipe. Lost circulation in uncontrolled pressure zones can cause blow-outs and result loss of the well.

As stated by Caenn R., lost circulation can occur because of two reasons:

- Fractures induced by higher hydrostatic pressure due to mud weight, into preexisting open fractures.
- Fluid flow into large openings, formations with high permeability (such as large pores or solution channels). [7]

Mostly there are 4 kinds of formations that cause lost circulation, these are:

1. High-permeability unconsolidated sands and gravel.
2. Cavernous or vugular zones in carbonates (limestone or dolomite).
3. Natural fractures, faults and transition zones in carbonates or hard shales.
4. Induced fractures from excessive pressure.

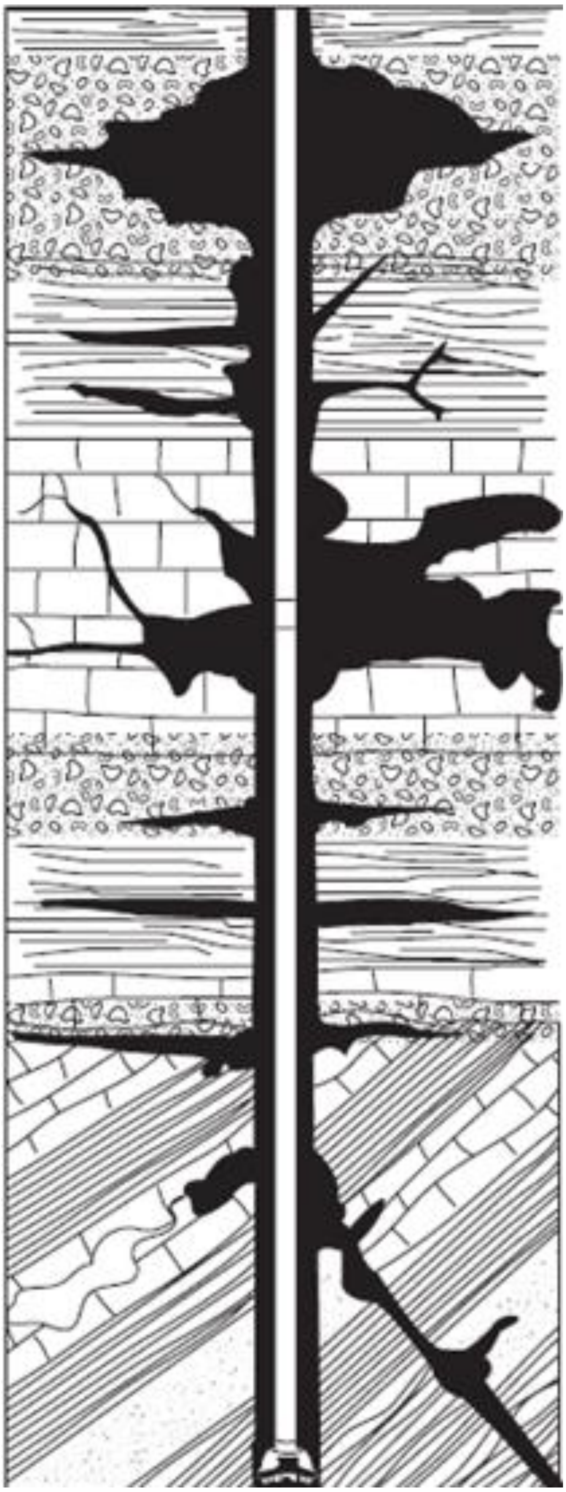

Figure 2. 2: Lost circulation sections [6]

Lost circulation can be few barrels in an hour to hundreds of barrels in an hour. Therefore to specify the loss clearly classification is made depending on the severity of loss in an hour. Since oil based muds (OBM) are more expensive and enviromentally more problematic, its classification is different from water based muds (WBM).

Table 2. 1: Lost rate classification [8]

Loss Rate, bbl/hr	**Classification**	**General Formation Type**
<25 WBM (<10 OBM)	Seepage	Porous, permeable sands
25 to 100 WBM (10 to 30 OBM)	Partial	Coarse sands and gravels
>100 WBM (>30 OBM)	Severe	Fractures, faults, vugs, caverns, reefs

The most effective method for lost circulation is preventing it before it happens. It is stated that 50% of total lost circulation problems can be solved by proper drilling optimizations. [9]

To have lower densities than water, there are 3 basic methods.

1. Water Based Muds (WBM) with light weight solids
2. Oil Based Systems
3. Underbalanced Drilling

In addition to decreasing the mud density, listed parameters should be taken care seriously:

- Minimizing downhole pressures
- Minimizing swab and surge pressures
- Optimizing rate of penetration (ROP)
- Maximizing BHA clearance
- Optimizing drilling fluid properties and minimize solid content of the drilling fluid
- Avoiding low quality filter cakes
- Designating proper casing depths according to formation changes [9]

2.1. Hollow Glass Spheres (HGS)

Hollow Glass Spheres (HGS) is used as a density reducing agent in many sectors from drilling industry to transportation, mining to construction. HGS is chemically stable, incompressible and virtually insoluable in water or oil. [10] Microscopic image of HGS can be seen in Figure 2.3. It is chosen because of its high strength-weight ratio and has similar chemical properties with soda-lime borosilicate glass.

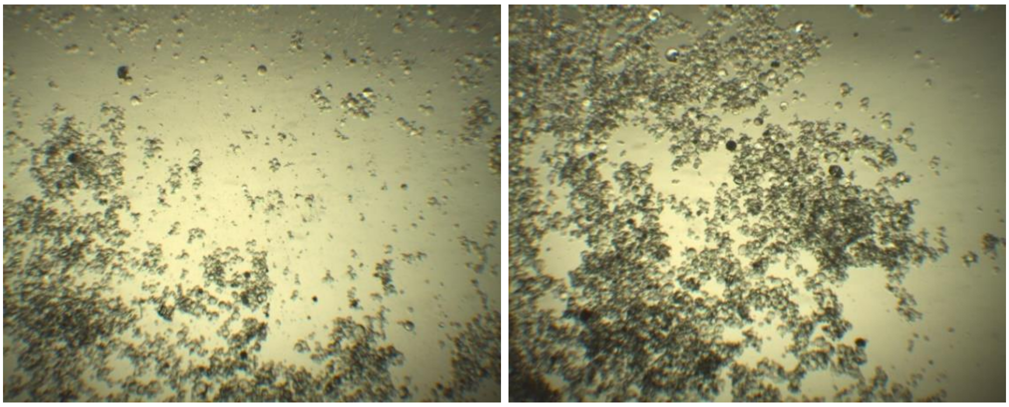

Figure 2. 3: Microscopic image of hollow glass spheres (HGS)

HGS has been first used in the oil field in 1970's in Russia to overcome severe lost circulation problems in Ural Mountains but the information about this application is limited. [11] The usage of HGS in the drilling fluid is fully resourced and supported in the year 1998. Afterwards different companies used HGS in different projects all over the world to achieve lower mud densities. [12]

Depending on the pressure resistance of the spheres, its density differs between 0.125 to 0.6 g/cc and its particle size distribution differs between 12-135 µm. Softening temperature of hollow glass spheres is 600ºC.

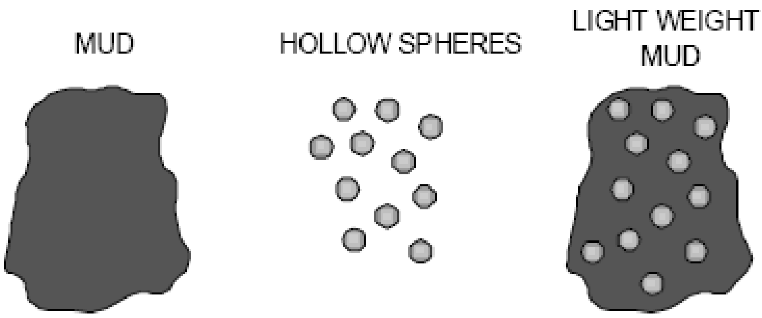

Figure 2. 4: Usage of hollow spheres in drilling fluids [11]

Drilling fluids mixed with HGS which can be seen in Figure 2.4 form a serious alternative to drill low pressure zones, depleted reservoirs, highly permeable formations and fractured zones. Economic and enviromental issues make water based muds (WBM) with HGS a good alternative for low weight drill-in fluids.

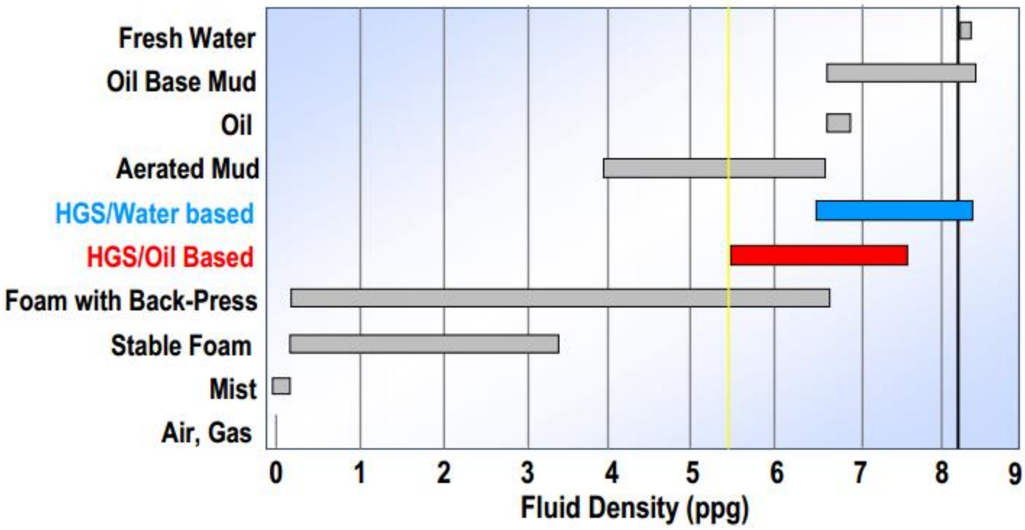

Figure 2. 5: Low density drilling fluids options [10]

Hollow Glass Spheres (HGS) are convenient to mix with any type of drilling fluid up to 50% by volumetric calculation. In this study water based muds are practiced with HGS. In Figure 2.5, lowest mud densities to be achieved are shown both with OBM and WBM.

2.1.1. Types of Hollow Glass Spheres (HGS)

Hollow Glass Spheres are categorized into different types according to its pressure resistance. For example in HGS5000, 5000 represents the pressure strength of the material. There are HGS which have pressure strength from 250 psi to 18000 psi. The comparison for particle size distribution and weight of HGS5000 and HGS8000X is as shown in Figure 2.6.

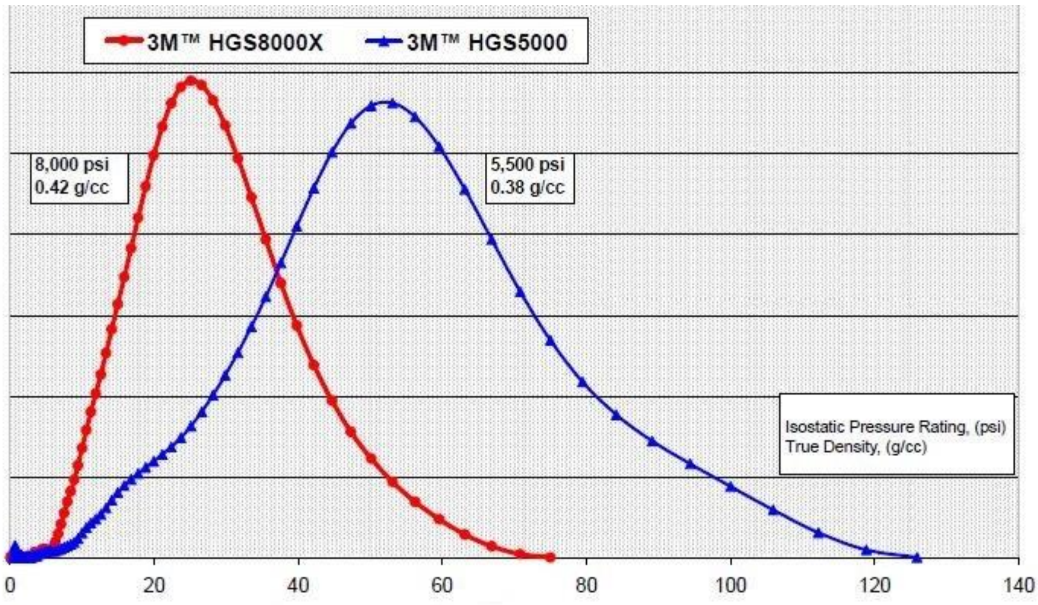

Figure 2. 6: Comparison between HGS5000 and HGS8000X [12]

Besides lowering mud density of drilling fluids, one of the advantages of HGS is it allows measurement while drilling (MWD). Lower hydrostatic pressures also result in:

- Higher penetration rates
- Elimination of differential sticking
- Minimization or elimination of loss circulation
- Decrease in formation damage [13]

Lost circulation is one of the most critical problems in low pressure reservoirs especially when there is gas present in it. It makes harder to control the well. As practiced in offshore field of Mumbai High, India region HGS based light weight drilling fluid decreased the rate of loss circulation from 100bbl/hr to 6-8bbl/hr. By using HGS4000 (in this case HGS which has a maximum pressure strength of 4000psi) mud density is decreased from 8.6-8.8ppg to 7.2-7.9ppg. [2]

6 ppg mud density is achieved with oil based mud in laboratory tests. In Motatan field which is in the western part of Venezuela, HGS based oil based mud is used. Mud

densities between 7.1-7.3 ppg are recorded. $CaCO_3$ is also used in the mud as a bridging agent. [14]

G.Chen tested the salt based drill-in fluid at a density of 8.06 ppg. 3% KCl is used in this study. Stated mud density is achieved by using 10% HGS in volumetric percentage. [15]

By using HGS5000 minimum mud density of 6 ppg is achieved but rheological properties, filtration loss and filter cake properties do not fulfill the necessities of mud properties.

2.1.2. Field Handling of Hollow Glass Spheres (HGS)

Hollow glass spheres (HGS) is flyer chemicals so unlike the other free flowing chemicals, it needs special handling. Firstly a large storage area is needed in the field because of its high volume. In addition to that, personel should wear the protection equipment while handling the chemical due to dust generation. Especially if the working area in the field is an indoor, special attention must be given. [15]

2.1.3. Drilling Fluid Preparation with Hollow Glass Spheres (HGS)

After preparing the base fluid, there are 2 common ways to mix the HGS into the drilling fluid.

1) Using gravity feed direct to the hopper tank: In this method, HGS is mixed with the fluid by the help of adding a fluid stream and causing siphon effect as seen in Figure 2.7. It also lowers dusting of the chemical.

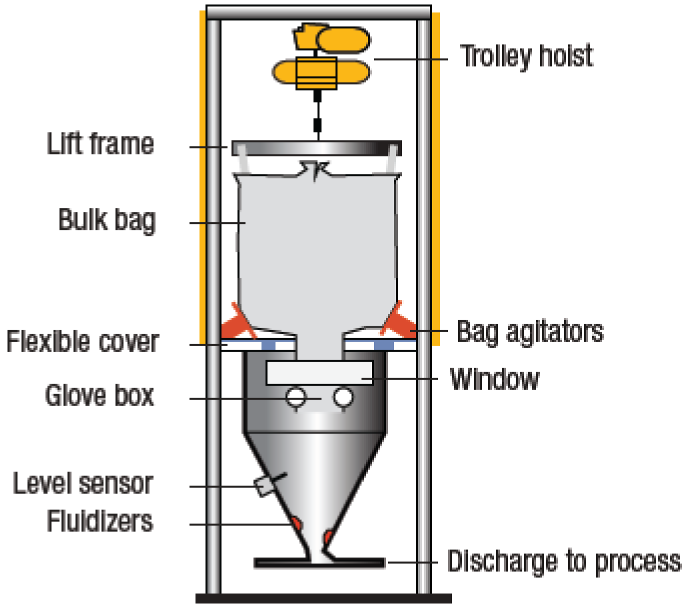

Figure 2. 7: Hollow glass sphere (HGS) transfer via direct gravity feed [16]

2) Another method is pulling HGS from the bulk bag using a suction wand and mixing it straight to hopper tank with the help of diaphragm pump as seen in Figure 2.8. In this method, pump must be kept clean and worked properly.

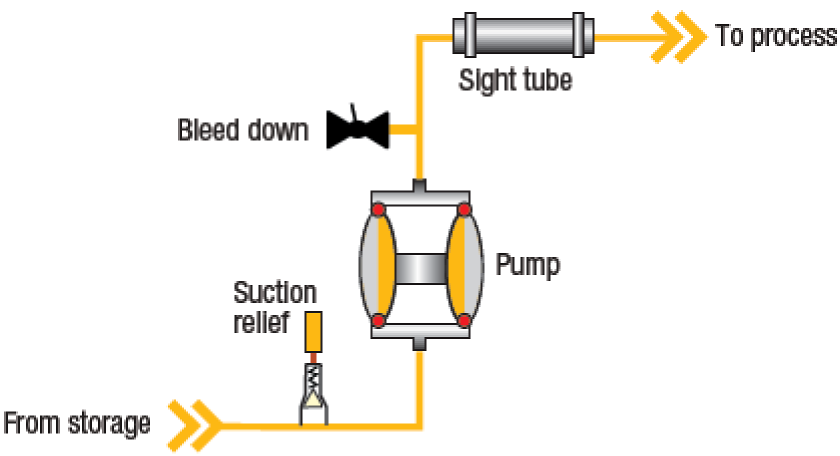

Figure 2. 8: Hollow glass sphere (HGS) transfer via double diaphragm pump [16]

Both methods can be used to mix hollow glass spheres with the base drilling fluid. The essential point is to have a homogeneous mixture of chemicals. HGS has lower density than the water so it tends to float on the surface. Eventhough high shear rate is not necessary, mixing equipment of the mud tanks must work effectively to keep the mixture homogeneous. Proper working pits, air pumps, subsurface guns and centrifugal pump in the premix tank is needed to mix HGS to the drilling fluid effectively.

The solid content of the drilling fluid mixed with HGS is critical. As indicated by Ovcharenko; solid content of the mixture including HGS and any other solid content such as cement, chalk etc should not exceed 40% by volume to not experience pumping problems. [17] That's why solids control equipment should be adjusted properly.

In field applications, keeping the spheres in the mud system is essential since when they are broken, they behave as a solid material and increase both mud density and plastic viscosity. Kutlu B. calculated that HGS mixed with drilling fluids have a survival ratio of 93% as subjected to high pressure. [18]

2.1.4. Solids Control Equipment

Shale Shakers: Shale shakers are the beginning of solid control systems. They are used to remove the largest cuttings in the drilling fluid. To prevent sphere loss, 150-160 mesh size screens are recommended but the case studies show that 120 mesh and lower mesh size screens work better when there is HGS in the drilling fluid. [5] Wet and dry sieve analysis results verify the case studies.

Hydrocyclones: Hydrocyclones are effective to remove solids as low as 20 microns in diameter without removing HGS. The reason for not removing HGS is that it is lighter than the drilled solids and moves through reverse direction. [6]

Centrifuge: Centrifuges are able to remove finer solids than both shale shakers and hydroclones**.** The decanting centrifuge uses a rotating bowl to create high centrifugal force to effect the separation of coarse and fine particles.

A conveyor screw rotates at a slightly slower speed to move the coarse solids to the underflow port. [4] To avoid clogging and loss of HGS, centrifuge should be worked half of its conventional rate. Also lower RPMs are needed in order not to remove HGS from the drilling fluid system.

