Study of the Rheological Properties of Various Oil-Based Drilling Fluids

By

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Dissertation submitted in partial fulfilment of
the requirement for the
Bachelor of Engineering (Hons)
Chemical Engineering

MAY 2013

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
Chemical Engineering Department
Universiti Teknologi PETRONAS
In partial fulfilment of the requirement for the
BACHELOR OF ENGINEERING (Hons)
CHEMICAL ENGINEERING

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MAY 2013

CERTIFICATE OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgments, and that the original work contained herein have not been undertaken or done by unspecified sources or person.

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MAY 2013

ABSTRACT

The rheology study of drilling fluid is important to understand the performance of drilling fluid to efficiently remove, transport and suspend cuttings, ~~to~~ maintain a stable wellbore and minimize mud pump requirements. Drilling fluid rheology is often maintained at required rheology standards through the use of additives or dilution depending on the needs of the operation. In this project, a rheology modifier named VisPlus is added into the drilling fluid to improve drilling fluid rheology. The objectives of this project is to study the rheology of invert emulsion drilling fluid or invert oil drilling fluid, which is a type of oil-based drilling fluid (OBM) using different concentrations of the rheology modifier, VisPlus. The rheology of drilling fluid with different concentrations of VisPlus were analyzed and compared against rheological requirements. This rheology study also includes the correlation of the experimental results against three rheological models namely Herschel-Bulkley, Casson and Power Law. From the correlation results, the most rheological model to predict drilling fluid rheology is identified. Experiments were conducted at oilfield units, which is convertible to SI unit. It was observed that the optimum concentration for VisPlus is 3 pounds-per-barrel (ppb), equivalent to 8.58 kilogram per cubic meter of drilling fluid. From the correlation results, the most accurate rheological model to represent drilling fluid rheology is the Herschel-Bulkley Rheological model.

ACKNOWLEDGEMENTS

I would like to express my deepest gratitude and appreciation to the following people for their support and guidance. This dissertation would not have been made possible without them.

First and foremost, my utmost gratitude for Mr. Zamri Abdullah, for his exemplary guidance and monitoring throughout this research project. His dedication and challenge constantly drive the author in the preparation and completion of this study.

I would like to thank Lab Technologists – Mr. Jukhairi and Mr. Saiful Nizam for their assistance in operating the equipment during the experiments. Their technical expertise and willingness to help were crucial in ensuring the success of this research.

I would also like to thank Mr Shukri Johari and Mr Hatta Daud for their willingness to share experience and knowledge regarding drilling fluid. Their resources, advice and technical expertise in drilling fluid testing were invaluable to this study.

Last but not least, I would like to extend a token of appreciation to family and friends for their support throughout this project.

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CHAPTER 1 :

INTRODUCTION

1.1 BACKGROUND

Rheology is defined as “the science of deformation and flow of matter”, more practically, the study of the properties of materials which determine their response to mechanical force. Interestingly, the term “rheology” did not come into existence until 1929 when it became a new discipline of physics. Nevertheless, concepts related to rheology is dated back to the 17th century, by which in 1687 Sir Isaac Newton explained the concept of resistance of an ideal fluid (Newtonian fluid) – known today as viscosity – as “the resistance which arises from the lack of slipperiness originating in a fluid is proportional to the velocity by which the parts of the fluid are being separated from each other.” Meanwhile, subsequent works from other renowned individuals such as Bingham (1922), Blair (1949) and Markowitz (1968) provided valuable resources in the study of rheology.

According to Bingham (1933), viscosity standards is made available by the use of centipoise as the absolute unit, and this also meant the start of designing materials of specified rheological properties. Notably in 1922, Bingham proposed a concept of “yield stress” to describe the flow of paints. Before that, experimental work by Schwedoff (1890), Trouton and Andrews (1904) needed a yield value or a small “initial stress” to obtain linearity between flow rate and stress. A Bingham Plastic fluid has a yield point, which is the shear stress that has to be overcome so that the fluid can start to flow. Equations of shear rate-dependent viscosities were further developed by Ostwald in 1925, which is also known as the Power Law and Herschel-Bulkley a year later (Walters, 2004).

In the petroleum industry, rheology is an extremely important property of drilling fluid. Mud rheology is measured on a continual basis while drilling, and adjusted accordingly with additives or dilution to meet the needs of the operation. Studies show that the rheology of drilling fluid is affected by temperature and pressure (Politte, 1985; Wolfe, Coffin & Byrd, 1983). Another study by Ali and Al-Marhoun (1990) show that mud rheology is also affected by aging. In 2004, a rheology study done by Ayeni and Osisanya showed that both water-based and oil-based drilling fluid matches the Herschel-Bulkley model with an accuracy of 96%. In the study of less toxic oil mud, Wolfe, Coffin and Byrd (1983) also found that the Herschel Bulkley law applies.

In this project, the drilling fluids used are the invert emulsion oil mud, which is the most commonly used oil-based mud. The rheology of the invert emulsion oil mud under the effect of downhole temperatures, downhole pressures and aging is investigated.

1.2 **PROBLEM STATEMENT**

Drilling fluid is a delicate mixture of different additives, each of these additives has its own specific function to improve the drilling fluid characteristics. One of the most important characteristics of drilling fluid is drilling fluid rheology. The rheology of drilling mud has to achieve required rheological values and standards, so that the drilling mud can perform well especially in cutting transport and borehole cleaning.

Rheology of drilling fluid is basically characteristics passed on to the drilling fluid by its additives such as emulsifier, viscosifier, rheology modifier and suspension agent. The additive which is being experimented in this project is a rheology modifier named VisPlus. It was required to determine the optimum concentration of VisPlus in drilling fluid. Due to drilling fluid being a mixture of additives, repeated testing were required to determine the optimum concentration of VisPlus and produce drilling fluid with the best rheological properties.

In order to understand drilling fluid rheology, rheological models are used. Early studies on this rheology have yielded rheological models such as the Bingham model (1925), the Ostwald de Waele or Power Law model (1925) and the Herschel-Bulkley model (1926). However, researchers do not agree on which rheological model to be the most accurate. This research will correlate the experimental data with the three rheological models i.e. Herschel-Bulkley, Casson and Power Law, and later determine the most suitable model with the highest accuracy.

1.3 OBJECTIVES

The objectives of this project include:

a) To formulate invert emulsion drilling fluid samples and investigates its rheological behavior.
b) To optimize drilling fluid rheology performance and determine the optimum VisPlus concentration.
c) To study the rheology and rheological models of drilling fluid, and select the most accurate model to represent its behavior.

1.4 SCOPE OF STUDY

This project involves the understanding of invert emulsion oil-based mud and its rheological properties. The scope of study for this project is divided into two parts. The first part of the project involves laboratory work where the oil-based mud (OBM) is formulated from a mixture of solids, chemical and fluids using a multimixer. In this stage, drilling fluid samples are formulated by varying the concentration of the rheology modifier which is VisPlus. Rheology tests are then conducted on these drilling fluid samples in addition to other tests, such as mud weight test, emulsion stability test and 50ml retort test. Rheology tests were done at different shear rates ranging from 5 s^{-1} to 1020 s^{-1}, which is an accurate representation of the downhole turbulence experienced by drilling fluid.

The second part of the project involves the analysis of drilling fluid rheology. This is the process where the properties of the OBMs are determined to understand their behavior such as rheology, filtrate loss characteristics and emulsion stability. The rheology data were compared against rheological requirements to determine the optimum concentration of VisPlus to obtain the best rheological performance. Besides, as part of the rheology study, rheological models are used to represent the drilling fluid rheology. The experimental rheology data were correlated against preexisting rheological models to select the most accurate rheological model and at the same time, to accurately predict the drilling fluid behavior.

1.5 RELEVANCY OF PROJECT

This project is geared towards the needs and requirements of the oil and gas industry. The base oil used in the project, Sarapar 147 is one of the most widely used in the industry for oil-based drilling fluid. The formulation of drilling fluid is based on a formulation that has been used before in an oilfield.

The methods used in the laboratory and experimental works follows American Petroleum Institute (API) standard, i.e. *API RP 13B-2: Field Testing for Oil-based Drilling Fluids*. This Recommended Practice provides standard procedures for determining the characteristics of oil-based drilling fluids, such as drilling fluid density (mud weight), viscosity and gel strength, filtration, oil, water and solids contents, alkalinity, chloride content and calcium content, electrical stability, lime and calcium contents, calcium chloride and sodium chloride contents, low-gravity solids and weighting material contents.

The knowledge of drilling fluid rheology is important to understand the behavior of drilling fluid in performing its functions such as cuttings transport and borehole cleaning. The use of rheological models to represent drilling fluid rheology is also important to accurately predict drilling fluid rheology using drilling fluid simulation softwares. Therefore, this project is relevant and has the potential to be applied in the oil and gas industry.

CHAPTER 2 :
LITERATURE REVIEW

2.1 DRILLING FLUID OVERVIEW

Drilling fluids or drilling mud that are used extensively in the upstream oil and gas exploration are critical in ensuring a safe and productive oil and gas well. During drilling, a large volume of drilling fluid is circulated in an open or semi-enclosed system at elevated temperatures with agitation. Drilling fluid represent 15-18% of the total cost of well petroleum drilling which was $65.5 billion in the United States, according to API's 2011 Joint Association Survey on Drilling Costs (API, 2013).

The drilling mud system as shown in Figure 1, plays an important role in drilling operations as it is the single component of the well-construction process that remains in contact with the wellbore throughout the entire drilling operation, as it also serves various purposes such as a medium for the transport of cuttings and cleaning the borehole. During a drilling operation, drilling fluid is pumped using mud pumps from the surface mud pits into the borehole through the drillstring and exiting at the drillbit. The drilling fluid then flows up the annulus and back to the surface for solids removal and treatments (Scomi Oiltools, 2008).

The main functions of the drilling fluid include:

- To clean the bottom of the borehole
- To transport cuttings to the surface
- To cool and lubricate the drill bit and drill stem
- To support the walls of wellbore with a layer of mud cake
- To exert hydrostatic pressure and prevent formation fluids from entering the well (Van Dyke, 2000; ASME, 2005).

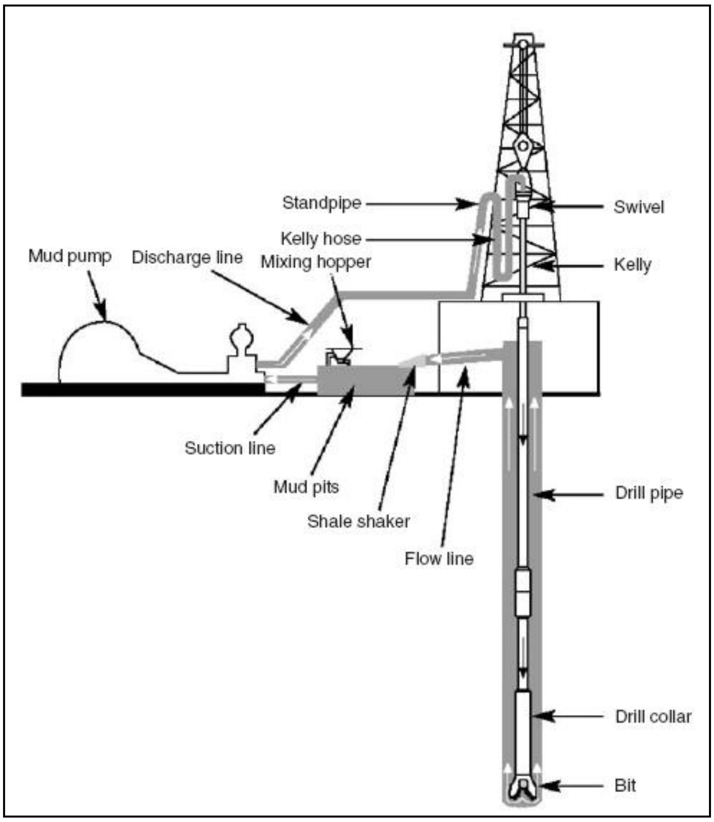


Figure 1: Mud Circulating System

2.2 DEVELOPMENT OF OIL-BASED DRILLING FLUID

The original drilling fluid was just mud. In 1901, the Spindletop well in Texas is considered to become the first instance where the use of mud for oil drilling is documented. An earthen pit was dug next to the drilling rig and filled with water. Then Colonel Lucas used a herd of cows to march through the pit to produce mud (Wooster and Sanders, 2013). Consequently, the earliest literatures of mud were published in 1914 and 1916 where mud was described by Heggem and Pollard as “a mixture of water with any clay material which will remain suspended in water for a considerable time”.

Decades of improvements has left drilling fluid vastly different from a mixture of water and clay. Modern drilling fluids are complex compounds and mixtures that are carefully designed for the wide variety of conditions found in modern wells. In the 1930’s, the idea and theory for the use of oil-based mud instead of water-based mud was reported when it was found that wells were blocked by water and caused disappointing production rates (Miller, 1946). In contrast, the addition of oil in drilling mud alleviated the sticky hole problem, improved the drilling rate and bit life in addition to other benefits. In the 1930s to 1950s, cases using oil-based mud in Paloma (California), Garvin County and Carter County (Oklahoma) proved to be successful and promoted further use of oil-based mud in drilling (Simpson *et al.*, 1961).

Despite the initial success, oil-based mud has faced challenges that threaten to cease its application in the petroleum exploration industry. Oil-based mud had to be constantly developed and reinvented in improved form in the face of challenges and industrial needs. The development of oil-based mud in the early years was focused on its initial engineering functions, which was to prevent the softening and sticking of clay cuttings to the drill string and pipe assembly. For this purpose, diesel oil mud is used. In the 1950s, researchers looked into emulsifiers to force water and oil to mix and the resulting mixture is called invert-emulsion mud, which produces similar performance to “true oil-based mud” but is more resistant to contaminant by groundwater (van Oort, 2000).

In the 1980s, technical, environmental and health considerations have influenced the development of oil-based mud. Environmental concerns were raised against the use of oil-based mud especially in offshore applications. Drill cuttings which are normally discharged into the sea contain 10-15% of the original diesel oil mud. The resulting toxic and polluting effects of diesel oil to the environment are causes for concern. As a result, offshore discharge of OBM is prohibited in the USA and severely restricted in the North Sea. In this period, a lot of research was done to replace diesel oil in oil-based mud with mineral oils (Andrew *et al.*, 2001; Bennett, 1984; Chandler, Rushing and Leuterman, 1980). More recently, low toxicity mineral oil-based fluids, highly refined mineral oils and synthetic fluids such as esters, paraffins and olefins have been used as base fluids. These fluids are less toxic due to reduced concentrations of aromatic compounds, and are less persistent in the environment (Melton *et al.*, 2004; Hinds and Clement, 1986). The historical development of base oil is tabulated in Table 1.

Table 1: Historical Development of Base Oil

Group I	Group I	Group I (early)	Group II	Group III (Late)
C2 and up Crude oil Naphthenes PAH	C8 and up Diesel Oil Naphthenes	C11-C20 Mineral oil Naphthenes	C11-C20 Low toxicity mineral oil Paraffins	Man-made C15-C30 Esters, ethers PAO, acetals LAB, LAO, IO, LP High refined paraffins
High aromatics FP 20-90°F	Aromatics 15-25% FP 120-180°F	Aromatics 1-20% FP 150-200°F	Aromatics <1% FP>200°F	No aromatics FP>200°F

The base oils used in this project is Sarapar 147, which is cleaner and less toxic compared to the past base oils. This base oils were up-to-date as part of the trend to replace diesel oil. In fact, after 1980s, The International Association of Oil and Gas Producers (OGP) and International Petroleum Industry Environmental Conservation Association (IPIECA) classified non-aqueous drilling fluids into three groups according to their aromatic hydrocarbon contents and toxicity levels. A comparison of the base oil properties in Table 2 with the standards set by OGP (2003) revealed that all three base oils were Group III non-aqueous fluids, with low to negligible aromatic content. The base oils have less than 0.2 mass percentage of aromatic (Melton *et al*, 2004; IPIECA, 2009).

Table 2: Classification of Base Oil

Non-aqueous category	Components	Aromatic content
Group I: high-aromatic content fluids	Crude oil, diesel oil, and conventional mineral oil	5-35%
Group II: medium-aromatic content fluids	Low-toxicity mineral oil	0.5-5%
Group III: low/negligible aromatic content fluids	Ester, LAO, IO, PAO, linear paraffin and highly processed mineral oil	<0.5% and PAH lower than 0.001%

2.3 CHEMISTRY AND FORMULATION OF OIL-BASED MUD (OBM)

The Spindletop mud in 1901 was a mixture of water and mud, and drilling mud composition remained the same for the next 20 years. Compared to the first drilling fluids, by the time oil-based mud were started to be used in the 1940s, the drilling fluid has became more complicated with the discovery of additives, some of which have remained in use until today. For example, in 1922, Stroud used barite for weight control, and in 1926, Harth and Cross issued patents on the use of bentonite as suspending and gelling agents. In the years ahead, more mud additives were added that makes drilling fluid composition as complex as it is today.

However, in an oil-based mud base oil is used as its liquid phase that acts as a solvent and its main component in contrast to water-based mud, which uses water as its liquid phase. For an oil-based mud to function properly all additives to it are oil dispersible. Water, if present, is in the form of emulsion (water droplets in oil).The table below shows the components that make up an oil-based mud and their respective functions:

Table 3: Mud Components and Functions

Material	Functions
Base Oil	The main phase (solvent) of an oil-based drilling fluid that dissolves certain additives and keeps others in emulsion or mixed homogenously in the drilling fluid. Formerly crude oil or diesel oil was used as base oil. However, recent years have seen less toxic materials such as mineral oil and synthetic fluids used as base oils.
Primary Emulsifier	Emulsifier is used to allow oil and water to mix in a homogenous mixture either in an oil-in-water or water-in-oil emulsion. Primary emulsifiers are long chain fatty acids, which will react with lime to form a calcium soap emulsion. Soap emulsion is a strong emulsifying agent, but takes time to form.
Secondary Emulsifier	Secondary emulsifiers consist of powerful oil-wetting chemicals which generally do not form emulsion but wet solids before the formation of emulsion. It is also used to prevent water intrusion.

Emulsifier Activator	Lime is used to activate the primary emulsifier to form a calcium soap emulsion, in order to improve emulsion stability (keeping the mud additives in emulsion). Lime is also added in excess, which is important to neutralize acid gases, CO_2 and H_2S.
Viscosifier	Viscosifier is normally clay, and in the case of oil-based mud, treated with amine to make them dispersible in oil. These organophilic clays, such as bentonite, are used to increase the viscosity of the drilling fluid.
Weighing Agent	Weighing agent is added to increase the density of the oil-based drilling fluid. Commonly used weighing agents are calcite and barite.
Brine	Brine is used to form the water phase in the water-in-oil emulsion in an invert oil mud. The addition of high concentration of salt into the water phase is important to balance the salinity of oil-based mud and the shale formation, this prevents water loss into the shale layers.
Oil Wetting Agent	Supplementary additives to oil-wet solids that became water-wet.
Filtration Control Agent	Additive to help the formation of filter cake and reduce the loss of fluids from the drilling fluid into the formation.
Bridging Agent	Additive to bridge or cover the pores in the formation so that fluid from the drilling fluid is not lost to the formation. Also has an effect as weighing agent.

The first paper on the formulation of an oil-based mud is by Hindry (1940) when stove oil was used as solvent; oyster shell, limestone or barite as weighing medium; lampblack to give gel strength and structure; and blown asphalt to produce plaster. An improved version of oil-based mud used at Elk Hills Naval Petroleum Reserve No. 1 was reported by Stuart (1943). In recent times, Melton *et al.* (2004) reported the mud composition as the figure below. The formulation by Melton is compared to a recent formulation used in Malaysia.

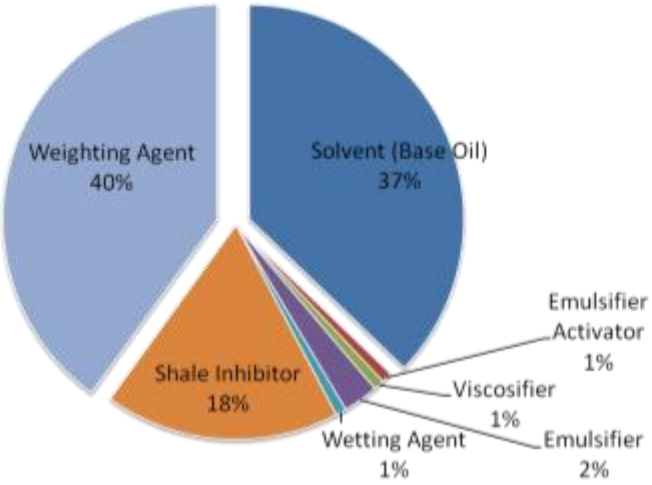


Figure 2: Sample Mud Composition in Malaysia

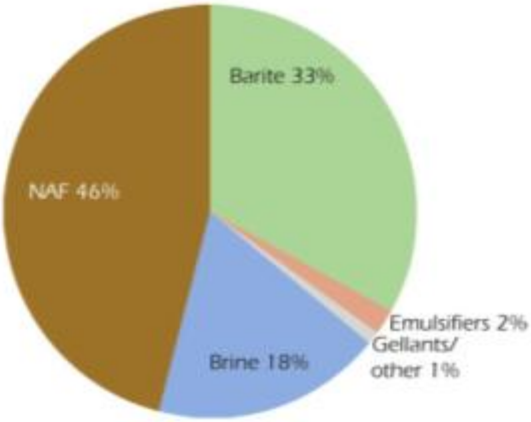


Figure 3: Mud Composition according to Melton *et al*. (2004)

The oil-based mud used in this project is the invert oil mud, a water-in-oil emulsion,~~,~~ by which an aqueous fluid is emulsified into a non-aqueous fluid. The invert oil mud is the direct opposite of an oil emulsion mud, which is an oil-in-water emulsion. While the use of oil emulsion mud started in the 1930's according to Lummus, Barrett and Allen (1953), and Simpson, Cowan and Beasley (1961), it took another 20 years for the first use of an invert emulsion oil mud was in the 1950s.

In an invert oil mud, a three-component liquid system is found, namely oil as the continuous phase, brine which is the discontinuous phase, and a surfactant package to stabilize the dispersion of brine in oil. Young, Stefano and Lee (2012) reported the use of fatty acid activated by reaction with lime to form calcium "soap". In the use of lignosulfonate as emulsifier, Browning (1955) reported the adsorption of the lignosulfonate molecule at the oil-water interface, which established a high order electrokinetic charge and also a semi-rigid film.

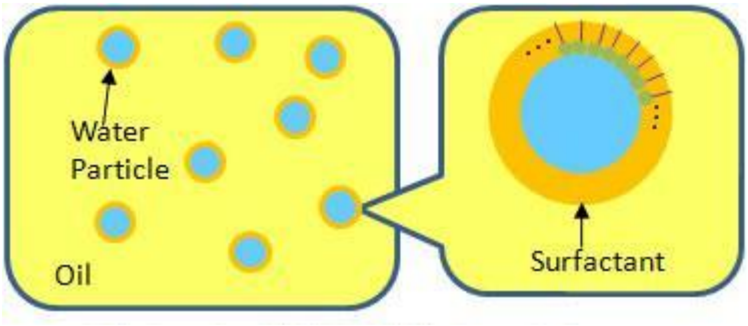


Figure 4: Stabilizing Effect of Surfactant on Water Particles

2.4 RHEOLOGY OF OIL-BASED MUD

As opposed to the findings of Newton, drilling fluid is a non-Newtonian fluid. Schwedoff's (1890) experimental work on colloidal gelatin solutions showed that the torque and angular velocity is not proportional in a non-Newtonian system. Trouton and Andrews (1904) had to include a yield value to obtain a flow rate proportional to the stress. The concept of non-Newtonian systems were further developed by Bingham (1922), Ostwald (1925) and Herschel and Bulkley (1926), and remain in use till today to characterize oil-based mud rheology.

