INVESTIGATION OF LOCAL BARITES IN DRILLING MUDS FORMULATION AT HTHP CONDITIONS

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CERTIFICATION

This is to certify that this Work "Investigation of Local Barites in Drilling Muds Formulation at HTHP Conditions" was carried out by OMEOKWE, IFEANYI KENECHUKWU with Registration Number 20154989718 in partial fulfillment for the award of the degree of (M.Eng in Petroleum Engineering in the department of Petroleum Engineering) of the Federal University of Technology Owerri.

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DEDICATION

I dedicate this work to my parents. Only through their love, invaluable advice, motivation, financial support and prayers have I been able to progress in my academic and personal life. I also dedicate this work to my siblings for their prayers during this program.

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During the course of this research, I was assisted by many people. Most credit goes to my Principal Supervisor Engr. Dr. U.I Duru and my Co-supervisor Engr. Dr. A. Kerunwa for their inestimable directive and contribution throughout the research.

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ABSTRACT

In order to counter-balance the formation pressure, the drilling mud is weighted up using a chemical additive, usually Barite. The usability of locally sourced Nigerian Barites on the major types of drilling fluids in conventional and High-Pressure-High-Temperature conditions is presented. Water-Based mud, Oil-Based mud and Synthetic oil-Based mud formulations with locally sourced Barite were tested according to the 'API RP 13B'. Hole cleaning capabilities of the formulations by the use of Cutting Carrying Index and Cutting Concentration as indicators show that Osina, Gabu and Obubra Nigerian Barites with SG's ranging from 4.0 to 4.6 are suitable for use as drilling fluid additives; with Cutting Carrying Index in the range of 23.27 to 120.54 for Water-Based mud, 0.89 to 3.98 for Oil-Based mud and 0.45 to 1.13 for Synthetic-Based mud, and Cutting Concentration of average of 4.15 vol. % at 355gpm and 300ft/hr ROP for Water-Based mud, Oil-Based mud and Synthetic-Based mud, with MAXROP of 364ft/hr under the same conditions. Moreso, laminar flow regime in the annulus is predicted for all the mud types under the same conditions and temperatures specified. CCI for water based mud decreased from ambient, 120°F, 180°F to 240°F, compared with API mud used as control sample. Oil extracted from *Irvingia Gabonensis* used to formulate the Synthetic-Based mud exhibited understandable physical properties such as SG of 0.836 at 60°C and a flash point of >300°C, and could serve as replacement for diesel used as base fluid in Oil-Based muds since it is also biodegradable, though the Synthetic-Based mud exhibited unfavourable characteristics in terms of low CCI value(s) and higher filter cake thickness. All the muds displayed flat or non-progressive gel; gel strengths that break with minimal initiation pressure. Locally sourced Nigerian barites have been shown to exhibit favourable properties in the mud formulations both in conventional and High-Pressure-High-Temperature drilling conditions.

Keywords: Cutting Carrying Index, Cutting Concentration, Barite, High-Pressure-High-Temperature, Mud Formulation

CHAPTER ONE

INTRODUCTION

1.1 Background of Study

Nigeria is one of the highest crude oil exporting countries in the world and therefore has various ongoing exploration and production activities. In order to produce crude oil, wells are drilled into the formation either as exploratory, production or appraisal wells. These wells must be drilled to satisfy three basic conditions;

i. It must be safe
ii. It must be usable
iii. It must be economical

Borehole stability is very crucial and requires constant monitoring throughout a drilling operation. A borehole is said to be stable when the formation pressure is less than or equal to the hydrostatic pressure. Drilling operations conventionally operate on an overbalance where the hydrostatic pressure is maintained slightly above the formation pressure. Where the hydrostatic pressure is lower than the formation pressure, the borehole is exposed to well problems such as sloughing, kick or blowout. The Rate of Penetration (ROP) of a drilling operation is what determines the speed and efficiency of a drilling project, (Paiaman et al, 2009). ROP can be defined as the rate at which the bit cuts across a unit length of the formation per unit time. The following factors have been identified to affect ROP - bit size, formation characteristics, hydraulic program (Drilling Fluid), and rotating speed, (Akpabio et al, 2015). Hydraulic program during drilling operations depends wholly on the rheological properties of the drilling fluid. ROP is a very important factor in the determination of total drilling cost of a well. In effect, the cost of drilling fluid affects the overall cost of well drilling, hence its importance.

Since the first drilling operations, drilling fluids have passed through major technological evolution. From using a simple mixture of water and clays, drilling fluids have advanced to complex mixtures of various specific organic and inorganic components for specific drilling operations. These components improve fluid density, rheological properties and filtration capabilities, allowing bits to penetrate heterogeneous geological formations under the best conditions. The effectiveness of the drilling fluid to perform its primary functions is based on certain properties, which are formulated continuously to meet formation conditions during drilling operations. Failure of the drilling fluid to meet its designed functions can be extremely costly in terms of loss of materials and time or ultimately, life.

Several drilling problems in the past have been attributed to improper choice of drilling fluid. Such drilling problems like stuck pipe, differential sticking, kick and blow out have direct or indirect link to the drilling fluid. Therefore, drilling fluids must be carefully selected and/or formulated to satisfy their purpose in the drilling process. Functions of a drilling fluid include but not limited to the following;

i. Carry cuttings from the wellbore to the surface.
ii. Maintain wellbore stability.
iii. Prevent formation fluids from entering the wellbore.
iv. Cool and lubricate the bit.
v. Transmit hydraulic horsepower to the bit.

1.2 Statement of Problem

Conventional drilling involves maintaining the hydrostatic pressure slightly above the formation pressure. As drilling goes deeper the formation, the formation pressure exerted on the well increases and hence an increase in the hydrostatic pressure is required for well control. This is done by increasing the mud weight of the drilling fluid by addition of weighting materials. Barite, an additive used as a weighting material in the formulation of almost all types of drilling fluids is being imported en masse into the country, whereas Nigeria is blessed with this mineral in commercial quantities. The mineral is left untapped or under-produced due to very low demand. There are reports that claim that Nigerian barite is not up to the required API standard of 4.1 SG. In a country where drilling operations are carried out daily, it is beneficial to its economy that the materials used in carrying out these activities are sourced locally. This will enable easy and cheaper procurement of materials for operating companies, create employment opportunities for the locals and encourage local content which the Government of Nigeria has been advocating for through the Nigerian Content Development and Monitoring Board (NCDMB).

1.3 Aim And Objectives

The main objective of this research is to determine the usability of Nigerian barite as an additive in drilling fluid that can be used especially in high temperature and high pressure environments as compared to imported barite. The specific objectives include:

1) Investigating the effect of Nigerian barite on the density and rheological properties of the various types of drilling fluid.

2) To determine the effect of high temperature and pressure on the performance of Nigerian Barite as an additive in drilling fluids.

3) Compare the rheological properties of Nigerian barites with that of imported barite (API BARITE) weighted mud.