2.2. Alternative Methods

2.2.1. Underbalanced Drilling (UBD)

Underbalanced drilling is described as "deliberately drilling into a formation in which the formation pressure, or pore pressure, is greater than the pressure exerted by the annular fluid or gas column." [19]

Aerated liquids and foam are the basic types of underbalanced drilling material. Aerated liquid drilling is mixing gas (nitrogen or air) to the base fluid which can be water based mud or oil based mud. For foam drilling surfactants as foaming agents, corrosion inhibitors and drying agents may be needed depending on the condition of the drilling operation.

Advantages of UBD are as follows:

- Elimination of lost circulation since there is no fluid in the system, there is no extra cost for fluid or lost circulation materials.
- Minimized differential sticking risk
- Increased drilling rate

On the other hand, UBD has several disadvantages:

- Increased operational diversity; because of the additional equipment such as compressors, boosters, foam generators. Need for extra space for the equipment and trained drilling crew.
- Safety comcerns due to existing gas and pressure differential like blow-outs, explosion and loss of control.
- Higher operational costs due to extra equipment and need for trained crew.
- Formation damage, as stated by Bennion and Thomas, 1994; UBD does not rule out all the damage mechanisms owing to not having a filter cake and not having a fluid to conduct heat. [20]

2.2.2. Oil Based Systems

Unlike water based mud systems where the water is the continuous phase, oil is the continuous phase in oil based mud systems. Its filtrate is oil. The oil used in this type of drilling fluids range from crude oil to diesel. In addition to conventional type of oils, inert fluids such as pseudo oil and synthetic fluids are common because of enviromental reasons.

The properties of oil based muds are influenced by oil/water ratio, emulsifier concentration of the fluid, solid concentration and downhole conditions. The initial cost of OBM is higher than water based mud systems but overall drilling costs should be taken into consideration. The advantages and disadvantages of oil based systems are as follows:

Advantages

- Re-usable so that it can be stored for a long time and can be used in another well since bacterial contamination is prevented.
- High solids tolerance
- Reduced formation damage

- Increased lubrication helps to use OBM in deviated wells and reduce the risk of differential sticking by lowering the friction.
- High temperature zones can be drilled since the temperature tolerance of OBM is up to 550ºF.
- Reduced corrosion

Disadvantages

- Initial costs are high.
- Kick detection is harder than water based muds since gas solubility is high in OBM.
- Enviromental concerns due to cuttings disposal, mud pit and disposal of the oil mud.
- In lost circulation situations, costs get higher.
- Electric logging must be modified since OBM are non-conductive. For this reason logs that measure resistivity will not work in this type of systems.
- Oil based muds are more compressible than water based muds so that mud density measured at the surface can be different from the actual mud density in downhole conditions. [21]

CHAPTER 3

STATEMENT OF PROBLEM

Drilling low pressure reservoirs and depleted zones require lower density drill-in fluids (LDDIF). Having mud densities higher than calculated limits could cause; partial or total losses which is one of the main problems in drilling industry, extended drilling time and higher costs. Furthermore excess overbalance could cause fracturing the formation and formation damage. There are limited ways to ensure low hydrostatic pressure such as underbalanced drilling, using oil based mud and adding hollow glass spheres to base drilling fluid to lower mud density.

The aim of this study is to find the optimum composition with a selected type of hollow glass sphere (HGS) in a water based mud for a depleted gas storage well in Thrace Region in Turkey at a TVD of 1193m which has a formation pressure of 1400 psi. During the laboratory tests both physical and chemical properties of muds are examined. The test results of different water based muds and different HGS are compared. After selecting the proper water based mud and HGS, optimization on the selected water based mud is carried out.

CHAPTER 4

EXPERIMENTAL SET-UP AND PROCEDURE

4.1 Experimental Set-Up

4.1.1 Preparation of Base Fluid

The chemicals that the drilling fluid has are prepared following API Spec 13A with Precisa Electronic Balance. Each chemical is added to distilled water in 1± 0.1 minute and mixed for 3±0.1 minutes with Multi Mixer to ensure homogenity. Multi Mixer works at a rate of 11500±500 rpm (Model 9B with 9B29X impellers, API Spec 13A). [22]

4.1.2 Determination of Hollow Glass Spheres HGS amount to achieve 6.88 ppg mud density

After preparing the base fluid, mud density is measured in each composition. To decrease the mud density to 6.88 ppg, 3M- excel sheet which is the product of 3M Company is used for HGS5000 and HGS 8000X. It calculates the amount of HGS should be added to base fluid to achieve desired density by formulating base fluids' and HGSs' density.

4.1.3 Mixing Hollow Glass Spheres (HGS) to the mixture

After preparing the base fluid, Hollow Glass Spheres (HGS) are added to the drilling fluid. Since HGS are light and flyer materials, they do not mix with the drilling fluid by Multi Mixer as figured in Figure 4.1. Firstly, HGS is added to the drilling fluid and mixed with a spatula until the mixture be homogenous. After that, the mixture is mixed with Multi Mixer for five minutes.

Figure 4. 1: Chemicals mixing in the Multi-Mixer

4.2 Experimental Procedure

After preparing the hollow glass sphere added based light weight drilling fluid, physical and chemical tests are conducted.

4.2.1 Mud Density Measurement

Mud density is measured with mud balance according to API RP 13B-1 / ISO 10414-1 Mud Weight (Density). [23] Before measuring it, air in the chamber is removed carefully.

4.2.2 Rheological Properties

Rheological properties are measured with Fann Viscometer acccording to API RP 13B1 Direct Indicating Viscometer as figured in Figure 4.2. [23] Measurements are carried out at 120ºF. Mud is heated on Fann Viscometer Cup. Plastic Viscosity (PV) and Yield Point (YP) values are calculated according to these formulas:

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

$YP = \theta_{600} - PV$

Where;

PV is in centipoise (cp),

YP is in $lb/100ft^2$,

θ_{600} is the 600 rpm reading,

θ_{300} is the 300 rpm reading

4.2.3 Gel Strengths

After recording rheologies, samples are stirred for 15 seconds at 600rpm and motor is shut for 10 seconds and 3 rpm readings are recorded. This value is called 10 second gel strength. And also the readings for 10 minute gel strengths are also recorded with the same procedure only waited for 10 minutes instead of 10 seconds.

Figure 4. 2: Rheology measurements with Fann viscometers

4.2.4 Fluid Loss, Filter Cake Analysis

Fluid loss and filter cake analyses are conducted following API RP 13B-1/ISO 10414-1, Low-Temperature/Low-Pressure Test. [23]

Fluid Loss: Fluid loss is measured by giving 100 psi pressure to the drilling fluid for 30 minutes as shown in Figure 4.3.

Filter Cake Analysis: After removing the mud from the cell and cleaning the filter cake, interpretations about the thickness, quality and permeability is conducted.

Figure 4. 3: Fluid loss measurement

4.2.5 pH Measurement

The pH of a solution is a measure of its hydrogen ion concentration [24] and is measured directly from the mud with a pH meter according to API RP 13B-1. [23]

4.2.6 Particle Size Analysis

Particle size analyses are performed with Ro-Tap Sieve Shaker. Both dry sieve analysis and wet sieve analysis are conducted according to ASTM STP 447-B. [25]

CHAPTER 5

RESULTS AND DISCUSSION

A gas storage well to be drilled in Thrace basin in Turkey targets 1193 m. depth at a formation pressure of 1400 psi. 6.88 ppg mud density is needed to prevent lost circulation. (2) To achieve the target mud density of 6.88 ppg, two types of Hollow Glass Spheres (HGS) are tested with different types of water based drilling fluids. HGS5000 and HGS 8000X are tested with three types of water based muds. Elimination method is used in these laboratory tests, firstly water based mud is selected, afterwards proper HGS type is determined and lastly optimization is done on the selected drilling fluid.

5.1. Selection of Water Based Mud (WBM)

Three types of water based muds are tested. 6.88 ppg mud density is achieved with different types of muds and different types of hollow glass spheres in every composition. Calcium carbonate which is one of the most commonly used bridging agent in non-damaging drilling fluids since it dissolves in hydrochloric acid [26] is tested in each WBM. Calcium carbonate used in these tests is fine size calcium carbonate.

- Flo-Pro
- KCl/Polymer
- Polymer Based

5.1.1 Flo-Pro

Flo-pro which is the drill-in fluid of M-I Swaco Company has 2 different compositions. One composition is with the bridging agent calcium carbonate ($CaCO_3$) and one that does not.

5.1.1.1 Flo-Pro with HGS5000

Flo-Pro is tested with 2 different combinations to achieve a 6.88 ppg mud density. Table 5.1 shows the base fluids and the compositions with HGS5000. Base fluid-1 is the composition that does not have $CaCO_3$. Base Fluid-2 has 15 ppb $CaCO_3$.

Flo-Pro's base fluid additives and HGS5000 concentrations are given in Table 5.1:

Table 5. 1: Flo-Pro mud additives and HGS5000 concentrations

ADDITIVES	Flo Pro-1	1.TD*:6.88	Flo Pro-2	2.TD*:6.88
Soda Ash, ppb	0.25	0.25	0.25	0.25
Citric Acid, ppb	0.25	0.25	0.25	0.25
Flo-vis, ppb	1.75	1.75	1.75	1.75
Flo-trol, ppb	4	4	4	4
$CaCO_3$, ppb	-	-	15	15
HGS5000, ppb	-	43.87	-	52.8
Volume of base fluid, bbl	1	0.871	1	0.803
Flo-pro, cc	350	304.85	350	281.1

*:Target Density, ppg

Volumes of the HGS added are calculated with respect to 3M-HGS5000 excel sheet. The amounts of HGS added differ because of different $CaCO_3$ concentrations. Since $CaCO_3$ is a bridging and weighting agent, the fluid with $CaCO_3$ has a density higher than the one without $CaCO_3$. The amount of HGS used in the first composition is more than the second composition and also the amount of fluid mixed with HGS is lower than the second composition.

Table 5. 2: Flo-Pro mud and with HGS5000 concentrations test results

RESULTS	**Flo Pro-1**	**1.TD*:6.88**	**Flo Pro-2**	**2.TD*:6.88**
600 rpm	48	94	70	150
300 rpm	40	78	53	124
200 rpm	36	69	44	109
100 rpm	30	57	36	89
6 rpm	16	28	21	40
3 rpm	14	25	19	35
pH	8.5	8.1	8.7	8.2
PV, cp	8	16	17	26
YP, lb/100ft^2	32	62	36	98
Gel Strength, 10sec/10min	14/19	21/25	20/25	31/35
Fluid Loss, cc	45	17	8	50
Mud Density, ppg	8.35	6.86	8.6	6.84

*:Target Density, ppg

- Rheological properties of both (first and second) drilling fluids are high, but the parameters of the second composition which has 15 ppb $CaCO_3$ is higher than the first composition value. Yield points are above the limits. Viscosities of both drilling fluids are high.
- Gel strengths of the second composition are higher than the first composition.
- First drilling fluids' fluid loss decreased according to Base Fluid-1 from 45 cc to 17 cc. That is because of the hollow glass spheres bridging effect but 17 cc is also a high value for fluid loss. Its filter cake is permeable and weak. Fluid loss of the second drilling fluid is 50 cc and has also a thick, permeable and weak filter cake. Fluid loss increased rapidly with respect to Base Fluid-2.
- In both drilling fluids, targeted mud density of 6.88 ppg is achieved. Small differences are caused because of the small amount of air stayed in the mud balance.
- Optimum pH range of Flo-Pro mud is lower than conventional water based muds. Addition of hollow glass spheres (HGS) decreased pH slightly in both drilling fluids.

5.1.1.2. Flo-Pro with HGS8000X

Flo-Pro is tested with 2 different combinations to achieve a 6.88 ppg mud density. In section 5.1.1.1 test results of HGS5000 can be seen, in this section test results of HGS8000X is presented.

Flo-Pro's base fluid additives and HGS8000X concentrations are given below:

Table 5. 3: Flo-Pro mud additives and HGS8000X concentrations

ADDITIVES	Flo Pro-1	1.TD*:6.88	Flo Pro-2	2.TD*:6.88
Soda Ash, ppb	0.25	0.25	0.25	0.25
Citric Acid, ppb	0.25	0.25	0.25	0.25
Flo-vis, ppb	1.75	1.75	1.75	1.75
Flo-trol, ppb	4	4	4	4
$CaCO_3$, ppb	-	-	15	15
HGS8000, ppb	-	44.5	-	52
Volume of base fluid, bbl	1	0.7	1	0.65
Flo-pro, cc	350	273	350	227.5

*:Target Density, ppg

The amount of HGS8000X added to the drilling fluids differs due to different base fluid mud densities. The amount of HGS8000X added to the mixtures is calculated with respect to 3M-HGS8000X excel sheet. In the first composition; mud density of the base fluid is 8.35 ppg and lower than the second base fluids' mud density which is 8.65. Thus 44.5 ppb HGS8000X is added to 273 cc drilling fluid in the first drilling fluid and 52 ppb added to 227.5 cc base fluid for the second composition.

Table 5. 4: Flo-Pro mud and with HGS8000X concentrations test results

RESULTS	Flo Pro-1	1.TD*: 6.88	Flo Pro-2	2.TD*:6.88
600 rpm	48	92	70	213
300 rpm	40	75	53	166
200 rpm	36	58	44	141
100 rpm	30	51	36	108
6 rpm	16	28	21	40
3 rpm	14	22	19	34
pH	8.5	8.1	8.6	8.2
PV, cp	8	17	17	47
YP, lb/100ft^2	32	58	36	99
Gel Strength, 10sec/10min	14/19	22/27	20/25	33/41
Fluid Loss, cc	45	140	8	120
Mud Density, ppg	8.35	**	8.65	6.82

*:Target Density, ppg. **: Not Applicable

- Mud density of the first drilling fluid could not be measured accurately because of the air present in it. Even though a defoamer is used, bubbles still existed in the mud balance because of flo pro mud’s chemical properties, causing the mud density to be lower than it should be.
- Fluid losses of both drilling fluids are above 100 cc and both filter cakes are weak and thick.
- In the second composition, HGS8000X caused an increase in the yield point from 36 lb/100ft^2 to 99 lb/100ft^2 and made the fluid too viscous.

- Plastic Viscosity (PV) is also higher in both HGS compositions than the base fluids. HGS8000X behaved as a solid material when mixed with $CaCO_3$.
- Gel strengths of both drilling fluids are not so aggressive and easy to break.
- pH values decrease slightly with addition of hollow glass spheres (HGS) in both drilling fluids with respect to their base fluid.

5.1.2. KCl/Polymer

In this section; 5% KCl concentration which is equal to 18.1 ppb KCl concentration is examined with HGS5000 and HGS8000X.

5% KCl/Polymer mud have tested in 2 different compositions. One composition is with the bridging agent Calcium carbonate ($CaCO_3$) and one that does not. Calcium carbonate used in these tests is fine size calcium carbonate.

5.1.2.1. KCl/Polymer with HGS5000

In this section test results of 5% KCl/Polymer mud with HGS5000 is presented. One composition is with the bridging agent Calcium carbonate ($CaCO_3$) and one that does not as can be seen in Table 5.5.

5% KCl/Polymer mud’s base fluid additives and HGS5000 concentrations are given below:

Table 5. 5: 5% KCl/Polymer mud additives and with HGS5000 concentrations

ADDITIVES	**KCl/ Polymer-1**	**1.TD*:6.88**	**KCl/ Polymer-2**	**2.TD*:6.88**
Water, cc	350	350	350	350
KCl, ppb	18.1	18.1	18.1	18.1
Modified Starch, ppb	4	4	4	4
Pac-Lv, ppb	3	3	3	3
XCD, ppb	0.25	0.25	0.25	0.25
$CaCO_3$, ppb	-	-	15	15
NaOH, ppb	0.1	0.1	0.1	0.1
HGS5000, ppb	-	48.5	-	55.45
Volume of base fluid, bbl	1	0.84	1	0.78
Mud, cc	350	292.6	350	272.1

*:Target Density, ppg

The amount of HGS5000 added to the drilling fluids differs due to different base fluid mud densities. The amount of HGS5000 added to the mixtures are calculated with respect to 3M-HGS5000 excel sheet. In the first composition 48.5 ppb HGS5000 is added to 292.6 cc mud to achieve a density of 6.88 ppg. For the second composition 55.45 ppb HGS5000 is needed for a 272.1 cc mud to have 6.88 ppg mud densities. The difference is occured in consequence of base fluids density. Table 5.6 shows the test results of both base fluids and different hollow glasss sphere concentrations:

Table 5. 6: 5% KCl/Polymer mud and with HGS5000 concentrations test results

RESULTS	Base Fluid-1	1.TD*:6.88	Base Fluid-2	2.TD*:6.88
600 rpm	20	70	25	180
300 rpm	12	42	15	110
200 rpm	8	31	11	81
100 rpm	6	19	7	48
6 rpm	3	4	2	7
3 rpm	2	3	1	4
pH	11.2	10.7	11.5	10.8
PV, cp	8	28	10	**70**
YP, $lb/100ft^2$	4	14	5	**40**
Gel Strength, 10sec/10min	1/2	3/7	1/2	5/8
Fluid Loss, cc	24	13	6.1	11.5
Mud Density, ppg	8.73	6.88	8.9	6.87

*:Target Density, ppg

- In both drilling fluids, 6.88 ppg mud densities are achieved.
- In the first composition; fluid loss decreased compared to Base Fluid-1, hollow glass spheres behave as a bridging agent and reduce fluid loss. For the second composition; fluid loss increases compared to Base Fluid-2 which has $CaCO_3$ as a bridging agent. Both compositions' filter cakes are not in very good condition but similar to Pratama's study [27], glass bubble combined with calcium carbonate acts as a bridging agent and forms a better filter cake.

- Rheological properties of the first composition are reasonable. But for the second composition, rheological properties are very high. 70 cp plastic viscosity shows that HGS behave as a solid material in that composition and 40 lb/100ft^2 yield point is also high.
- Gelation is not observed. 10 seconds and 10 minutes gel strengths are both in the limits.
- pH slightly decreases in both combinations with respect to their base fluid.

5.1.2.2. KCl/Polymer with HGS8000X

5% KCl/Polymer mud with HGS8000X are examined. One composition is with the bridging agent Calcium carbonate ($CaCO_3$) and one that does not. In this section test results of 5% KCl/Polymer mud with HGS8000X is presented.

5% KCl/Polymer mud's base fluid additives and HGS8000X concentrations are given below:

Table 5. 7: 5% KCl/Polymer mud additives and with HGS8000X concentrations

ADDITIVES	**KCl/ Polymer-1**	**1.TD*:6.88**	**KCl/ Polymer-2**	**2.TD*:6.88**
Water, cc	350	350	350	350
KCl, ppb	18.1	18.1	18.1	18.1
Modified Starch, ppb	4	4	4	4
Pac-Lv, ppb	3	3	3	3
XCD, ppb	0.25	0.25	0.25	0.25
$CaCO_3$, ppb	-	-	15	15
HGS8000X, ppb	-	57.2	-	54.5
Volume of base fluid, bbl	1	0.81	1	0.63
Mud, cc	350	284.2	350	220.5

*:Target Density, ppg

The amount of HGS8000X added to the drilling fluids differs due to different base fluid mud densities. The amount of 8000X added to the mixtures are calculated with respect to 3M-HGS8000X excel sheet. In the first composition; mud density of the base fluid is 8.73 ppg and lower than the second base fluids' mud density which is 8.9. Thus 57.2 ppb HGS8000X is added to 284.2 cc drilling fluid in the first drilling fluid and 54.5 ppb added to 220.5 cc base fluid for the second composition.