While rheology is described by the models above, however, when measuring the rheology of drilling fluid there are a few rheological values such as shear stress, gel strength, viscosity and yield point that need to be recorded in order to produce a suitable rheological model. These rheological properties were obtained from drilling mud testing. In the years after Spindletop, drilling mud test was not introduced until 1929 when the first commercial drilling mud test was run by Baroid Division of the National Lead Company in Houston, Texas. Before that, the old-timers tested their mud by "rule of thumb". However, between 1917 and 1922 when college degrees were first awarded in the field of Petroleum Engineering, mud testing began to receive serious attention from both scholars and manufacturers.

Jones and Babson (1935) and Hindry (1940) reported the use of MacMichael type or Stormer viscometer, which measured the friction of a liquid against a disc suspended from a calibrated wire, in a cup of liquid which was rotating at a constant speed. It was in the 1950s when Fann viscometers were introduced. They were also known as direct-indicating viscometer, used to measure viscosity and gel strength of a drilling fluid. The direct-indicating viscometer made up of a rotational cylinder and bob. Two speeds of rotation, 300 and 600 rpm, are available in all instruments, but a six-speed instrument allows speeds of 3 rpm, 6 rpm, 100 rpm, 200 rpm, 300 rpm and 600 rpm.

The six speed viscometer tells us the plastic viscosity (PV) and yield point (YP), derived through the readings of the six speeds. However, Pazos (2012) mentioned that the six readings give additional information as well. As drilling fluid moves past the drillbit, it moves through annular spaces of different sizes. The annular space is smallest at the drill collars, bigger going up around the drill pipe, and even bigger going up the casings and open hole. As the annular size grows larger, the fluid moves slower. The different speeds on the viscometer reflect the flow properties of a drilling fluid as it moves up the hole. Generally, it is easier to remove cuttings near the drillbit and drill collars, as the annular velocity (shear rate) is the highest. When the drilling fluid is just below the surface, it becomes the hardest to push cuttings to the surface separation systems shakers. 600 rpm tells us the flow behavior around the drillbit and 3 rpm tells us about the flow behavior in a high diameter annulus.

2.4.1 PLASTIC VISCOSITY

Plastic viscosity relates to the resistance to flow due to inter-particle friction. The friction is affected by the amount of solids in the mud, the size and shape of those solids and the viscosity of the continuous liquid phase. Plastic viscosity is the theoretical minimum viscosity a mud can have as shear rate approaches infinity. The value of plastic viscosity is obtained by subtracting the 300rpm reading from the 600rpm reading of viscometer. Below is the formula to determine plastic viscosity:

Plastic Viscosity (PV) = (600 rpm reading) – (300 rpm reading)

2.4.2 YIELD POINT

Yield Point is the yield stress extrapolated to a shear rate of zero (Schlumberger Oilfield Glossary: Yield Point), practically, it means the stress that must be applied to a material for it to begin to flow. Zouaghi (2012) mentioned the use of YP to predict the hole cleaning around the high shear zones, as it is made up of high shear rate viscosity value (HSRV). Yield point can be calculated by subtracting the 300rpm dial reading of viscometer with plastic viscosity calculated. Below is the formula to determine yield point:

Yield Point (YP) = 300 rpm reading – Plastic Viscosity (PV)

2.4.3 GEL STRENGTH

The gel strength is the shear stress of drilling mud that is measured at low shear rate after the drilling mud is static for a certain period of time. The gel strength is one of the important drilling fluid properties because it demonstrates the ability of the drilling mud to suspend drill solids and weighting material when circulation is ceased (Gel Strength of Drilling Mud 2012). The 3-rpm reading will be used, which will be recorded after stirring the drilling fluid at 600 rpm from a rheometer. Normally, the first reading is noted after the mud is in a static condition for 10 seconds. The second reading and the third reading will be 10 minutes and 30 minutes, respectively. Gel strength readings show the tendency of the mud to form a gel after an extensive period of time.

2.4.4 SHEAR THINNING CHARACTERISTICS AGAINST SHEAR THICKENING CHARACTERISTICS

For non-Newtonian fluids, the slope of the shear stress versus shear rate curve will not be constant as the shear rates change. When the viscosity decreases with increasing shear rate, the fluid is called shear-thinning. In the opposite case where the viscosity increases as the fluid is subjected to a higher shear rate, the fluid is called shear-thickening. Shear-thinning behaviour (or also called is pseudoplastic) is more common than shear-thickening. A typical shear stress versus shear rate plot for a shear-thinning and shear-thickening fluid is given in Figure 5.

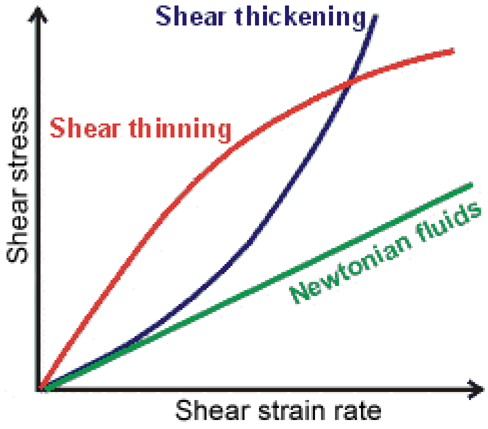


Figure 5: Shear Thinning and Shear Thickening Characteristics

2.5 RHEOLOGICAL MODELS OF OIL-BASED MUD

The first rheological model was proposed by Maxwell on the dynamic theory of gas in 1867. However, in the petroleum industry, only three rheological models have gained widespread usage: the Bingham Plastic model, the Ostwald-de Weale or Power Law model, and the Herschel-Bulkley model. The rheological models are mathematical models used to describe the flow behavior of drilling mud.

Authors in the past preferred the Bingham model to describe drilling fluids. In their studies, Herrick (1932), Babson and Jones (1935) and Fitzpatrick (1955) decided that Bingham model is the accepted theory. Another author to suggest the same was Politte (1985). Meanwhile, Alderman *et al*. (1988), Kenny (1996), Ayeni and Osisanya (2004) and Maglione *et al*. (1996) preferred the Herschel-Bulkley model to describe WBM and OBM under HPHT conditions. Houwen and Geehan (1986), on the other hand, reported that Casson model is more accurate than Herschel-Bulkley model for extrapolation purposes, but both were equally accurate in experiments.

2.5.1 BINGHAM PLASTIC MODEL

The Bingham Plastic model was introduced by Eugene C. Bingham in 1922. The Bingham Plastic model is a two-parameter rheological model widely used in the drilling fluids industry to describe flow characteristics of many types of mud. It can be described mathematically as fluids that exhibit a linear shear-stress/shear-rate behavior after an initial shear stress threshold has been reached. Plastic viscosity (PV) is the slope of the line and yield point (YP) is the threshold stress. Herrick (1932), Babson & Jones (1935) and Fitzpatrick (1955) preferred the Bingham model to describe drilling fluids.

$$\tau = YP + PV(\gamma)$$

τ = measured shear stress in lb/100 ft2
γ = shear rate in sec^{-1}
YP = Yield point
PV = Plastic viscosity

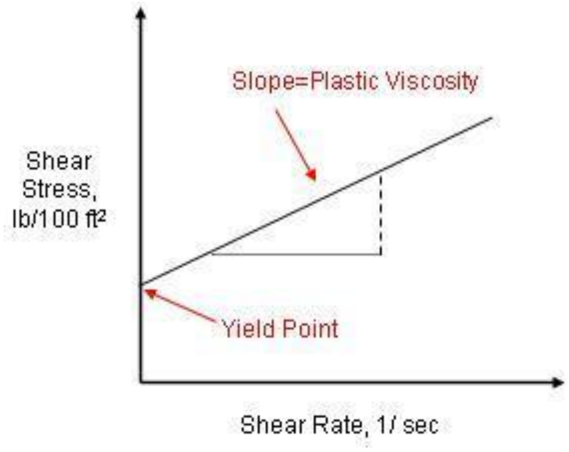


Figure 6: Bingham Plastic Model

2.5.2 POWER LAW MODEL

Power Law Model was formed through the literatures of Ostwald (1925) and de Waele (1923). It is a two-parameter rheological model of a pseudoplastic fluid, or a fluid whose viscosity decreases as shear rate increases. The Power Law is represented by the following equation, which when plotted on log-log coordinates, will form a straight line over an interval of shear rate:

$$\tau = \mu \times (\gamma)^n$$

Where

τ = measured shear stress in lb/100 ft2
μ = fluid's consistency index in cP or lb/100 ft sec2 (PV)
n = fluid's flow index
γ = shear rate in sec^{-1}

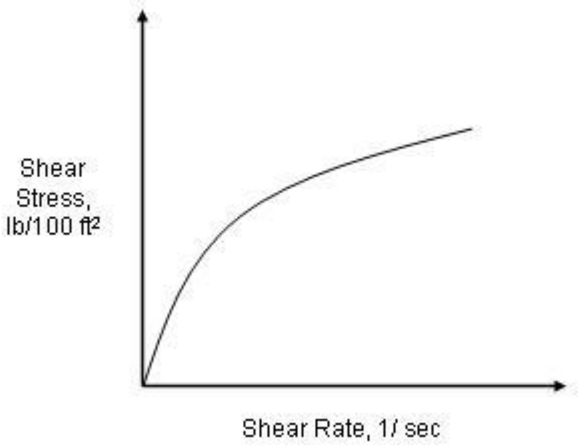


Figure 7: Power Law Model

2.5.3 HERSCHEL-BULKLEY MODEL

In 1926, Herschel and Bulkley introduced a new rheological model merges the theoretical and practical aspects of Bingham and power law models. The Herschel-Bulkley model is thought to represent the flow behaviour of drilling fluids very well by Houwen and Geehan (1986), Ayeni and Osisanya (2004) and Maglione *et al.* (1996). According to Hemphill, Campos and Pilehvari (1993), the Herschel-Bulkley equation is preferred to power law or Bingham relationships because it results in more accurate models of rheological behavior when adequate experimental data are available. This model is called the Herschel-Bulkley model or the yield power law model, and is represented by the following equation:

$$\tau = \tau_o + \mu \times (\gamma)^n$$

Where

τ = measured shear stress in lb/100 ft2

τo = fluid's yield stress (shear stress at zero shear rate) in lb/100 ft2

μ = fluid's consistency index in cP or lb/100 ft sec2 (PV)

n = fluid's flow index

γ = shear rate in sec^{-1}

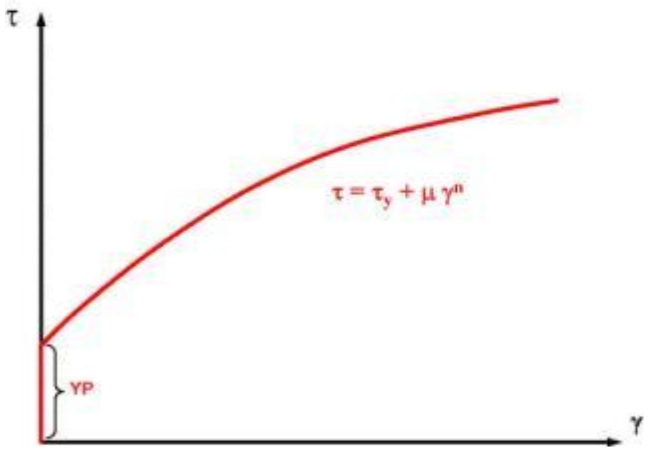


Figure 8: Herschel-Bulkley Model

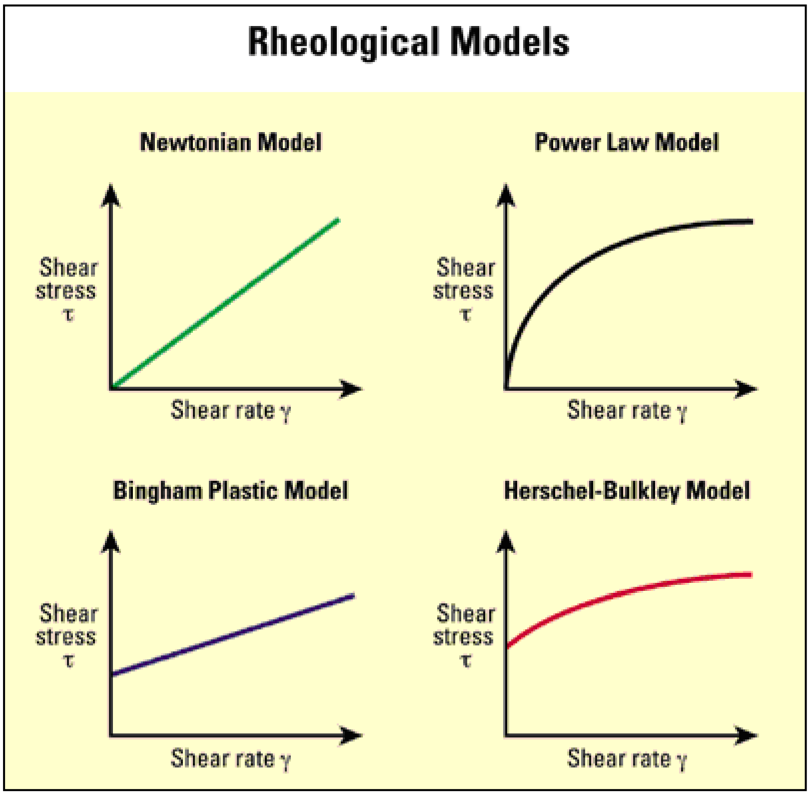


Figure 9: Comparison of Rheological Models

2.6 DOWNHOLE CHARACTERISTICS OF A DRILLED WELL

As shown in Figure 10, drilling fluid is pumped into a drilled well through the drillpipe by using a mud pump on the drilling rig. The pressurized drilling fluid passes through the drillpipe and comes out at the bottom of the well via bit nozzles located at the drillbit. The bit nozzle is usually small (around 0.25 inches in diameter), which causes even higher pressure of drilling fluid and leading to high-velocity and turbulent jets below the nozzles. The high velocity and turbulence is important for blasting the cuttings away from the bottom of the well, so that the drilling bit can drill into undrilled formation.

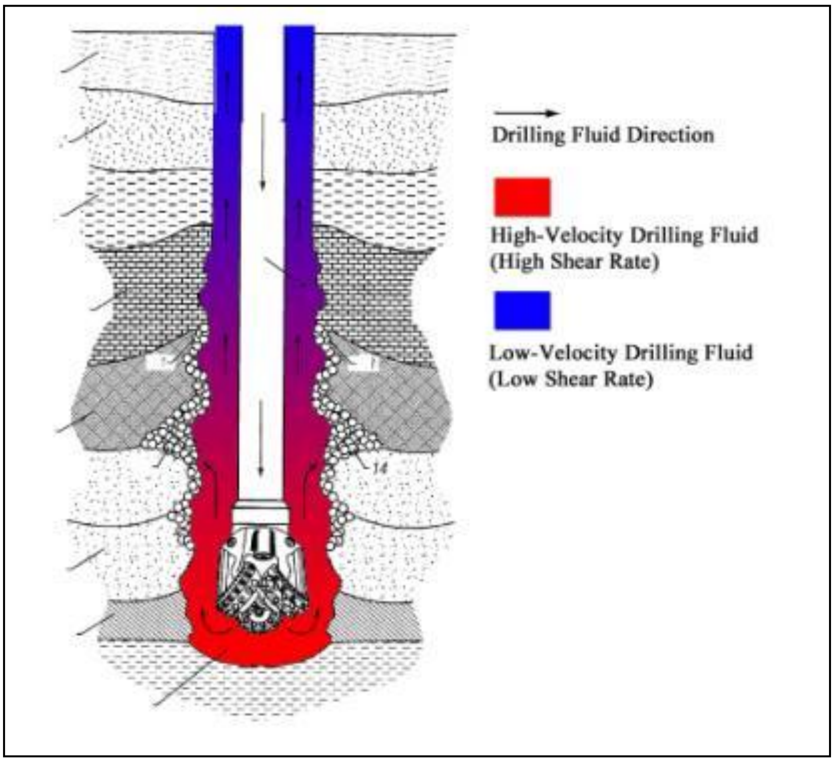
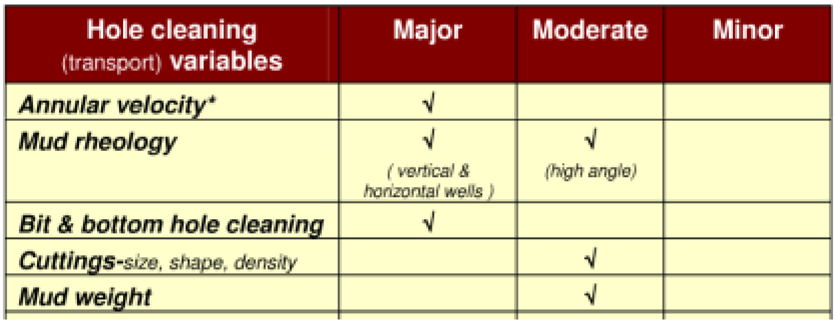


Figure 10: Shear Rates in a Drilled Well

The drilling fluid then carries the drill cuttings away from the bottom and up the annulus, so that they can be removed at the surface later on. As the cutting transportation continues, friction occurs and the annular space increases, which leads to lower velocity flow going up the annulus. Therefore, the velocity and turbulence is the highest at the bottom of the well, and decreases gradually going up the annulus to surface. The table below shows that annular velocity and mud rheology are two major variables in the process of cleaning the well.

Table 4: Hole Cleaning Variables



Hole cleaning (transport) variables	Major	Moderate	Minor
Annular velocity*	√		
Mud rheology	√ (vertical & horizontal wells)	√ (high angle)	
Bit & bottom hole cleaning	√		
***Cuttings**-size, shape, density*		√	
Mud weight		√	

The rule of thumb is that for effective hole cleaning and stability, annular velocity should be between 60ft/s to 120ft/s. According to Combs (1967), the annular velocity can be related by shear rates using the formula:

$$\gamma = \frac{12\,V}{D_H - D_P}$$

where γ is shear rates in reciprocal seconds, s^{-1}

V is the annular velocity in ft/s

D_H and D_P are diameters in ft

On the other hand, Willis *et al* (1973) related the shear rates to nozzle velocity by the following formula:

$$Shear\ rate, \gamma = \frac{96\ \times nozzle\ velocity\ (\frac{ft}{s})}{nozzle\ size\ (in.)}$$

From Combs (1967) and Willis (1973), the drilling mud flow rates can be represented by shear rates. As the annular velocity drops going up the annulus, an accurate representation of the velocities can be done by using a suitable range of shear rates in experiments.

Annular velocity can also be calculated using the following formula:

$$Annular\ velocity, AV = \frac{1029.4\ \times pump\ output\ (bpm)}{ID^2 - OD^2}$$

Becker, Azar and Okrajni (1991) ran flow tests at annular velocities of 120 to 240 ft/min. According to their research, the rotary speed on a Fann viscometer (rpm) corresponding to the average annular shear rate is given by, where n is derived from Power Law:

$$v(rpm) = \left(1 - 0.877^{\frac{1}{n}}\right)\left(\frac{15n}{\pi}\right)\left(\frac{2n+1}{n+1}\right)\left(\frac{48\ \bar{v}}{d_e - d_i}\right)$$

According to Stiff-Robertson (1976), the annular flow rate is related to the shear rate based on the expression below, which is similar to Cones (1967) but with the addition of two variables B and C:

$$\gamma = \frac{2B+1}{3B} \times \frac{12u}{d_1 - d_2} + \frac{C}{2B}$$

$$C = \frac{\gamma_{min}\gamma_{max} - \gamma^2}{2\gamma - \gamma_{min} - \gamma_{max}}$$

$$B = \frac{N\sum(PQ) - \sum P \sum Q}{N\sum P^2 - \left(\sum P\right)^2}$$

Where u is annular velocity in ft/s

d_1-d_2 is the annular distance

P =log $(\gamma + C)$

Q=log τ

Based on Stiff-Robertson's Method, it is found that annular velocity is related to shear rates through the relationship below. It is fair to say the drilling fluid velocity near the bottom of the well is represented by 300 to 600 rpm on the viscometer.

Table 5: High Shear Rates near the Drillbit

Annular Flow Rate, u (ft/s)	d1-d2, 10-5 (ft)	B	C	Shear Rates (s-1)	Rev per min, rpm
60	5	0.422203	330.2071	600.7419	352.9623462
90	5	0.422203	330.2071	705.5866	414.5632235
120	5	0.422203	330.2071	810.4313	476.1641008

Using Combs' Method, as drilling fluid moves closer to the surface, the annular space increases and the velocity of drilling fluid decreases. Depending on the diameter difference between the conductor casing and drillpipe, which is about 15 to 20 feet, the relationship between annular velocity and shear rate is shown below. Therefore, the flow chacteristics of drilling fluid near the surface can be measured by three to six revolutions per minute on the viscometer.

Table 6: Low Shear Rates in the Mud Pit

Annular Flow Rate, u (ft/s)	d1-d2 (ft)	Shear Rates (s-1)
1	15	0.8
1	20	0.6
5	15	4
5	20	3
10	15	8
10	20	6

2.7 HEALTH, SAFETY AND ENVIRONMENTAL ASPECTS OF HANDLING OIL-BASED MUD

When working with drilling fluids, four routes of exposure are observed: dermal, inhalation, oral and other. Dermal (skin) exposure to drilling fluids is reported to cause skin irritation and contact dermatitis. IPIECA (2009) reported that skin irritation can be associated with C8-C14 paraffins, which do not penetrate the skin, but are absorbed into the skin, causing irritation. Care must be taken because the C8-C14 paraffin is the main ingredient of the three base oils used in this project. Besides, calcium chloride which is used as the discontinuous phase (brine), was classified as an eye irritant. Awareness on the hazardous materials, potential exposures and their health effects are critical. Material Safety Data Sheets (MSDS) should be provided for drilling fluid systems, components and additives. MSDS for all drilling fluid system components and additives should be reviewed prior to working with the chemicals.

The use of personal protective equipment (PPE) is recommended to minimize the direct contact to drilling fluid. PPEs may include chemical splash goggles, gloves, rubber boots and coveralls. Wearing chemical resistant gloves and laboratory clothing is the primary method used to prevent skin exposure to hazardous chemicals. When working with drilling fluids, if ventilation is not adequate it is recommended that goggles and self-contained respirators are worn at all times.

2.8 RECOMMENDED DRILLING FLUID PROPERTIES

The recommended upper and lower limits of the plastic viscosity and the yield point are shown in the following table.

Table 7: API Requirements for OBM Rheological Properties

Rheological Properties	Requirement
Plastic viscosity, PV (cp)	< 65
Yield point, YP	15 – 30
$CaCl_2$, wt %	20 – 25
ES Reading , volts	> 400
Excess Lime, ppb	1 – 3

CHAPTER 3 :
METHODOLOGY

Methodologies are divided into four main phases which are literature review, consultation session, laboratory work and experimental work. The phases are briefly described below:

A. Literature Review

i. Define study objectives
ii. Study on published journals and final year reports on the rheology study of oil-based drilling fluid.
iii. Study of parameters that will be used for experimental study
iv. Planning of equipments, materials and experiments
v. List all materials and equipments required for experimental study

B. Consultation Session with Service Company

i. Electronic mail correspondence to discuss about the direction and requirements of the project.
ii. Meeting and discussion on the project to obtain advice and experience.