4) Investigate the use of oil extracted from Irvingia Gabonesis as base fluid for synthetic oil based mud.

1.4 Scope of Study

This laboratory investigation covers rheological and filtration properties of formulated water-, oil-, and synthetic based drilling fluids using Nigerian barites as weighting material.

1.5 Limitation of Study

In this study, the chemical analysis of Nigerian barites and Irvingia Gabonesis oil was not considered but its specific gravity and flash point respectively were determined.

1.6 Significance of Study

The knowledge acquired in this study can be beneficial to drilling operators when taking decision on choice of weighting materials.

This experimental investigation aims to show that Nigerian barite can be used in the formulation of all kinds of drilling fluids used in HTHP wells (wells with bottomhole temperature of 150^oC and require a BOP rating of >10,000psi) and can be used instead of the more expensive imported barite.

With the results obtained from this study it can be seen that Nigerian Barites are resourceful in the Nigerian oil and gas industry. The results obtained from this study should encourage the mining of Barite in Cross River state and other parts of Nigeria. This research also shows the need for local barite processing plants in order to produce premium grade finished product.

CHAPTER TWO

LITERATURE REVIEW

2.1 Background Information

Hydrocarbon has been discovered to accumulate thousands of feet beneath the surface of the earth. In order to exploit it, a conduit must be created from the surface to the reservoir containing the hydrocarbon. This conduit is called a well. A well is drilled from the surface to thousands of feet below the earth in order to produce hydrocarbon to the surface. Due to varying formation conditions, several challenges are faced when drilling these wells e.g. stuck pipe, sloughing, kick, differential sticking. Drilling a hole involves penetrating through several strata of formation and requires special technique to economically and safely reach the target depth.

A typical drilling operation can be divided into several systems that work simultaneously, the power system, the rotary system, the hoisting system, the well control system, the well monitoring equipment and the circulatory system. Each system performs specific roles that aim to achieve a successful drilling operation. The mud rotary method of drilling is a process in which a hole is drilled into the ground by rotating a drill stem with a bit attached to its end. As the bit is rotated, it cuts the formation and breaks it down to smaller cuttings and chippings. Simultaneously, a circulating fluid is forced down the inside of the drill pipe and forced out through ports (nozzles) in the bit. Below the bit, the fluid picks up the cuttings and flushes them out of the hole through the annulus between the drill pipe and the hole wall (Papp,2001; Sadiq et al., 2003; Khodja, 2008 and Adewole et al., 2010).

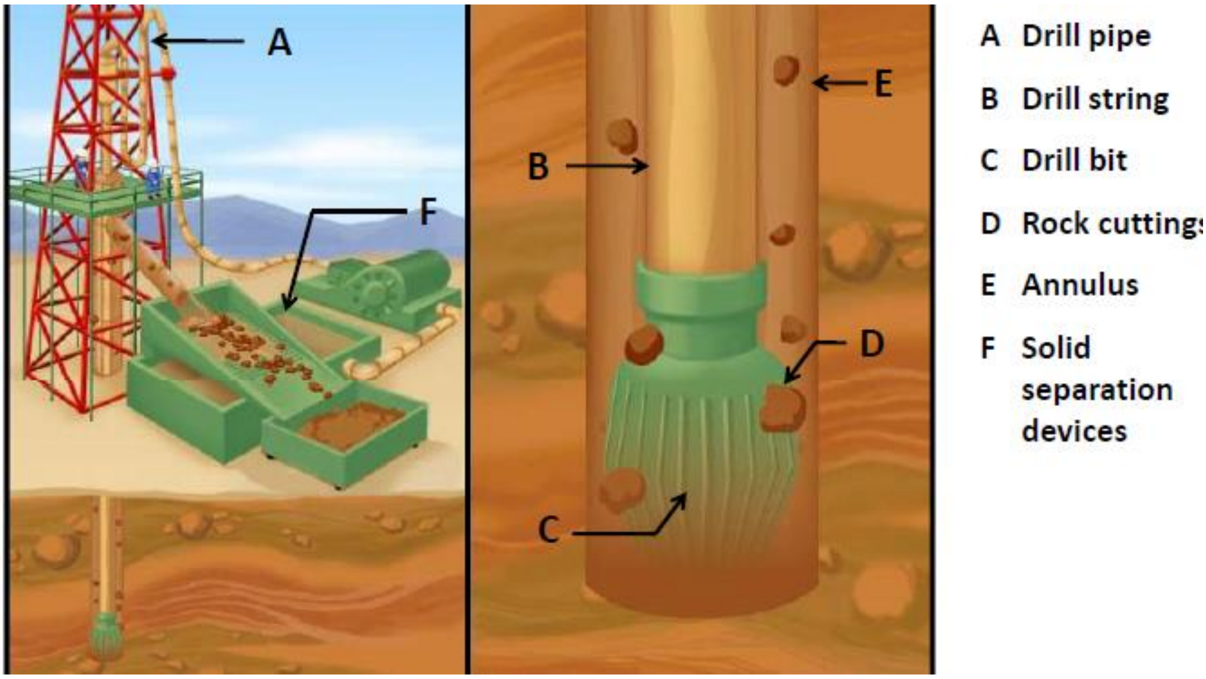


Fig. 2.1: Downhole drilling operation (Source: Schlumberger Excellence in Educational Development (SEED), 2005).

Drilling fluids are generally the "blood" of all drilling operations and the petroleum industry especially. The industry has continued to make increasing use of these fluids, the cost of which can account for over 20% of total operating costs. To minimise the cost as well as improve performance and safety, *Oyeneyin 2004,* stated that other generic types of these fluids are continuously being developed mainly to meet the increasing challenges of:

- Deeper well drilling/completion especially in high temperature and pressure environment.
- Increasing use of advanced wells (ERD, multilateral and horizontal wells)
- Stiff environmental regulations

2.2 Functions of Drilling Fluids

According to Khodja et al. (2010), a drilling fluid must generally comply with three important requirements: they must be easy to use, not too expensive, and environmentally friendly. The fluid of choice for most drilling operations is the drilling mud (Papp, 2001). This, according to the author, is preferred due to its viscous nature, versatility and ease of handling. Drilling fluids are used basically to provide hydrostatic pressure in order to prevent formation fluids from entering into the well bore, cooling and lubricating the drill bit and rods (Gonzalez et al., 2011). They are also used for extrusion of drill cuttings and the suspension of drill cuttings when there is a pause in drilling and/or when the drilling assembly is tripping in or out of hole (Khodja, 2008; Khodja et al., 2010).