Table 5. 8: 5% KCl/Polymer mud and with HGS8000X concentrations test results

RESULTS	KCl/ Polymer-1	1.TD*:6.88	KCl/ Polymer-2	2.TD*:6.88
600 rpm	20	72	25	105
300 rpm	12	44	15	65
200 rpm	8	33	11	46
100 rpm	6	20	7	28
6 rpm	3	5	2	5
3 rpm	2	4	1	4
pH	11.2	10.3	11.5	10.3
PV, cp	8	28	10	40
YP, $lb/100ft^2$	4	16	5	25
Gel Strength, 10sec/10min	1/2	4/8	½	7/12
Fluid Loss, cc	24	47	6.1	12.4
Mud Density, ppg	8.73	6.87	8.9	6.86

*:Target Density, ppg

- In both combinations, mud densities close to 6.88 ppg are achieved. The small differences in the mud density measurement can be ignored.
- Fluid loss of the first fluid is 47 cc and has a very thick and weak filter cake. Second fluid’s fluid loss is 12.4 cc and higher than the Base Fluid-2. Both fluid losses are above acceptable limits for a drilling fluid.
- Plastic viscosity and yield point values of both fluids increase sharply with respect to Base Fluid-1 and Base Fluid-2. It can be easily seen in Table 5.8 that second fluids’ rheological parameters are higher than the first fluid.

- 10 second and 10 minute gel strengths of both fluids increases with respect to Base Fluid-1 and Base Fluid-2. Second drilling fluids' gelation is higher due to calcium carbonate addition.
- pH slightly decreases in both combinations with respect to their base fluid.

5.1.3. Polymer Based Mud

Polymer based muds are different from KCl/Polymer muds in terms of not containing any type of salts. For that reason mud density of the base fluids are lower than the compositions that contain any type of salt such as KCl, NaCl etc.

Polymer based mud is also tested with 2 types of hollow glass spheres namely HGS5000 and HGS8000X.

5.1.3.1. Polymer Based Mud with HGS5000

Polymer based mud with HGS5000 are examined. One composition is with the bridging agent Calcium carbonate ($CaCO_3$) and one that does not. In this section test results of Polymer based mud with HGS5000 is presented.

Polymer based mud additives and HGS5000 concentrations are given below:

Table 5. 9: Polymer based mud additives and HGS5000 concentrations

ADDITIVES	**Polymer-1**	**1.TD*:6.88**	**Polymer-2**	**2.TD*:6.88**
Water, cc	350	350	350	350
Modified Starch, ppb	4	4	4	4
Pac-Lv, ppb	3	3	3	3
XCD, ppb	0.25	0.25	0.25	0.25
$CaCO_3$, ppb	-	-	15	15
NaOH, ppb	0.1	0.1	0.1	0.1
HGS5000, ppb	-	46.2	-	48.3
Volume of base fluid, bbl	1	0.85	1	0.84
Mud, cc	350	298.7	350	294

*:Target Density, ppg

The amount of HGS5000 added to the drilling fluids differs due to different base fluid mud densities. The amount of HGS5000 added to the mixtures is calculated with respect to 3M-HGS5000 excel sheet. In the first composition; mud density of the base fluid is 8.35 ppg and lower than the second base fluids' mud density which is 8.55. Thus 46.2 ppb HGS5000 is added to 298.7 cc drilling fluid in the first drilling fluid and 48.3 ppb added to 294 cc base fluid for the second drilling fluid.

Table 5. 10: Polymer based mud and with HGS5000 test results

RESULTS	Polymer-1	1.TD*:6.88	Polymer-2	2.TD*:6.88
600 rpm	36	89	31	92
300 rpm	22	53	18	54
200 rpm	16	39	13	40
100 rpm	9	23	8	24
6 rpm	2	5	2	4
3 rpm	1	4	1	3
pH	10.7	9.9	10.5	9.8
PV, cp	14	36	13	38
YP, $lb/100ft^2$	8	17	5	16
Gel Strength, 10sec/10min	1/2	3/4	1/1	¾
Fluid Loss, cc	100	6	12	6.5
Mud Density, ppg	8.35	6.88	8.55	6.88

*:Target Density, ppg

- 6.88 ppg mud densities are achieved in both compositions.
- Rheological properties of both drilling fluids increase after adding HGS5000 but in terms of plastic viscosity and yield point, test results are good. The first drilling fluids' plastic viscosity is 36 cp and yield point is 17, which are 14 and 8 respectively in Base Fluid-1. It shows that hollow glass spheres behave as a solid material in drilling fluid but yield point doesn't increase very much. A similar behavior can be seen in the second drilling fluid; plastic viscosity and yield point

values increased from 13 & 5 to 38 & 16 in sequence with respect to Base Fluid-2.

- Gelation does not occur in both drilling fluids and has same 10 seconds and 10 miutes gel strengths numerically 3&4.
- In both drilling fluids, HGS5000 addition decreases fluid losses with respect to Base Fluid-1 and Base Fluid-2. Both compositions' fluid losses are low and they have good quality filter cakes. **Second drilling fluids' filter cake has the best properties: impermeable, thin and strong. The bridging agent- $CaCO_3$ and HGS5000 give the best results.** Detailed tests for seeing the effect of $CaCO_3$ is conducted in the $CaCO_3$ optimization section.
- pH values of both drilling fluids decrease slightly with respect to their base fluids.

5.1.3.2. Polymer Based Mud with HGS8000X

Polymer based mud with HGS8000X is examined. One composition is with the bridging agent calcium carbonate ($CaCO_3$) and one that does not. In this section test results of Polymer based mud with HGS8000X is presented. Polymer based mud additives and HGS8000X concentrations are given in Table 5.11.

The amount of HGS8000X added to the drilling fluids differs due to different base fluid mud densities. The amount of HGS8000X added to the mixtures is calculated with respect to 3M- HGS8000X excel sheet. In the first composition; mud density of the base fluid is 8.35 ppg and lower than the second base fluids' mud density which is 8.55. Thus 45 ppb HGS8000X is added to 241.5 cc drilling fluid in the first drilling fluid and 47 ppb added to 238 cc base fluid for the second drilling fluid.

Table 5. 11: Polymer based mud additives and HGS8000X concentrations

ADDITIVES	Polymer-1	1.TD*:6.88	Polymer-2	2.TD*:6.88
Water, cc	350	350	350	350
Modified Starch, ppb	4	4	4	4
Pac-Lv, ppb	3	3	3	3
XCD, ppb	0.25	0.25	0.25	0.25
$CaCO_3$, ppb	-	-	15	15
NaOH, ppb	0.1	0.1	0.1	0.1
HGS8000X, ppb	-	45	-	47
Volume of base fluid, bbl	1	0.69	1	0.68
Mud, cc	350	241.5	350	238

*:Target Density, ppg

- Targeted mud densities are attained in both fluids.
- The rheological properties of both drilling fluids are fine in terms of plastic viscosity and yield point values. The first drilling fluids' plastic viscosity is 33 cp and yield point is 15, which are 14 and 8 respectively in Base Fluid-1. It shows that hollow glass spheres behave as a solid material in fluid but yield point doesn't increase very much. A similar behavior can be seen in the second drilling fluid; plastic viscosity and yield point values increased from 13 & 5 to 34 & 13 in sequence with respect to Base Fluid-2.

Table 5. 12: Polymer based mud and with HGS8000X concentrations test results

RESULTS	Base Fluid-1	1.TD*:6.88	Base Fluid-2	2.TD*:6.88
600	36	81	31	81
300	22	48	18	47
200	16	30	13	35
100	9	20	8	21
6	2	3	2	3
3	1	2	1	2
pH	10.7	9.9	10.5	9.8
PV, cp	14	33	13	34
YP, lb/100ft^2	8	15	5	13
Gel Strength, 10sec/10min	1/2	3/4	1/1	3/5
Fluid Loss, cc	100	17.5	12	30
Mud Density, ppg	8.35	6.88	8.55	6.88

*:Target Density, ppg

- Fluid loss of the first drilling fluid decreases from 100 cc to 17.5 cc with respect to Base Fluid-1 since there is no bridging agent in the first composition. HGS8000X behaves as a bridging agent but still fluid loss is high, its filter cake is thick and weak. For the second drilling fluid which contains calcium carbonate as a bridging agent, addition of HGS8000X increases fluid loss.
- Gelation does not occur in both drilling fluids. First fluid has a gel strength of 3 & 4 as 10 second and 10 minute gel strength, alike the first drilling fluid second drilling fluid has gel strength of 3&5 respectively which are low.
- Similar to the test results of other types of drilling fluids, HGS does not have a significant effect on pH.

5.2. Selection of HGS

After conducting tests with 3 types of water based muds, performance of HGS5000 and HGS8000X are compared in terms of mud properties. Each water based mud has 2 different combinations as tested with calcium carbonate and without calcium carbonate. To obtain high performance in terms of physical and chemical mud properties; fluid loss, plastic viscosity, yield point and gel strengths of different type of water based muds are compared.

HGS5000 is an engineered hollow glass sphere that has a pressure resistance of 5000 psi. It has a density of 0.38 g/cc. It is tested with 3 types of water based muds to lower mud density and obtain high performance mud properties. Along with mud densities and rheologies, the bridging affect of the material is inspected in terms of fluid loss values and filter cake properties.

HGS8000X is another type of hollow glass sphere which has a pressure resistance up to 8000 psi. Its density is higher than HGS5000 and its particle size diameter is lower than HGS5000. HGS8000X is also tested with different types of water based muds to achieve a mud density of 6.88 ppg and proper physical and chemical mud properties.

The fluid loss comparisons of two different hollow glass spheres in different types of water based muds are given in Figures 5.1 through Figure 5.24.