C. Laboratory Work

i. Mud formulation
ii. Acquisition and preparation of raw materials
iii. Mixing of drilling fluid according to procedure
iv. Decision on the sequence of experiments
v. Preparation of equipments
vi. Study of experimental procedures

D. Analysis on Rheology Data

i. Tabulation of results
ii. Graphing of rheology data
iii. Correlation of rheological data to various rheological models
iv. Data analysis and discussion

3.1 PROJECT ACTIVITIES

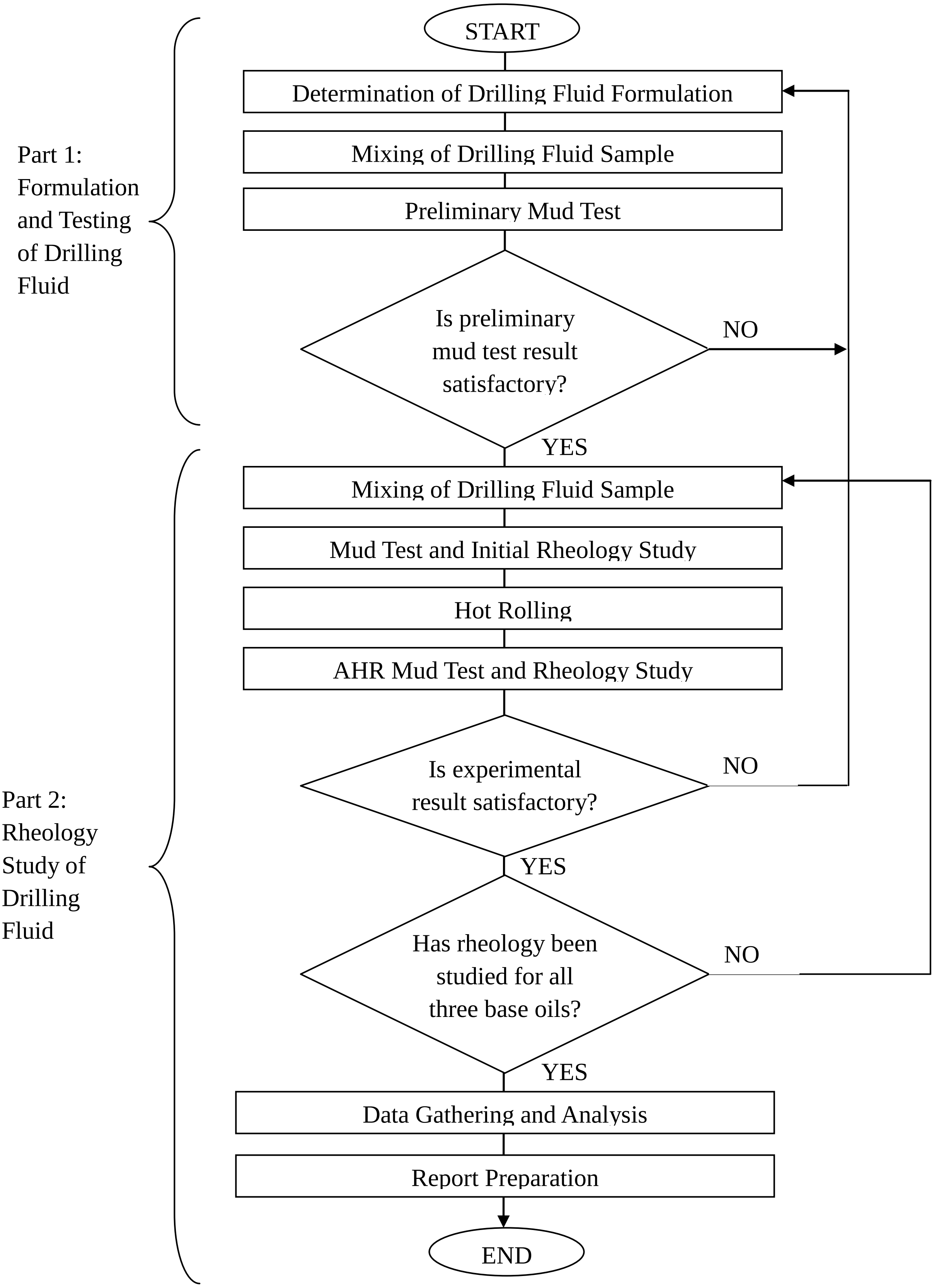


Figure 11: Project Activities

3.2 TOOLS REQUIRED

Equipment, materials and apparatus required for this study are listed as below:

Table 8: Materials Required

Sequence	Materials	Function	Concentration (ppb)	Amount Needed (kg)
1	Base Oil (Sarapar 147)	Solvent	0.58 bbl/bbl	5L
2	EZ MUL	Secondary Emulsifier	8.0	1L
3	INVER MUL	Primary Emulsifier	4.0	1L
4	Lime	Activator for Primary Emulsifier	4.0	2.0
5	ADAPTA	Filtration Control Agent	1.5	2.0
6	25 wt% CaCl2 brine	Prevent Shale Hydration	0.28 bbl/bbl	
7	Geltone II	Viscosifier	2.0	2.0
8	Baracarb 5	Bridging Agent	5.0	2.0
9	Baracarb 25	Bridging Agent	2.0	2.0
10	Barite	Weighing Agent	285.0 (or as required)	2.0
11	Driltreat	Oil Wetting Agent	1.0	1L
12	VisPlus	Suspension Agent		1L

Table 9: Equipment and Apparatus Required

Equipment/Apparatus	Model	Function
Electronic Mass Balance	Fann EP214C	To weigh mud components
Thermometer	OFITE 170-01-3	To measure mud temperature
Multimixer	Fann 9A	To mix OBMs
Mud Balance	Fann 140	To measure density of OBMs
50ml Retort Kit	Fann	To measure Oil Water Ratio (OWR)
Viscometer	OFITE 1100	To measure rheological properties of OBM: YP, PV, GS
Electrical Stability Kit	OFITE 131-50	To measure emulsion stability
Roller Oven	Fann 705Es	For hot rolling mud at high temperature
HTHP Filter Press	OFITE 170-01-3	To measure filtrate loss characteristics
Apparatus : 1L beaker, 100ml measuring cylinder, spatula, rough paper, 10ml syringe, filter paper, wire gauss, hex key		
PPE : Gloves, lab coat, googles, oven gloves		

3.3 **KEY MILESTONES**

Detailed project activities are as below:

3.3.1 PRE-EXPERIMENT STAGE

In this stage, the main activities are to research on the project topic and to plan for the equipments, materials and experiments. Studies are done in order to increase the knowledge about the project, to understand how the OBM components and parameters work, and to understand how the related experiments are conducted. After that, planning for the project is done. Confirmation has to be done on the types and amounts of materials needed, their acquisition and transportation, the parameters that will be tested in the project, and the procedures to perform the lab and experimental works. While performing the planning, documents that need to prepared are the Material Safety and Data Sheet (MSDS), job safety analysis and lab booking form.

Below is the planning for the experiments, where the manipulated parameters are type of base oil, temperature and pressure and contamination (Rommetveit and Bjorkevoll, 1997). A gantt chart, as in Table 14 was drafted to indicate the expected the progress and acts as a guide for project progress through the final year project.

3.3.2 EXPERIMENT STAGE

The experiment stage is divided into two parts, as shown in Section 3.1, which are:

i) Part one: optimization of drilling fluid rheology, and
ii) Part two: rheology study of oil-based drilling fluid.

Part One is a prerequisite of Part Two. The focus of Part One is to formulate a drilling fluid which has the suitable properties, so that it is workable in the industry. Drilling fluid is a delicate mixture of materials as shown in Table 3, with each material having a specific function to improve the drilling fluid. However, having so many components in a drilling fluid makes the process of finding the suitable formulation difficult. Besides rheology (shear stress, yield point and gel strength), other test requirements of a drilling fluid are the mud weight, emulsion stability, oil-water ratio and filtrate loss. A good drilling fluid is one that achieves desired performances in each of the tests. The requirements are as below:

Table 10: Drilling Fluid Requirements

Requirements	Description
Sagging	No sagging before and after hot rolling
Density	12-14 ppg
Oil-Water Ratio	80/20
Emulsion Stability	>400
YP	14-25
Gel strength	Progressive over time
HPHT Filtrate Loss	No free water (<4ml)

To achieve a suitable drilling fluid formulation, the experimental procedures below are followed. The following process is repeated until the drilling fluid requirements are achieved.

Table 11: Experimental Procedures and Functions

No	Procedure	Function
1	Mud Formulation (Until Baracarb 25)	Mud formulation
2	Mud Weight test (To decide amount of barite to add)	To decide the amount of barite to add to achieve target mud weight
3	Mud Formulation (Adding Driltreat)	Mud formulation
4	Mud Weight test	To measure mud weight and decide whether it is close to intended mud weight (12ppg = 1440kg/m^3)
5	Electrical Stability test	To measure stability of emulsion, a strong emulsion will not have phase separation
6	Viscometer test	To measure rheology: viscosity, yield point and gel strength
7	Retort test	To measure Oil-water ratio (OWR) and decide whether it is close to desired OWR of 80/20

8	Hot Rolling	To simulate downhole and dynamic conditions
9	AHR Mud Weight test	To measure mud weight and determine any change in mud weight (12ppg = 1440kg/m^3)
10	Electrical Stability test	To measure emulsion strength and oil-wetting qualities of drilling fluid. Low emulsion strength will cause phase separation between oil and water. Poor oil-wetting means water-wet solids will settle
11	AHR Viscometer test	To measure rheology: viscosity, yield point and gel strength. These rheological properties were used to relate to well-cleaning abilities, cuttings lifting ability and suspension property. Readings were taken at different shear rates (rpm). Different rpms reflect the drilling fluid rheology at different sections of the annular space.
12	HTHP Filtrate test (30 mins)	To measure filtration behaviour of drilling fluid under elevated temperature and pressure at 120C and 500psi. HTHP filtrate volume is times two because of smaller filtrate area.
13	Visual observations were also noted throughout the process	

Part Two is the rheology study of the drilling fluid obtained from Part One. In Part One, drilling fluid is subjected to shear rates from 5.1 s^{-1} to 1020 s^{-1}, and the corresponding shear stresses are obtained using the Fann 35 rheometer. In Part Two, the results are tabulated and a graph of shear stress against shear rates is drawn using graphing software named “Graph”. The data points are connected using rheological models such as Herschel-Bulkley, Casson and Power Law model. Correlations to the models are then done to measure the suitability of each model for the drilling fluids by comparing the coefficient of determination, R^2.

3.3.3 PREPARATION OF MUD SAMPLE

Equipment: Fann 9B Multimixer, Electronic Mass Balance, stopwatch, thermometer, 1 lab barrel mud cup

Figure 12: Fann 9B Multimixer

OBM samples are prepared through mixing all of the components using the Fann 9B multimixer. The materials have to be mixed in following a set sequence. After the mixing time which is 60 minutes, the resulting mud sample has a volume of 1 lab barrel or 350ml. The procedures are as follows:

1. Required amount of base oil (Saraline 185v, Sarapar 147, Escaid 110), which is approximately 252ml, is added into the mixing container.
2. 10 grams of emulsifier is added into the mixture and stirred for 2 minutes.
3. 4 grams of viscosifier is added into the mixture and stirred for 2 minutes.
4. 4 grams of lime is added into the mixture and stirred for2 minutes.
5. 70ml of calcium chloride, $CaCl_2$ solution is added into the mixture and stirred for 15 minutes.
6. 63.2 grams of weighing agent (barite) is added into the mixture and stirred for 2 minutes.
7. 3 grams of contaminant is added into the mixture and stirred for 2 minutes. (if applicable)

8. The mixture is stirred until the total time, inclusive of steps 1 to 7, reaches 1 hour.

The experiment will be conducted according to the standard which has stipulated in American Petroleum Institute - API 13B-2: Recommended Practice for Testing Oil-Based Drilling Fluid.

3.3.4 MUD BALANCE

Equipment: Mud balance

Figure 13: Mud Balance

Procedure:

1. The instrument base should be set on a flat, level surface.
2. Measure the temperature of the mud and record on the Drilling Mud Report form.
3. Fill the clean, dry cup with mud to be tested; put the cap on the filled mud cup and rotate the cap until it is firmly seated. Insure that some of the mud is expelled through the hole in the cup in order to free any trapped air or gas.
4. Holding cap firmly on mud cup was and wipe the outside of the cup clean and dry.
5. Place the beam on the base support and balance it by moving the rider along the graduated scale. Balance is achieved when the bubble is under the centre line.
6. Read the mud weight at edge of the rider toward the mud cup. Make appropriate corrections when a range extender used.

3.3.5 50 ML RETORT KIT

Figure 14: 50ml Retort Kit

A retort kit is used to determine the percentages of water, oil and solids which make up the drilling fluid. A 50 ml retort kit measures the amount of water and oil that is present in 50 ml of drilling fluid. A retort kit is composed of a 50 ml sampling chamber, measuring lid, upper boiling chamber containing steel wool and condenser. The 50 ml of drilling fluid sample is heated up to a temperature of 498°C as specified by API standard, in order to heat the fluid components (oil and water) into vapor state before condensing them and collecting them in collecting tube. The volumes of oil and water are measured to calculate the oil water ratio (OWR).

Procedure:

1. The retort assembly is lifted out of the heating compartment.
2. The sample chamber is unscrewed from the upper chamber using the square bar retort wrench.
3. The upper chamber is packed with steel wool
4. The sample chamber is filled with drilling fluid sample. Excess sample is allowed to escape and wiped clean.
5. Retort threads is cleaned and lubricated with high temperature lubricant.
6. Sample chamber with lid is screwed into the upper chamber and is hand-tightened using the wrench.
7. The retort assembly is replaced in the heating compartment and insulating cover is put in place.

8. A drop of wetting agent is added to the receiver and the receiver is placed under the drain port of the condenser.
9. The heater is turned on and the ON/OFF switched is turned on.
10. The retort is allowed to heat until the pilot lamp went off. The switch is turned off after the completion of test.
11. The volume of oil and water is read.
12. An analysis of the result is as shown below.

Table 12: Sample Analysis for Retort Test

Retort test	
Mud sample (ml)	50
Collected Fluid (ml)	39.5
Collected Oil Volume (ml)	31.5
Collected Water Volume (ml)	8
Oil Volume %	79.75
Water Volume %	20.25

3.3.6 VISCOMETER

Equipments: Fann 35 Viscometer, stopwatch.

Figure 15: Viscometer

Procedures:

1. Stir the sample at 600 rpm while the sample is heating to 120°F (48.9°C).
2. Once the temperature reach 120°F, start noting the result of dial reading at 600, 300, 200, 100, 6, and 3 rpm speeds. Ensure the dial reading has stabilized at each speed before noting the value.
3. After done with 3 rpm reading, stir the sample at 600 rpm for 30 seconds before taking the 10-second gel. The gel is taken by stopping the motor and left the mud in static mode for 10 seconds. Then initiate the mud with 3 rpm speeds and take the highest deflection of the dial reading.
4. Restir the sample at 600 rpm for 30 seconds and leave it undisturbed for 10 minutes in order to measure the 10-min gel.

$$PV = \theta 600 - \theta 300 = 21cP$$

$$YP = \theta 300 - PV = \frac{5lb}{100ft^2}$$

3.3.7 EMULSION STABILITY TEST

Equipment: Electrical Stability Kit

Figure 16: Electrical Stability Kit

Procedures:

1. Place the clean probe of ES meter in the sample at 120°F (48.9°C) and use it to stir the fluid to ensure homogeneity.
2. Position the probe so it does not touch the bottom or sides of the heated cup in order to get more accurate result and ensure that the tip of the electrode is completely immersed.
3. Press the button to initiate the voltage ramp and holding the probe still until the end point is reached and a steady reading is seen in the digital display.
4. Note the reading and repeat the test for three times for calculating average value.

3.3.8 HOT ROLLING

Equipment: Roller oven, aging cells

Figure 17: Roller Oven

Procedures (Fann Instrument Company, 2003):

1. The oven must be preheated first to the required temperature, which is 120°C.
2. The sample is stirred for 5 minutes on Hamilton Beach Mixer.
3. Then, the sample is transferred into aging cell container. The aging cell is tightened.
4. The aging cell is pressurized at 100 psi.
5. The aging cell is then placed in the roller oven and start rolling the sample. The sample is rolled for 16 hours.

3.3.9 HPHT FILTRATION TEST

Equipment: HPHT Filter Press, HPHT Filtration Cells (Diameter 3” x Height 3”), Filter paper (Diameter 2.5”), High Pressure CO_2 supply, stopwatch, and measuring cylinder.

Figure 18: HPHT Filter Press

Procedures:

1. The heating jacket is preheated to the required temperature.
2. Tighten the bottom valve stem and fill the cell to about 0.5 inch from the rim.
3. Place a filter paper on the rim and put the lid on the cell. Ensure the lid stem is open while doing this to avoid damaging the filter paper.
4. Tighten the six studs in the cell and close the lid stem.
5. Place the cell in the heating jacket with the lid facing downwards. Rotate the cell until it seats on the locking pin.
6. Place CO_2 cartridge in each regulator and tighten up the retainers.
7. Place the top regulator on the stem and engage the locking pin. Close the bleed off valve and turn the regulator clockwise until 100 psi is showing on the gauge.
8. Repeat the process with the bottom regulator.
9. Turn the top valve stem ¼ to ½ turn anti clockwise to pressure up the cell to 100 psi.
10. When the cell reach required test temperature, open the bottom stem with ½ turn and then increase the pressure on the top regulator to 600 psi. Start the stopwatch timing.

11. After 30 minutes, close the top and bottom valve stems. Slack off the regulator on the bottom collection vessel. Bleed off the filtrate into the graduated cylinder. Disconnect bottom collection vessel, fully open the bleed off valve and tip any residual filtrate into the graduated cylinder.
12. Bleed the pressure off the top regulator.
13. Disconnect the top regulator and remove the cell from the heating jacket, allowing it to cool in water bath.
14. When the cell has cooled, bleed off the trapped pressure by slowly opening the top valve with the cell in an upright position. With the residual pressure bled off, loosen the six studs and remove the lid.
15. Examine the filter paper and report the thickness of cake built in millimeter and the filtrate produced in milliliter.

3.4 STUDY PLAN (GANTT CHART)

Table 13: Gantt Chart/Key Milestone

No.		Milestones / Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
		FYP I														
1		Planning Stage					■	■	■	■	■	■	■	■	■	
2		Consultation with Supervisor and Industry	■	■	■	■	■	■	■	■	■	■	■	■	■	■
3		Acquisition of Drilling Fluids and Additives												■	■	■
4		Documentation										■	■	■	■	
		FYP II														
5	Part 1: Optimization of Mud Rheology/Formulation	Preparation of Mud Sample	■	■	■	■	■	■	■	■						
6		Complete Mud Test	■	■	■	■	■	■	■	■						
		Mud Balance	■	■	■	■	■	■	■	■						
		50ml Retort Test	■	■	■	■	■	■	■	■						
		Electrical Stability (ES) Test	■	■	■	■	■	■	■	■						
		Rheology Measurement	■	■	■	■	■	■	■	■						
		Hot Rolling	■	■	■	■	■	■	■	■						
		Electrical Stability (ES) Test	■	■	■	■	■	■	■	■						
		Rheology Measurement	■	■	■	■	■	■	■	■						
		HPHT Filtrate Test	■	■	■	■	■	■	■	■						
7	Part 2: Rheology Study of Oil-based Drilling Fluid	Preparation of Mud Sample									■	■				
8		Complete Mud Test									■	■				
		Mud Balance									■	■				
		50ml Retort Test									■	■				
		Electrical Stability (ES) Test									■	■				
		HPHT Rheology Measurement									■	■				
		Hot Rolling									■	■				
		Electrical Stability (ES) Test									■	■				
		HPHT Rheology Measurement									■	■				
		HPHT Filtrate Test									■	■				
9		Consultation with Supervisor and Industry	■	■	■	■	■	■	■	■	■	■	■			
10		Data Analysis							■	■	■	■	■			
11		Documentation									■	■	■			

CHAPTER 4 :

RESULT AND DISCUSSION

4.1 RESULTS

4.1.1 DRILLING FLUID FORMULATION

The first drilling fluid formulated was on 28th May. The formulation is as below.

Table 14: First Formulation of Oil-based Drilling Fluid

Sequence	Materials	Function	Concentration (ppb)	Time (min)
1	Base Oil (Sarapar 147)	Solvent	0.70 bbl/bbl = 175ml	
2	EZ MUL	Secondary Emulsifier	8.0	5
3	INVER MUL	Primary Emulsifier	4.0	5
4	Lime	Activator for Primary Emulsifier	4.0	5
5	ADAPTA	Filtration Control Agent	1.5	10
6	25 wt% CaCl2 brine	Prevent Shale Hydration	0.20 bbl/bbl = 70ml	5
7	Geltone II	Viscosifier	2.0	10
8	Baracarb 5	Bridging Agent	5.0	3
9	Baracarb 25	Bridging Agent	2.0	3
10	Barite	Weighing Agent	285.0	5
11	Driltreat	Oil Wetting Agent	1.0	5

The concentrations of materials used in the preliminary mud test were the minimum recommendation in order to detect any weakness present in the formulation, so that suitable modifications can be performed to produce an improved mud formulation by increasing the additive concentrations. The amount of barite added is based on the following calculation:

$$Barite(g) = \frac{1470(\rho_2 - \rho_1)}{35 - \rho_2} = \frac{1470(12 - 7.55)}{23} = 284.41g$$

ρ_2=target mud weight in ppg

ρ_1=current mud weight in ppg

Figure 19: From L to R (Weighing additives for Mud Formulation, Mixing of Mud Using Fann multimixer, Mud Weight Test Using Mud Balance)

4.1.2 TEST #1

The experimental result from the mud formulation is tabulated below:

Table 15: Experimental Results for Test #1

Properties	Values	Recommended Values
Mixing Time (mins)	60	
Temperature (C)	25	
CaCl2 brine (wt%)	25	
Density (ppg)	12	12-14
3 rpm	2.5	10
6 rpm	3	10
100 rpm	11	
200 rpm	18	
300 rpm	26	
600 rpm	47	
Plastic Viscosity, PV (cp)	21	<65
Yield Point, YP (lb/100ft2)	5	15-24
10s gels	3	12
10min gels	5	20
30min gels	NA	
Electrical Stability	250	>400
API Filtrate	NA	

$$PV = \theta600 - \theta300 = 21cP$$

$$YP = \theta300 - PV = \frac{5lb}{100ft^2}$$

Figure 20: Mud Rheology Test Using Fann 35A Viscometer

The areas highlighted in red in Table 15 serves to compare between the experimental data and the recommended rheology values. From the comparison, the result was not acceptable due to the low yield point and emulsion stability value. The rheology values in general are lower than required. The reason for this low rheology may be due to the low concentration of materials used, a review of the mud formulation may be necessary.

4.1.3 TEST #2

In order to check whether the same rheology trend applies to other base oils, Sarapar 147 was substituted by Saraline 185v as the base oil in the second formulation of drilling fluid, the formulation for other materials remained the same. The results are tabulated as below and are compared to the first formulation.

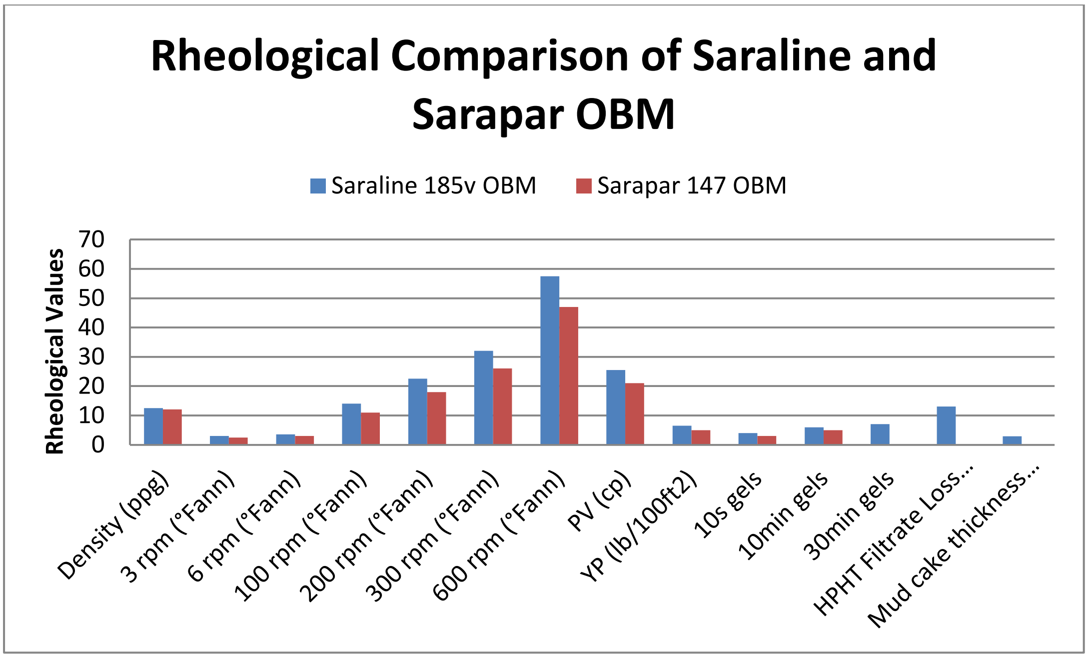


Figure 21: Rheology Comparison of Test #1 and Test #2

It was observed that the rheology trend faced by the first mud formulation was also faced by the second formulation, which shows that the rheology at this stage is more affected by the additives rather than base oil. However, the values still show a lower than required rheology and weak emulsion. In fact, for both drilling fluids, sagging was observed after a few hours. The oil-based mud separates into two layers: a light-coloured base oil at the top and a muddy layer at the bottom. The reason for this may be due to the weak emulsion, as shown by the low emulsion stability reading.