Other functions and characteristics that are expected of drilling fluids in rotary drilling include (1) clear the rock fragments from beneath the bit and carry them to the surface, (2) exert sufficient hydrostatic pressure against subsurface formations to prevent inflow fluids into the well, (3) keep the newly drilled borehole open until steel casing can be cemented in the hole (Bourgoyne *et al.*, 1986). In addition to serving these functions, the drilling fluid should not (1) have properties detrimental to use of planned formation evaluation techniques, (2) cause any adverse effects upon the formation penetrated, or (3) cause any corrosion(or damage) of the drilling equipment and subsurface tubulars. The bentonite usually used in drilling fluid is montmorillonite clay (Chilingarian *et al*., 1983). It is added to fresh water to (1) increase the hole cleaning properties, (2) reduce water seepage or filtration into permeable formation, (3) form a thin filter cake of low permeability, (4) promote holes stability in poorly cemented formation, and (5) avoid or overcome loss of circulation. As the well is drilled deeper, there is need to increase the hydrostatic pressure to suppress the formation pressure. To achieve this, the mud is usually weighted up using an additive called Barite.

2.3 Components (Composition) of Drilling Fluids

Drilling mud may consist of bentonite clay, with additives such as barium sulphate or hematite, partially hydrolyzed polyacrylamide (PHPA), drilling detergents and sodium carbonate (soda ash) (Papp, 2001). Thickeners such as guar gum, glycol, carboxy methyl cellulose (CMC), polyanionic cellulose (PAC), starch and other additives, are added to obtain the optimum viscosity of the fluid. Reis (1996) stated that many of the components of additive in disposed drilling muds may be toxic to the environment. In a study of a cross-section of water well drillers in Nigeria, it was found that the basic composition of drilling fluid that they use most commonly consists of bentonite clay (gel) with additives such as calcium carbonate (chalk) and barite. The additives most readily available in the local market are CMC, PAC and starch. The most common mixing ratio is 100 bags of bentonite: 10 bags of PAC: 10 bags of CMC: 10 bags of caustic soda (10:1:1:1).

Each additive is aimed to improve on a specific property of the mud and is mixed in specific proportions for desired results in a project. There are viscosifiers, pH modifiers, filtration loss control additives, hardness control additives, emulsifiers, weighting agents. Some additives react with other components of the mud, so proper care should be taken when selecting the right additives. The effect of the additives on the formation should also be taken into consideration. Generally a good drilling fluid should contain minimum number of additives.

Brobst and Buszka (2007) investigated the effect of each of three different drilling fluids on ground water samples. It was observed that the bentonite and guar drilling fluids temporarily caused deviations in the chemical oxygen demand (COD) of ground water samples collected from the monitoring wells. The elevated COD levels were attributed to the large concentrations of oxidizable carbon present in the guar bean drilling fluid and in the organic polymers present in the bentonite drilling fluid. It was stressed that future research should evaluate the physical and geochemical interactions of various drilling fluid compositions with a variety of geologic matrices and drilling, well development and well purging techniques. It was also observed by Hinwood et al (1994) that the volume of cuttings emanating from a borehole depends on the type of drilling fluid used.

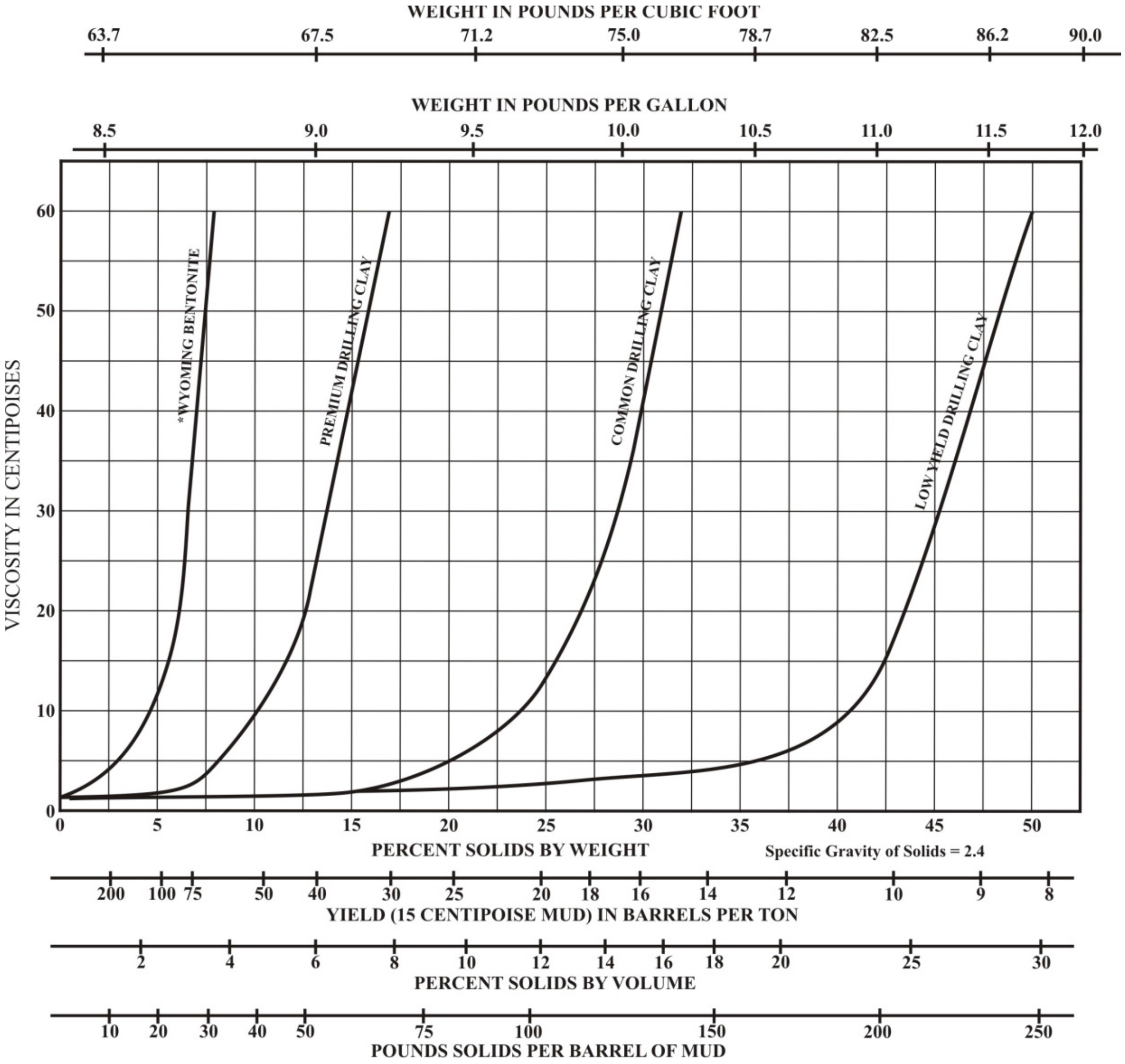


Fig. 2.2: Composition and nature of most drilling fluid (Gatlin 1960)

2.4 Types of Drilling Fluids

There are different types of drilling fluids currently used in the drilling industry with each type having a favourable operating condition and producing individually distinct results from the other types. There are different criteria that must be to be taken into consideration before selecting a drilling fluid type for a drilling operation. There are basically three types of drilling fluids; water based mud, oil based mud and synthetic based mud.