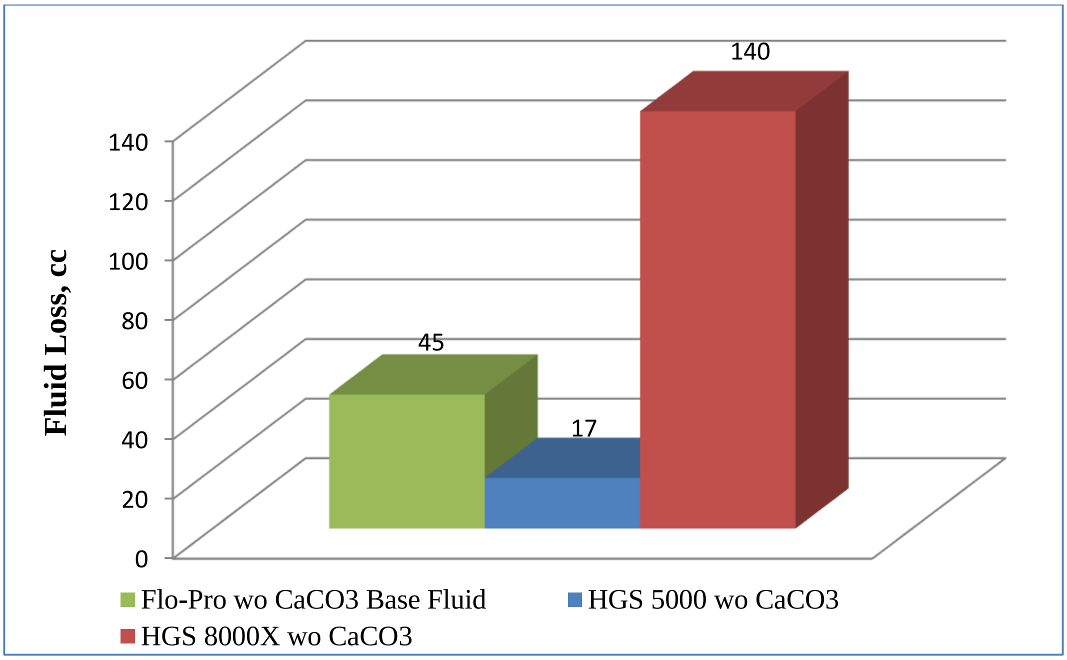

Figure 5. 1: Fluid loss comparison for Flo-Pro mud without $CaCO_3$

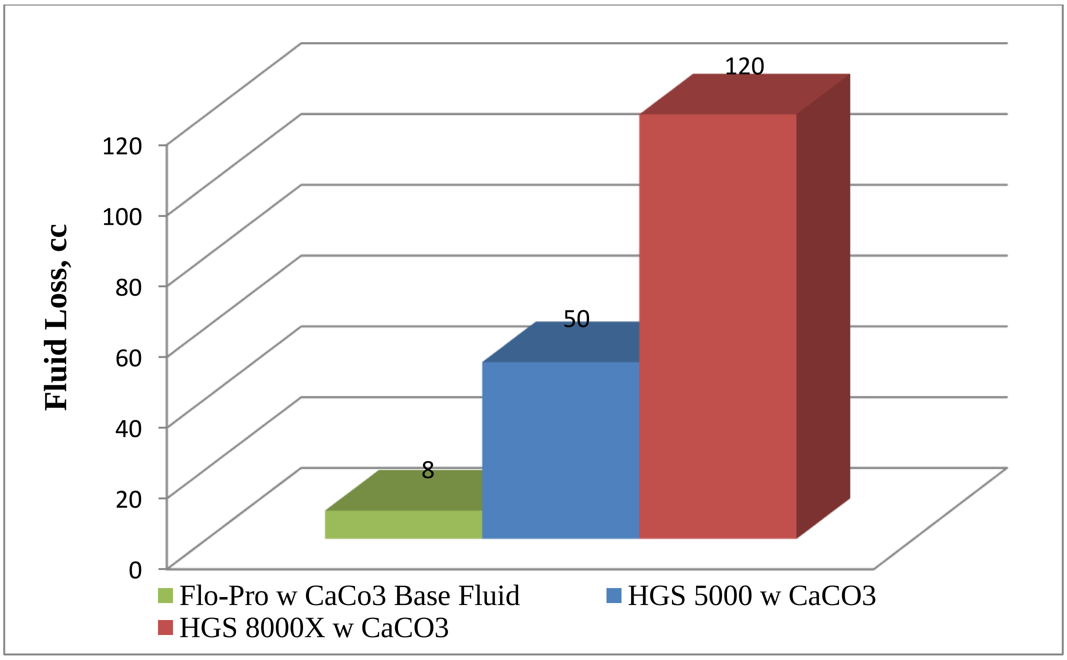

Figure 5. 2: Fluid loss comparison for Flo-Pro mud with $CaCO_3$

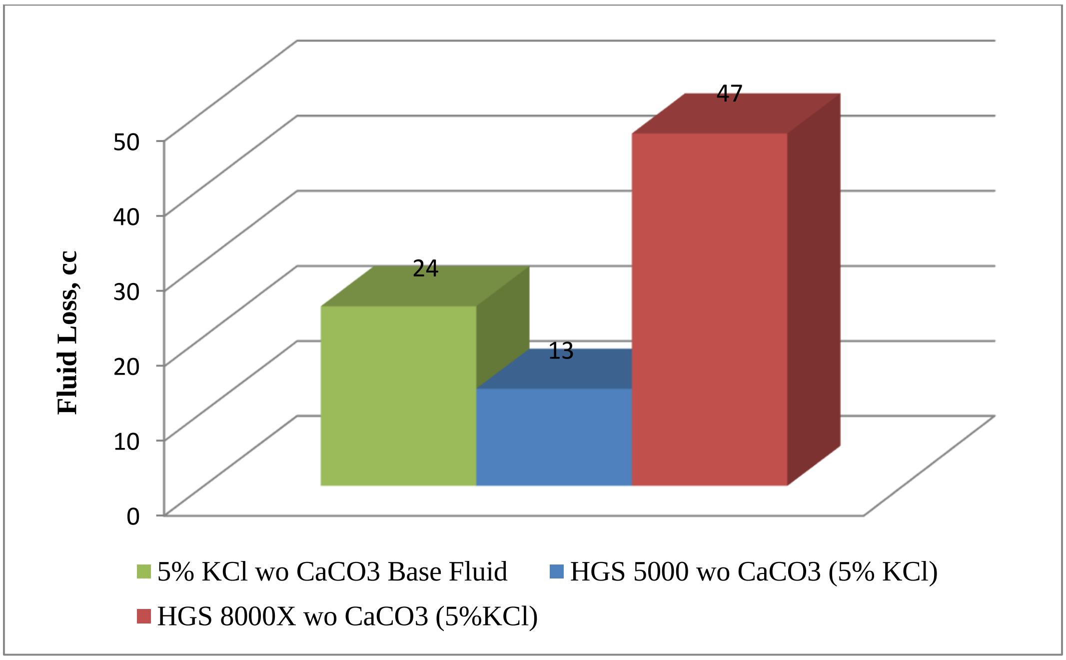

Figure 5. 3: Fluid loss comparison for 5% KCl/Polymer mud without $CaCO_3$

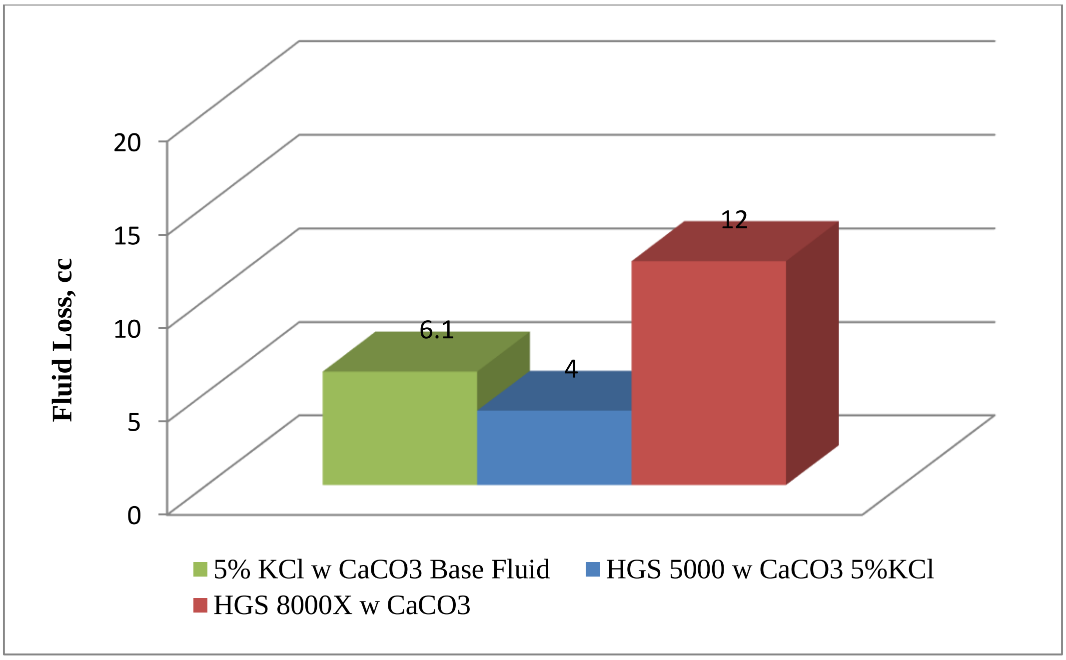

Figure 5. 4: Fluid loss comparison for 5% KCl/Polymer mud with $CaCO_3$

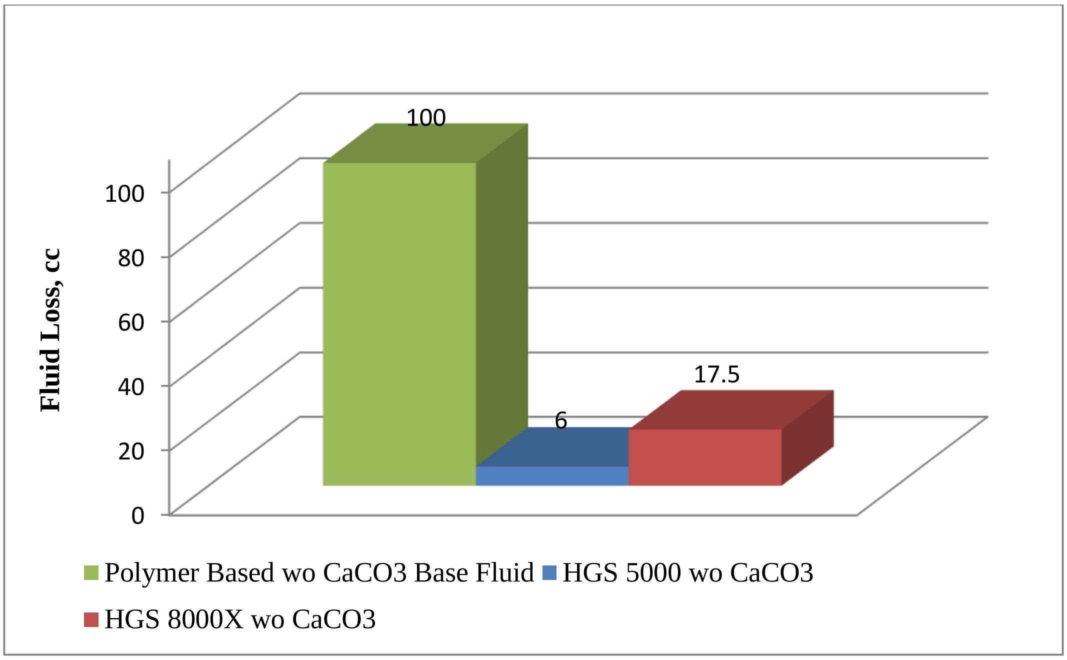

Figure 5. 5: Fluid loss comparison for Polymer based mud without $CaCO_3$

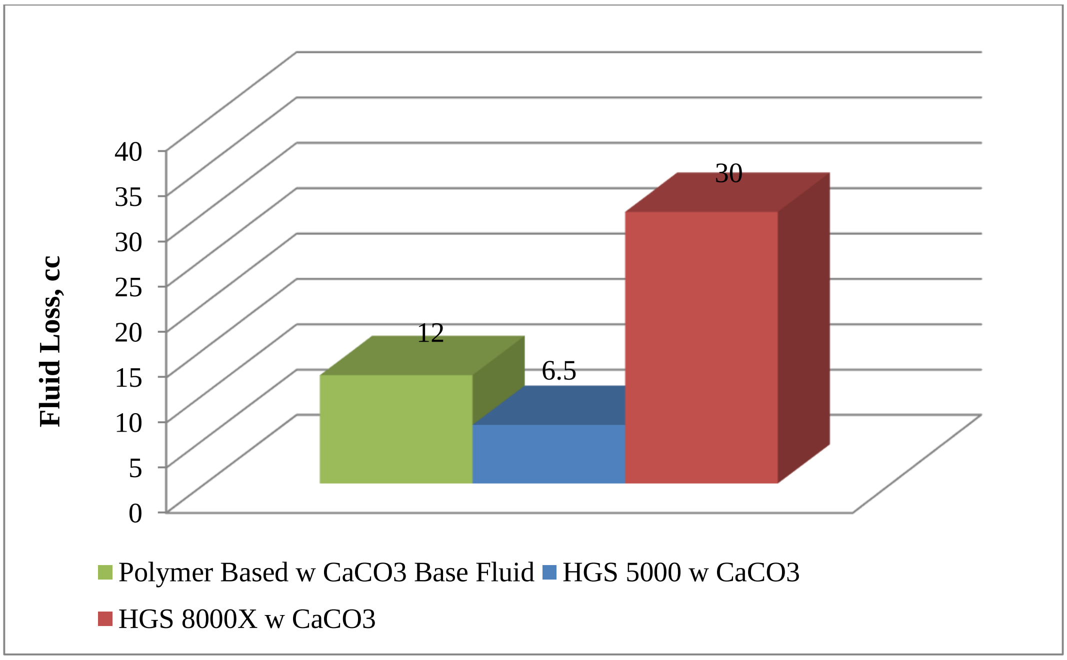

Figure 5. 6: Fluid loss comparison for Polymer based mud with $CaCO_3$

Fluid loss comparisons are made to see the behavior of different hollow glass spheres in 3 different water based mud types. HGS5000 has lower fluid losses than HGS8000X in all combinations. In Flo-Pro mud, fluid losses for HGS8000X are both very high without and with calcium carbonate ($CaCO_3$) concentrations respectively 140cc and 120cc.

In 5% KCl/Polymer mud and Polymer based mud, HGS5000 behaves as a bridging agent and lowers fluid losses both combinations with and without calcium carbonate($CaCO_3$) as seen in Figures 5.3, 5.4, 5.5 and 5.6. HGS8000X's fluid loss values are high in comparison with HGS5000.

The plastic viscosity (PV) comparisons of two different hollow glass spheres in different types of water based muds are as follows:

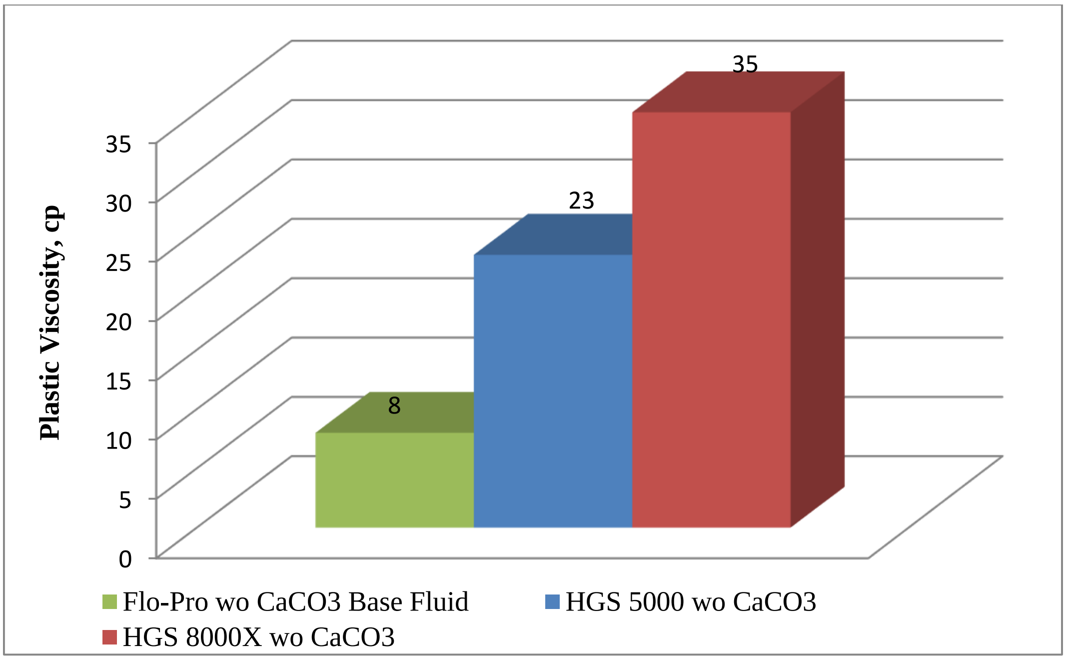

Figure 5. 7: Plastic viscosity comparison of Flo-Pro mud without $CaCO_3$

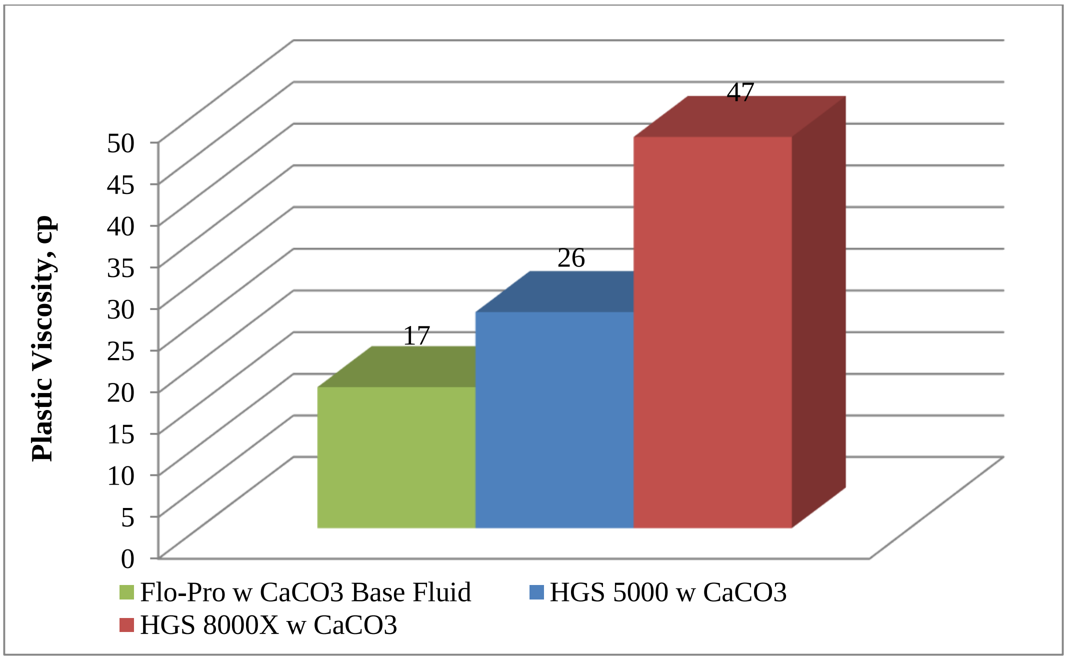

Figure 5. 8: Plastic viscosity comparison of Flo-Pro mud with $CaCO_3$

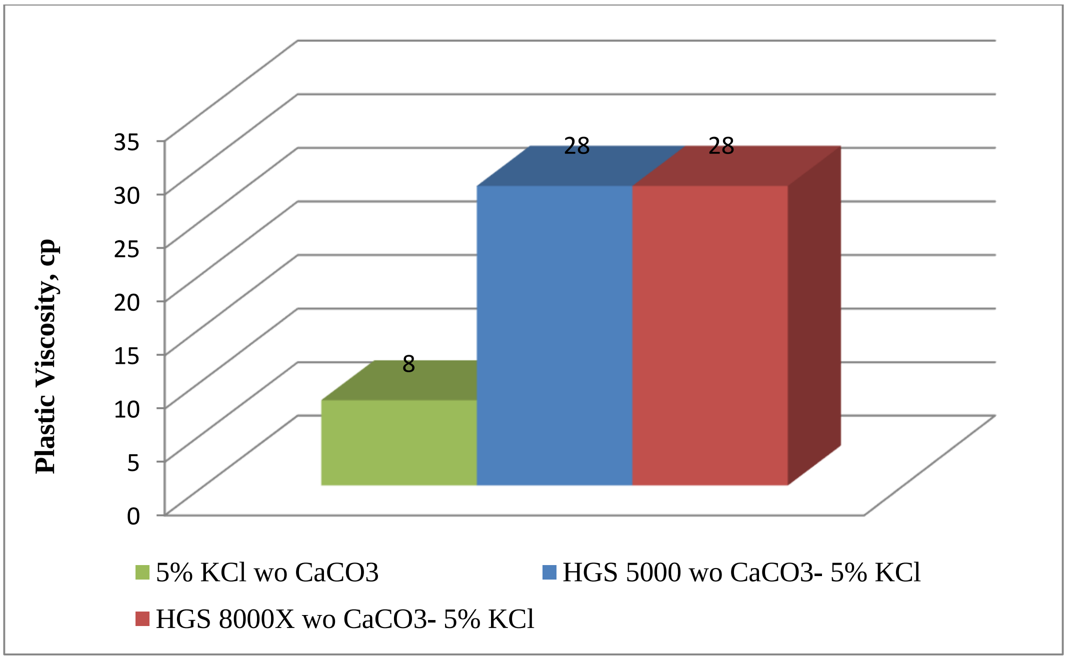

Figure 5. 9: Plastic viscosity comparison of 5% KCl/Polymer mud without $CaCO_3$

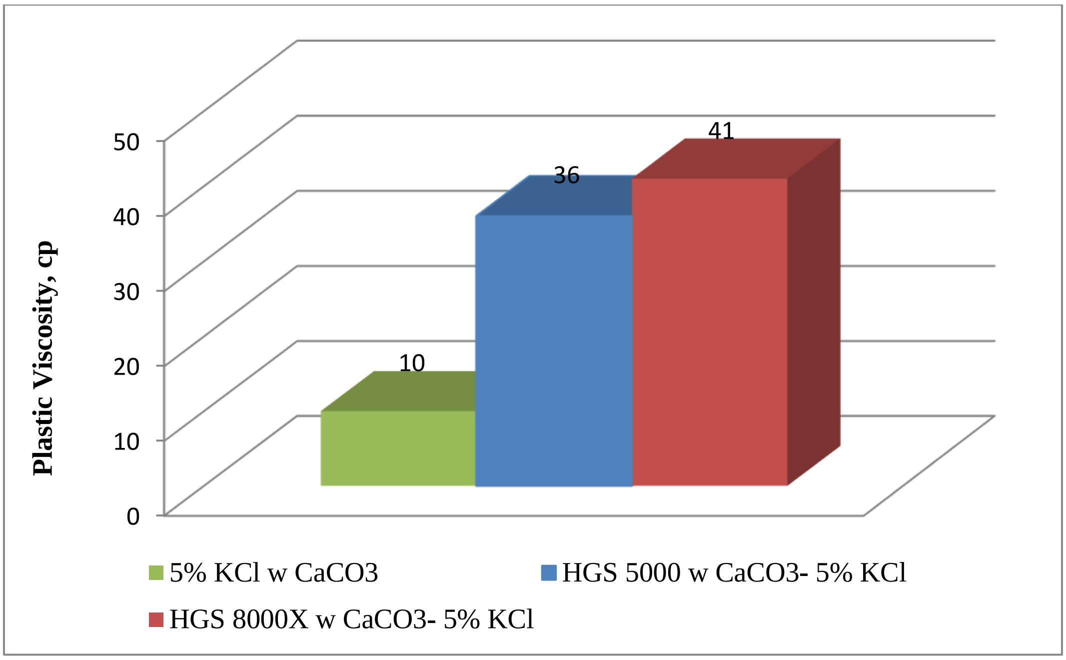

Figure 5. 10: Plastic viscosity comparison of 5% KCl/Polymer mud with $CaCO_3$

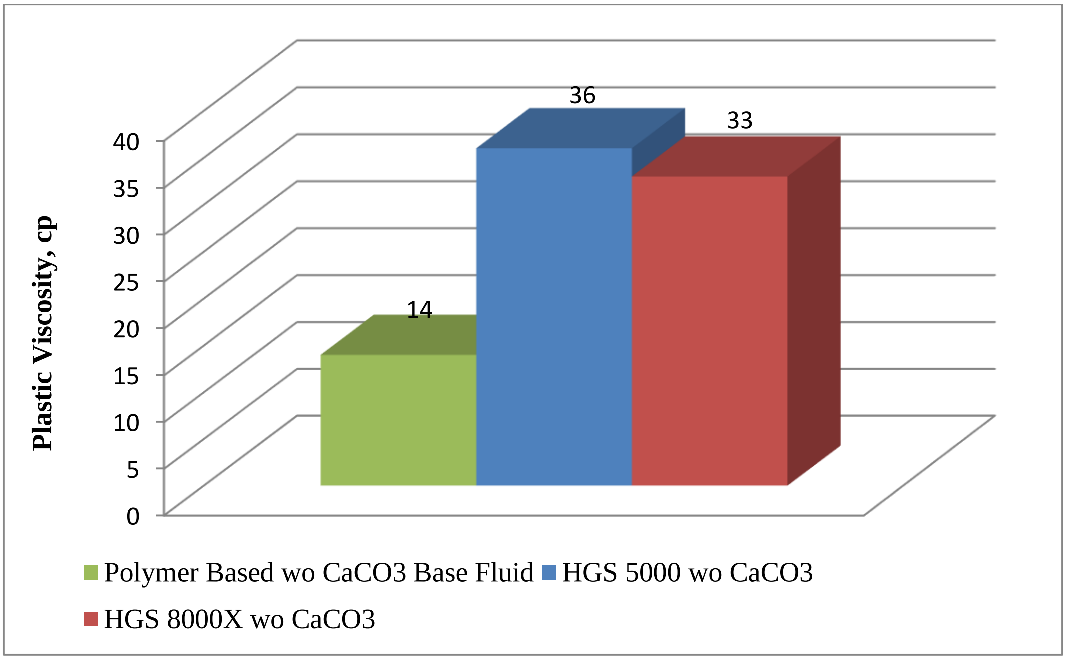

Figure 5. 11: Plastic viscosity comparison of Polymer based mud without $CaCO_3$

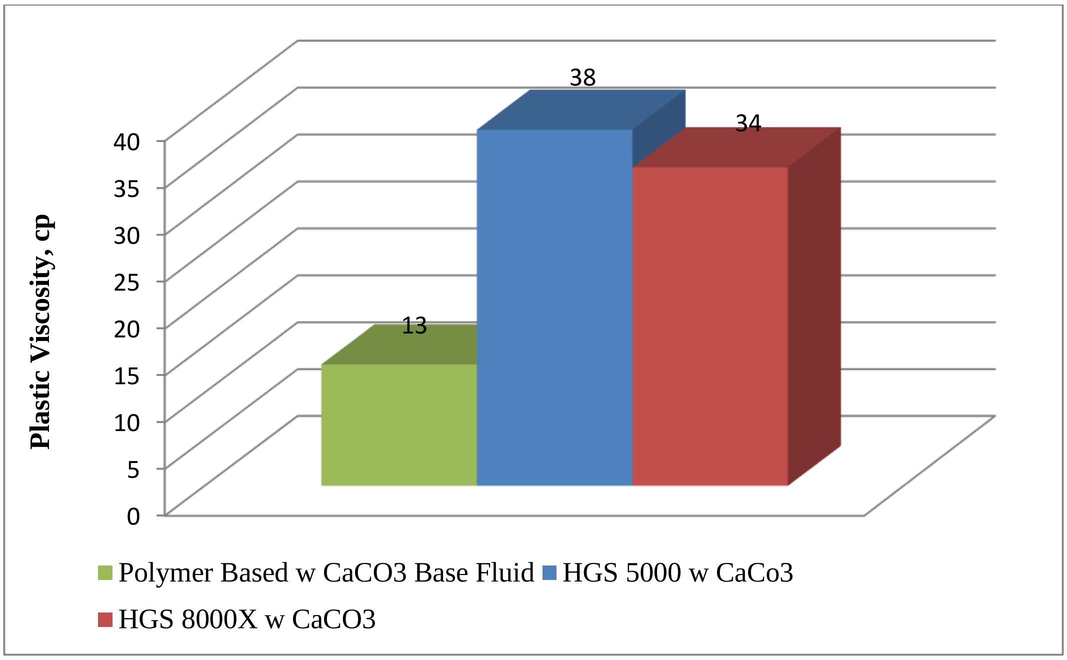

Figure 5. 12: Plastic viscosity comparison of Polymer based mud with $CaCO_3$

As seen in Figure 5.7 and Figure 5.8, plastic viscosity (PV) of both Flo-Pro concentrations increase with addition of hollow glass spheres. HGS8000X's plastic viscosity values are higher than of HGS5000's.

For 5% KCl/Polymer mud and Polymer based mud, plastic viscosity also increases with addition of both hollow glass spheres. As illustrated in Figure 5.9, 5.10, 5.11 and 5.12, plastic viscosity does not go above 41 cp in 5% KCl/Polymer and Polymer based muds which is acceptable.