Figure 22: Barite Sagging

In addition, retort test was done for this mud formulation, which returned a result of an oil-water ratio of 70-30, compared with the desired OWR of 80-20. The results are as shown.

Table 16: Retort Test for Test #2

Retort test	
Mud sample (ml)	50
Collected Fluid (ml)	40
Collected Oil Volume (ml)	28
Collected Water Volume (ml)	12
Oil Volume %	70
Water Volume %	30

After hot rolling to simulate the downhole conditions, it was also observed that the rheology increases after hot rolling. The increase in rheology may be due to the effect of Geltone. It is expected that under elevated temperature and with extra time, Geltone (the viscosifier) will provide more viscosity, therefore improving the rheology. However, the rheology is still too low; therefore a review of mud formulation is necessary.

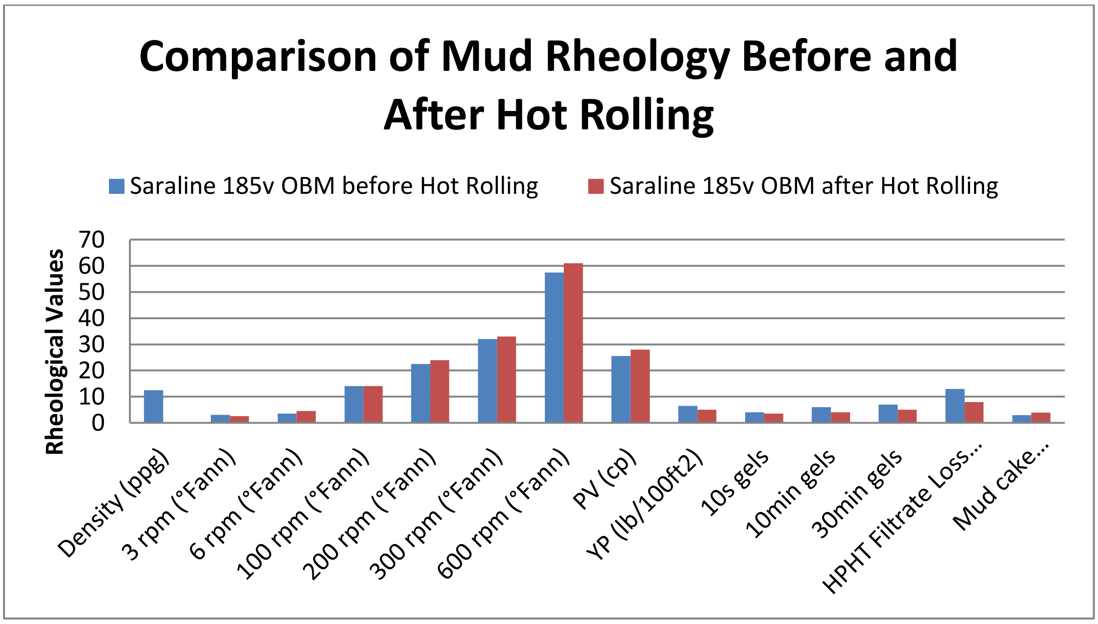
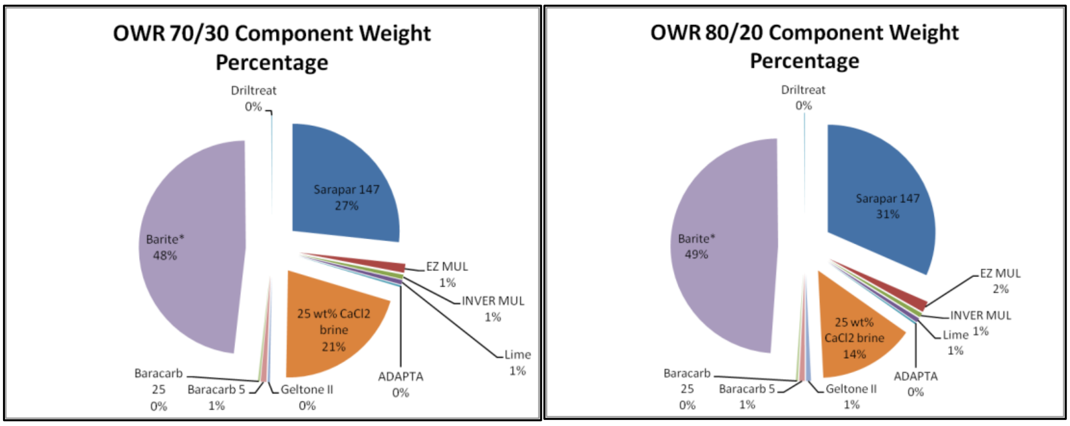


Figure 23: Comparison of Mud Rheology Before and After Hot Rolling

From Test #1 and Test #2, the results obtained show that the mud formulation is not ideal because of its low emulsion stability, sagging and low rheology. It is assumed that a higher concentration of Geltone II (viscosifier), EZ Mul and InverMul (emulsifiers) are needed. A change in the mud formulation perhaps in the form of increasing the concentrations of viscosifier and emulsifier may help to address the low rheology. In order to change the OWR from 70-30 to 80-20, the concentration of base oil needs to be increased and the concentration of brine needs to be reduced.

4.1.4 TEST #3 (0 PPB)

The purpose of test #3 is to change the mud formulation from 70/30 oil-water ratio to 80/20 oil-water ratio. The change in oil-water ratio is achieved by changing the concentration of base oil and brine. In addition, as a long-term target of achieving the right mud rheology, the concentration of viscosifier and emulsifiers was changed. Below is the comparison of the additives concentration before and after.


OWR 70/30 Component Weight Percentage

OWR 80/20 Component Weight Percentage

Figure 24: Comparison of OWR 70/30 and OWR 80/20 Mud Component

Table 17: Comparison of Mud Formulation of Test #2 and Test #3

		Before	After	Trend
Sequence	Materials	Test #2: OWR 70/30 Concentration (ppb)	Test #3: OWR 80/20 Concentration (ppb)	
1	Sarapar 147	0.58 bbl/bbl	0.70 bbl/bbl	Increased from 203 ml per lab barrel to 245 ml per lab barrel.
2	EZ MUL	8 (ppb)	10 (ppb)	Increased by 2 gm per lab barrel.

3	INVER MUL	4 (ppb)	4 (ppb)	
4	Lime	4 (ppb)	4 (ppb)	
5	ADAPTA	1.5 (ppb)	1.5 (ppb)	
6	25 wt% CaCl2 brine	0.28 bbl/bbl	0.20 bbl/bbl	Decreased from 98 ml per lab barrel to 70 ml per lab barrel.
7	Geltone II	2(ppb)	4.5 (ppb)	Increased by 2.5 gm per lab barrel.
8	Baracarb 5	5 (ppb)	5 (ppb)	
9	Baracarb 25	2 (ppb)	2 (ppb)	
10	Barite*	285	295	Increased by 10 gm due to lower initial weight, due to increased in oil and decrease in water.
11	Driltreat	1 (ppb)	1 (ppb)	
12	Vis-Plus**	0	0	

The experimental results are as below:

Table 18: Comparison of Test #2 and Test #3 Results

	Test #2		Test #3		
Properties	Before Hot Rolling	After Hot Rolling (16hours @120C, 100psi)	Before Hot Rolling	After Hot Rolling (16hours @120C, 100psi)	Recommended Values
Mixing Time (mins)	60		60		
Temperature (C)	25		25		
CaCl2 brine (wt%)	25		25		
Density (ppg)	12.5	12.5	12.1	12.1	12-14
3 rpm	3	2.5	2.5	3	10
6 rpm	3.5	4.5	4	3.5	10
100 rpm	14	14	11	14	
200 rpm	22.5	24	18	23	
300 rpm	32	33	25	31	
600 rpm	57.5	61	45	54	
PV (cp)	25.5	28	20	23	<65
YP (lb/100ft2)	6.5	5	5	8	15-24
10s gels	4	3.5	4	4	12
10min gels	6	4	4.5	4.5	20
30min gels	7	5	5	5	
Electrical Stability	275	260	375	365	>400
HPHT Filtrate Loss (ml) x2	13	8		38	
Mud cake thickness (mm)	2.94	3.88		11.6	

Figure 25: L-R: Mud Cake, Filtrate Loss, AHR Mud Sample, HPHT Filtrate Test

Test 2 results show similar low rheology to test 1, even though the concentrations of viscosifier (Geltone) and emulsifier (EZ Mul) are increased. The Yield Point value (1 to 8) is lower than the required values (15-24). The reason may be due to the insufficient increase of Geltone and EZ Mul concentrations added to the drilling fluid. A higher increase of the viscosifier and emulsifier concentrations may be needed to obtain more satisfactory results. However, the increase of emulsifier has resulted in the increase in emulsion stability from a reading of 270 to 370. However, it is still lower than the required value of at least 400. Due to the low emulsion stability, sagging is observed before and after hot rolling. Besides, clumping or flocculation was observed at the aging cell after hot rolling.

Figure 26: L-R: Clumping in the Aging Cell, Barite Sagging AHR and BHR

However, results from the 50 ml retort test was encouraging. The drilling fluid was successfully changed from 70/30 OWR to 80/20 OWR. Therefore, the mud formulation can be used as a base for further modifications in subsequent tests.

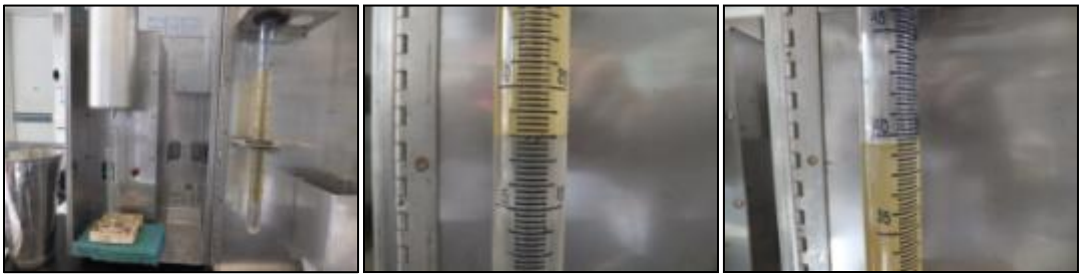


Figure 27: Retort Test

Table 19: Retort Test Result

Retort test	Test #2	Test #3
Mud sample (ml)	50	50
Collected Fluid (ml)	40	39.5
Collected Oil Volume (ml)	28	31.5
Collected Water Volume (ml)	12	8
Oil Volume %	70	79.75
Water Volume %	30	20.25
OWR	70/30	80/20

A recommendation for test #3 is to:

a) further increase the concentration of viscosifier and emulsifier, or
b) replace the viscosifier/emulsifier with other chemicals, as previous test #1 and test #2 results show that they are not as effective as expected.

The rotation speed of the viscometer bob in terms of rotations per minute (rpm) can also be converted into reciprocal seconds (s^{-1}), based on the formula below:

$$Shear\ Rate\ (\ s^{-1}) = Shear\ Rate(rpm) \times 1.702$$

From the shear stress values obtained from the Fann 35 viscometer, the shear stress can be calculated in terms of Pascal (Pa) units, based on the formula below:

$$Shear\ Stress\ (Pa) = Shear\ Stress\ (\deg Fann)\ \times 0.511$$

Meanwhile, viscosity in terms of Centipoise (cP) is obtained from the shear rate and shear stress values:

$$Viscosity\ (cP) = 300 \times \frac{Shear\ Stress\ (\deg Fann)}{Shear\ Rate\ (rpm)}$$

Therefore, further data analysis of the rheology test results yields the following:

Table 20: Mud Rheology Before Hot Rolling (BHR)

Shear Rate		Shear Stress		Viscosity	Plastic Viscosity	Yield Point
rpm	s-1	deg Fann	Pa	cP	cP	lb/100ft2
3	5.106	2.5	1.2775	250	20	5
6	10.212	4	2.044	200		
100	170.2	11	5.621	33		
200	340.4	18	9.198	27		
300	510.6	25	12.775	25		
600	1021.2	45	22.995	22.5		

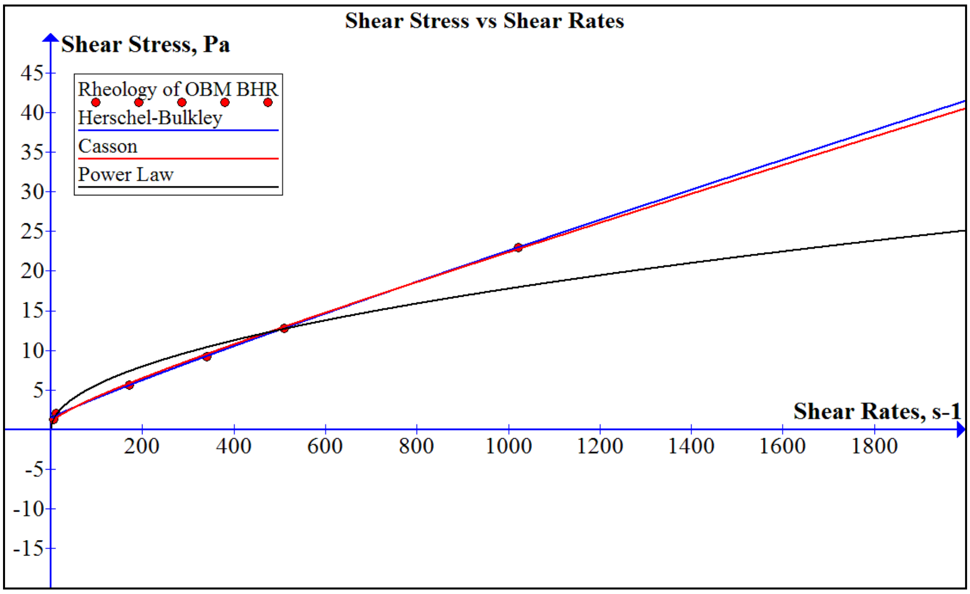


Figure 28: Graph of Shear Strength vs Shear Rates BHR

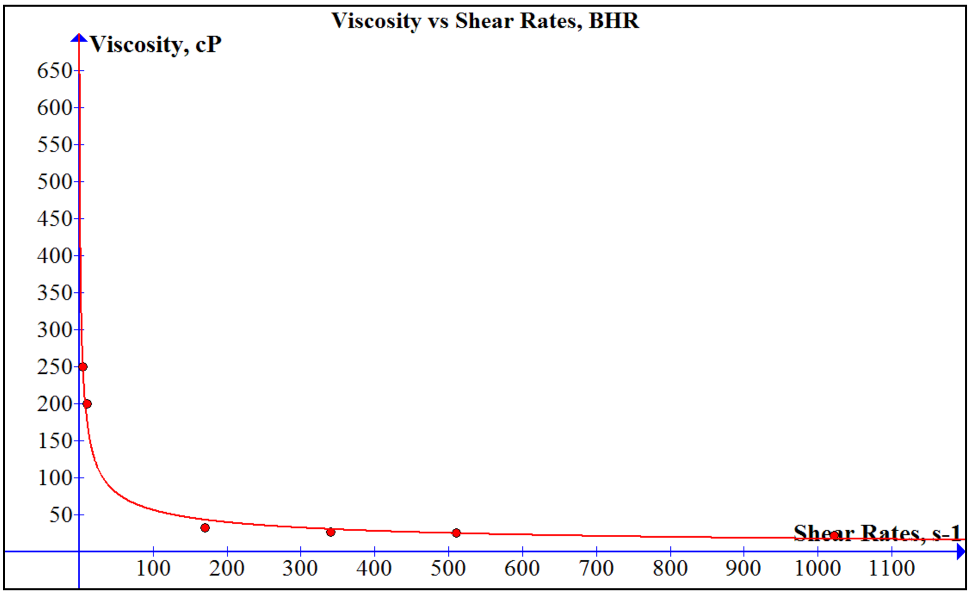


Figure 29: Graph of Viscosity vs Shear Rates, BHR

Table 21: Mud Rheology After Hot Rolling (AHR)

Shear Rate		Shear Stress		Viscosity	Plastic Viscosity	Yield Point
rpm	s-1	deg Fann	Pa	cP	cP	lb/100ft2
3	5.106	3	1.533	300	23	8
6	10.212	3.5	1.7885	175		
100	170.2	14	7.154	42		
200	340.4	23	11.753	34.5		
300	510.6	31	15.841	31		
600	1021.2	54	27.594	27		

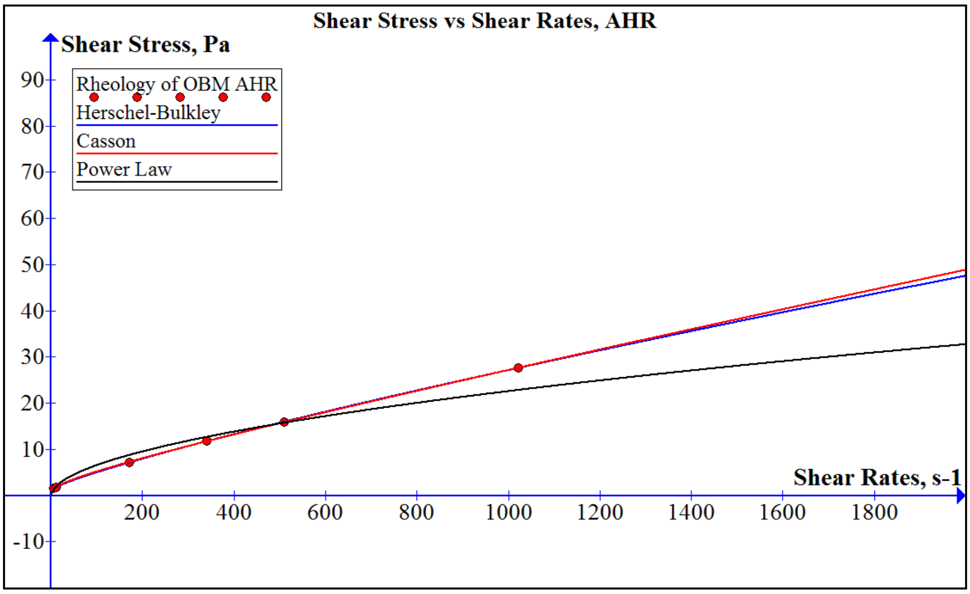


Figure 30: Graph of Shear Stress vs Shear Rates AHR

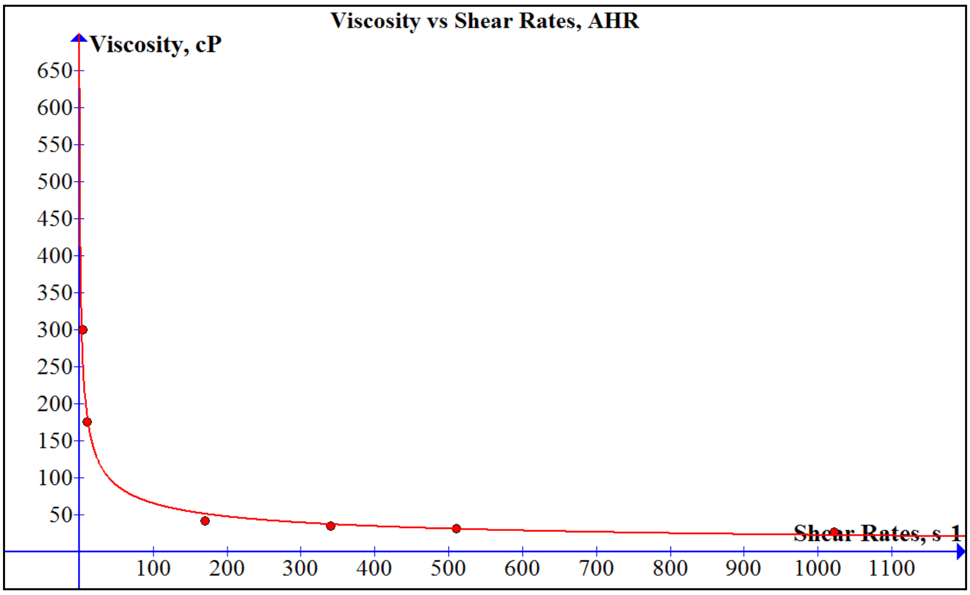


Figure 31: Graph of Viscosity vs Shear Rates AHR

Both the graphs for rheology and viscosity show a shear thinning rheology. Data correlations were done against rheological models, which are Power Law, Herschel-Bulkley and Casson. It was found that the viscosity prediction is performed equally well by Herschel-Bulkley and Casson, which obtained coefficient of determination value of close to 1.

4.1.5 TEST #4 (2PPB)

Subsequent tests after Test #3 were focused in varying the concentration of VisPlus in order to obtain the required rheology from oil-based drilling fluid. The details of the VisPlus concentration variation are tabulated as below.

Table 22: Drilling Fluid Formulation for Test #3-#7

Material	Test #3	Test #4	Test #5	Test #6	Test #7	Mix. Time
Base Oil (Saraline)	0.70 bbl/bbl	0.70 bbl/bbl	0.70 bbl/bbl	0.70 bbl/bbl	0.70 bbl/bbl	
EZ Mul	10 ppb	12.5 ppb	12.5 ppb	12.5 ppb	12.5	5 mins
Lime	4 ppb	4 ppb	4 ppb	4 ppb	4 ppb	5 mins
ADAPTA	1.5 ppb	3 ppb	3 ppb	3 ppb	3 ppb	5 mins
CaCl2 brine	0.20 bbl/bbl	0.20 bbl/bbl	0.20 bbl/bbl	0.20 bbl/bbl	0.20 bbl/bbl	5 mins
Geltone	4.5 ppb	5 ppb	5 ppb	5 ppb	5 ppb	20 mins
Baracarb 5	5 ppb	5 ppb	5 ppb	5 ppb	5 ppb	5 mins
Baracarb 25	2 ppb	10 ppb	10 ppb	10 ppb	10 ppb	5 mins
Barite	295 ppb	285 ppb	285 ppb	285 ppb	285 ppb	5 mins
VISPLUS	0	2 ppb	3 ppb	4 ppb	5 ppb	5 mins

The results for the rheology tests are then recorded in the following sections.

Table 23: Rheology Readings of Test #4

Properties	Test #4 Before Hot Rolling	Test #4 After Hot Rolling (16hours @120C, 100psi)	Recommended Values
Mixing Time (mins)	60		
Temperature (C)	25		

CaCl2 brine (wt%)	25		
Density (ppg)	12	12	12-14
3 rpm (°Fann)	10	5	10-15
6 rpm (°Fann)	11	6	10-15
100 rpm (°Fann)	25	18	
200 rpm (°Fann)	35.5	29	
300 rpm (°Fann)	45	38.5	
600 rpm (°Fann)	72.5	70	
PV (cp)	27.5	31.5	<65
YP (lb/100ft2)	17.5	7	15-24
10s gels	9	6	12
10min gels	10	6	20
30min gels	11	6	
Electrical Stability	601	407	>400
HPHT Filtrate Loss (ml) x2		7	
Mud cake thickness (mm)		2.8	

The rheology of oil-based mud with 2 ppb VisPlus concentration is better compared to 0 ppb VisPlus concentration. When compared to rheological requirements, the rheology of 2 ppb VisPlus oil-based drilling fluid is nearer to the lower limits of the rheological requirement. A higher concentration of VisPlus is required for improved rheological properties.