2.4.1 Water Based Muds

Water alone may be used as a drilling fluid. However, most drilling fluids require some degree of viscosity to suspend the Barites and to carry drilled cuttings up the annulus of the wellbore. The viscosity of water based muds is generated by the addition of clay or polymers. However the cheapest and most widely used additive for viscosity control is clay. The clay material in water based mud is responsible for two beneficial effects: an increase in viscosity which improves the lifting capacity of the mud to carry cuttings to the surface. (This is especially helpful in larger holes where annular velocity is low) and Building a thin wall cake in permeable zones, thus preventing fluid loss. For any type of water based drilling fluid, a gel strength in the range of 3.35Pa (7lbf/100ft^2) to 4.79Pa (9.0lbf/100ft^2) is sufficient to remove the cuttings at more than 0.50 of transport ratio, even when the annular velocity is about 0.25m/s(50ft/min). *(Jose Carlos et al, 1990)*

The clays are not the only solids in a drilling fluid. There are two types of solids which may be present in a water based mud:

- Active solid - these are solids which will react with water and can be controlled by chemical treatment. These may be commercial clays or hydratable clays from the formations being drilled.
- Inactive or inert solids - these are solids which do not readily react with water. These may be drill solids such as limestone or sand. Barite is also an inert solid.

Water based mud basically comprises of a mixture of water (salt or fresh) and bentonite clays with other additives such as barite. Water based mud is relatively cheap and readily available, constitutes little or no harm to the environment which makes for easy disposal. However they are generally unstable in very high temperatures and may react with shale to cause swelling. Water based mud is usually used in shallow wells where the temperature and pressure conditions are moderate. There are new discoveries on water based muds that allow them to be used in HTHP wells. There are additives that can be added to the mud to enable a high performance water based mud to perform optimally at a temperature of about 450°F. There are also innovations where drilling fluids are formulated without the use of clay.

Omotioma et al, 2015 used cassava starch as an additive to improve the rheological properties of water based muds by altering its concentration. They discovered that cassava starch improves the rheological properties of water based muds and suggested an optimum composition of 4% starch in a drilling mud.

2.4.2 Oil Based Muds

An oil-based mud is one in which the base fluid from which the mud is made up is oil. Since the 1930's it has been recognised that better productivity is achieved from reservoirs when oil based fluids rather than water based fluids are used to drill through the reservoir. This is largely because the oil does not cause the clays in the reservoir to swell or cause changes in wettability of the formations. Crude oil was first used to drill through the pay zone, but it suffered from several disadvantages (low gel strength, limited viscosity and safety hazard due to low flash point). Modern oil-based muds use low-toxicity base oils and a variety of chemical additives to build good mud properties. The use of oil in the drilling fluid does have several disadvantages:

- Higher initial cost
- More stringent pollution controls required
- Reduced effectiveness of some logging tools (resistivity logs)
- Detection of kicks more difficult due to gas solubility in base oil

However for some applications oil-based muds are very cost effective. These include:

- To drill and core pay zones

- To drill troublesome formations (e.g. shale, salt)
- To add lubricity in directional drilling (preventing stuck pipe)
- To reduce corrosion
- As a completion fluid (during perforating and workovers)

Many studies have dealt with the formation damage caused by drilling fluids, which is an interesting interdisciplinary subject that attracts many researchers. Ventresca et al. (1995) quantified the magnitude of the damage caused to the reservoir by inverted oil muds and selected chemical system, which is able to reduce this damage.

2.4.3 Synthetic Based Muds

The general definition of a synthetic material is something that is produced by chemical synthesis. Synthetic fluids are used as the base fluid or continuous phase of invert emulsion muds. These muds behave like oil-base muds. The products used to make and maintain SBMs are similar to, or in some cases, are the same as those used to build and maintain oil-base muds. These products are emulsifiers, wetting agents, Low-Shear-Rate Viscosity (LSRV) modifiers, filtration-control additives, viscosifiers and thinners.

Synthetic drilling fluids emanated from the need to reduce the environmental pollutions caused by the diesel oil based muds which have been in use. Synthetic based muds are designed with environmentally friendly base fluid to have very similar characteristics and properties with the diesel oil based mud. Olefins, Paraffins and lately Esters are groups of some of the base fluids used in the formulation of synthetic based fluids. The best formula is based on the properties of the formation the fluid is to be used on. Vegetable oils obtained from plant leaves and seeds have also been discovered usable.

Since they have similar characteristics with the oil based mud, they are used in similar situations. However, because of its very high initial cost, they are used in special cases where there are very strict environmental laws in place.

Like all chemicals, SBMs can be health hazards if handled improperly. The synthetic liquids used to make SBMs are less toxic and less irritating than the oils used in oil-base muds. However, SBMs are difficult to remove from the skin, and contain some irritating chemicals such as calcium chloride and lime. This means that SBMs can be quite irritating to the skin and eyes if certain precautions are not taken. Likewise, mist and vapour from SBMs, especially in the area around the shakers, can be irritating to the respiratory system (Adesina et al 2012).

Proper safety measures should be taken when working with SBMs because of the nature of its compositions. Avoid unnecessary contact with skin and keep stairs and rig floors clean (Bourgoyne et al 1986).

Although synthetic base fluids may be more environmentally acceptable than oil-base muds, the price of these fluids dictates that discharges of these fluids must be minimized. Rigs that use synthetic-base muds can be fitted out with the same equipment as those using oil-base muds but should be modified to prevent the mud system from being contaminated by external substances, the BOP elastomers must be checked for compatibility with the base fluid. Solids-control equipment should be designed to handle maximum flow and drilling rates (Baker Hughes Drilling reference manual, 2006).

Synthetic based muds are efficient in Deviated wells, Extended reach, Horizontal and Extreme azimuth changes. They can be applied on rigs with limited torque, re-entries using workover rigs. SBMs are very efficient in exploratory wells with good offset data. On the other hand, it is inefficient in routine exploratory wells without good offset data and also wells where zero discharge is required. They are expensive and possess high risk of Lost Circulation.

2.5 Soxhlet Extraction

This is a method of extracting liquids from solid materials using a soxhlet extractor. A Soxhlet extractor is a piece of laboratory apparatus invented in 1879 by Franz von Soxhlet. It was originally designed for the extraction of a lipid from a solid material. Typically, a Soxhlet extraction is used when the desired compound has a limited solubility in a solvent, and the impurity is insoluble in that solvent. It allows for unmonitored and unmanaged operation while efficiently recycling a small amount of solvent to dissolve a larger amount of material. A Soxhlet Extractor has three main sections: A percolator (boiler and reflux) which circulates the solvent, a thimble (usually made of thick filter paper) which retains the solid to be laved, and a siphon mechanism, which periodically empties the thimble (Jensen 2007). In this thesis, hexane was used as a solvent for its relatively low boiling point, 40-60^{o}C.