Yield point (YP) comparisons of two different hollow glass spheres in different types of water based muds are as follows:

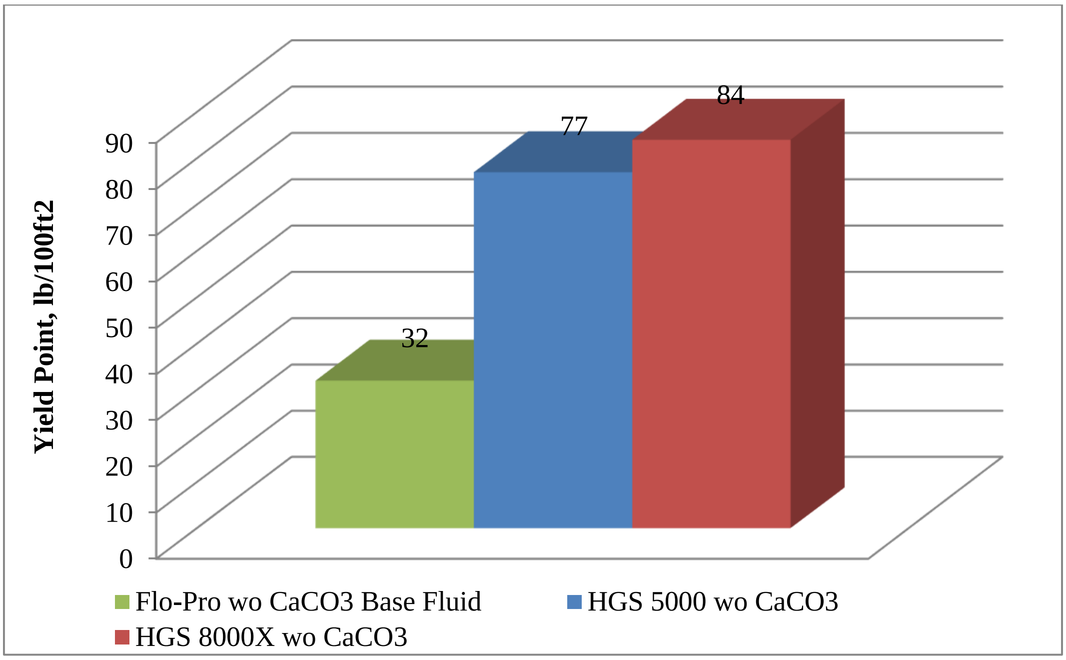

Figure 5. 13: Yield point comparison of Flo-Pro mud without $CaCO_3$

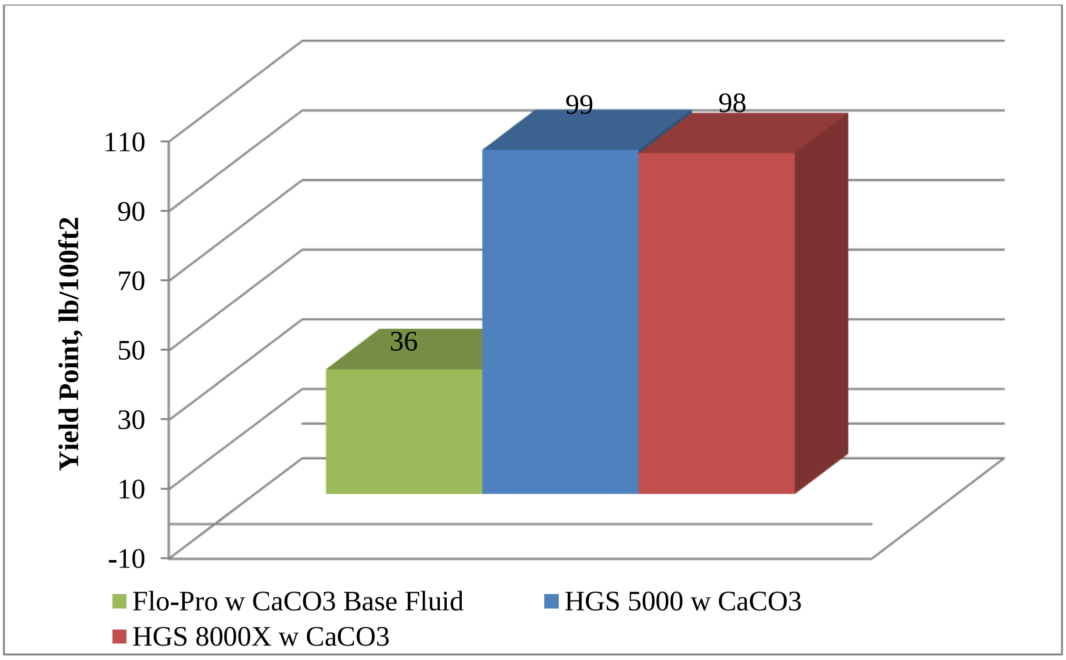

Figure 5. 14: Yield point comparison of Flo-Pro mud with $CaCO_3$

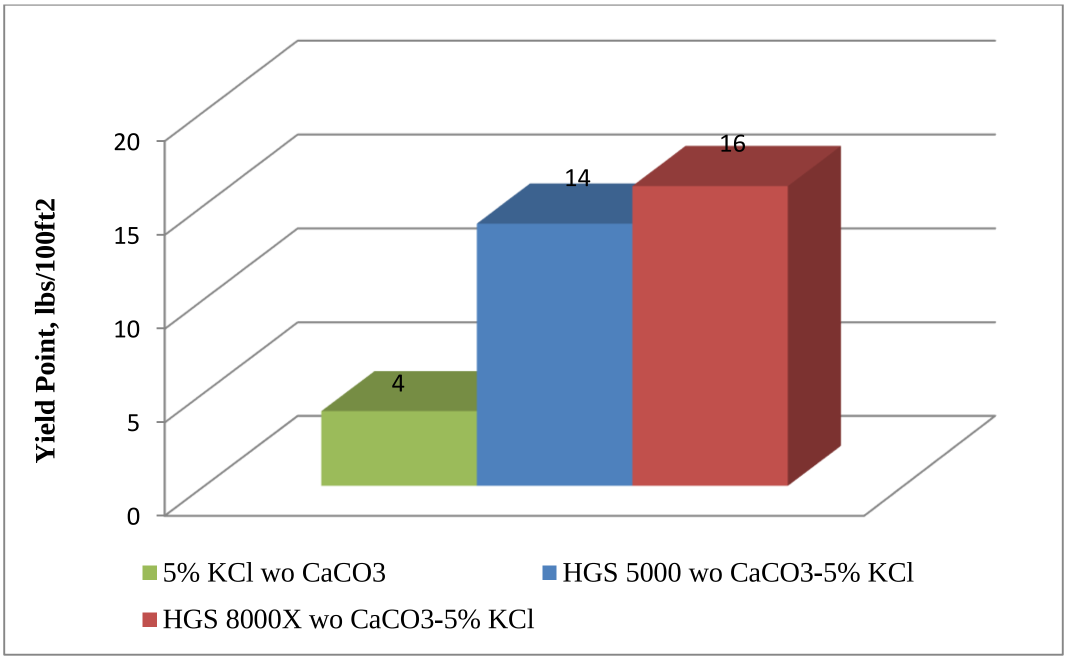

Figure 5. 15: Yield point comparison of 5% KCl/Polymer mud without $CaCO_3$

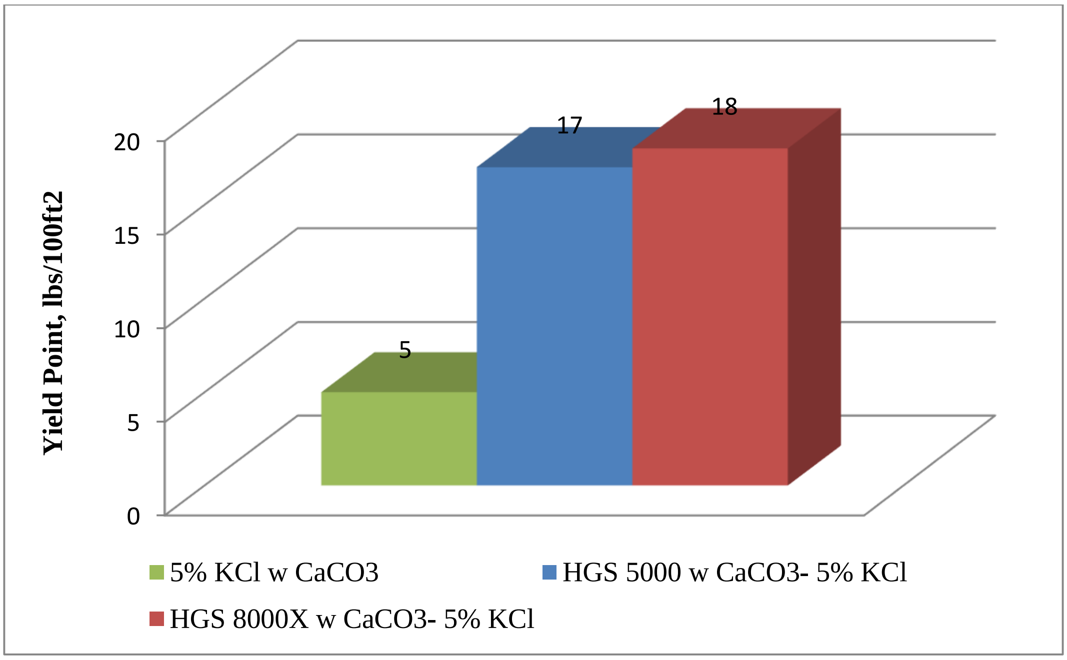

Figure 5. 16: Yield point comparison of 5%KCl/Polymer mud without $CaCO_3$

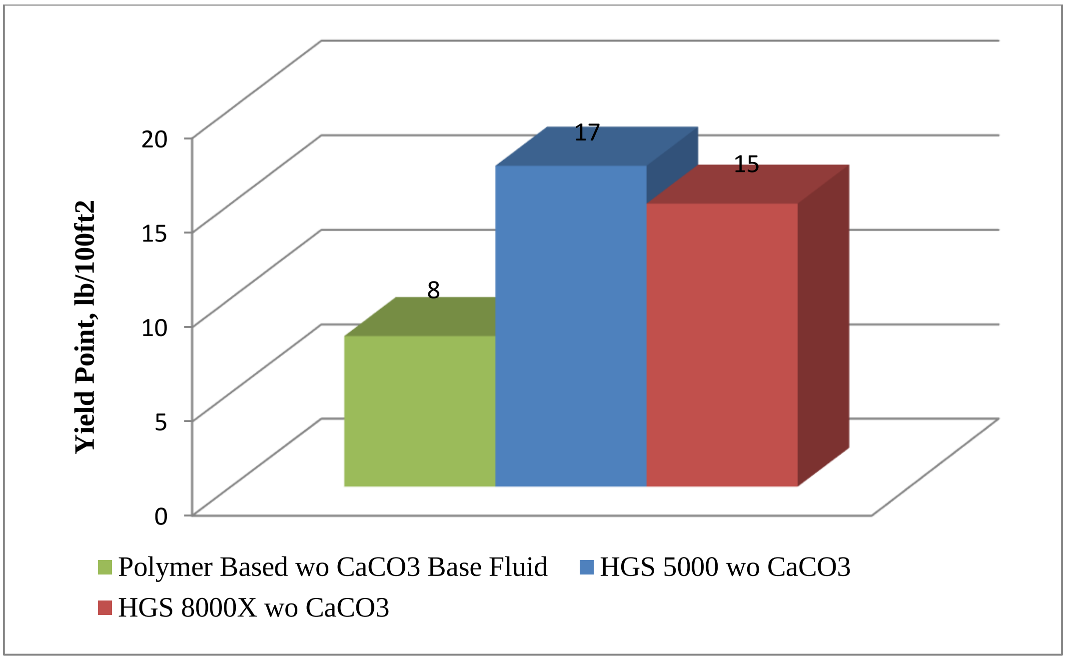

Figure 5. 17: Yield point comparison of Polymer based mud without $CaCO_3$

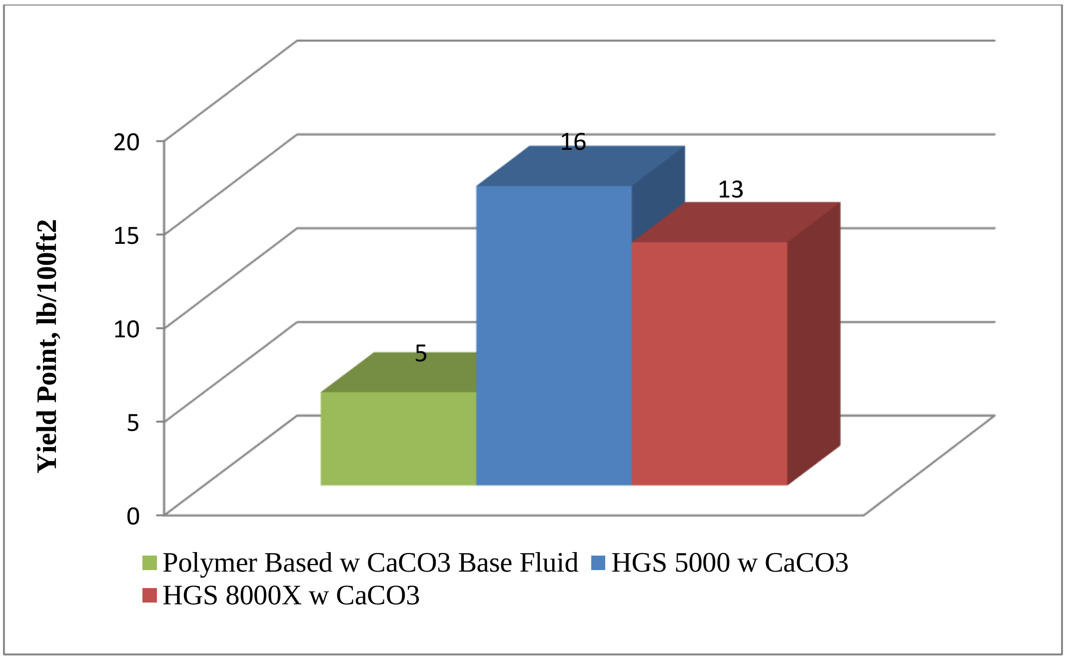

Figure 5. 18: Yield point comparison of Polymer based mud with $CaCO_3$

The rheological properties of Flo-Pro mud are very high. Yield point values of Flo-Pro mud with HGS5000 and HGS8000 compositions without calcium carbonate are respectively 77 and 84 lb/100ft^2 as figured in 5.13.

For Flo-Pro mud with calcium carbonate, yield point values of HGS5000 and HGS8000X are respectively 99 and 98 lb/100ft^2 as figured in 5.14.

As illustrated in Figure 5.15 and 5.16; yield point values of HGS8000X and HGS5000 are close to each other and not very high in both combinations with and without calcium carbonate.

For polymer based mud tests, HGS8000X's yield point values are slightly lower than HGS5000's in combinations with and without calcium carbonate. All four values are in the acceptable range.

10 seconds and 10 minutes gel strength comparisons of two different hollow glass spheres in different types of water based muds are as follows:

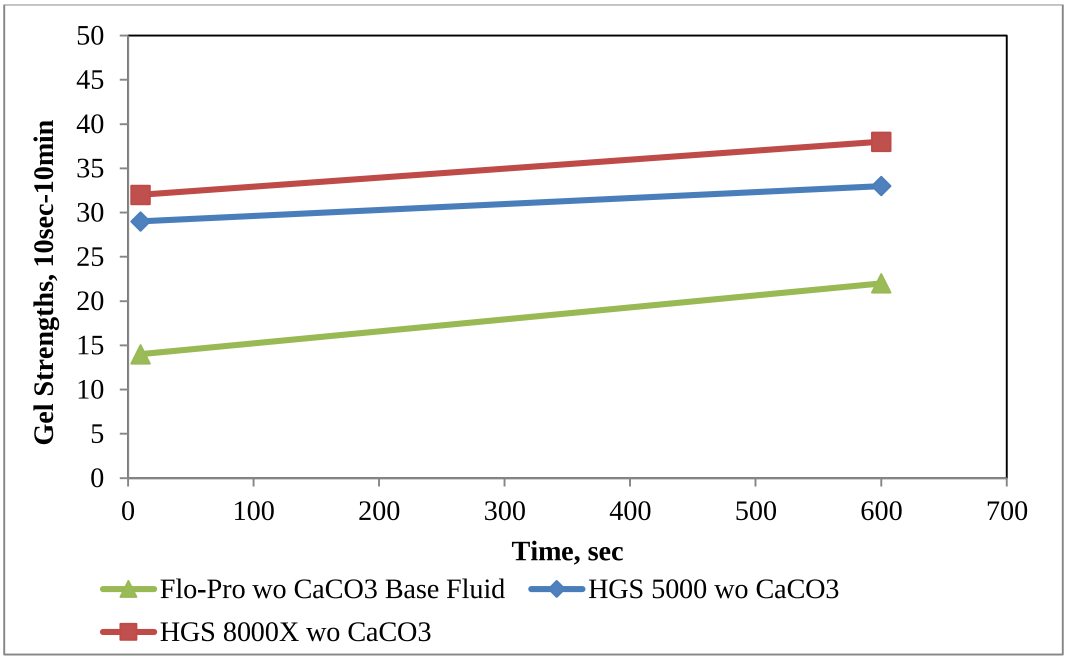

Figure 5. 19: Gel strength comparison of Flo-Pro mud without $CaCO_3$

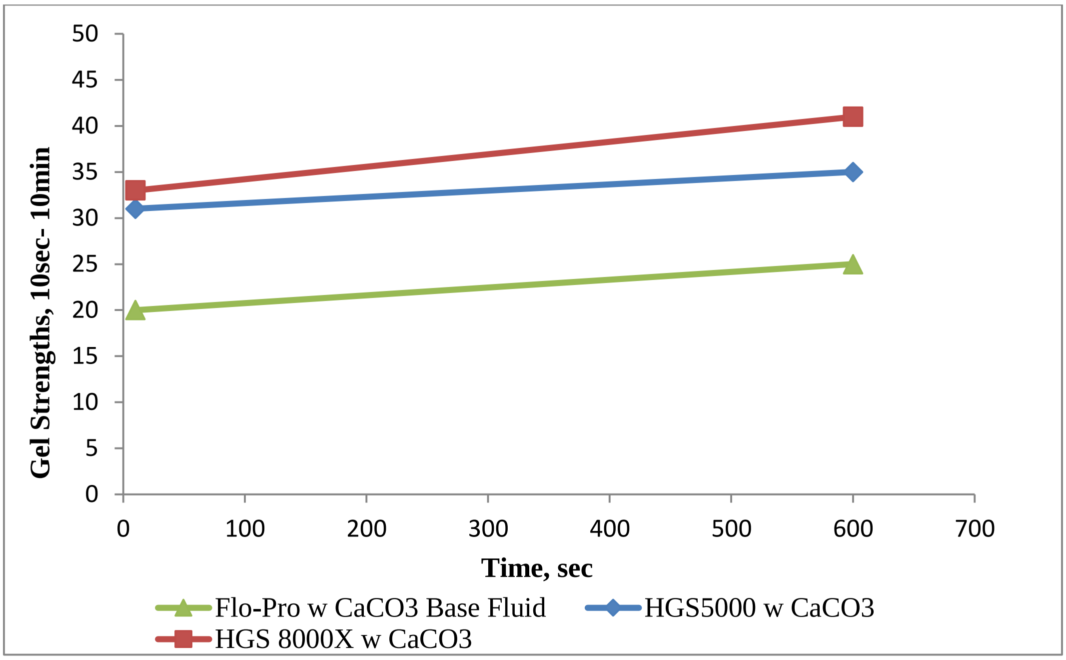

Figure 5. 20: Gel strength comparison of Flo-Pro mud with $CaCO_3$

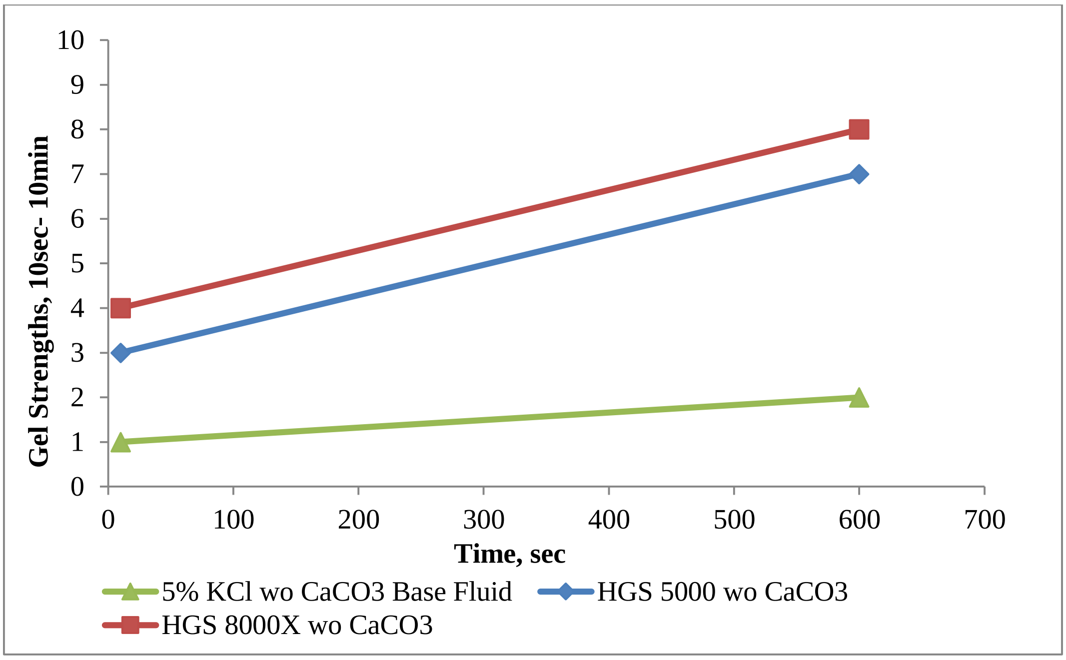

Figure 5. 21: Gel strength comparison of 5% KCl/Polymer mud without $CaCO_3$

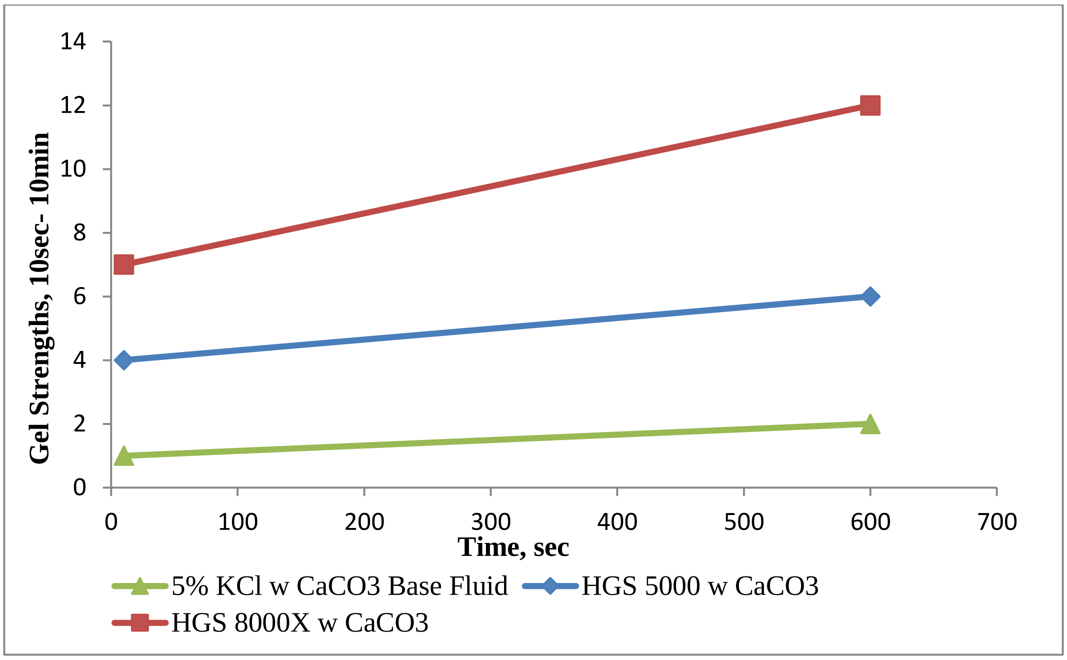

Figure 5. 22: Gel strength comparison of 5% KCl/Polymer mud with $CaCO_3$

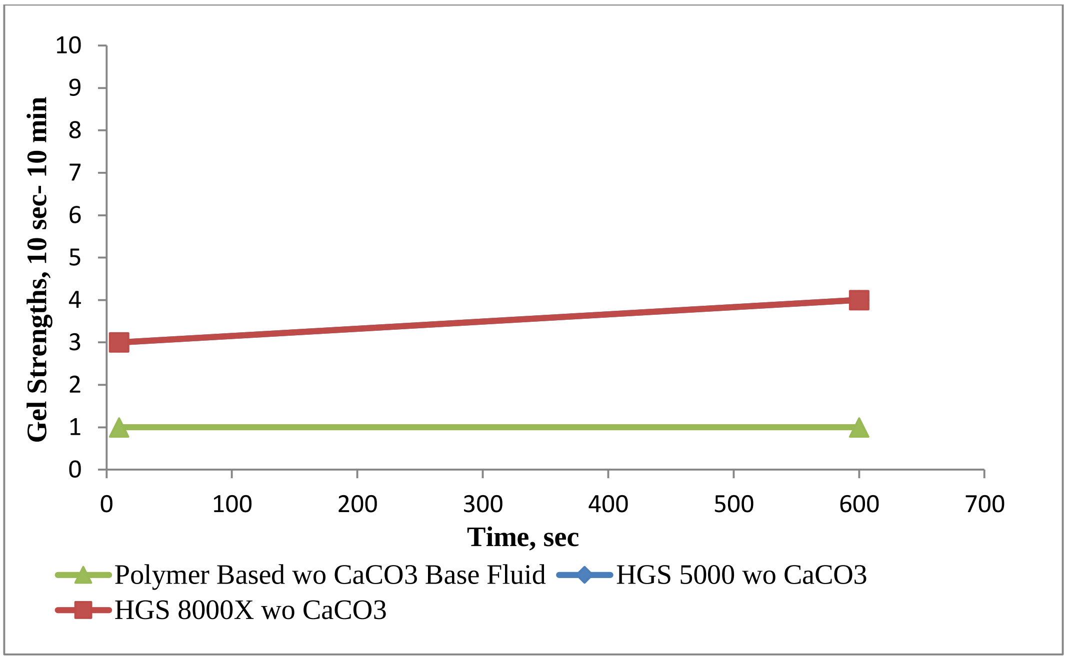

Figure 5. 23: Gel strength comparison of Polymer based mud without $CaCO_3$

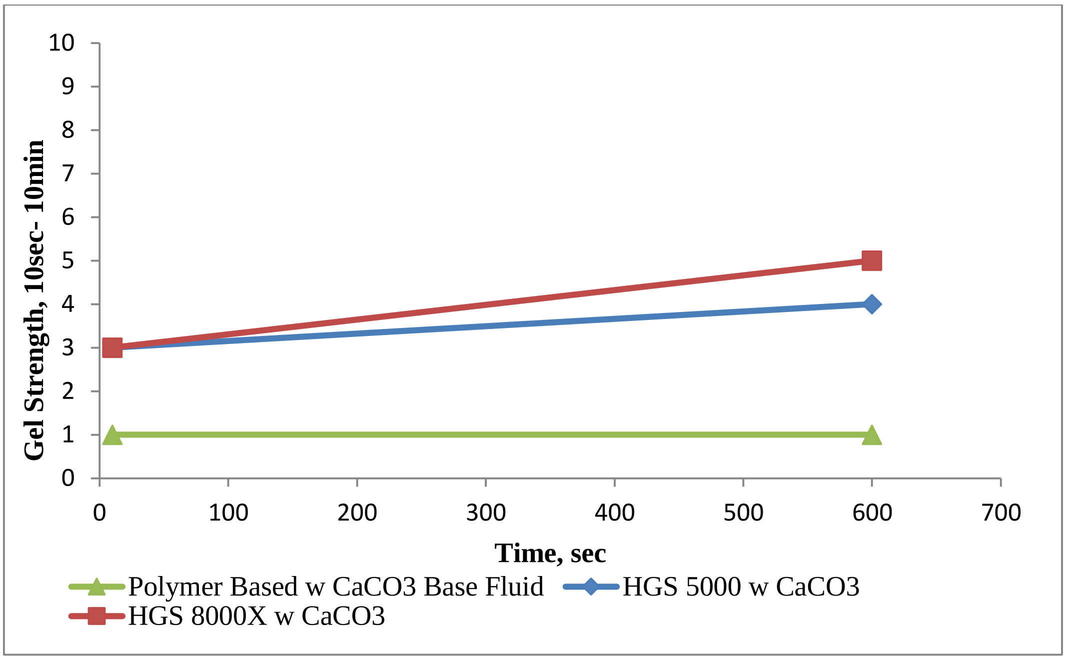

Figure 5. 24: Gel strength comparison of Polymer based mud with $CaCO_3$

Hollow glass spheres cause gelation in different rates. For Flo-Pro mud, gel strengths of the base fluid are high and with addition of hollow glass spheres 10 seconds and 10 minutes gel strengths become aggressive and have an increasing trend as seen in Figure 5.19 and 5.20.

Gel strengths of 5% KCl/Polymer mud with hollow glass spheres are not aggressive and easy to break as it can be seen from Figure 5.21 and 5.22 that HGS8000X's gelation values are higher than HGS5000's.

10 second and 10 minute gel strengths of polymer based mud with each hollow glass spheres are also not high. As figured in 5.23; gel strengths of HGS5000 and HGS8000X are the same in polymer based mud without calcium carbonate, 3 and 4 lb/100ft^2 respectively.

By interpreting the test results, it can be said that HGS5000 shows better performance than HGS8000X in terms of physical and chemical mud properties namely: fluid loss, plastic viscosity, yield point and gel strength.

Sieve Analysis of HGS5000

Sieve analysis is performed to see the behavior of HGS5000 in the solids control equipment namely shaker screens in the field operations. Two types of sieve analysis; wet sieve analysis and dry sieve analysis of HGS5000 are carried out following ASTM STP 447-B. [25] Dry sieve analysis is conducted with 100, 120 and 200 mesh size sieves. As figured in Table 5.14; residue greater than 100 mesh and 120 mesh size sieves are 0%, residue greater than 200 mesh is 3.11%. It can be said that 120 mesh, 100 mesh and lower size sieves are appropriate to use in the field operations while using a drilling fluid having HGS5000.

Table 5. 13: Dry sieve analysis results of HGS5000

Residue greater than;	%
200 mesh	3.11
120 mesh	0
100 mesh	0

Wet sieve analysis of HGS5000 results is templated in Table 5.14. Test is conducted with 200 mesh and 325 mesh size sieves. It is seen that residue greater than 200 mesh and 325 mesh size sieves are 7.65% and 37.3% respectively.

Table 5. 14: Wet sieve analysis results of HGS5000

Residue greater than;	%
200 mesh	7.63
325 mesh	37.3

As a result of dry and wet sieve analyses, it is concluded that sieves above 120 mesh are not applicable to HGS5000. For field applications, shaker screens lower than 120 mesh is recommended.

5.3. Optimization of Selected Drilling Fluid

After selecting the drilling fluid as polymer based mud and selecting hollow glass sphere type as HGS5000, optimization on the selected drilling fluid is conducted to achieve higher performance in low density drilling fluids in terms of chemical and physical properties.

In this section; $CaCO_3$ optimization, polymer optimization and PHPA optimization are presented. Elimination method is used in every part, 3 different concentrations are tested.

5.3.1. $CaCO_3$ Optimization

Bridging material used in all tests is calcium carbonate ($CaCO_3$). In this section optimization of calcium carbonate amount is performed. In these tests fine size calcium carbonate are used. 5ppb, 10ppb and 15ppb concentrations are tested. The amount of calcium carbonate is determined.

Table 5.15 states three drilling flluids with different amounts of fine size calcium carbonates:

Table 5. 15: Different $CaCO_3$ concentrations

ADDITIVES	1.TD*:6.88	2.TD*:6.88	3.TD*:6.88
Water, cc	350	350	350
M. Starch, ppb	4	4	4
Pac-Lv, ppb	3	3	3
XCD, ppb	0.25	0.25	0.25
CaCO3, ppb (fine-60EXT)	5	10	15
NaOH, ppb	0.1	0.1	0.1
HGS5000, ppb	46.20	48.47	48.3
Volume of base fluid, bbl	0.85	0.84	0.84
Mud, cc	298.6	292.6	294
Density, ppg	8.4	8.49	8.55

*:Target Density, ppg

The amount of HGS5000 added to the drilling fluids differs due to different base fluid mud densities. The amounts of HGS5000 added to the drilling fluids are calculated with respect to 3M-HGS5000 excel sheet. In the first composition 46.2 ppb HGS5000 is added to 298.6cc mud to achieve a density of 6.88 ppg. For the second composition 48.47ppb HGS5000 is needed for a 292.6cc mud to have 6.88 ppg mud densities. 48.3ppb HGS5000 added to 294cc drilling fluid in the third composition. The difference is occured in consequence of base fluids density because of the difference in $CaCO_3$ amount.

Table 5.16 shows the test results of different $CaCO_3$ concentrations:

Table 5. 16: Test results of different $CaCO_3$ concentrations

RESULTS	**1.TD*:6.88**	**2.TD*:6.88**	**3.TD*:6.88**
600 rpm	91	87	92
300 rpm	53	50	54
200 rpm	39	36	40
100 rpm	23	21	24
6 rpm	4	3	4
3 rpm	3	2	3
pH	9.9	9.7	9.8
PV, cp	38	37	38
YP, $lb/100ft^2$	15	13	16
Gel Strength 10sec/10min	3/4	3/4	3/4
Fluid Loss, cc	7.5	3.9	6.5
Density, ppg	6.88	6.88	6.88

*:Target Density, ppg

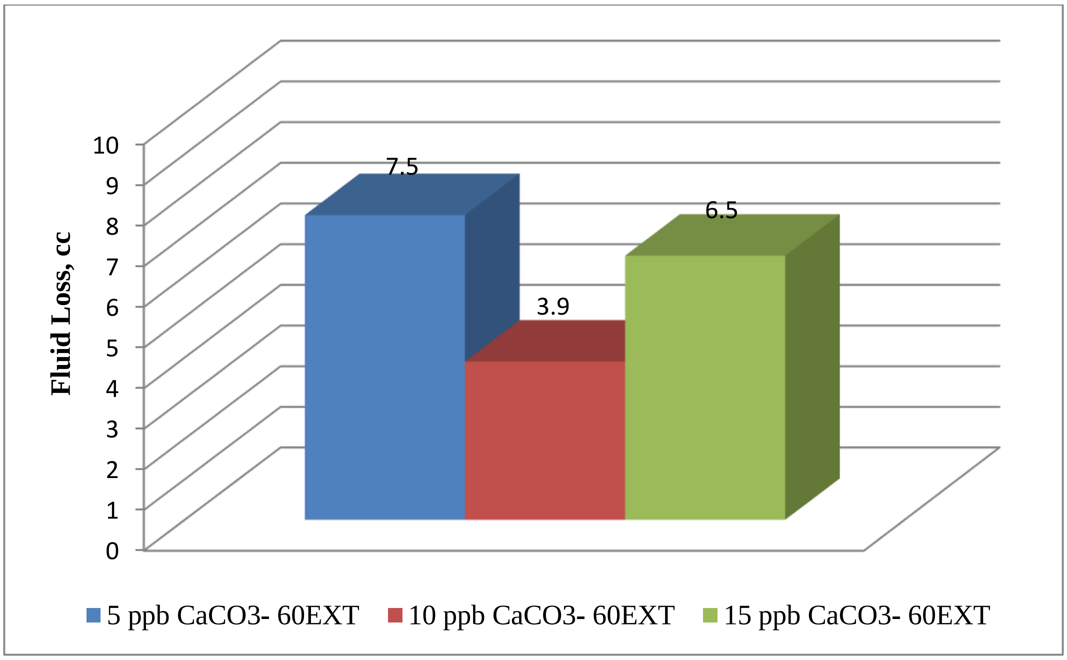

Figure 5. 25: Fluid loss of different $CaCO_3$ concentrations

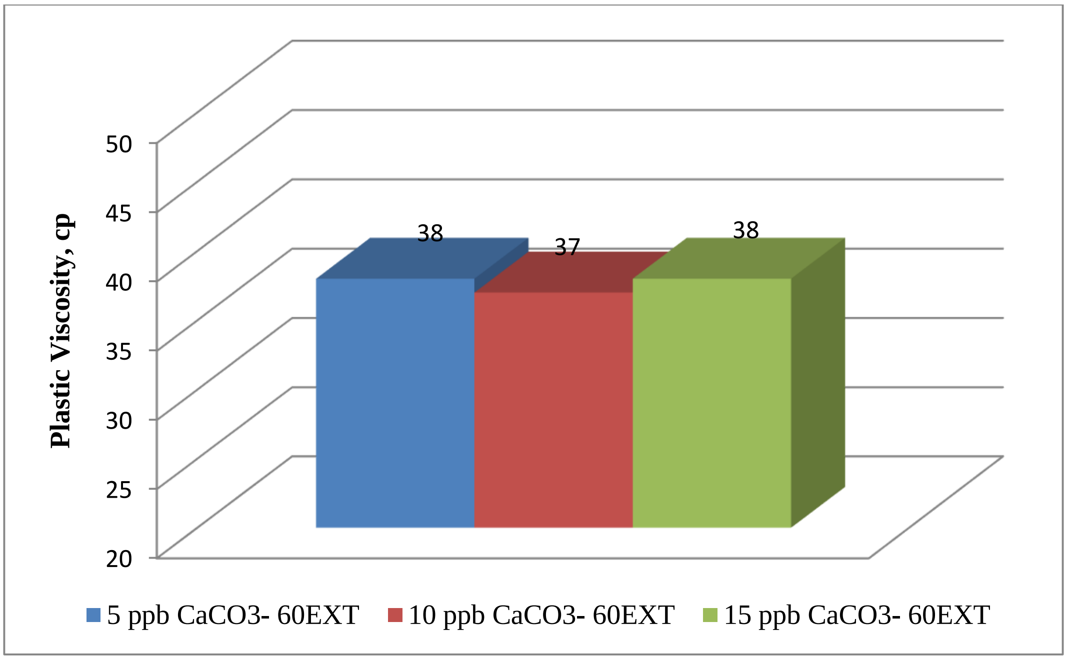

Figure 5. 26: Plastic viscosity of different $CaCO_3$ concentrations

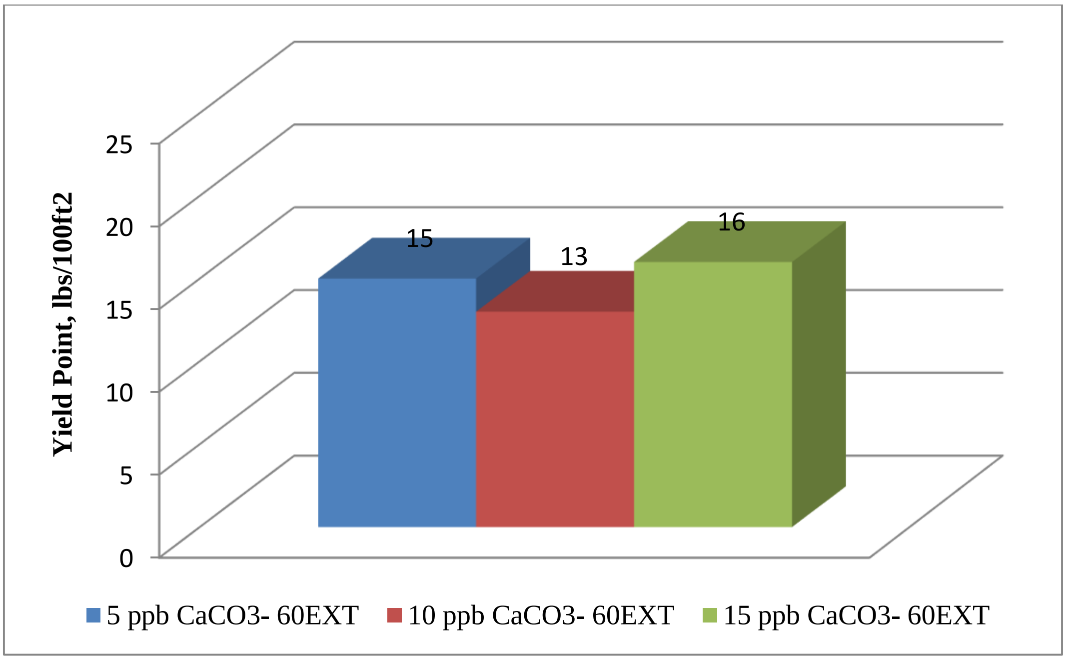

Figure 5. 27: Yield point of different $CaCO_3$ concentrations

- As it is templated in Table 5.13 and figured in Figure 5.26; plastic viscosity does not change depending on calcium carbonate amount. Plastic viscosities of 5ppb, 10ppb and 15ppb are respectively: 38 cp, 37 cp and 38 cp which are not very high.