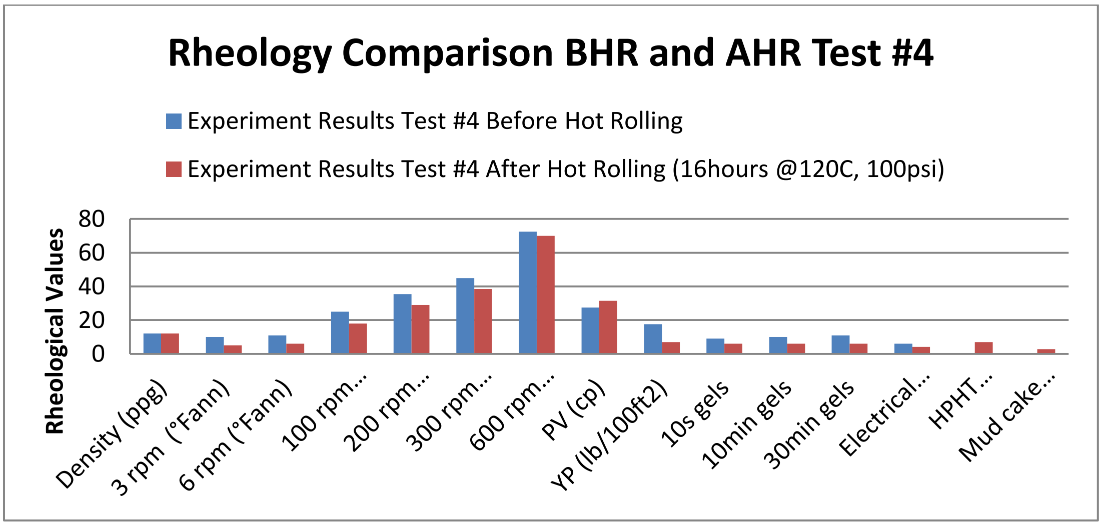


Figure 32: Rheology Comparison Between Before and After Hot Rolling (2ppb VisPlus)

The rheology of oil-based drilling mud shows a general decreasing trend after hot rolling.

Table 24: Rheology of 2 ppb VisPlus Oil-based Drilling Fluid Before Hot Rolling

Shear Rate		Shear Stress		Viscosity	Plastic Viscosity	Yield Point	Yield Point
rpm	s-1	deg Fann	Pa	cP	cP	lb/100ft2	Pa
3	5.106	10	5.11	1000	27.5	17.5	8.37320574
6	10.212	11	5.621	550			
100	170.2	25	12.775	75			
200	340.4	35.5	18.1405	53.25			
300	510.6	45	22.995	45			
600	1021.2	72.5	37.0475	36.25			

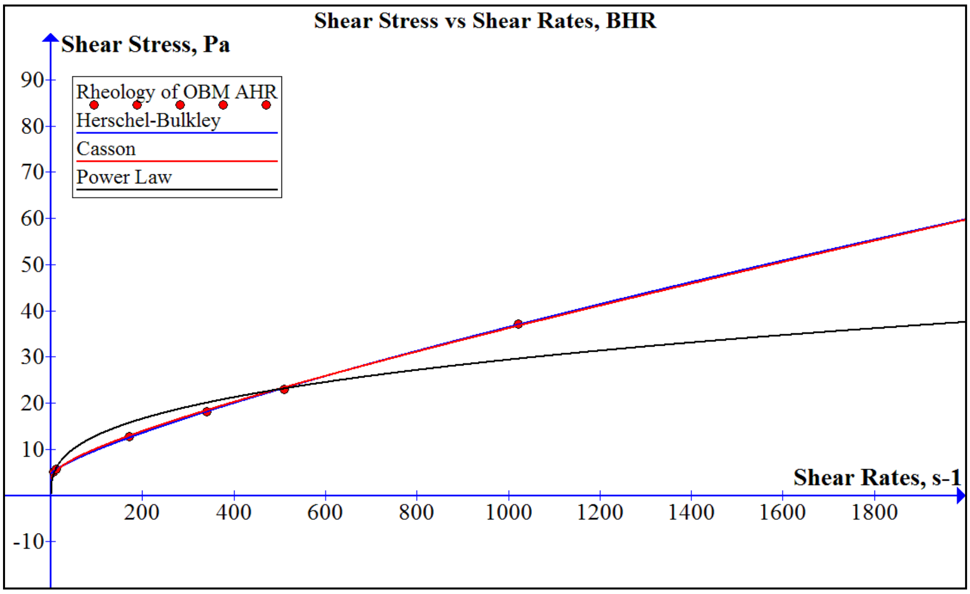


Figure 33: Graph of Shear Stress vs Shear Rates Before Hot Rolling (2 ppb)

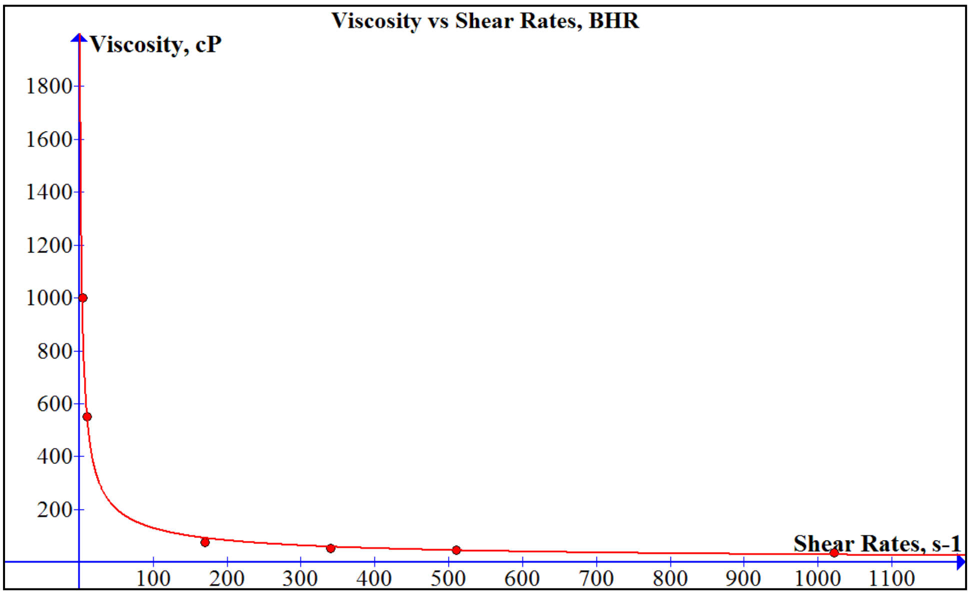


Figure 34: Graph of Viscosity vs Shear Rates Before Hot Rolling (2 ppb)

Table 25: Rheology of 2 ppb VisPlus Oil-based Drilling Fluid After Hot Rolling

Shear Rate		Shear Stress		Viscosity	Plastic Viscosity	Yield Point	Yield Point
rpm	s-1	deg Fann	Pa	cP	cP	lb/100ft2	Pa
3	5.106	5	2.555	500	31.5	7	3.349282
6	10.212	6	3.066	300			
100	170.2	18	9.198	54			
200	340.4	29	14.819	43.5			
300	510.6	38.5	19.6735	38.5			
600	1021.2	70	35.77	35			

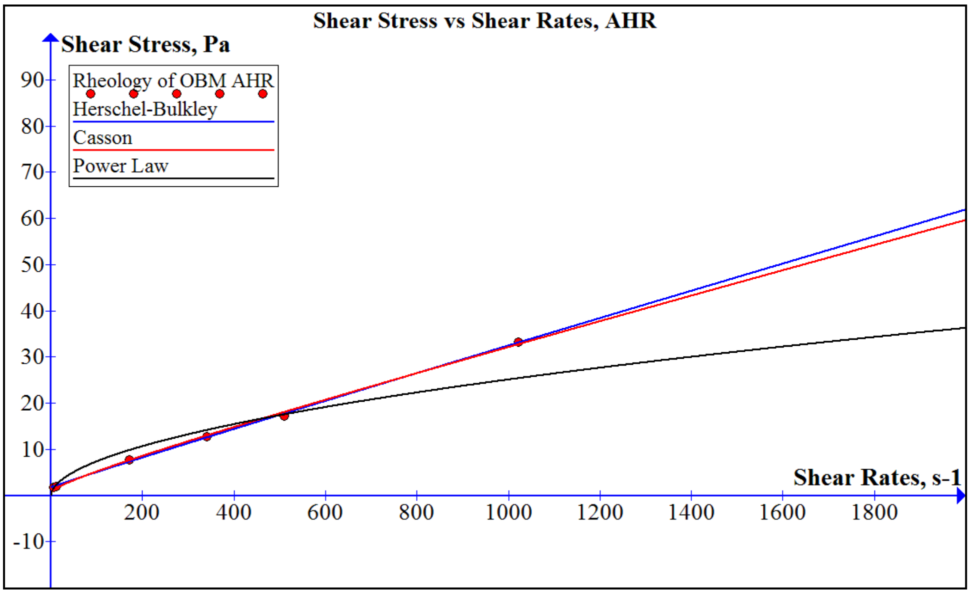


Figure 35: Shear Stress vs Shear Rates After Hot Rolling (2 ppb)

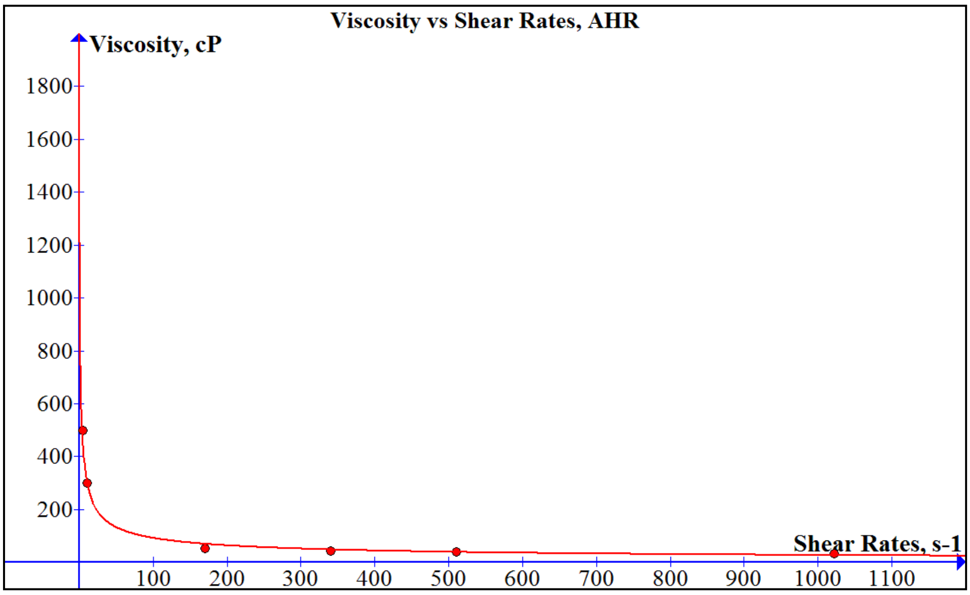


Figure 36: Graph of Viscosity vs Shear Rates After Hot Rolling (2 ppb)

4.1.6 TEST #5 (3PPB)

Table 26: Rheology Reading of Test #5

Properties	Test #5 Before Hot Rolling	Test #5 After Hot Rolling (16hours @120C, 100psi)	Recommended Values
Mixing Time (mins)	60		
Temperature (C)	25		
CaCl2 brine (wt%)	25		
Density (ppg)	12.1	12.1	12-14
3 rpm (°Fann)	14	4	10-15
6 rpm (°Fann)	15	5	10-15
100 rpm (°Fann)	28	15	
200 rpm (°Fann)	44.5	23	
300 rpm (°Fann)	54	32	
600 rpm (°Fann)	85	69	
PV (cp)	31	37	<65
YP (lb/100ft2)	23	-5	15-24
10s gels	12	5	12
10min gels	15	6	20
30min gels	16	6.5	
Electrical Stability	630	304	>400
HPHT Filtrate Loss (ml) x2		7	
Mud cake thickness (mm)		2	

The rheology of 3 ppb VisPlus oil-based drilling fluid is better compared to 2 ppb VisPlus oil-based drilling fluid. The rheological values are within range of the rheological requirements.

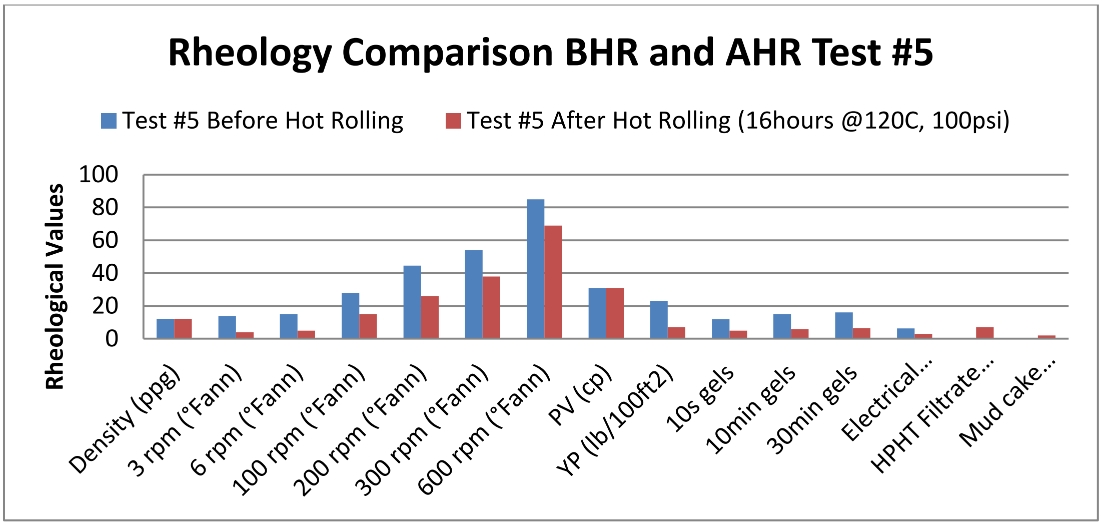


Figure 37: Rheology Comparison Between Before and After Hot Rolling (3ppb VisPlus)

Table 27: Rheology of 3 ppb VisPlus Oil-based Drilling Fluid Before Hot Rolling

Shear Rate		Shear Stress		Viscosity	Plastic Viscosity	Yield Point	Yield Point
rpm	s-1	deg Fann	Pa	cP	cP	lb/100ft2	Pa
3	5.106	14	7.154	1400	31	23	11.00478
6	10.212	15	7.665	750			
100	170.2	28	14.308	84			
200	340.4	44.5	22.7395	66.75			
300	510.6	54	27.594	54			
600	1021.2	85	43.435	42.5			

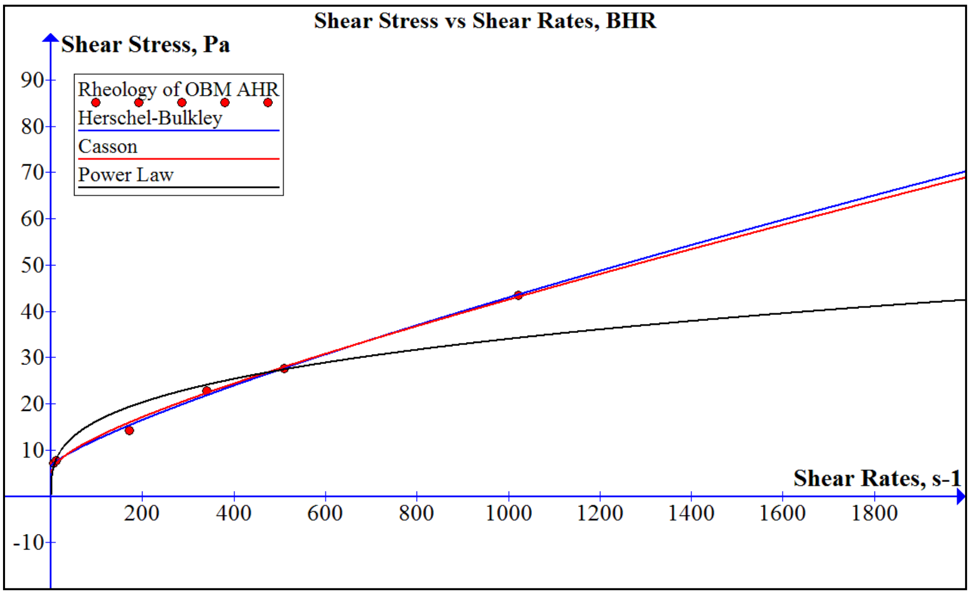


Figure 38: Shear Stress vs Shear Rates Before Hot Rolling (3 ppb)

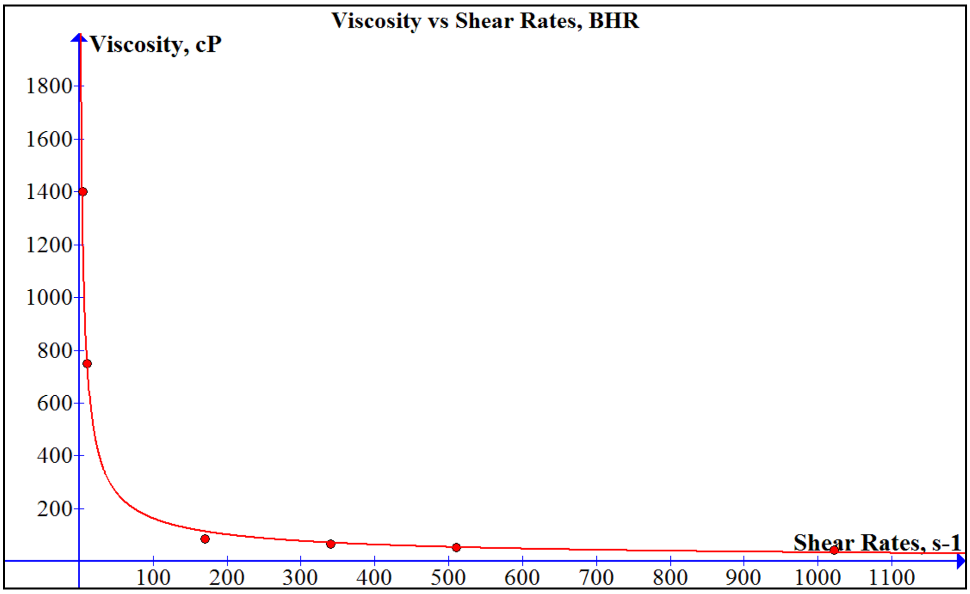


Figure 39: Graph of Viscosity vs Shear Rates Before Hot Rolling (3 ppb)

Table 28: Rheology of 3 ppb VisPlus Oil-based Drilling Fluid After Hot Rolling

Shear Rate		Shear Stress		Viscosity	Plastic Viscosity	Yield Point	Yield Point
rpm	s-1	deg Fann	Pa	cP	cP	lb/100ft2	Pa
3	5.106	4	2.044	400	31	7	3.349282
6	10.212	5	2.555	250			
100	170.2	15	7.665	45			
200	340.4	26	13.286	39			
300	510.6	38	19.418	38			
600	1021.2	69	35.259	34.5			

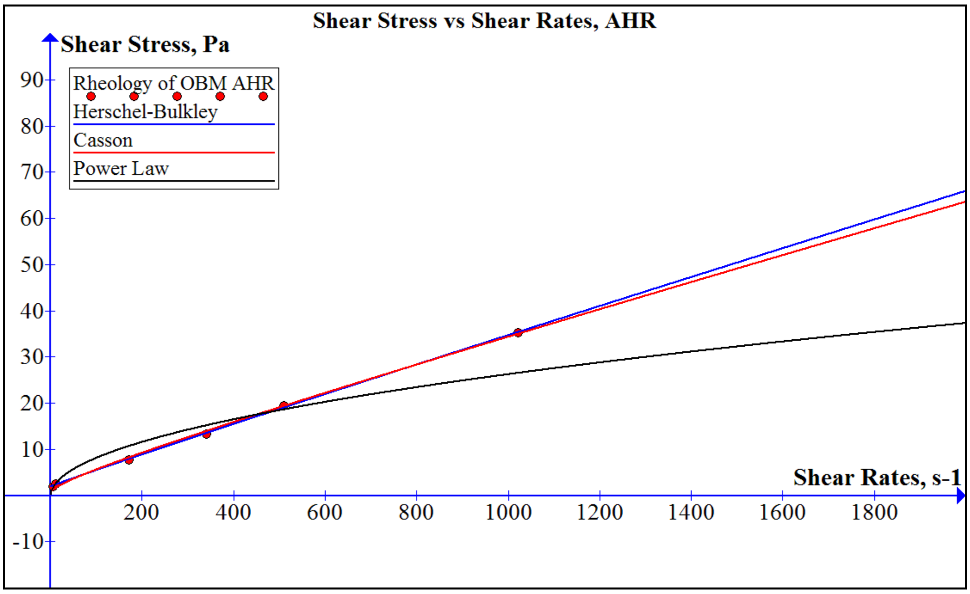


Figure 40: Shear Stress vs Shear Rates After Hot Rolling (3 ppb)

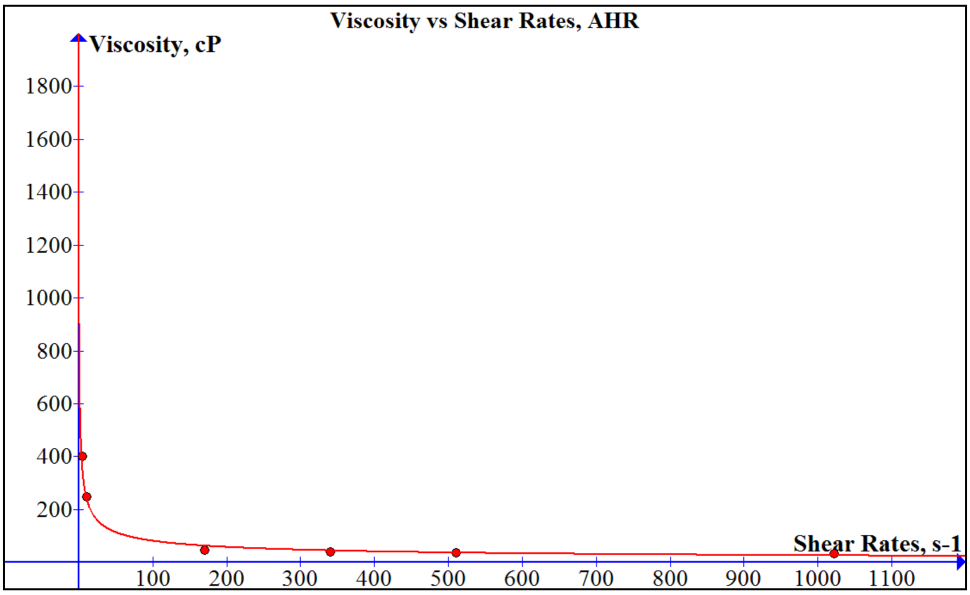


Figure 41: Graph of Viscosity vs Shear Rates After Hot Rolling (3 ppb)

4.1.7 TEST #6 (4PPB)

Table 29: Rheology Reading of Test #6

Properties	Test #6 Before Hot Rolling	Test #6 After Hot Rolling (16hours @120C, 100psi)	Recommended Values
Mixing Time (mins)	60		
Temperature (C)	25		
CaCl2 brine (wt%)	25		

Density (ppg)	12	12	12-14
3 rpm (°Fann)	18.5	3.5	10-15
6 rpm (°Fann)	20	4	10-15
100 rpm (°Fann)	30	15	
200 rpm (°Fann)	53	25	
300 rpm (°Fann)	61	33.5	
600 rpm (°Fann)	96	65	
PV (cp)	35	31.5	<65
YP (lb/100ft2)	26	2	15-24
10s gels	15	4	12
10min gels	18	5	20
30min gels	21	5	
Electrical Stability	641	250	>400
HPHT Filtrate Loss (ml) x2		7	
Mud cake thickness (mm)		1.2	

The rheology of 4ppb VisPlus concentration oil-based drilling fluid increases with the concentration of VisPlus. However, the rheological values of the drilling fluid has exceeded the rheological requirements. A lower concentration of VisPlus is preferred.