The solvent is heated to reflux. The solvent vapour travels up a distillation arm and floods into the chamber housing the thimble of solid. The condenser ensures that any solvent vapour cools, and drips back down into the chamber housing the solid material. The chamber containing the solid material slowly fills with warm solvent. Some of the desired compound dissolves in the warm solvent. When the Soxhlet chamber is almost full, the chamber is emptied by the siphon. The solvent is returned to the distillation flask. The thimble ensures that the rapid motion of the solvent does not transport any solid material to the still pot. This cycle may be allowed to repeat many times, over hours or days. During each cycle, a portion of the non-volatile compound dissolves in the solvent. After many cycles the desired compound is concentrated in the distillation flask. The advantage of this system is that instead of many portions of warm solvent being passed through the sample, just one batch of solvent is recycled. After extraction the solvent is removed, typically by means of a rotary evaporator, yielding the extracted compound. The non-soluble portion of the extracted solid remains in the thimble, and is usually discarded.

This process has been used by many researchers and scientists to extract oil from solids (Jensen 2007). This is the process used to extract oil from the seeds of Irvingia Gabonesis.

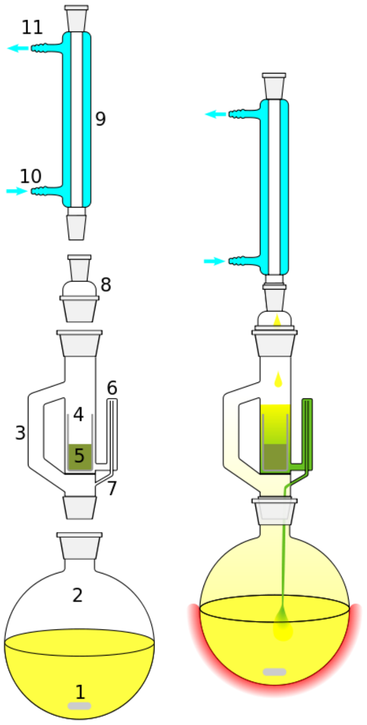


Fig. 2.3: Schematic of Soxhlet Extraction (Source: Jensen 2007)

1: Stirrer bar 2: Still pot 3: Distillation path 4: Thimble 5: Solid 6: Siphon top 7: Siphon exit 8: Expansion adapter 9: Condenser 10: Cooling water in 11: Cooling water out

2.6 Rheological Properties of Drilling Fluid

Rheology is the study of deformation and flow of matter. The rheological property of drilling fluids describes the ability of the fluid to transport cuttings while drilling and suspend them when circulation is interrupted. The rheological parameters of all the mud samples were investigated and calculated. The objective of rheology tests is to measure the viscosity and gel strength that relate to the flow properties of mud. *Wami et al 2015* investigated the use of potato starch as a viscosifier in drilling fluids and fluid loss agent. Its effect on drilling fluids was compared to PAC and it came out favourable in other rheological properties but at par with

PAC in terms of viscosity. They also stated that using potato starch alone cannot improve rheology significantly, but can be used in a proportionate mixture with PAC.

To appreciate the rheology calculations it is important to discuss on some of the basic drilling fluid flow properties and determination of the rheological parameters which best describes the flow behaviour of the fluid.

1. Viscosity

Viscosity is basically the fluid resistance to flow. Viscosity can be measured in the field using marsh funnel or using a viscometer. However, in drilling fluid rheology there are two types of viscosity that are of keen interest; the apparent and plastic viscosity (Bourgoyne et al 1986). A viscometer was used to obtain these parameters in this study. Lignite is used as a thinner to reduce viscosity and a fluid loss additive.

i. Apparent viscosity

Apparent viscosity indicates the amount of force required to move one layer of fluid in relation to another. It measures the shear rate of drilling fluid specified by API. Apparent viscosity is expressed in centipoise (cp), it is calculated from rheometer readings. The apparent viscosity can be calculated simply by dividing the 600 dial reading by 2. The apparent viscosity is often called the effective viscosity (Bourgoyne et al 1986).

ii. Plastic viscosity

This is the shearing stress in excess of yield point that will induce a unit rate of shear. It is that part of flow resistance caused by mechanical friction which occurs between the solids in the mud, between the solids and the liquid that surrounds them, and with the shearing of the liquid itself. Therefore, all practical purposes, plastic viscosity depends on the concentration of mud solids. The plastic viscosity can be calculated by subtracting the 300dial reading from the 600dial reading (Bourgoyne et al 1986).

2. Yield Point

Yield point is the second component of resistance to flow in drilling fluid. It is a measurement of electro-chemical or attractive forces in a fluid under flow conditions. These forces are a result of negative charges located on or near the particle surfaces and are dependent on: (1) the surface properties of mud solids, (2) volume concentration of the solids, and (3) the electro-chemical environment of ions present. Yield point may be regulated by the use of chemical additives. Therefore, it dictates the nature and degree of treatment necessary to maintain a desirable fluid viscosity (Bourgoyne et al 1986). The yield point value can be calculated by subtracting the plastic viscosity from the 300dial reading and its ranges value that used in well drilling is also showed in Figure 2.4.

3. Gel strength

Gel strength is a measurement of the thixotropic properties of drilling fluid under static conditions. Similar to yield point, gel strength is a measure of the electro-chemical attractive forces between solid particles. Yield point and gel strength are result of the flocculation forces of a thixotropic fluid. Gel strengths are measured by rotational speed of 3 rpm. The drilling fluid is allowed to stand undisturbed for 10 seconds and 10 minutes that is referred to initial gel strengths and 10 minutes gel strength respectively, at which time of outer cup is rotated at 3 rpm and the maximum deflection of the dial is recorded. Gel strengths are reported in lb/100 ft^2 (Bourgoyne et al 1986).