- Yield point also does not change with $CaCO_3$ amount change as figured in Figure 5.27. Yield points of 5ppb, 10ppb and 15ppb are respectively: 15 lb/100ft^2, 13 lb/100ft^2 and 16 lb/100ft^2. Change in yield points is because of measurement uncertanities and heterogenity.

- 10 second and 10 minute gel strenghts of all three compositions are the same and 3&4 respectively as can be seen in Table 5.13.

- Fluid loss is the essential parameter on choosing the amount of $CaCO_3$ to be used. 5ppb $CaCO_3$ composition has a 7.5cc fluid loss which is above acceptable limits and its filter cake is thick and permeable. Fluid losses of 10ppb and 15ppb compositions are 3.9cc and 6.5cc respectively as figured in 5.25 and templated in

5.13. Eventough, in theory increasing bridging material leads to decrease in fluid losses, it differs in laboratory tests. 10ppb $CaCO_3$ composition has the lowest fluid loss of 3.9cc and has the best filter cake. The filter cake of 15ppb $CaCO_3$ composition is also strong and impermeable but thicker than 10ppb $CaCO_3$ composition's. That's why 10ppb is the optimum amount of $CaCO_3$ as a bridging material.

- As Medley [28] stated; after adding a certain amount of hollow glass spheres, with the increase in percentage of hollow glass spheres, fluid loss increases. Since the base fluid of 15ppb $CaCO_3$ compositions' mud density is higher, the amount of HGS need to be added is also higher than other compositions. Fluid loss of 15 ppb $CaCO_3$ composition is higher than fluid loss of 10ppb $CaCO_3$.

5.3.2. Polymer Optimization

After selecting hollow glass spheres (HGS) and water based mud, optimization of polymer concentration is carried out. 7 ppb (4 ppb Pac-Lv + 3 ppb Modified Starch) is used on the tests for HGS and drilling fluid selection. In order to find the optimum polymer concentration, different compositions such as 11 ppb (6 ppb Pac-Lv + 5 ppb Modified Starch) and 3.5 ppb (2 ppb Pac-Lv + 1.5 ppb Modified Starch) are tested.

Table 5. 17: Different polymer concentrations and its test results

ADDITIVES	**1.TD*:6.88**	**2.TD*:6.88**	**3.TD*:6.88**
Water, cc	350	350	350
M. Starch, ppb	4	6	2
Pac-Lv, ppb	3	5	1.5
XCD, ppb	0.25	0.25	0.25
CaCO3, ppb	10 (60 EXT)	10 (60EXT)	10 (60EXT)
NaOH, ppb	0.1	0.1	0.1
HGS5000, ppb	48.44	48.44	48.44
Volume of base fluid, bbl	0.84	0.84	0.84
Mud, cc	292.6	292.6	292.6
Density, ppg	8.5	8.5	8.5
RESULTS	**TD*:6.88**	**TD*:6.88**	**TD*:6.88**
600 rpm	87	**300**	66
300 rpm	50	222	40
200 rpm	36	174	30
100 rpm	21	106	18
6 rpm	3	13	3
3 rpm	2	8	2
pH	9.7	9.6	9.7
PV, cp	37	78	26
YP, $lb/100ft^2$	13	144	14
Gel Strength 10sec/10min	3/4	8/10	2/3
Fluid Loss, cc	3.8	3.6	100
Density, ppg	6.9	6.9	6.9

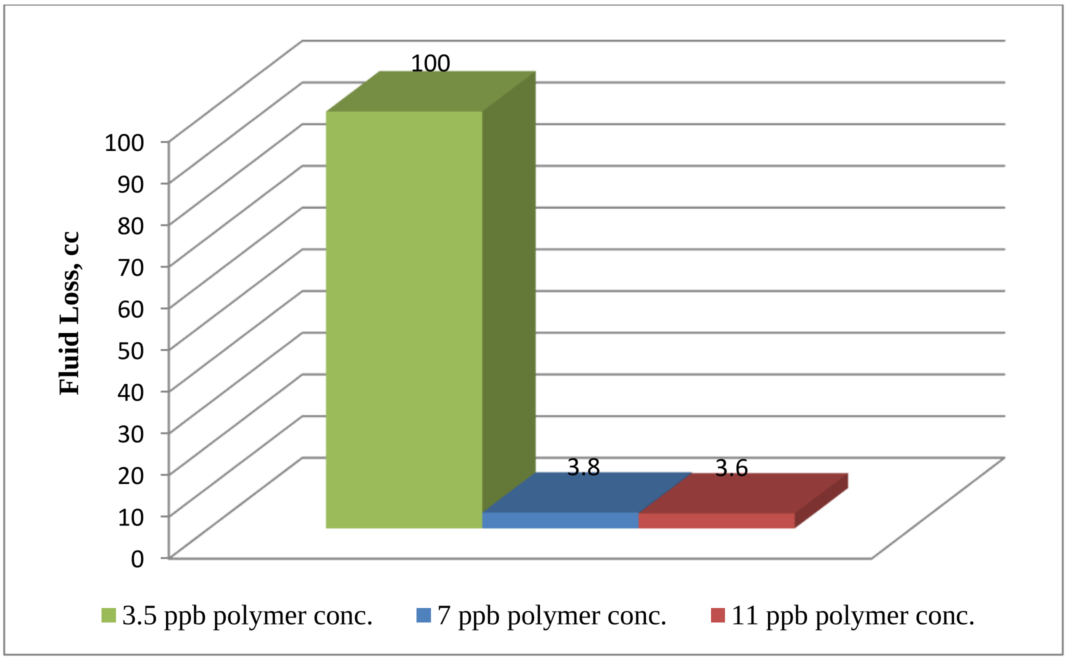

Figure 5. 28: Fluid loss of different polymer concentrations

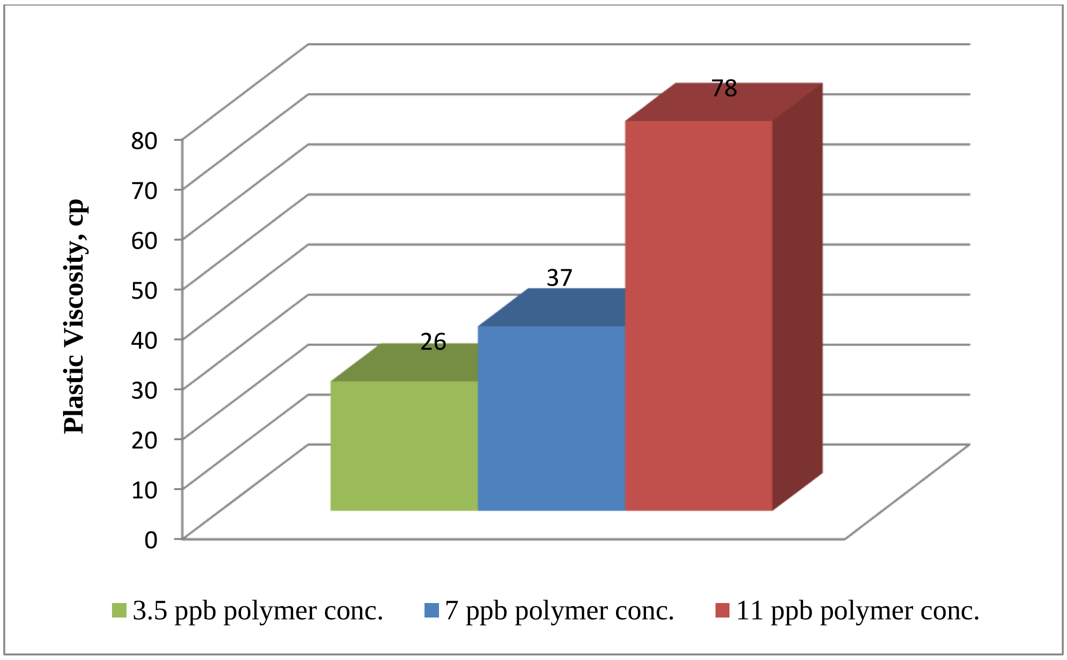

Figure 5. 29: Plastic viscosity of different polymer concentrations

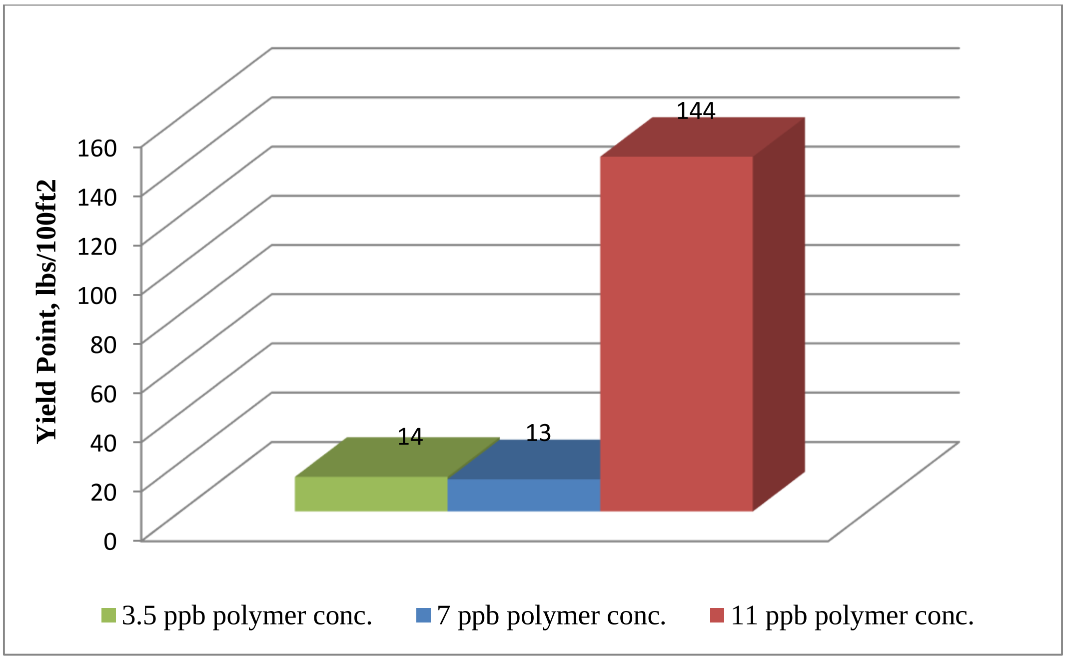

Figure 5. 30: Yield point of different polymer concentrations

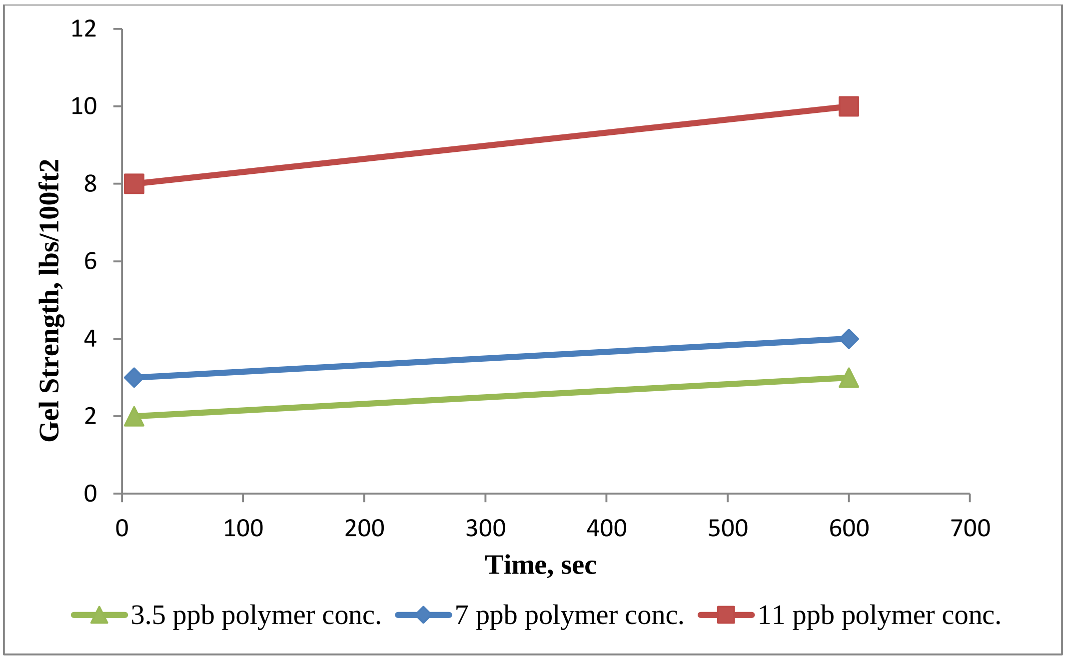

Figure 5. 31: Gel strengths of different polymer concentrations

- As templated in Table 5.14 and figured in 5.7 fluid loss of 3.5 ppb (2 ppb Pac-Lv+ 1.5 ppb Modified Starch) polymer concentration is higher than other two compositions. 7 ppb (4 ppb Pac-Lv+ 3 ppb Modified Starch) and 11 ppb (6 ppb Pac-Lv+ 5 ppb Modified Starch) polymer concentrations give similar results in terms of fluid loss.

- 600 rpm reading of 11 ppb (6 ppb Pac-Lv+ 5 ppb Modified Starch) polymer concentration is above 300 and could not be read exactly. For plastic viscosity (PV) and yield point (YP) calculations, 600 rpm reading is recorded as 300.

- Gel Strengths of 11 ppb (6 ppb Pac-Lv+ 5 ppb Modified Starch) polymer concentration is also higher than other two compositions as figured in Figure 5.10. The excess usages of polymers cause gelation. 7 ppb (4 ppb Pac-Lv+ 3 ppb Modified Starch) and 3.5 ppb (2 ppb Pac-Lv+ 1.5 ppb Modified Starch) concentrations have similar 10 seconds and 10 minutes gel strengths and they are not too aggressive.

- As it can be seen from Figure 5.8, plastic viscosity (PV) increases with increasing polymer concentration. Eventhough PV values of 7 ppb (4 ppb Pac-Lv+ 3 ppb Modified Starch) and 3.5 ppb (2 ppb Pac-Lv+ 1.5 ppb Modified Starch) concentrations which are 37 cp and 26 cp respectively are reasonable, 78 cp of 11 ppb (6 ppb Pac-Lv+ 5 ppb Modified Starch) concentration is very high.

- pH values do not differ depending on polymer concentrations. All three values are close to each other.

- Higher polymer concentrations affect rheological properties of drilling fluid as plotted in Figure 5.9. 11 ppb (6 ppb Pac-Lv+ 5 ppb Modified Starch) concentration has a yield point (YP) of 144 lbs/100ft^2. Other two compositions have similar YP values and fine flow properties physically.

- In the light of these interprets, polymer concentration of the base drilling fluid is determined as 7 ppb (4ppb Pac-Lc+ 3ppb Modified Starch).

5.3.3. PHPA

PHPA which is an acrylic copolymer is a dispersible additive used for cuttings encapsulation, shale stabilization and micro fracture sealing. [29] It is commonly used in drilling of shale and clay based formations where shale stabilization is an issue. Table 5.18 shows the compositions and test results of different PHPA concentrations with HGS5000 to achieve a mud density of 6.88ppg.

Table 5. 18: Different PHPA concentrations and its test results

ADDITIVES	**1.TD*:6.88**	**2.TD*:6.88**	**3.TD*:6.88**	**4.TD*:6.88**
Water, cc	350	350	350	350
M. Starch, ppb	4	4	4	4
Pac-Lv, ppb	3	3	3	3
XCD, ppb	0.25	0.25	0.25	0.25
CaCO3, ppb	10	10	10	10
NaOH, ppb	0.1	0.1	0.1	0.1
PHPA, ppb	-	0.5	1	1.5
HGS5000, ppb	48.44	48.44	48.44	48.44
Volume of base fluid, bbl	0.84	0.84	0.84	0.84
Mud, cc	292.6	292.6	292.6	292.6
Density, ppg	8.5	8.5	8.5	8.5
RESULTS	**TD*:6.88**	**TD*:6.88**	**TD*:6.88**	**TD*:6.88**
600 rpm	87	124	150	255
300 rpm	50	83	99	144
200 rpm	36	62	75	106
100 rpm	21	38	47	65
6 rpm	3	5	8	16
3 rpm	2	3	5	11
pH	9.7	9.7	9.5	9.4
PV, cp	37	41	51	111
YP, $lb/100ft^2$	13	42	48	33
Gel Strength 10sec/10min	3/4	3/4	6/7	11/14
Fluid Loss, cc	3.8	4.2	8.5	14.6