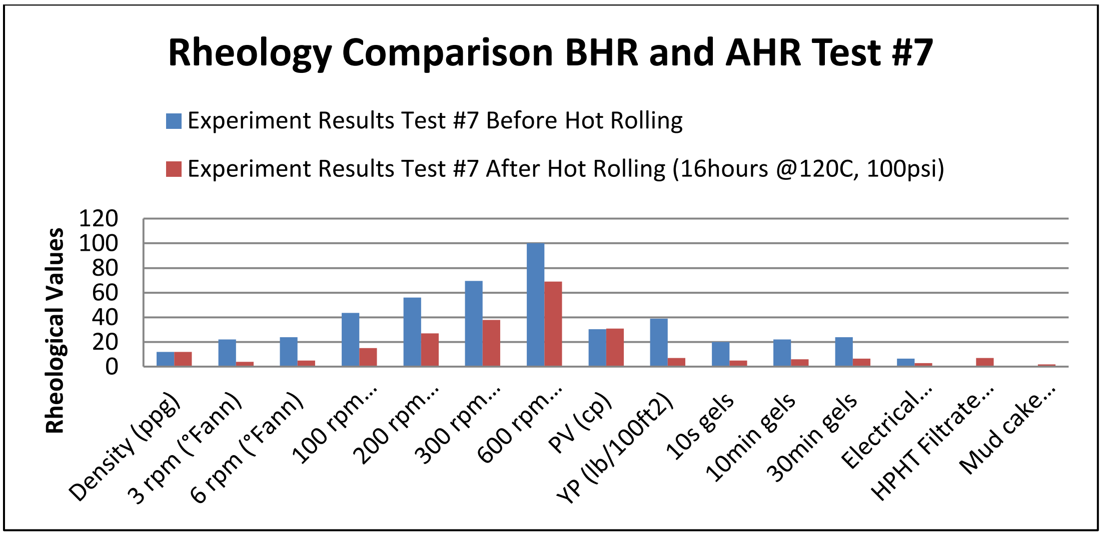


Figure 42: Rheology Comparison Between Before and After Hot Rolling (4ppb VisPlus)

Table 30: Rheology of 4 ppb VisPlus Oil-based Drilling Fluid Before Hot Rolling

Shear Rate		Shear Stress		Viscosity	Plastic Viscosity	Yield Point	Yield Point
rpm	s-1	deg Fann	Pa	cP	cP	lb/100ft2	Pa
3	5.106	18.5	9.4535	1850	35	26	12.44019
6	10.212	20	10.22	1000			
100	170.2	30	15.33	90			
200	340.4	53	27.083	79.5			
300	510.6	61	31.171	61			
600	1021.2	96	49.056	48			

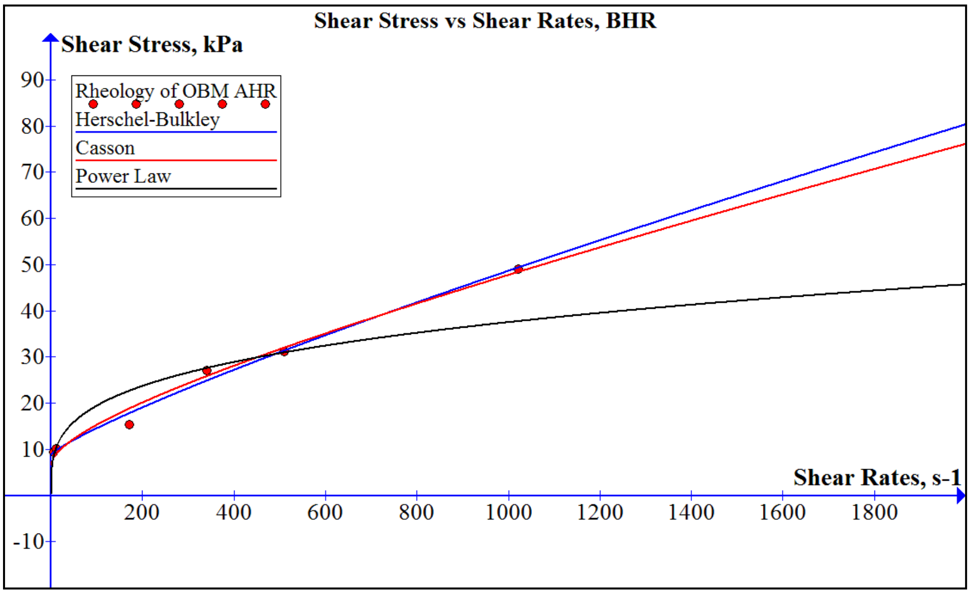


Figure 43: Shear Stress vs Shear Rates Before Hot Rolling (4 ppb)

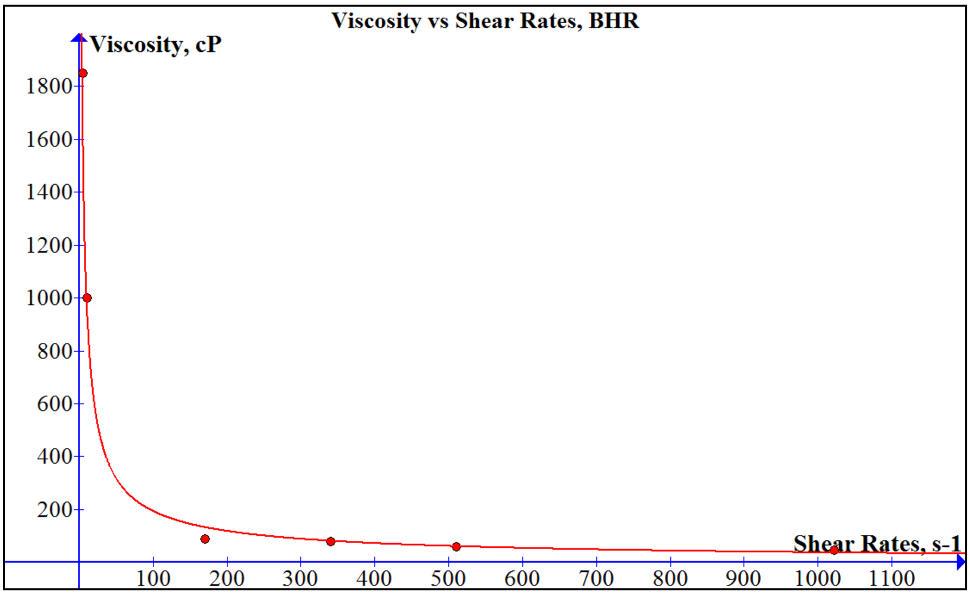


Figure 44: Graph of Viscosity vs Shear Rate Before Hot Rolling (4 ppb)

Table 31: Rheology of 4 ppb VisPlus Oil-based Drilling Fluid After Hot Rolling

Shear Rate		Shear Stress		Viscosity	Plastic Viscosity	Yield Point	Yield Point
rpm	s-1	deg Fann	Pa	cP	cP	lb/100ft2	Pa
3	5.106	3.5	1.7885	350	31.5	2	0.956938
6	10.212	4	2.044	200			
100	170.2	15	7.665	45			
200	340.4	25	12.775	37.5			
300	510.6	33.5	17.1185	33.5			
600	1021.2	65	33.215	32.5			

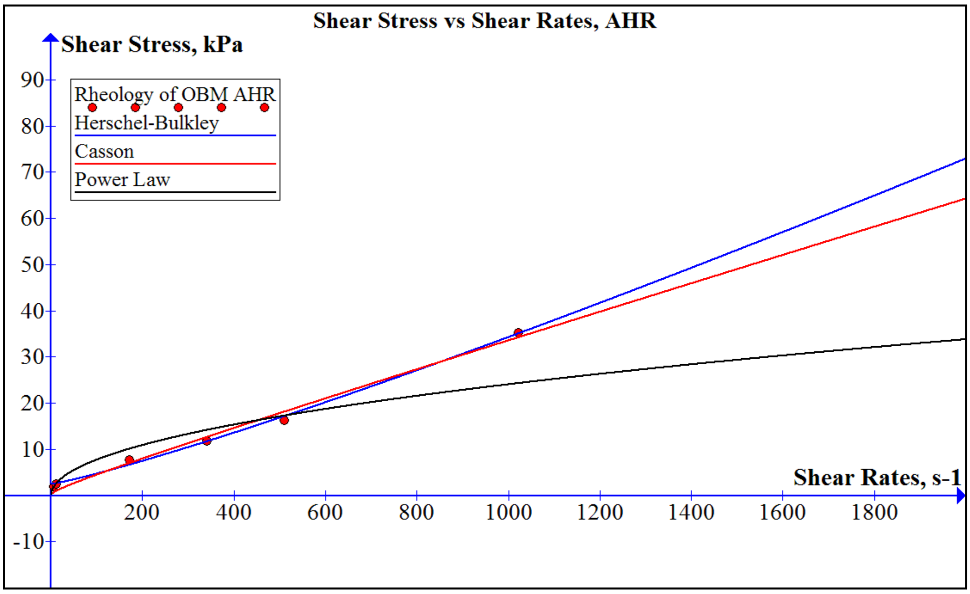


Figure 45: Shear Stress vs Shear Rates After Hot Rolling (4 ppb)

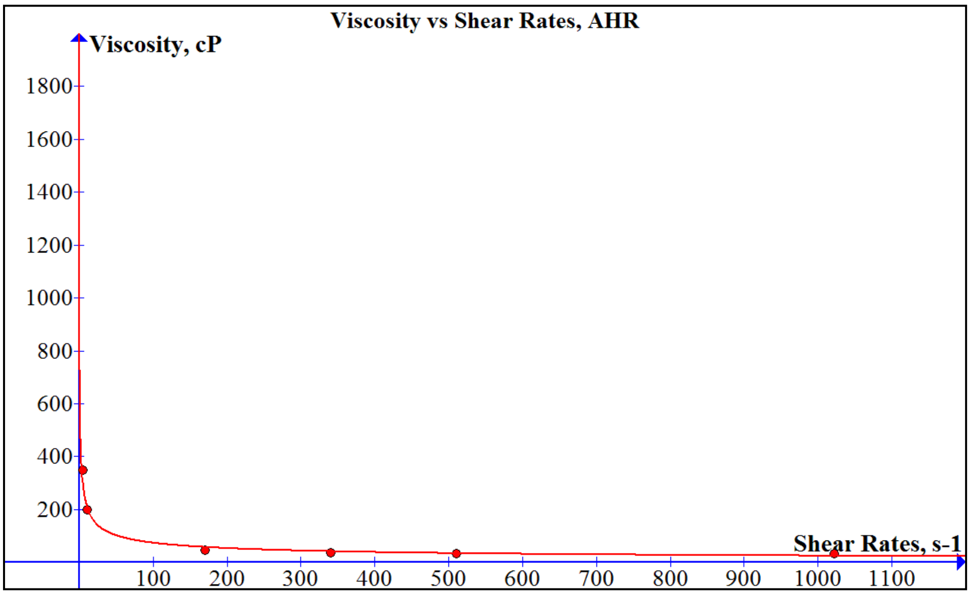


Figure 46: Graph of Viscosity vs Shear Rates After Hot Rolling (4 ppb)

4.1.8 TEST #7 (5PPB)

Table 32: Rheology Reading of Test #7

Properties	Test #7 Before Hot Rolling	Test #7 After Hot Rolling (16hours @120C, 100psi)	Recommended Values
Mixing Time (mins)	60		
Temperature (C)	25		
CaCl2 brine (wt%)	25		
Density (ppg)	12.1	12.1	12-14
3 rpm (°Fann)	22	4	10-15
6 rpm (°Fann)	24	5	10-15
100 rpm (°Fann)	43.5	15	
200 rpm (°Fann)	56	23	
300 rpm (°Fann)	69.5	32	
600 rpm (°Fann)	100	69	
PV (cp)	30.5	37	<65
YP (lb/100ft2)	39	-5	15-24
10s gels	20	5	12
10min gels	22	6	20
30min gels	24	6.5	
Electrical Stability	644	304	>400
HPHT Filtrate Loss (ml) x2		7	
Mud cake thickness (mm)		2	

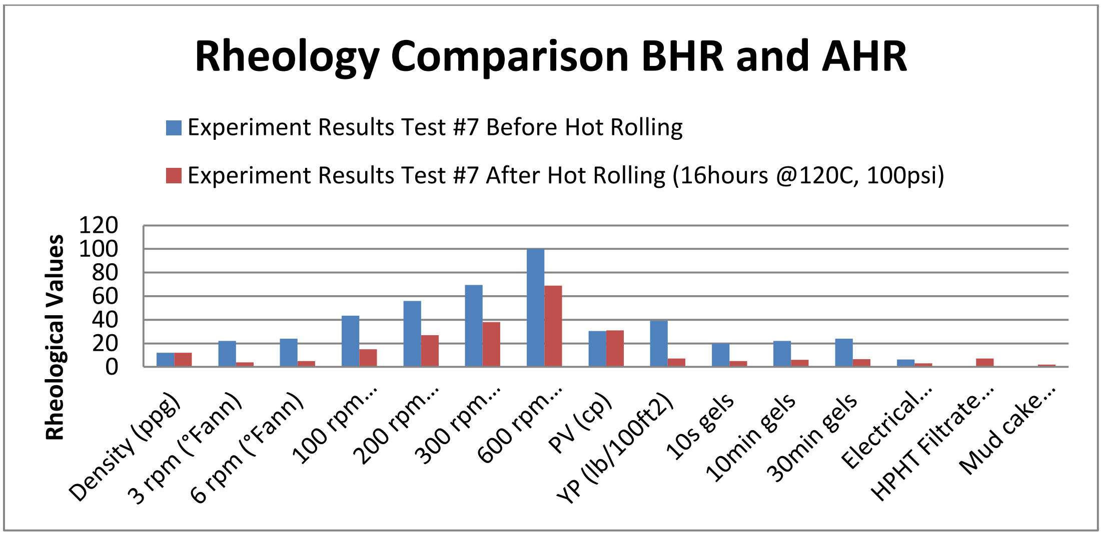


Figure 47: Rheology Comparison Between Before and After Hot Rolling (5ppb VisPlus)

Table 33: Rheology of 5 ppb VisPlus Oil-based Drilling Fluid Before Hot Rolling

Shear Rate		Shear Stress		Viscosity	Plastic Viscosity	Yield Point	Yield Point
rpm	s^{-1}	deg Fann	Pa	cP	cP	lb/100ft^2	Pa
3	5.106	22	11.242	2200	30.5	39	18.66029
6	10.212	24	12.264	1200			
100	170.2	43.5	22.2285	130.5			
200	340.4	56	28.616	84			
300	510.6	69.5	35.5145	69.5			
600	1021.2	100	51.1	50			

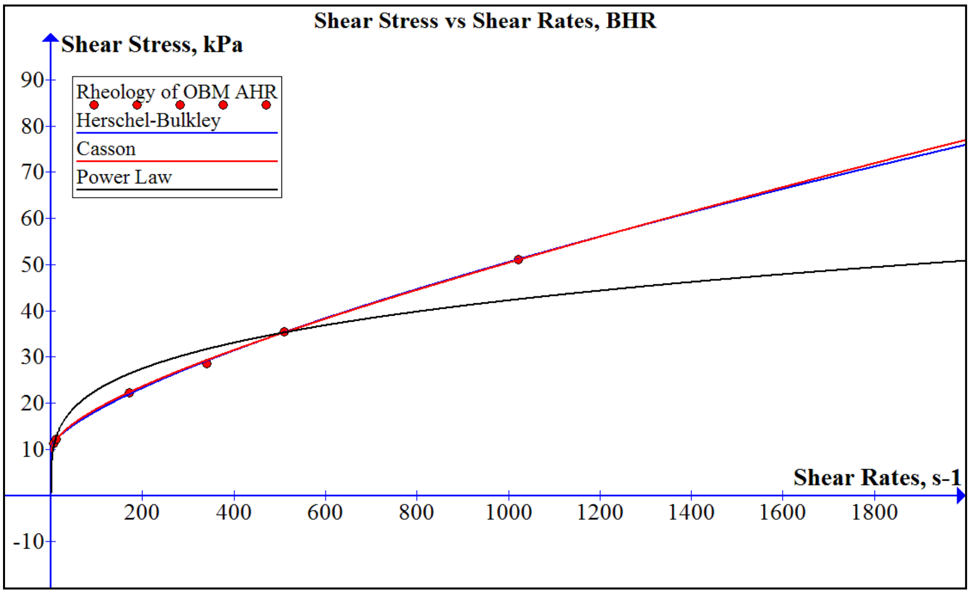


Figure 48: Shear Stress vs Shear Rates Before Hot Rolling (5 ppb)

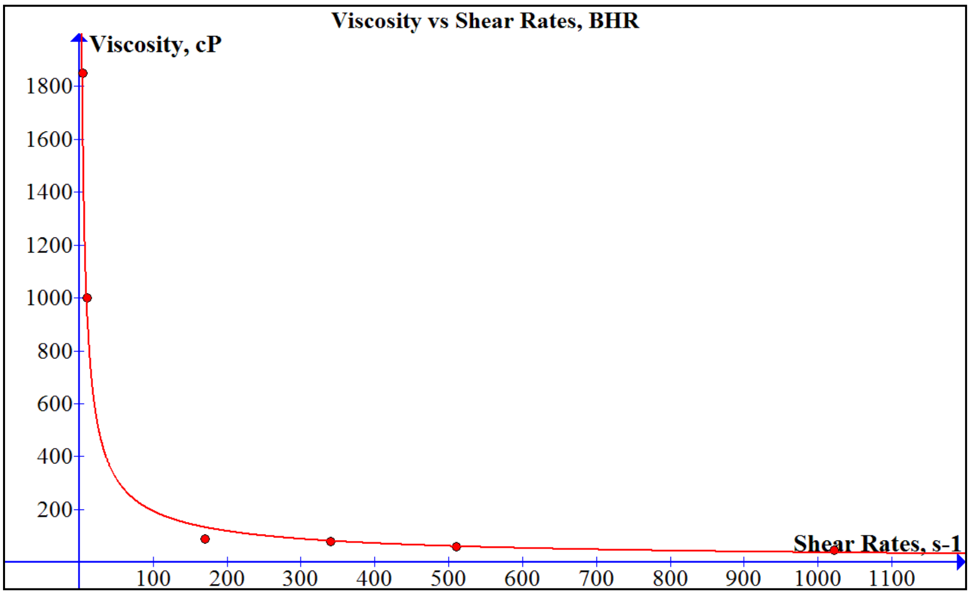


Figure 49: Graph of Viscosity vs Shear Rates Before Hot Rolling (5 ppb)

Table 34: Rheology of 5 ppb VisPlus Oil-based Drilling Fluid After Hot Rolling

Shear Rate		Shear Stress		Viscosity	Plastic Viscosity	Yield Point	Yield Point
rpm	s^{-1}	deg Fann	Pa	cP	cP	$lb/100ft^2$	Pa
3	5.106	4	2.044	400	37	-5	-2.39234
6	10.212	5	2.555	250			
100	170.2	15	7.665	45			
200	340.4	23	11.753	34.5			
300	510.6	32	16.352	32			
600	1021.2	69	35.259	34.5			

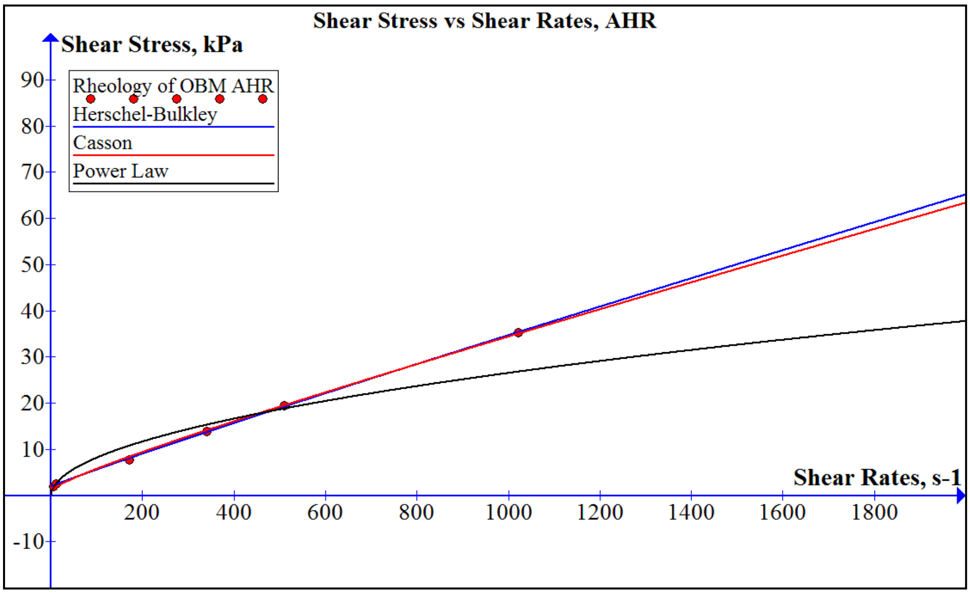


Figure 50: Shear Stress vs Shear Rates After Hot Rolling (5 ppb)

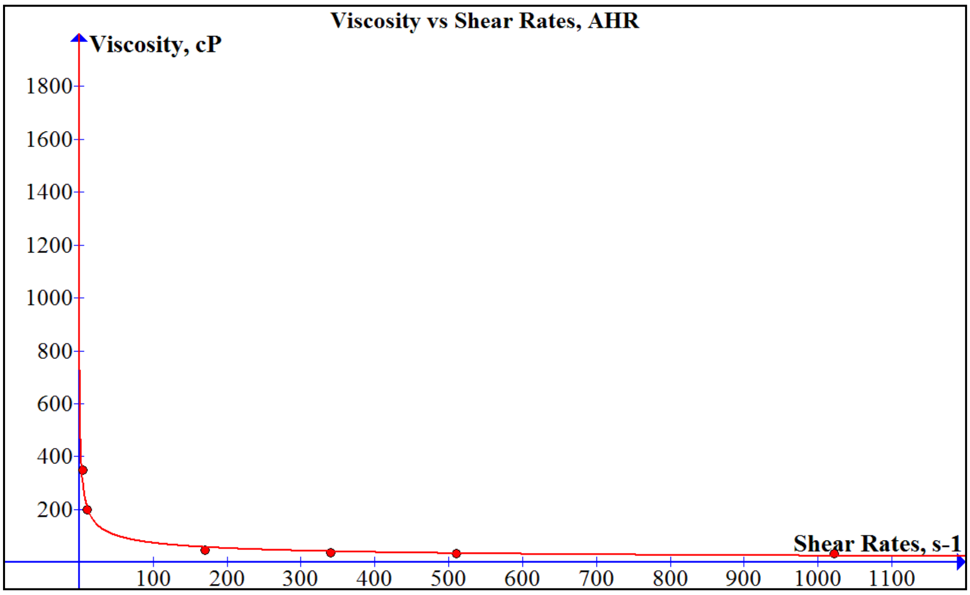


Figure 51: Graph of Viscosity vs Shear Rates After Hot Rolling (5 ppb)