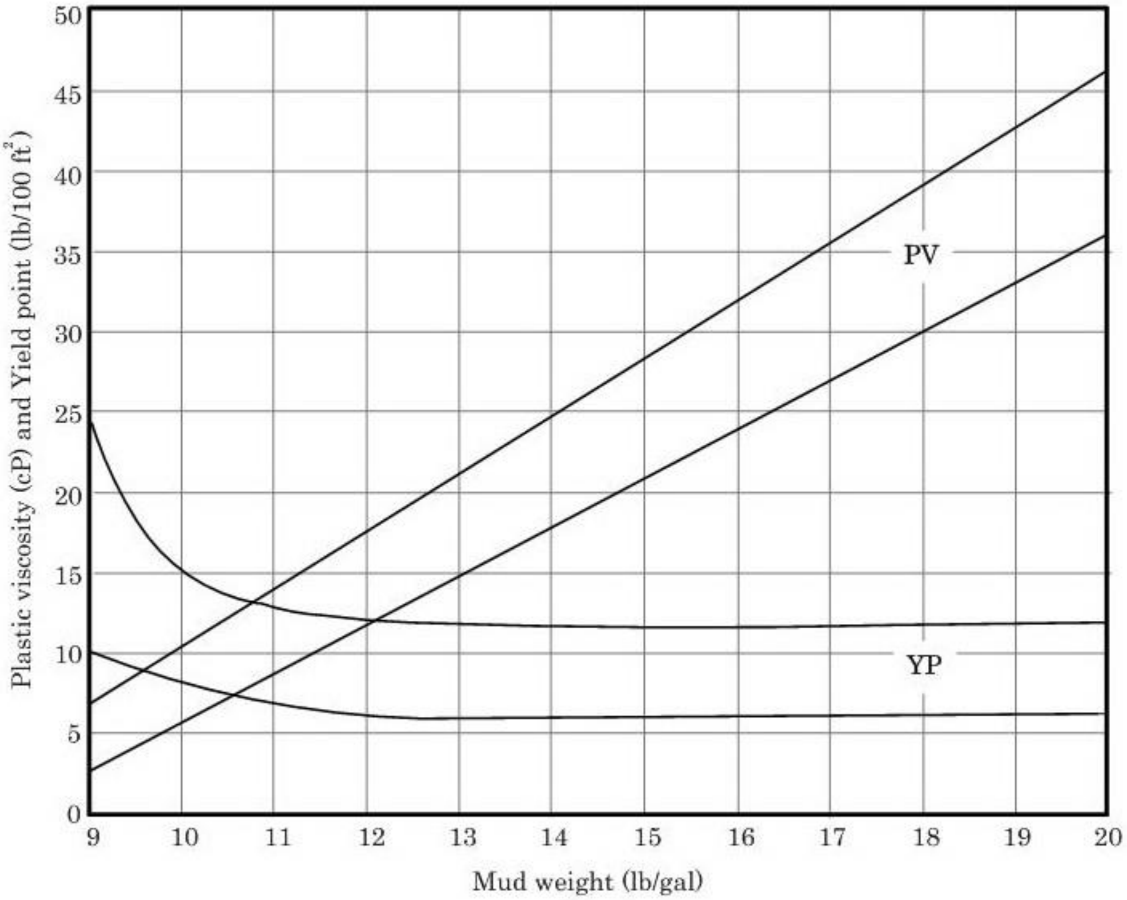


Fig. 2.4: Plastic viscosity and yield point ranges for water-base mud (modified from MI Swaco, 1998).

4. Filtration Loss

The objective of filtration test is to simulate the fluid loss invaded through borehole formation while hydrostatic pore pressure is greater than pressure of fluid in the pore of the formation. The test is indicative of the rate at which permeable formations are sealed by the deposition of a mudcake after being penetrated by the bit. Two type of filtration are involved in drilling an oil well, there are static and dynamic filtration. Static filtration occurs when the mud is not being circulated and the filter cake grows undisturbed. Dynamic filtration occurs when the mud is being circulated and the growth of filter cake is limited by the erosion action of the mud stream. Static filtration was conducted in this research using the OFITE 175ml HPHT filter press.

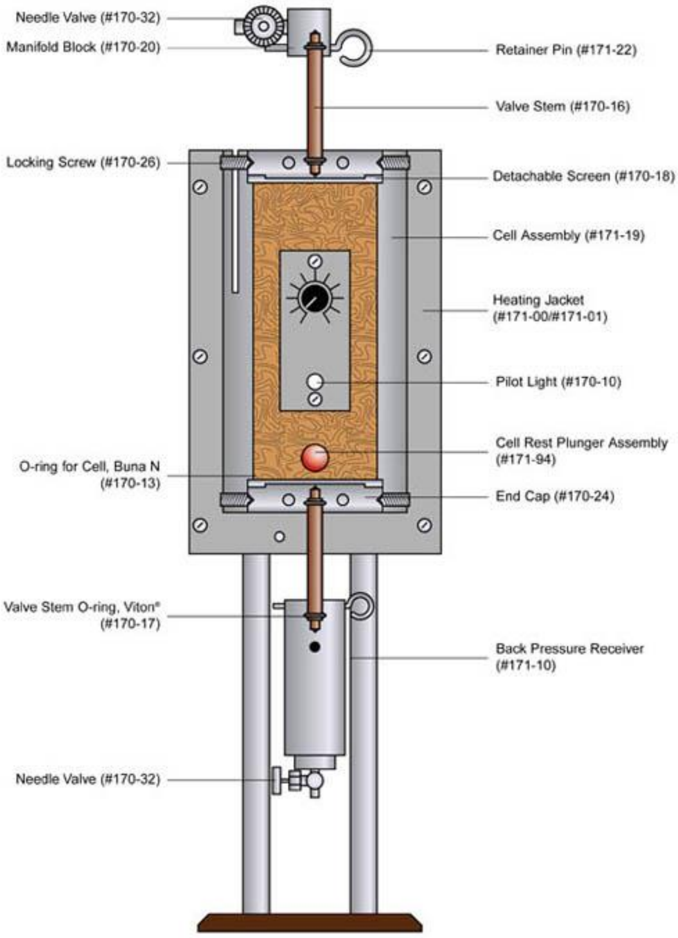


Fig. 2.5: HTHP Filter Press (Source: OFITE 900 user manual)

5. Hydrogen ion (pH)

The hydrogen ion (pH) measurements of the fluids were conducted using pH meter. Measurements and adjustments of pH are fundamental of drilling fluid control. Clay interactions, solubility of various components and effectiveness of additives are all dependent on pH, as in control of acidic and sulfide corrosion processes. The test procedures followed the recommended practice of standard procedure for field testing drilling fluid (API Recommended Practice, 2014). Drilling fluids are required to have an alkaline pH range between 9.5-12.5.

6. Hole Cleaning

This is the effective and efficient transport of drilled solids from the well bore to the surface. Inability of the drilling fluid to efficiently transport the drilled cuttings will lead to a formation of cutting beds along the walls of the well. This is prominent problem in deviated wells. The cutting bed reduces the hole size and can cause drilling problems like stuck pipe, excessive ECD, hole pack-off, high rotary torque, formation breakdown, low ROP and a difficulty in running casing and logs, (Ofesi et al 2017).

For a horizontal or near horizontal well bore, hole cleaning is more efficient if a low viscosity fluid is pumped in a turbulent flow regime rather than a high viscosity fluid in a lamina regime (Walker et al 2000). Walker et al 2000, compared water, HEC and Xanvis polymers; they found out that the amount of solids that can be transported by a given volume of liquid is dependent on the rheological properties of the liquid. They found that Xanvis and HEC polymer based fluids are more effective than water in terms of carrying capacity but cannot erode a stationary bed. They also experimented with water and Xanvis, for the vertical well bore, hole cleaning is more efficient if a high viscosity fluid is pumped in a laminar flow regime rather than a low viscosity fluid in a turbulent flow.