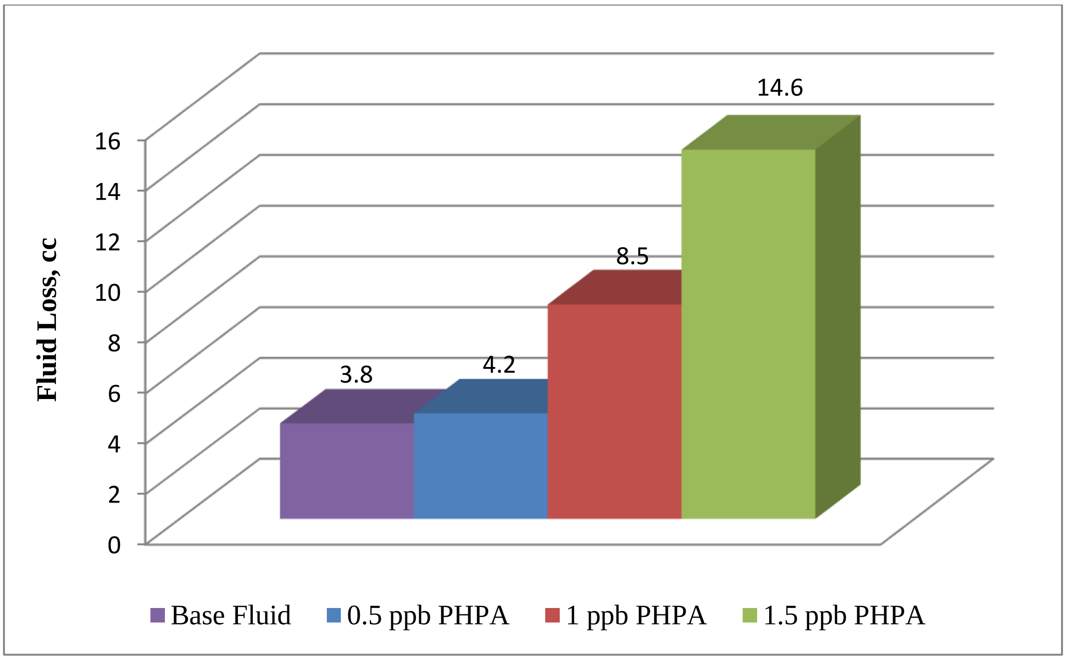

Figure 5. 32: Fluid loss of different PHPA concentrations

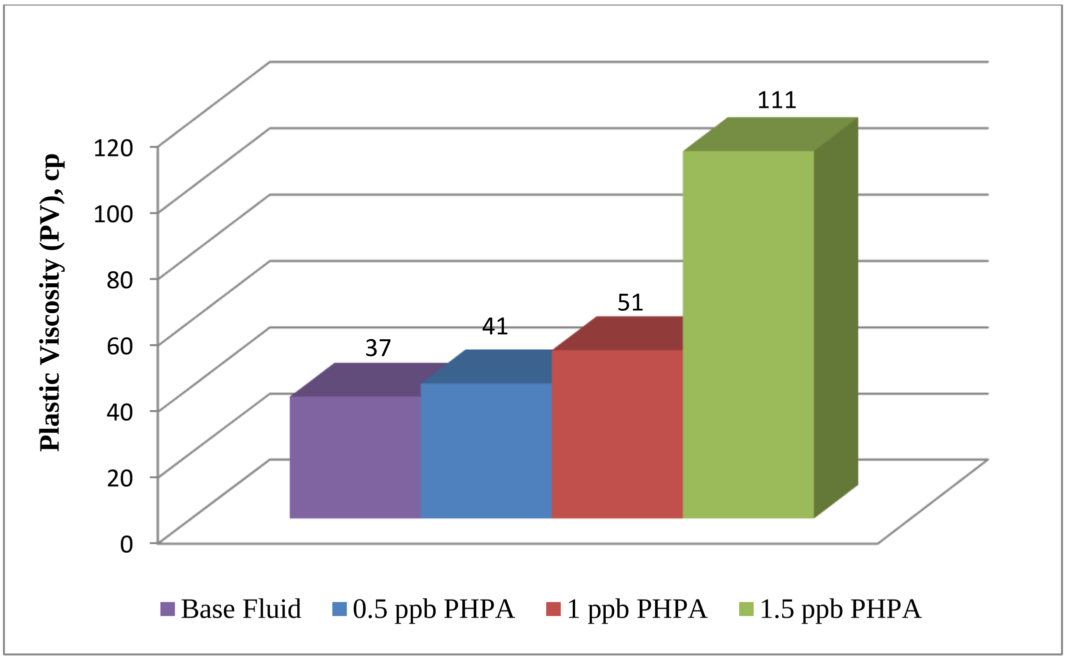

Figure 5. 33: Plastic viscosity of different PHPA concentrations

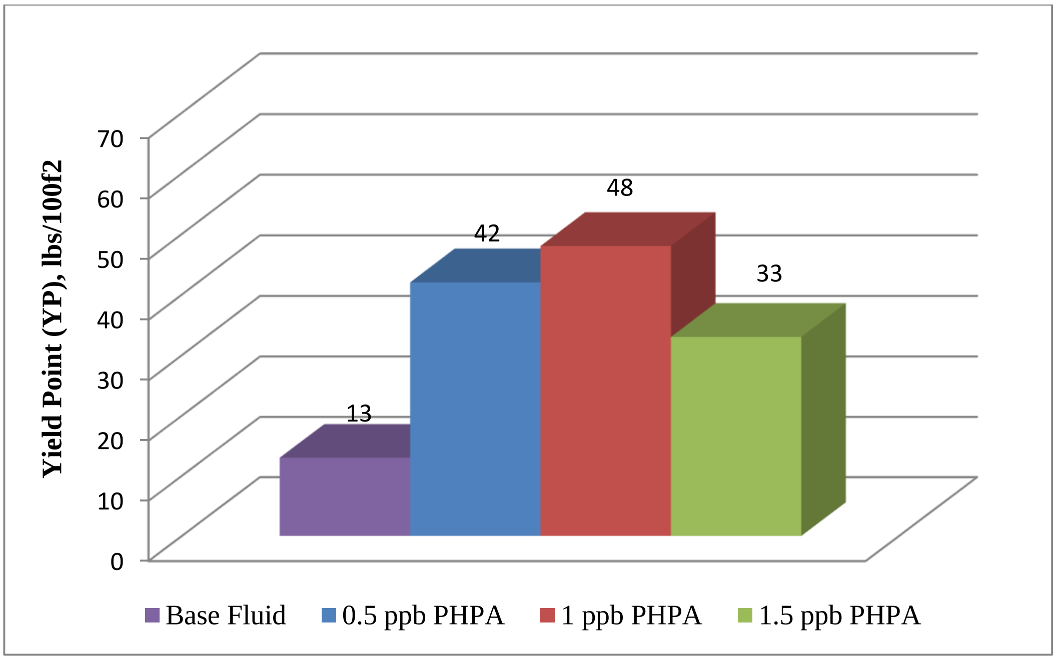

Figure 5. 34: Yield point of different PHPA concentrations

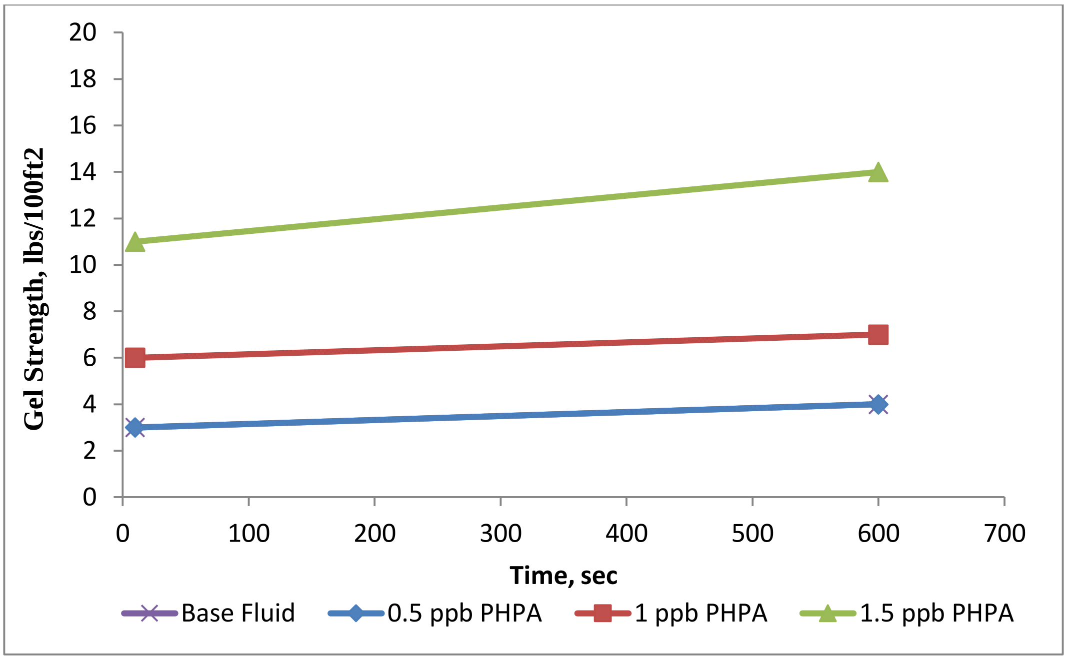

Figure 5. 35: Gel strengths of different PHPA concentrations

- Fluid loss values increase with increasing PHPA concentration. As the capacity for holding cuttings on suspension increases, settling rate decreases and it reduces the quality of filter cake.

- As templated in Table 5.16, Plastic viscosity increases sharply due to increase in PHPA concentration. It can be easily seen from Figure 5.13. 1.5 ppb PHPA concentration has a PV value of 111 cp which is way above acceptable limits.

- Rheological properties of all three drilling fluids are high and it affects flow properties negatively. Figure 5.14 shows the difference between base fluid and PHPA added mixtures.

- 10 seconds and 10 minutes gel strengths of base fluid and 0.5 ppb PHPA concentration are even and 3 and 4 respectively. Gel strengths of 1 ppb PHPA concentration are also fair and 6 and 7 respectively but gel strengths of 1.5 ppb PHPA concentration is high; numerically 11 and 14 and tends to be more aggressive which can be seen in Figure 5.15.

- The optimum pH range for PHPA is between 8.5 and 10.5. [29] Figure 5.16 shows that PHPA causes a slight decrease in pH with increasing concentration however the decrease in pH is not remarkable.

- PHPA is the chemical to be used in shale stabilization and micro fracture sealing. The main aim of this study is finding the optimum concentration for a drilling fluid with a density of 6.88 ppg to drill low pressure reservoirs. Since, there is no shale or clay based formations in reservoir sections, shale stabilization is not a necessity. Also sealing micro fractures in reservoir section could cause plugging in production stage.

- The need for PHPA in a low pressure reservoir is not important and laboratory test results show that different concentrations of PHPA cause increase in plastic viscosity and gel strength.

- By contrast with SPE paper "Use of Hollow Glass Spheres for Underbalanced Drilling Fluids" [28]; PHPA is not efficient in low density drilling fluids according to laboratory test results. Not only it affects the chemical properties, but also affects the flow of the drilling fluid physically.

Filter Cake Analysis

In the selection of proper mud type with proper HGS, achieving 6.88 ppg mud density was the most important parameter. Physical and chemical mud properties are also investigated in each composition. Fluid loss values and filter cake properties are the leading parameters on the selections. Table 5.19 shows the filter cake thicknesses of tested mud types with different HGSs.

Table 5. 19: Filter cake thickness of different mud types

HGS added mud/ Bridging agent	without $CaCO_3$	with $CaCO_3$
Flo-Pro with HGS5000	5/32"	7/32"
Flo-Pro with HGS8000	11/32"	11/32"
KCl/Polymer with HGS5000	4/32"	4/32"
KCl/Polymer with HGS8000	8/32"	4/32"
Polymer based with HGS5000	2/32"	2/32"
Polymer based with HGS8000	5/32"	7/32"

Polymer based mud with HGS5000 has the lowest filter cake thicknesses with and without $CaCO_3$. To have the thinnest and the strongest filter cake, 3 different concentrations of $CaCO_3$ are tested. Table 5.20 shows the thickness of different concentrations of $CaCO_3$ and it is seen that 10 ppb $CaCO_3$ has the thinnest filter cake. Figure 5.36 shows the picture of it.

Table 5. 20: Filter cake thickness of different concentrations of $CaCO_3$

HGS added mud/ Bridging agent	5 ppb $CaCO_3$	10 ppb $CaCO_3$	15 ppb $CaCO_3$
Polymer based with HGS5000	3/32”	1/32”	2/32”

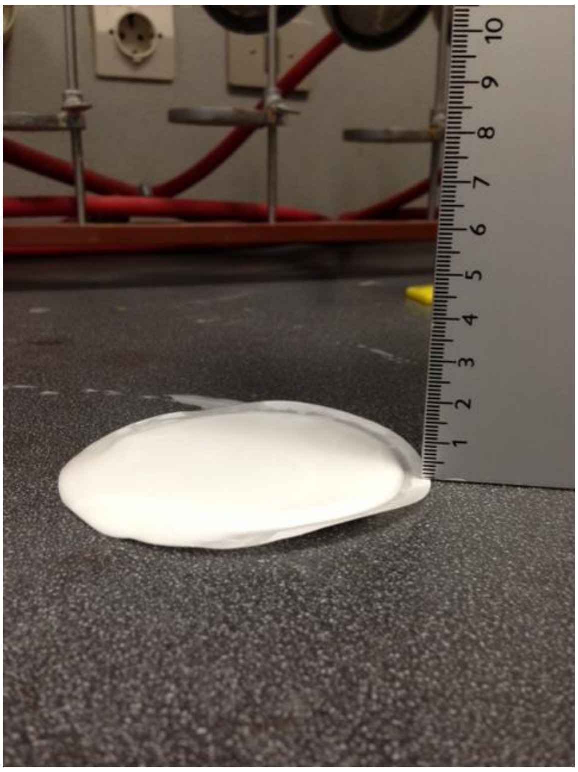

Figure 5. 36: Filter cake of polymer based (10ppb $CaCO_3$) with HGS5000

Repeatability

Throughout this study, every test is repeated at least two times and if the results are not close, numbers of tests conducted are increased until achiving consistent results. To illustrate, fluid loss value of 7 ppb total polymer concentration is 3.9 cc when first tested in $CaCO_3$ optimization part as seen in Table 5.16. For the same composition; fluid loss value is 3.9 cc when tested for polymer optimization part as seen in Table 5.17. Since the tested material is a fluid with many additives, small differences on the results can be ignored.

CHAPTER 6

CONCLUSIONS

During this study, performance of light weight drilling fluids which contain hollow glas spheres (HGS) is examined. Different water based muds with different types of HGS are tested. Laboratory tests are conducted in TPAO Research Center. The results are interpreted and the following conclusions are drawn from the study:

- Water based mud is selected between Flo-Pro, KCl/Polymer and Polymer based muds with tests carried out both HGS5000 and HGS8000X. Polymer based mud is seen to be the best option in terms of chemical and physical properties.

- Since the base fluid density of KCl/Polymer mud is higher than Polymer based mud, the amount of HGS needed to achieve 6.88ppg is higher. Laboratory tests show that, homogenity of the drilling fluid affects the test results sharply. It is seen that; as the amount of HGS in the drilling fluid increases, homogenity of the drilling fluid decreases thus its mud properties do not fulfill the necessities.

- Polymer based mud without potassium chloride (KCl) gives the best result in terms of fluid loss, filter cake properties, rheological properties and gelation. Its filter cake is strong, impermeable and thin. Rheological properties do not increase too much. 10 second and 10 minute gel strengths do not increase aggressively.

- Hollow glass sphere (HGS) selection is made. As the pressure in the well to encounter is lower than 5000 psi, pressure resistances of HGSs are higher than 5000psi. HGS5000 and HGS8000X are tested with different water based muds.
- Eventhough HGS8000X is more resistant to pressure than HGS5000; muds with HGS8000X do not fulfill the necessities. Especially, fluid losses are much higher with HGS8000X in every water based mud composition. Filter cake thicknesses

are measured and qualities are observed. Compositions with HGS5000 has lower filter cake thicknesses and it is selected as the optimum HGS.

- Different amounts of calcium carbonate are tested with the selected drilling fluid. It is seen that from some point, increasing the calcium carbonate ratio does not lower the fluid loss. 10 ppb $CaCO_3$ gives the best fluid loss and best filter cake.

- Distinctly from mixing chemicals in conventional methods to the drilling fluid. HGS need more attention to be mixed. Since the material is light and flyer. Homogenity should be ensured. The mixture of HGS and drilling fluid should be stable.

- In field applications; proper working pits, good mixing equipment, subsurface guns and air pumps are needed to ensure the homogenity of drilling fluid.

- The lowest mud density achieved is 6 ppg. But its filter cake is thick and weak, rheological properties, fluid loss and gelation are very high.

CHAPTER 7

RECOMMENDATIONS

This study is an important step to understand the behavior of lower density fluids by adding HGS. Throughout this study, laboratory tests are conducted on room conditions. For upcoming studies:

- Tests can be carried out under pressure for increasing pressures up to 5000 psi for HGS5000 and 8000 psi for HGS8000X to see the rheological properties of the drilling fluid. Studies on the resistance of HGS and its effect on plastic viscosity under pressure may be investigated.

- Oil based mud (OBM) can be tested with HGS for lower mud densities.

- For geothermal wells and high pressure and high temperature (HPHT) wells, tests can be made at higher temperatures and pressures.

- To decrease filter loss and to increase filter cake quality; different types of bridging materials can be used for further studies.

REFERENCES

[1] Use of 3M Glass Bubbles in Drilling Fluids, General Guidelines, (2012).

[2] Thyagaraju, B. A., Pratap, K. K., Pangtey, K. S., Trivedi, Y. N., Garg, S., Georges, G. P., Goff, D. A., & Devadass, M. (2009, October). *Case Study Using Hollow Glass Microspheres to Reduce the Density of Drilling Fluids in the Mumbai High, India and Subsequent Field Trial at GTI Catoosa Test Facility*. SPE/IADC Middle East Drilling Technology Conference Exhibition, Manama, Bahrain.

[3] Alberty, M. W., & Mclean, M. R. (2001). *Fracture Gradients in Depleted Reservoirs- Drilling Wells in Late Reservoir Life*. SPE/IADC Drilling Conference, Amsterdam, The Netherlands.

[4] *Fluid Facts Engineering Handbook*. (Rev. ed., Vol. C). Baker Hughes INTEQ, (1999).

[5] Hawker, D. (2001). *Abnormal Formation Pressure Analysis*. (ver ed., 2.1). Datalog.

[6] Drilling Fluids Engineering Manual. M-I Swaco, (1998).

[7] Caenn, R., Darley, H. C. H., & Gray, G. R. (2001). *Composition and Properties of Drilling and Completion Fluids*. (6th ed.).

[8] *Prevention and Control of Lost Circulation: Best practices, Reference Manual*. ARCO- Baker Hughes INTEQ, (1999).

[9] Bernadette, G. (2006, November). *Well Services SWBT IT Modules*.

[10] Mata, C. (2011). *Unique Density Reduction Technology for Fluids*. 3M Energy and Advanced Materials Division.

[11] Mcdonald, W. J., Cohen, J. H., & Hightower, C. M. (n.d.). *New Lightweight Fluids for Underbalanced Drilling*. Houston, Texas: Maurer Engineering INC.

[12] Devadass, M. (2007). *Glass Bubbles in O&G Applications*. 3M Glass Bubbles for Drilling Fluids.

[13] 3M Glass Bubbles, HGS Series, Product Information, (2009).

[14] Blanco, J., Ramirez, F., Mata, F., Ojeda, A., & Atencio, B. (2002, May). *Field Application of Glass Bubbles as a Density Reducing Agent in an Oil Base Drilling Fluid for Marginal/Low-permeability/Low-pressure Reservoirs*. SPE Gas Technology Symposium, Calgary, Alberta, Canada.

[15] Chen, G., & Burnett, D. (2003, May). *Improving Performance of Low Density Drill in Fluids with Hollow Glass Spheres*. SPE European Formation Damage Conference, The Hague, The Netherlands.

[16] 3M Glass Microspheres, Compounding and Injection Molding Guidelines, 2008.

[17] Ovcharenko, A. V., Vietsovpetro, J. V., & Devadass, M. (2010, February). *Assessment on the Performance of Hollow Glass Microspheres in Low Density Fluids for Workover Programs in Fractured Basement Reservoir at the White Tiger Oil Fields, Cuu Long Basin, Vietnam*. SPE/IADC Managed Pressure Drilling and Underbalanced Operations Conference and Exhibition, Kuala Lumpur, Malaysia.

[18] Kutlu, B. (2013, October). *Rheological Properties of Drilling Fluids Mixed with Lightweight Solid Additives*. SPE International Student Paper Contest at the SPE Annual Technical Conference and Exhibiton, New Orleans, Louisiana, USA.

[19] IBD HSE Form, IADC, (2002).

[20] Bennion, D. B., & Thomas, F. B. (1994, February). *Underbalanced Drilling of Horizontal Wells: Does It Really Eliminate Formation Damage?*. SPE Intl. Symposium on Formation Damage Control, Lafayette, Louisiana.

[21] *Drilling Fluids Manual*. (Rev. Ed. 6/94). Amoco Production Company.

[22] API Spec 13A, *Specification for Drilling Fluids- Specifications and Testing.* (ver ed. 18th). American Petroleum Institute, (2010).

[23] *Recommended Practice for Field Testing Water-Based Drilling Fluids*. (ver ed. 4th). ANSI/API Recommended Practice 13B-1, (2009).

[24] Annis, M. R. & Smith, M. V. (1996). *Drilling Fluids Technology*. USA: Exxon.

[25] *Manual on Test Sieving Methods, STP 447B*. American Society for Testing and Materials (ASTM), (1985).

[26] Rabia, H. *Well Engineering & Construction*.

[27] Pratama, E., Ghany R., S., Martin, Y., & Purwanto, A. (2010, October). *Lightweight Water based Mud Using Glass Bubbles for Drilling a 6-in Horizontal Section in a Gunung Kembang Development Well*. SPE Asia Pasific Oil& Gas Conference and Exhibition, Brisbane, Queensland, Australia.

[28] Medley, Jr, G. H., Maurer, W. C., & Garkasi, A. Y. (1995, October). *Use of Hollow Glass Spheres for Underbalanced Drilling Fluids*. SPE Annual Technical Conference and Exhibiton, Dallas, Texas.

[29] *Poly-plus Product Bulletin*. MI Swaco, (2007).