4.1.9 RESULT ANALYSIS

Table 35: Rheology Result Against VisPlus Concentration

VisPlus Concentration (ppg)	0 ppb	2 ppb	3 ppb	4 ppb	5 ppb
3 rpm (°Fann)	2.5	10	14	18.5	22
6 rpm (°Fann)	4	11	15	20	24
100 rpm (°Fann)	11	25	28	30	43.5
200 rpm (°Fann)	17	35.5	44.5	53	56
300 rpm (°Fann)	23	45	54	61	69.5
600 rpm (°Fann)	45	72.5	85	96	100
PV (cp)	22	27.5	31	35	30.5
YP (lb/100ft2)	1	17.5	23	26	39
10s gels	4	9	12	15	20
10min gels	4.5	10	15	18	22
30min gels	5	11	16	21	24
Electrical Stability	375	601	630	641	644

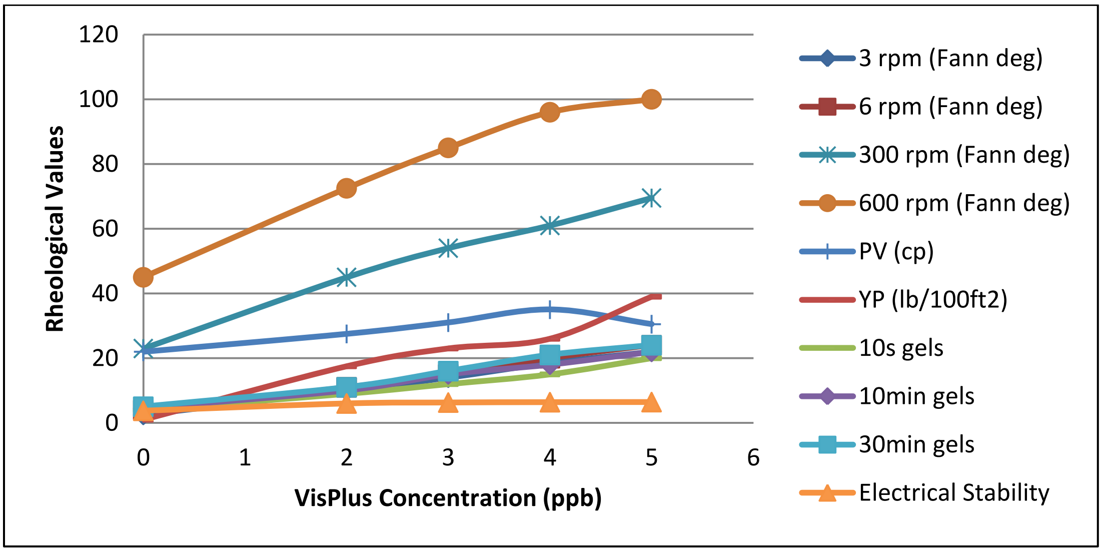


Figure 52: Rheology vs VisPlus Concentration

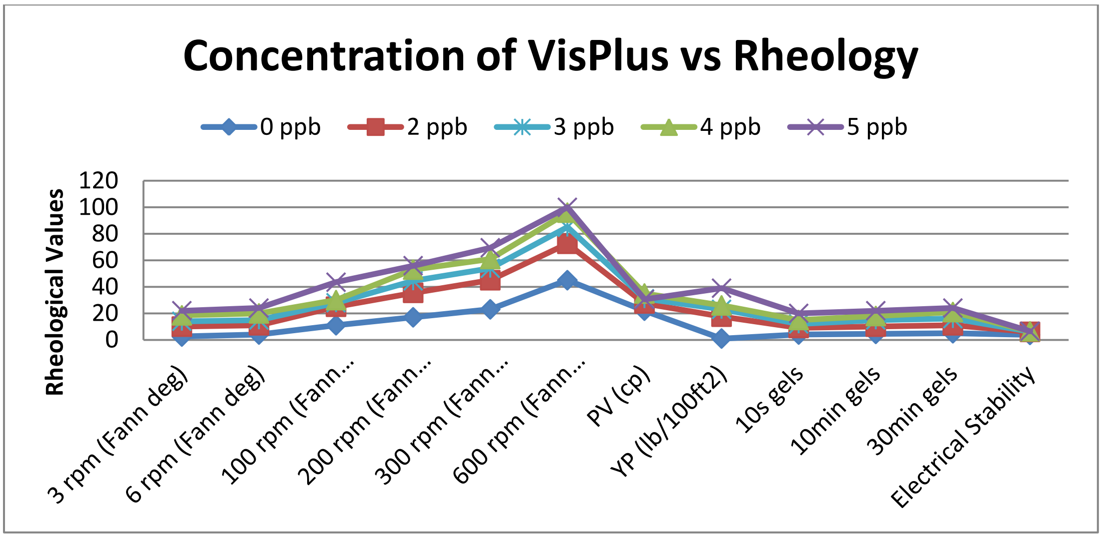


Figure 53: Rheology vs VisPlus Concentration

Figure 52 and Figure 53 shows the progression of rheological values with the variance in VisPlus concentration. The purposes of these graphs are to identify any trends in terms of rheological changes with the change in the concentration of the rheology modifier, which is VisPlus. The rheological properties which are focused on are low shear rate viscosity value (LSRV), high shear rate viscosity value (HSRV), plastic viscosity, yield point and gel strength.

Low shear rate viscosity values and high shear rate viscosity values are the rheology of oil-based drilling fluid near the surface facilities and the wellbore respectively. Plastic viscosity is a measure of viscosity of drilling fluid. Yield point is the ability of drilling fluid to suspend and lift cuttings. Gel strength is the ability of drilling fluid to hold solids in suspension and retain gel form. From Figure 52 and 53, it was found that the rheology of oil-based drilling fluid increases with increasing concentration of VisPlus.

From Figure 54 and 55, it is observed that as the concentration of rheology modifier (VisPlus) increases, the higher the viscosity and rheology values.

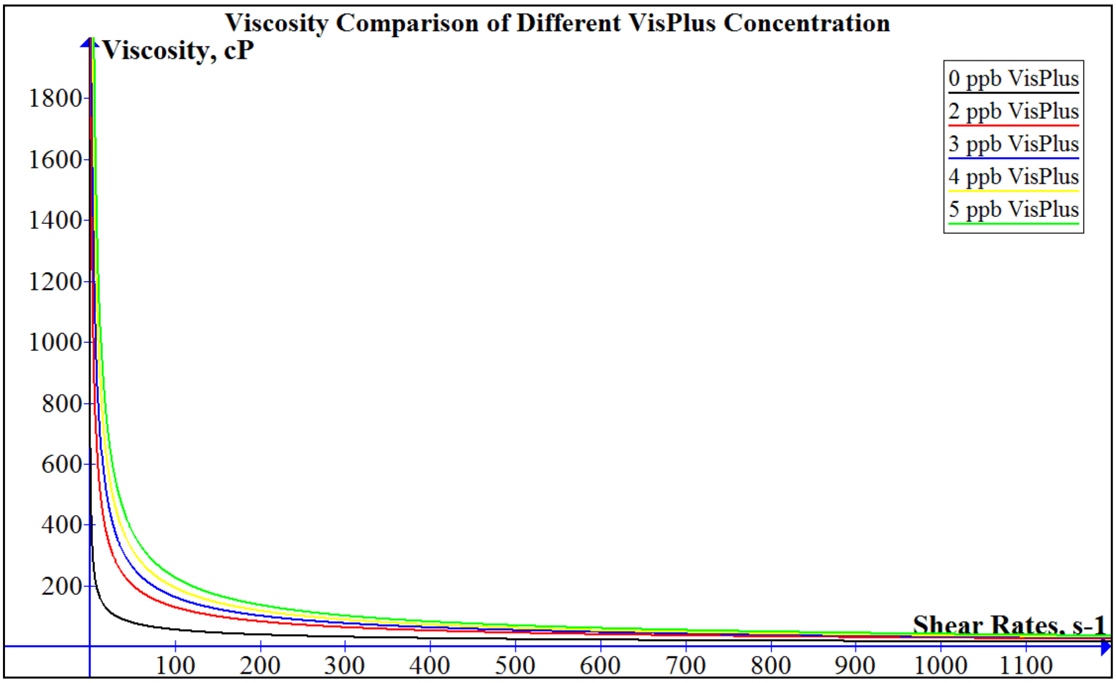


Figure 54: Graph of Viscosity Comparison for Different VisPlus Concentration

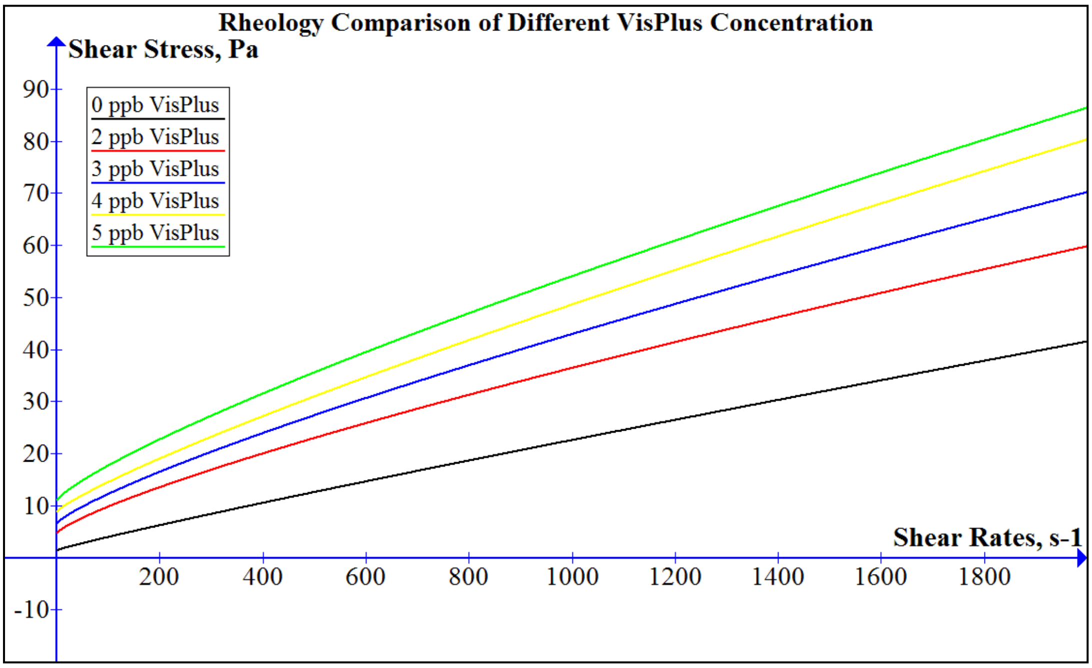


Figure 55: Graph of Rheology Comparison for Different VisPlus Concentration

4.2 DISCUSSION

4.2.1 OIL-BASED DRILLING FLUID RHEOLOGY

The rheology is an important property of drilling fluids. Rheological properties are used to assess the functionality of the mud system. Drilling fluids behave with non-Newtonian fluid ~~flow~~ properties. The viscosity is not only influenced by temperature and pressure changes, but also very dependent on the velocity at which the drilling fluid flows through the hydraulic system. Therefore, it is important to know the rheological properties of a drilling fluid in the complete range of shear rates experienced by the drilling fluid in the system. In fact, drilling fluid is subjected to very different shear rates, from very low values in the mud pit to very high values at the bit nozzle.

These shear rates are closely related to the velocity of the drilling fluid at different parts of the well. Combs (1967) measure the shear rates at low annular flow rates at 1 to 8 rpm. According to Stiff and Robertson (1976), the shear rates at the bit nozzle is from 600 to 800s^{-1} (350 to 480 rpm). The 6-speed viscometers used on the oilfield allows measurements of 3, 6, 100, 200, 300 and 600 rpm, which allows rheology to be measured at the whole range of shear rates in a mud circulation system.

Table 36: Shear Rates at Low Shear Regions

Annular Flow Rate, u (ft/s)	d1-d2 (ft)	Shear Rates (s-1)
1	15	0.8
1	20	0.6
5	15	4
5	20	3
10	15	8
10	20	6

Table 37: Shear Rates at High Shear Regions

Annular Flow Rate, u (ft/s)	d1-d2, 10-5 (ft)	B	C	Shear Rates (s-1)	Rev per min , rpm
60	5	0.422203	330.2071	600.7419	352.9623462
90	5	0.422203	330.2071	705.5866	414.5632235
120	5	0.422203	330.2071	810.4313	476.1641008

The six-point shear stress corresponding to the shear rates are plotted on a graph. Rheological models can be fitted on these six measurements and provide a curve which describe mathematically the relationship between shear stress and shear rates of a drilling fluid. From test#1 to test#3, rheology of the drilling fluid is measured using a six-speed viscometer. However, it was found that the rheology measured was lower than required. A low rheology will provide a bad performance in hole cleaning and cutting transport, in addition to barite sagging.

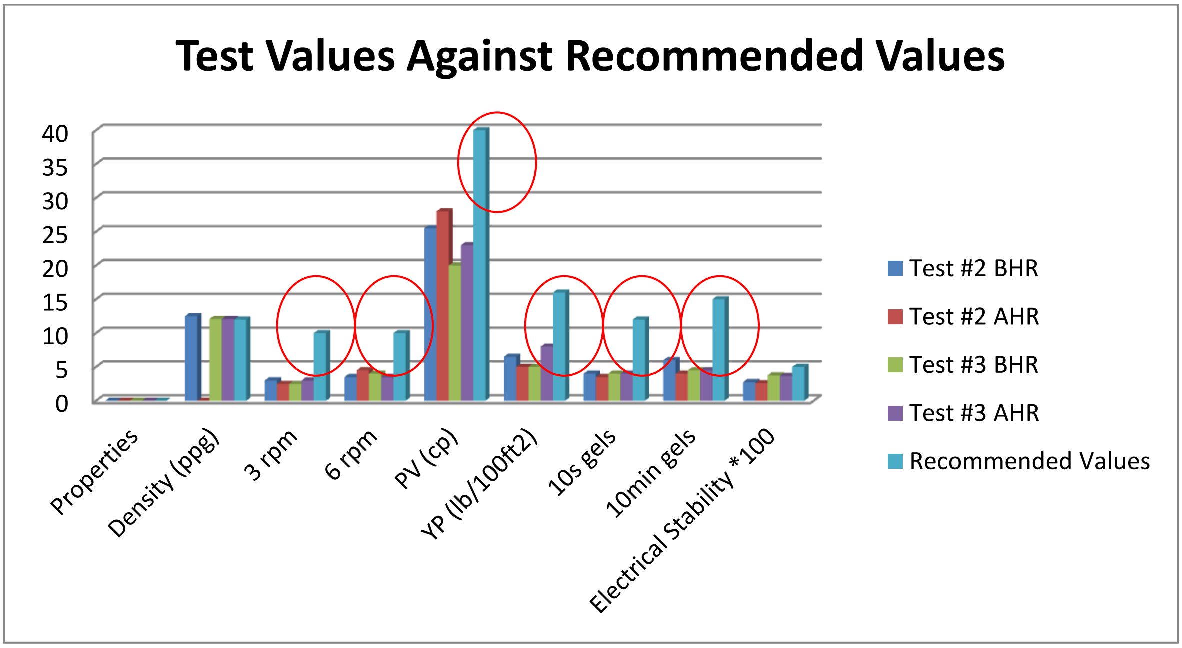


Figure 56: Graph of Test Values against Recommended Values

In the graph above, the areas circled in red show the low rheology values compared against eh recommended values. These low values impact the oil-based drilling fluid in different ways:

a) 3 and 6 rpms Fann Viscometer readings are important for hole cleaning and barite suspension. The low readings are the reason for the barite sagging which is observed.
b) PV is the measurement of the viscosity of a mud when extrapolated to infinite shear rate. A lower than recommended PV value will also mean weaker ability to transport cuttings.
c) Yield point is the amount of force required to move a drilling fluid from a stationary position to a dynamic position. A high YP value means that a non-Newtonian fluid has better cuttings transport ability.
d) Gel strength is the ability of the drilling fluid to suspend solids when it is stopped from moving. Weak gel strength means that heavier solids will settle to the bottom and causes sagging.

The main contributors in a drilling fluid to its rheology are two mud additives: emulsifier and viscosifier. Emulsifier lowers the interfacial tension between oil and water, which allows stable emulsions with small drops to be formed. Emulsifiers also form clusters in the oil phase and adsorb into solids. The combination of the emulsifier and water or solid stabilizes the invert oil emulsion and imparts suitable rheology. Viscosifiers are used for providing viscosity to a drilling fluid. Therefore, a low drilling fluid rheology is often caused by the insufficient amount of both emulsifier and viscosifier. A higher concentration of both chemicals is required to increase the mud rheology.

At the same time, low emulsion stability was also observed with the drilling fluids. An increase in stability was observed in test#3 upon the increase in concentration of emulsifier. However, the stability was not good enough and barite sagging was observed, which means water was separated from the emulsion and caused the additives to be water-wet and sink to the bottom. A higher concentration of emulsifier is required to obtain a useable drilling fluid.

From test#1 and test#2, it was found that the type of base oil does not give a significant effect on the rheology changes. The two base oils, Sarapar 147 and Saraline 185v, produced drilling fluid having similar properties. Even though the compositions of the Sarapar and Saraline are slightly different, it can be assumed that the composition do not have much effect on rheology.

Rheological models that are fitted into the rheology measurements are the Herschel-Bulkley Model, Casson Model and Power Law Model. After these rheological models are fitted, it was found that the Power Law Model provided the worst fit, while Herschel-Bulkley and Casson fitted the measurements equally well, as shown by previous authors before this. Further tests will continue to utilize these two models and measure their accuracy in predicting mud rheology. Based on the shape of the rheological models, it is observed that the drilling fluid exhibit shear thinning characteristics. At the same time, drilling fluid was not observed to contain any rheopectic or thixotropic properties, due to the same rheological values regardless of the test sequence.

Comparing the rheological values obtained from experimental tests against the required values, it is found that the rheological values of the oil-based drilling fluid ranges from below the lower limit to above the upper limit of the required rheological values, along with the increase in VisPlus concentration. For Low Shear Rheology Values and Yield Point, the required Fann reading at 3 and 6 rpms are tabulated as below:

Table 38: Rheological Requirements of Drilling Fluid

	Low Shear Rheology Values	Yield Point
Upper Limit	15	24
Lower Limit	10	15

From Figures 57 and 58, it was found that the only drilling fluid samples that are within the rheological requirements are drilling fluid with 2 ppb and 3 ppb (grams per lab barrel, 350 ml) VisPlus concentration.

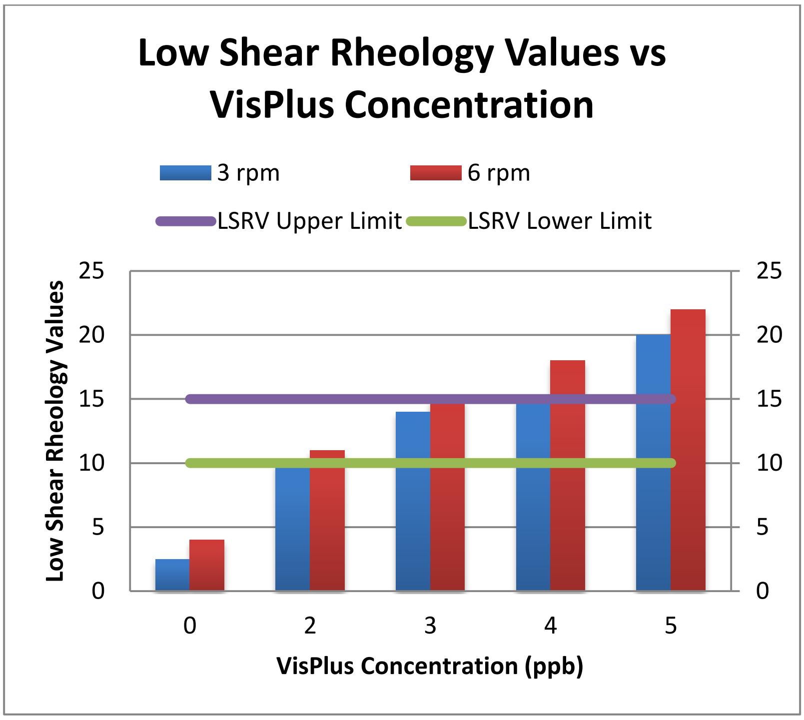


Figure 57: Bar Chart of LSRV vs VisPlus Concentration

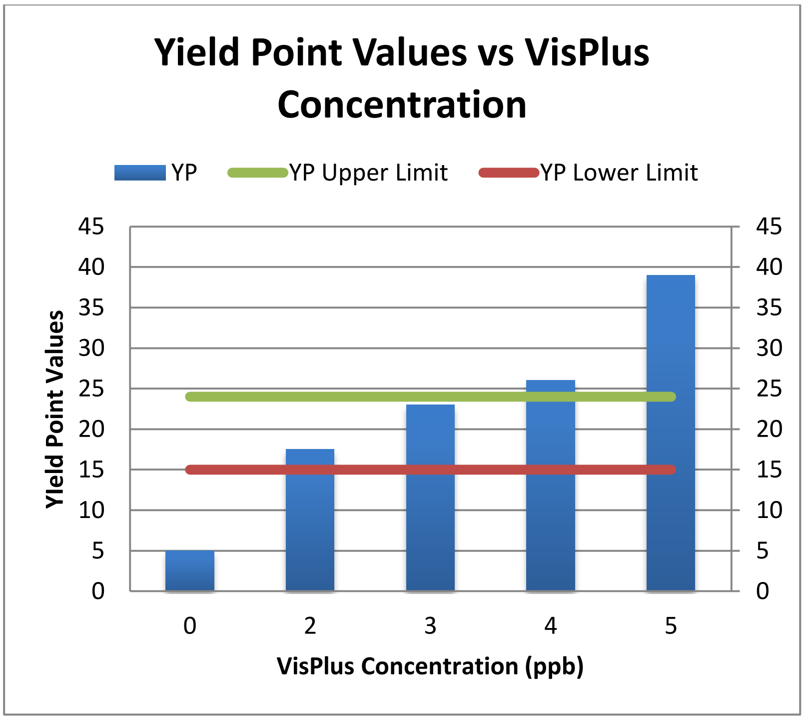


Figure 58: Bar Chart of Yield Point Values vs VisPlus Concentration

4.2.2 CORRELATION TO RHEOLOGICAL MODELS

Rheological data obtained from experiments are plotted in a graph and correlated to three rheological models, namely Herschel-Bulkley model, Casson model and Power Law model. It was found that the Power Law model is the least accurate of the three, and Herschel-Bulkley model is marginally more accurate than the Casson model in predicting the rheology of drilling fluid. The correlation results are tabulated below:

A. Herschel-Bulkley Rheological Model

$$\tau = \tau_0 + \mu(\gamma)^n$$

Table 39: Correlation of Drilling Fluid Rheology to Herschel-Bulkley Model

VisPlus Concentration (ppb)	0	2	3	4	5
τ_0	1.4279	4.7712	6.5868	8.8832	10.5303
μ	0.0362	0.1278	0.1371	0.1147	0.2963
n	0.9223	0.7979	0.8078	0.8465	0.7099
Coefficient of Determination, R^2	0.9994	0.9997	0.9998	0.9903	0.9996

B. Casson Rheological Model

$$\tau = k_0{}^2 + 2k_0k_1\gamma^{0.5} + k_1{}^2\gamma$$

Table 40: Correlation of Drilling Fluid Rheology to Casson Model

VisPlus Concentration (ppb)	0	2	3	4	5
k_0	0.7771	1.8873	2.2115	2.5248	3.0501
k_0^2	0.603884	3.561901	4.890732	6.374615	9.30311
k_1	0.125	0.1305	0.1361	0.1386	0.1279
Coefficient of Determination, R^2	0.9979	0.9992	0.9958	0.9841	0.9995

C. Power Law Model

$$\tau = K\gamma^n$$

Table 41: Correlation of Drilling Fluid Rheology to Power Law Model

VisPlus Concentration (ppb)	0	2	3	4	5
K	0.5642	2.5497	3.7253	5.2289	6.6703
n	0.4993	0.3537	0.32	0.2851	0.267
R^2	0.9092	0.9061	0.8831	0.8422	0.911