Different models have been developed to provide assistance in characterizing fluid flow, but none of these models can completely describe rheological properties of drilling fluids over their entire shear-rate range. Robinson et al 1993, used the following model to test hole cleaning properties at optimum flow rates.

$$CCI = \frac{K * AV * MW}{400000}. \qquad \text{Equation 2.1}$$

Where;

CCI is Cuttings Carrying index

AV is annular velocity in ft/min.

MW is mud weight in ppg.

K is a Power Law Constant.

The Power Law constant (K) can be calculated from the equation below:

$$k = (511)^{1-n}(PV + YP) \qquad \text{Equation 2.2}$$

Where;

PV is plastic viscosity in centipoises.

YP is yield point in lb/100sqft

n is flow behavior index.

The flow behavior index (n) can be determined by the following equation:

$$n = 3.322 log \frac{(2PV+YP)}{(PV+YP)} \qquad \text{Equation 2.3}$$

Annular velocity can be determined from the following equation

$$AV = \frac{25.4q}{d_h^2 - d_p^2} \qquad \text{Equation 2.4}$$

Where;

q is flow rate in gpm

d_h is hole diameter in inches

d_p is drill pipe outer diameter in inches

7. Mud Weight

This is a measure of the density of the drilling fluid usually expressed in pounds per gallon (ppg). It is directly related to the amount of pressure the column of drilling mud exerts at the bottom of the hole. The mud weight plays a huge role in wellbore stability by maintaining a desired hydrostatic head. The mud weight is influenced by the addition of weighting materials in desired quantities depending on the head required. Barite is a typical example of a weighting agent.

Eckel (1954, 1967) used Reynolds number to relate bit hydraulics, fluid rheology and ROP under "The Full range of Reynolds numbers". He identified mud density as key factor that affects the flow pattern of these fluids under normal operating conditions. (Bourgoyne, 2003) The field reports by Beck et al., showed that the Rate of Penetration increased by lowering mud density and consequently raising Reynolds number and that conventional hydraulics were essentially the same. They further stated that even though the hydraulics horse power at the bit remains constant there is a change in PR observed in the field. This change was attributed to change in mud density. Hemphill and Clark (1994), demonstrated how the type of bit and mud chemistry affects penetration rates in their work on "PDC-Bit Selection and Mud Chemistry effects on Drilling Rates".

2.7 Weighting Materials

The choice of weighting agents to be used in drilling fluids is determined by many factors. One of the most important factors is to provide low rheology in high density fluids and low sag *(Zamora and Bell 2004).*

There are specialized weighting agents such as Manganese tetraoxide (Mn_3O_4) or treated micronized Barium Sulfate with an average particle size of 1micron. These can provide high density fluids with low sag, low rheology and are less damaging to the formation. Mn_3O_4 is used in both drilling and completion fluids when low sag, low rheology and low ECD management is required *(Svenden et al 1995)*

Ilmenite was first introduced into the industry with a particle size of 30-45microns as a weighting material in 1976 *(Haaland et al 1976, Saasen et al 2001, Bloomberg and Melberg 1984).* However its use was limited because of its abrasiveness to drilling equipment.

Results from experiments carried out by *Xiao et al 2013* shows that ilmenite has a sag factor of <0.3 and a PV range of 25-30cp which is lower than barite. HTHP filtration tests under static conditions showed filter cake had a thickness of 0.18in and 2.9cm^3 of filtrate volume, while under dynamic condition filter cake thickness was 0.15in and filter cake volume 2.2cm^3. Micronized ilmenites requires less viscosifiers to be well dispersed, needs slightly more dispersant and wetting agents when compared to API Barite.

Onu et al, 2014 attempted to substitute “tiro”(modified antimony sulphide also known as stibnite) for barite as a weighting material, and on comparison, discovered that barite gave a better weighting strength than “tiro” and barite also had less effect on the pH but “tiro” was more favourable in terms of mud viscosity.

Bloomberg et al, 1983 carried out a field and laboratory evaluation on the use of ilmenite as a weighting material. They observed that there is a flow induced abrasion when ilmenite is used in drilling fluids and they sort to laboratory for confirmation. They discovered the abrasiveness was due to particle size distribution and recommended a distribution of <3% particles greater than 45microns. They also discovered other problems related to the use of ilmenite viz – dust, dispersion of ilmenite in water, air entrainment and foaming. They recommended a reduction in concentration of flotation chemicals as a remedy. They also stated that ilmenite is currently more expensive than barite but its cost is expected to decrease in future.

2.8 Functions of Weighting Materials

Formation damage occurs when drilling fluid invades the formation and blocks the pore spaces thereby leading to a reduction in the permeability of the formation. The drilling fluid invasion occurs especially when the hydrostatic head is greater than the formation pressure. The hydrostatic pressure is usually maintained between the drilling window - a range between the well bore stability pressure and the fracture pressure, for a safe drilling operation.

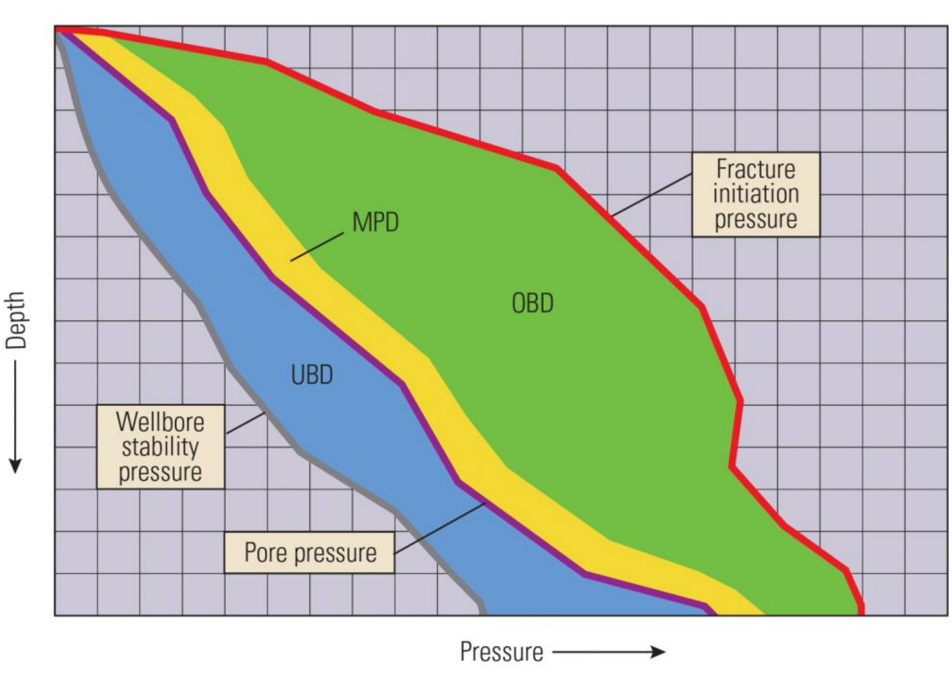


Fig. 2.6: Drilling Window *(Source: Schlumberger Oilfield Glossary, 2014)*

Controlling the pressure of the formation is one of the basic functions of the drilling fluid in order to prevent the influx of formation fluid into the well. This is achieved by controlling the density of the fluid with weighting agents such as barite. The hydrostatic pressure exerted by the drilling fluid must be equal or higher (preferably higher) than the formation pressure. This exerted pressure is a function of the True Vertical Depth (TVD). Geologists and Petrophysicists will provide a prognosis of the formation pressure. In the mud program, the drilling fluid density specification is given as a pressure gradient, usually specific gravity or pounds per gallon *(Dahlem, 2013)*.