Table 42: Correlation Results of 0ppb VisPlus Concentration Drilling Fluid

		Calculated Shear Stress, Pa			Percentage Error, %		
Shear Rate, s^{-1}	Shear Stress, Pa	Herschel-Bulkley	Casson	Power Law	Herschel-Bulkley	Casson	Power Law
5.11	1.28	1.59	1.12	1.27	24.52	12.12	0.32
10.21	2.04	1.74	1.38	1.80	15.04	32.28	11.94
170.20	5.62	5.56	5.80	7.33	1.06	3.15	30.48
340.40	9.20	9.26	9.51	10.37	0.69	3.36	12.71
510.60	12.78	12.81	12.97	12.69	0.30	1.54	0.64
1021.20	23.00	23.01	22.77	17.94	0.05	0.99	21.97
			Average Error Percentage, %		6.94	8.90	13.01
			Standard Deviation		10.39	12.14	11.84

Table 43: Correlation Results of 2ppb VisPlus Concentration Drilling Fluid

		Calculated Shear Stress, Pa			Percentage Error, %		
Shear Rate, s^{-1}	Shear Stress, Pa	Herschel-Bulkley	Casson	Power Law	Herschel-Bulkley	Casson	Power Law
5.11	5.11	5.24	4.76	4.54	2.56	6.81	11.18
10.21	5.62	5.59	5.31	5.80	0.60	5.53	3.18
170.20	12.78	12.47	12.89	15.69	2.36	0.87	22.81
340.40	18.14	18.16	18.45	20.05	0.12	1.69	10.51
510.60	23.00	23.28	23.39	23.14	1.23	1.71	0.62
1021.20	37.05	36.94	36.69	29.57	0.28	0.95	20.19
			Average Error Percentage, %		1.19	2.93	11.42
			Standard Deviation		1.05	2.57	8.85

Table 44: Correlation Results of 3ppb VisPlus Concentration Drilling Fluid

		Calculated Shear Stress, Pa			Percentage Error, %		
Shear Rate, s^{-1}	Shear Stress, Pa	Herschel-Bulkley	Casson	Power Law	Herschel-Bulkley	Casson	Power Law
5.11	7.15	7.10	6.35	6.28	0.78	11.30	12.26
10.21	7.67	7.48	7.00	7.84	2.38	8.63	2.23
170.20	14.31	15.28	15.90	19.28	6.80	11.10	34.74
340.40	22.74	21.81	22.30	24.07	4.11	1.92	5.83
510.60	27.59	27.70	27.95	27.40	0.40	1.29	0.70
1021.20	43.44	43.55	43.04	34.20	0.27	0.90	21.25
			Average Error Percentage, %		2.45	5.86	12.84
			Standard Deviation		2.59	5.01	13.11

Table 45: Correlation Results of 4ppb VisPlus Concentration Drilling Fluid

		Calculated Shear Stress, Pa			Percentage Error, %		
Shear Rate, s^{-1}	Shear Stress, Pa	Herschel-Bulkley	Casson	Power Law	Herschel-Bulkley	Casson	Power Law
5.11	9.45	9.34	8.05	8.32	1.21	14.80	11.96
10.21	10.22	9.70	8.81	10.14	5.06	13.82	0.77
170.20	15.33	17.76	18.77	22.62	15.83	22.47	47.54
340.40	27.08	24.84	25.83	27.56	8.29	4.64	1.76
510.60	31.17	31.37	32.00	30.94	0.64	2.65	0.75
1021.20	49.06	49.32	48.36	37.70	0.54	1.42	23.15
			Average Error Percentage, %		5.26	9.97	14.32
			Standard Deviation		6.01	8.36	18.51

Table 46: Correlation Results of 5ppb VisPlus Concentration Drilling Fluid

		Calculated Shear Stress, Pa			Percentage Error, %		
Shear Rate, s^{-1}	Shear Stress, Pa	Herschel-Bulkley	Casson	Power Law	Herschel-Bulkley	Casson	Power Law
5.11	11.24	11.47	11.15	10.31	2.06	0.82	8.30
10.21	12.26	12.07	11.96	12.40	1.56	2.45	1.15
170.20	22.23	21.89	22.27	26.29	1.51	0.17	18.28
340.40	28.62	29.12	29.27	31.64	1.75	2.27	10.55
510.60	35.51	35.32	35.29	35.25	0.56	0.64	0.73
1021.20	51.10	51.07	50.94	42.42	0.06	0.31	16.98
			Average Error Percentage, %		1.25	1.11	9.33
			Standard Deviation		0.77	1.00	7.51

The correlation results of the drilling fluid rheology data to rheological models are tabulated in Table 44 to 48. The Herschel-Bulkley rheological model provided the best fit of rheological data and has the least average error percentage and error standard deviation. Graphical representation of the correlation results are shown in Figure 59 and 60.

For rheological models, error percentage and standard deviation are measures of accuracy and consistency of a rheological model. Low values for both categories are required in order to represent drilling fluid rheology accurately. The Herschel-Bulkley model is the most accurate model, a view also shared by Ayeni and Osisanya (2004) and Wolfe, Coffin and Byrd (1983). The next most accurate model is the Casson model followed by the Power Law model.

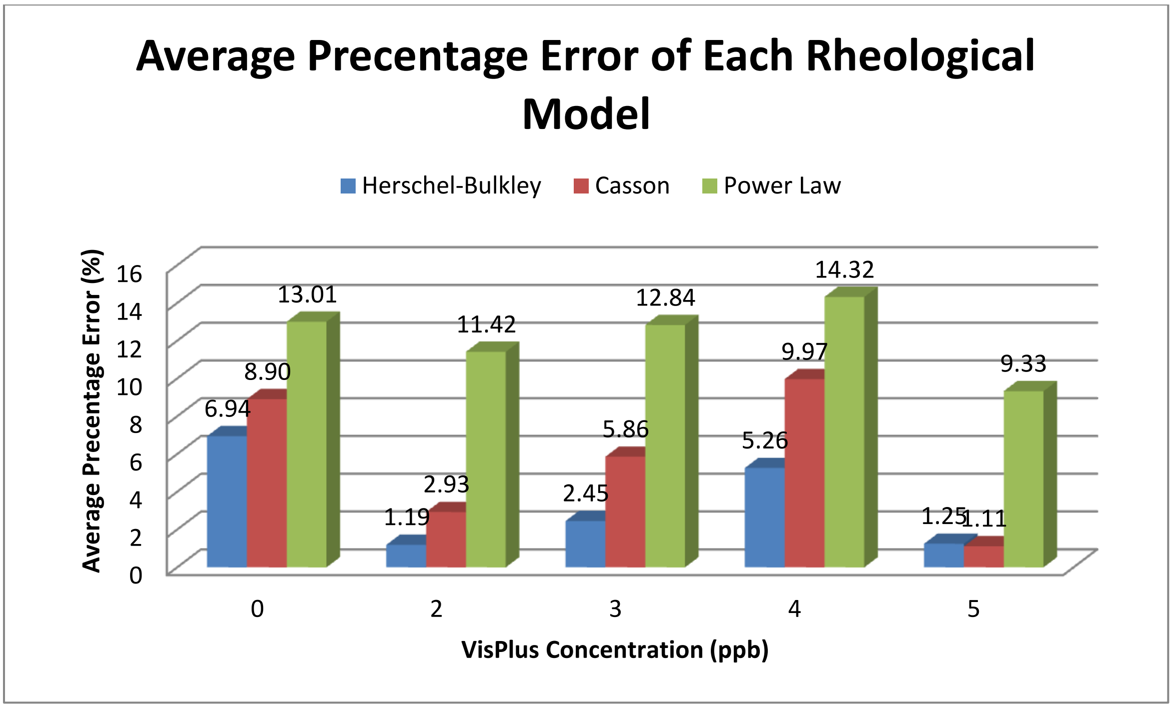


Figure 59: Average Percentage Error of Rheological Models

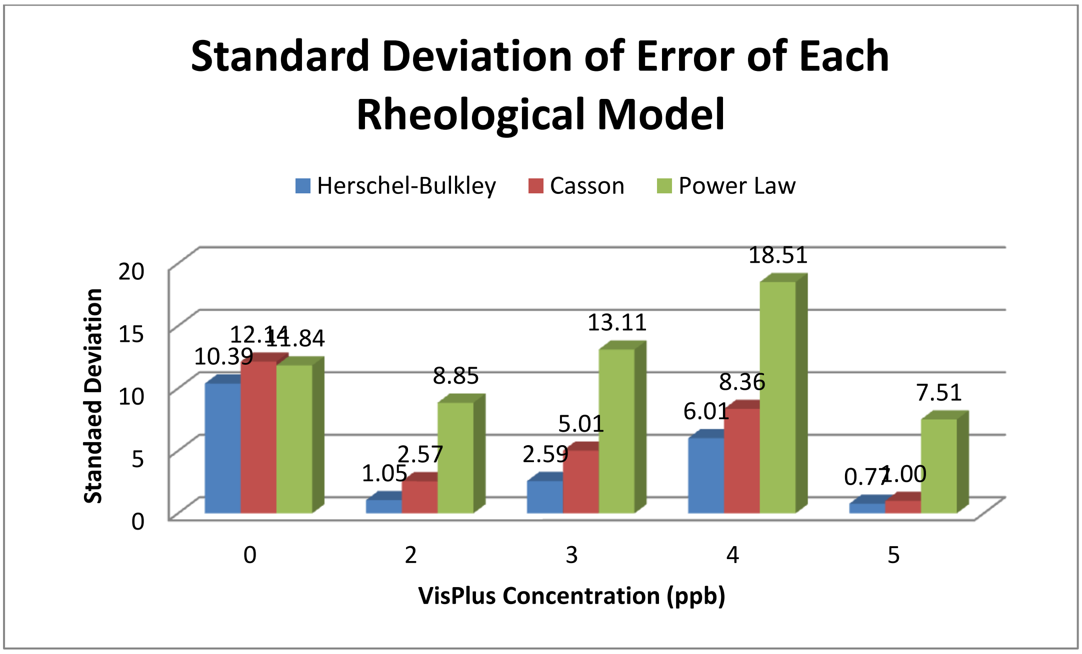


Figure 60: Standard Deviation of Rheological Model Error

4.2.3 ECONOMIC ANALYSIS

From field tests, the cost of VisPlus is generally USD 2.4 per pound per barrel. With an approximate of 2,000 barrels of drilling fluid used in a drilling operation, the total additional costs related to the usage of VisPlus is USD 24,000. However, the problems associated with drilling fluid will potentially cost USD 600,000 per well due to downtime delays. With the use of VisPlus, companies may achieve savings of USD 576,000 per well given no other problem occurs during drilling.

Table 47: Economic Analysis for the Use of VisPlus

COST	Amount	Unit
Additional Cost of VisPlus	12	USD/bbl
No. barrels of drilling fluid	2000	bbl
Total Additional Cost	24000	USD
POTENTIAL LOSSES		
Average daily drilling cost	150,000	USD/day
Average time lost	4	day
Average Downtime Cost	600000	USD
POTENTIAL SAVINGS		
Average Downtime Cost - Total Additional Cost	576000	USD

CHAPTER 5 :
CONCLUSION

The conclusion that can be obtained based on this project is that the addition of VisPlus increases the rheology of drilling fluid. However, to obtain the required rheology, the optimum concentration of VisPlus is 3 pounds per barrel, or equivalent to 8.5 kg per cubic metres. From the rheological model results, Casson model and Herschel-Bulkley model accurately measures drilling fluid rheology, but Herschel-Bulkley is marginally more accurate. The findings of this research will help engineers to predict the drilling fluid rheology accurately by using the most accurate model in relevant simulation softwares.

5.1 RECOMMENDATION

This project is a new area of research for UTP Chemical Engineering Department There is potential in the characterization of materials. The way the industry works currently, is to focus on usability more than characterization. Chemical Engineering Department can promote further understanding of these materials by performing the material characterization from the microscopic level. Therefore, new materials can be investigated and characterization of materials can be done.

Proceeding with the current research direction, the mud formulation can be changed. As long as the components of drilling fluid are maintained within the limits and the resulting drilling fluid satisfy the rheological requirement, further research can be done. In fact, in the table below are the parameters that can be changed with regards to mud formulation.

Table 48: Potential Modifications on Mud Formulation

Formulation of Oil-Based Mud	
Mud Weight: 10-14 ppg	
Salt Concentration: 20-25wt% $CaCl_2$ Brine	
Product	Weight (lbm/bbl)
Base Fluid	0.68 bbl/bbl
Lime	2.0 – 3.0
Organoclay	2.0 – 4.0
Emulsifier	8.0 – 12.0
Wetting Agent	1.5 – 3.0
$CaCl_2$ Brine	0.21 bbl/bbl
Barite	58.3 – 69

There is also potential in researching in the direction of sustainable development, in terms of limiting adverse effects of drilling fluid to the environment. OBM provides better performance than water-based mud, but its major limitation is that it is not environmental friendly. Green materials such as nano crystalline cellulose (NCC) or the reuse of waste such as palm oil ash has the potential to be used in mud formulation. Bio oils such as jatropha oil and vegetable oils can also be used as substitutes for base oil, but more research is needed.

The current drilling fluid formulation can also be subjected to well conditions to understand the drilling fluid rheology further. The knowledge of drilling fluid rheology under elevated temperature and pressure is useful to understand the changes within the drilling fluid under heat and pressure in an actual well. A caution is that the drilling fluid components must be resistant to heat and pressure, so that the drilling fluid rheology will not be destroyed, as shown in the after hot rolling results of this project.

CHAPTER 6 :
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CHAPTER 7 :
APPENDICES

7.1 APPENDIX A: PHYSICAL AND CHEMICAL PROPERTIES OF SARAPAR 147

Base Oil			Sarapar 147
Physical Properties		Units	Result
Physical State			Liquid at ambient temperature
Density at 15 deg C		kg/m3	774
Colour			Colourless
Odour			Odourless
Boiling Range	IBP	deg C	255
	90% recovered	deg C	285
	FBP	deg C	295
Vapour pressure @ 40 deg C		kPa	< 0.1
Kinematic viscosity at 40 deg C		mm2/s	2.67
Vapour density (air=1)			> 5
Sulphur		Ppm	< 3
Aromatics		% m	< 0.1
Pour point		deg C	9
Flash point		deg C	124
Aniline point		deg C	94
Auto-ignition point		deg C	216
Solubility in water			Insoluble
Chemical Properties			
C13 & lower		mass %	0.4
C14		mass %	24.8
C15		mass %	24.5
C16		mass %	23.3
C17		mass %	21.6
C18 & higher		mass %	5.4
Total n-parafin		mass %	93.2
Total methyl-branched paraffin		mass %	6.1
Total ethyl-branched paraffin		mass %	0.5

7.2 APPENDIX B: CALCULATION FOR HIGH SHEAR RATE REGION IN A WELL

Shear Rate		Shear Stress		C	P=log(γ+C)	Q=logT	P*Q	P^2	B
Rpm	s-1	deg Fann	Pa						
3	5.106	2.5	1.2775	330.2071	2.525450582	0.4252896	1.074048	6.377901	0.422
6	10.212	4	2.044		1.009110806	0.6294096	0.635144	1.018305	
100	170.2	11	5.621		2.230959556	1.0687423	2.384321	4.977181	
200	340.4	17	8.687		2.531989551	1.2577985	3.184733	6.410971	
300	510.6	23	11.753		2.70808081	1.3890774	3.761734	7.333702	
600	1021.2	45	22.995		3.009110806	1.6805621	5.056998	9.054748	
Total	2057.718				14.01470211	6.4508796	16.09698	35.17281	
Average	342.953								

Annular Flow Rate, u (ft/s)	d1-d2, 10-5 (ft)	B	C	Shear Rates (s-1)	Rev per mim , rpm
60	5	0.422203	330.2071	600.7419	352.9623462
90	5	0.422203	330.2071	705.5866	414.5632235
120	5	0.422203	330.2071	810.4313	476.1641008

7.3 APPENDIX C: MATERIAL SAFETY DATA SHEET: VISPLUS

HALLIBURTON

MATERIAL SAFETY DATA SHEET

Product Trade Name: **VIS-PLUS®**

Revision Date: 04-Jan-2011

1. CHEMICAL PRODUCT AND COMPANY IDENTIFICATION

Product Trade Name: VIS-PLUS®
Synonyms: None
Chemical Family: Organic acid
Application: Viscosifier

Manufacturer/Supplier
Baroid Fluid Services
Product Service Line of Halliburton
P.O. Box 1675
Houston, TX 77251
Telephone: (281) 871-4000
Emergency Telephone: (281) 575-5000

Prepared By
Chemical Compliance
Telephone: 1-580-251-4335
e-mail: fdunexchem@halliburton.com

2. COMPOSITION/INFORMATION ON INGREDIENTS

Substances	CAS Number	PERCENT	ACGIH TLV-TWA	OSHA PEL-TWA
Fatty acid		30 - 60%	Not applicable	Not applicable

3. HAZARDS IDENTIFICATION

Hazard Overview May cause eye, skin, and respiratory irritation.

4. FIRST AID MEASURES

Inhalation If inhaled, remove from area to fresh air. Get medical attention if respiratory irritation develops or if breathing becomes difficult.

Skin Wash with soap and water. Get medical attention if irritation persists.

Eyes In case of contact, immediately flush eyes with plenty of water for at least 15 minutes and get medical attention if irritation persists.

Ingestion Do not induce vomiting. Slowly dilute with 1-2 glasses of water or milk and seek medical attention. Never give anything by mouth to an unconscious person.

Notes to Physician Not Applicable

5. FIRE FIGHTING MEASURES

Flash Point/Range (F):	356
Flash Point/Range (C):	180
Flash Point Method:	COC
Autoignition Temperature (F):	Not Determined
Autoignition Temperature (C):	Not Determined
Flammability Limits in Air - Lower (%):	Not Determined
Flammability Limits in Air - Upper (%):	Not Determined

Fire Extinguishing Media	Carbon Dioxide, Dry Chemicals, Foam.
Special Exposure Hazards	Decomposition in fire may produce toxic gases. Organic dust in the presence of an ignition source can be explosive in high concentrations. Good housekeeping practices are required to minimize this potential.
Special Protective Equipment for Fire-Fighters	Full protective clothing and approved self-contained breathing apparatus required for fire fighting personnel.
NFPA Ratings:	Health 1, Flammability 1, Reactivity 0
HMIS Ratings:	Health 1, Flammability 1, Reactivity 0

6. ACCIDENTAL RELEASE MEASURES

Personal Precautionary Measures	Use appropriate protective equipment. Avoid creating and breathing dust.
Environmental Precautionary Measures	None known.
Procedure for Cleaning / Absorption	Scoop up and remove.

7. HANDLING AND STORAGE

Handling Precautions	Avoid contact with eyes, skin, or clothing. Avoid breathing vapors. Wash hands after use.
Storage Information	Store away from alkalis. Store away from oxidizers. Store in a cool, dry location.

8. EXPOSURE CONTROLS/PERSONAL PROTECTION

Engineering Controls	A well ventilated area to control dust levels.
Respiratory Protection	Dust/mist respirator. (95%)
Hand Protection	Normal work gloves.
Skin Protection	Normal work coveralls.
Eye Protection	Wear safety glasses or goggles to protect against exposure.
Other Precautions	None known.

9. PHYSICAL AND CHEMICAL PROPERTIES

Physical State:	Solid
Color:	White
Odor:	Mild fatty
pH:	Not Determined

9. PHYSICAL AND CHEMICAL PROPERTIES

Specific Gravity @ 20 C (Water=1):	0.85
Density @ 20 C (lbs./gallon):	Not Determined
Bulk Density @ 20 C (lbs/ft3):	Not Determined
Boiling Point/Range (F):	721
Boiling Point/Range (C):	383
Freezing Point/Range (F):	Not Determined
Freezing Point/Range (C):	Not Determined
Vapor Pressure @ 20 C (mmHg):	Not Determined
Vapor Density (Air=1):	9.8
Percent Volatiles:	0
Evaporation Rate (Butyl Acetate=1):	Not Determined
Solubility in Water (g/100ml):	Insoluble
Solubility in Solvents (g/100ml):	Not Determined
VOCs (lbs./gallon):	Not Determined
Viscosity, Dynamic @ 20 C (centipoise):	Not Determined
Viscosity, Kinematic @ 20 C (centistrokes):	Not Determined
Partition Coefficient/n-Octanol/Water:	> 3
Molecular Weight (g/mole):	Not Determined

10. STABILITY AND REACTIVITY

Stability Data:	Stable
Hazardous Polymerization:	Will Not Occur
Conditions to Avoid	Keep away from heat, sparks and flame.
Incompatibility (Materials to Avoid)	Strong alkalis.
Hazardous Decomposition Products	Carbon monoxide and carbon dioxide.
Additional Guidelines	Not Applicable

11. TOXICOLOGICAL INFORMATION

Principle Route of Exposure	Eye or skin contact, inhalation.
Inhalation	May cause respiratory irritation.
Skin Contact	May cause skin irritation.
Eye Contact	May cause eye irritation.
Ingestion	Irritation of the mouth, throat, and stomach. May act as obstruction if swallowed.
Aggravated Medical Conditions	None known.
Chronic Effects/Carcinogenicity	No data available to indicate product or components present at greater than 1% are chronic health hazards.
Other Information	None known.

Toxicity Tests

Oral Toxicity:	LD50: > 2000 mg/kg (Rat)
Dermal Toxicity:	LD50: > 5000 mg/kg (Rabbit)
Inhalation Toxicity:	Not determined

Primary Irritation Effect:	Not determined
Carcinogenicity	Not determined
Genotoxicity:	Not determined
Reproductive / Developmental Toxicity:	Not determined

12. ECOLOGICAL INFORMATION

Mobility (Water/Soil/Air)	Not determined
Persistence/Degradability	Readily biodegradable
Bio-accumulation	Not determined

Ecotoxicological Information

Acute Fish Toxicity:	Not determined
Acute Crustaceans Toxicity:	Not determined
Acute Algae Toxicity:	Not determined

Chemical Fate Information	Not determined
Other Information	Not applicable

13. DISPOSAL CONSIDERATIONS

Disposal Method	Bury in a licensed landfill according to federal, state, and local regulations.
Contaminated Packaging	Follow all applicable national or local regulations.

14. TRANSPORT INFORMATION

Land Transportation

DOT
Not restricted

Canadian TDG
Not restricted

ADR
Not restricted

Air Transportation

ICAO/IATA
Not restricted

Sea Transportation

IMDG
Not restricted

Other Shipping Information

Labels:	None

15. REGULATORY INFORMATION

US Regulations

US TSCA Inventory	All components listed on inventory or are exempt.
EPA SARA Title III Extremely Hazardous Substances	Not applicable
EPA SARA (311,312) Hazard Class	None
EPA SARA (313) Chemicals	This product does not contain a toxic chemical for routine annual "Toxic Chemical Release Reporting" under Section 313 (40 CFR 372).
EPA CERCLA/Superfund Reportable Spill Quantity	Not applicable.
EPA RCRA Hazardous Waste Classification	If product becomes a waste, it does NOT meet the criteria of a hazardous waste as defined by the US EPA.
California Proposition 65	All components listed do not apply to the California Proposition 65 Regulation.
MA Right-to-Know Law	Does not apply.
NJ Right-to-Know Law	Does not apply.
PA Right-to-Know Law	One or more components listed.

Canadian Regulations

Canadian DSL Inventory	All components listed on inventory.
WHMIS Hazard Class	Un-Controlled

16. OTHER INFORMATION

The following sections have been revised since the last issue of this MSDS
Not applicable

Additional Information	For additional information on the use of this product, contact your local Halliburton representative. For questions about the Material Safety Data Sheet for this or other Halliburton products, contact Chemical Compliance at 1-580-251-4335.
Disclaimer Statement	This information is furnished without warranty, expressed or implied, as to accuracy or completeness. The information is obtained from various sources including the manufacturer and other third party sources. The information may not be valid under all conditions nor if this material is used in combination with other materials or in any process. Final determination of suitability of any material is the sole responsibility of the user.

*****END OF MSDS*****