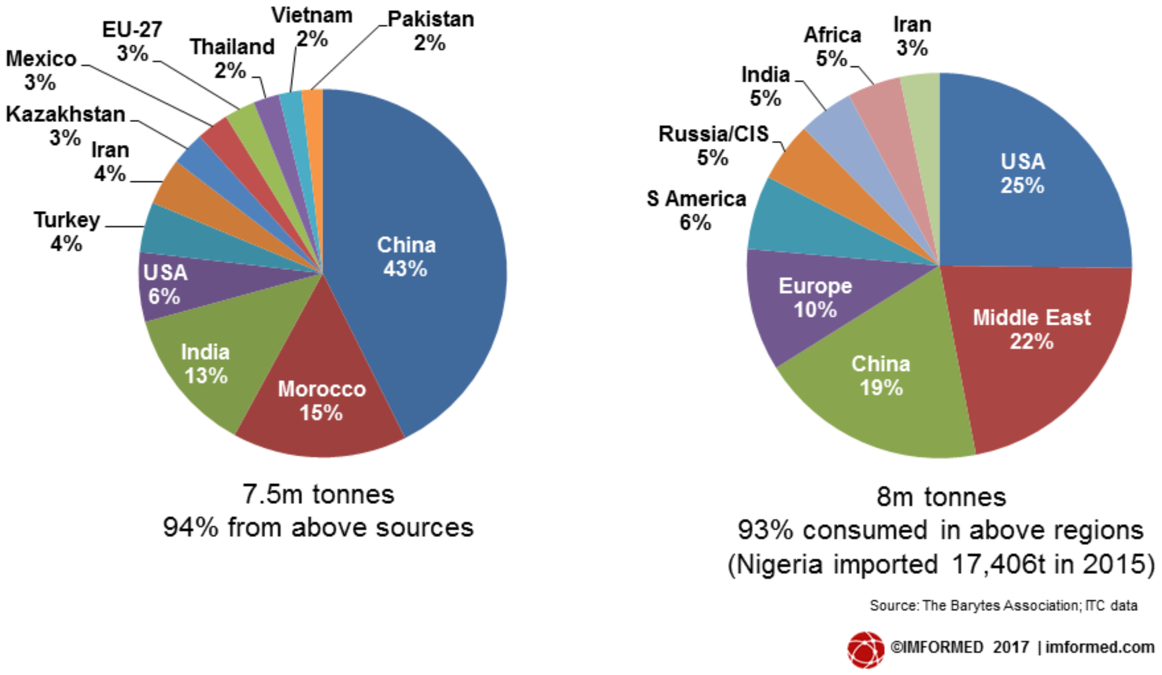
In case there is loss of well control (influx of formation fluid), a higher density fluid is pumped into the well to regain control of the well.

The density of a drilling fluid must be controlled to provide adequate hydrostatic head to prevent influx of formation fluid into the wellbore and also to achieve wellbore stability. The hydrostatic head should not be too high to avoid drilling problems like; loss circulation, poor drilling rate or even fracture the formation. The drilling widow profile of the formation should be taken into consideration before choosing the hydrostatic pressure to operate on. Normal pressure gradient by water is 0.433psi/ft or 433psi/1000ft.

The density of any fluid is directly related to the amount and average specific gravity of solids in the fluid. The control of density is critical since the hydrostatic pressure exerted by the column of fluid is required to contain formation pressure and aid in keeping the borehole open. The density of a drilling fluid should be dictated by the formation pressure encountered. Density is measured in pounds per gallon, ppg or pounds per cubic feet, ppft3.

2.9 Barite

Barite is a crystalline heavy material chemically composed basically of Barium Sulphate (BaSO4) usually 58.8% Barium. It is usually associated with impurities like Silicon (IV) oxide or Lead Sulphides. It is a heavy mineral compound that occurs naturally as large veins or beds. Barites can occur as gangue minerals in various mineral veins, in limestones, sandstones and like deposits *(*NGSA, *MMSD, 2010).* Barite is chemically inert and insoluble in water or oil. About 80% of barite in the world is used as a weighting material in drilling fluids in oil and gas exploration to suppress high formation pressures and prevent blow out (Etim, 2015). It is also used in the paint and pharmaceutical industries as well.



Source: The Barytes Association; ITC data

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Fig 2.7: World Barite Production and Consumption, 2015 *(Source: informed.com.2017)*

Nigeria is blessed with many Solid minerals, and Barite is one of those minerals found in commercial quantity. Barites in Nigeria occur as vein infilling materials, commonly associated with lead-zinc iodes and veins in the both Pre-Cambrian basement and Cretaceous sedimentary rocks of the lower and middle Benue valley. The mineral occurs mostly in white, reddish-brown and clear varieties with specific gravity varying between 3.5 - 4.4. The width of veins ranges from a few centimetres to 5.3meters. Length of veins also vary from few metres to >4500m-(NGSA, MMSD 2010). Preliminary survey carried out by the Geological Survey of Nigeria in 1959 put the estimated reserve at 41,000tonnes for the Benue valley deposits. Also the Nigerian mining Corporation estimated the resource at 70,000 tonnes in the Azarra deposit in Nassarawa State. Recently, the Nigerian Geological Survey Agency embarked on the evaluation of newly reported deposits in Cross River, Benue, Nassarawa, Plateau, Taraba States. The inferred resource estimated for four states where mining is considered viable is 21,123,913 metric tonnes – (NGSA, MMSD 2010). In the work of Otoijamun et al 2021, the characterization of some Nigerian barite samples showed they can be used for drilling fluid formulation for the oil and gas industry due to their good specific gravity greater than 4.15 for API. They also went on the say that all the samples can be used for other industrial applications including healthcare, construction, plastic, cosmetics, paper, and rubber industries due to their level of barium sulphate content in the range of 30 to 50%. Ekwueme et al 2015 in their research discovered that the chemical composition of the barite ores in a Cross River State region shows that they are of high industrial quality and suitable for use as weighting agent in drilling mud. The chemical compositions of the host rocks suggest that the source of the mineralizing fluids which facilitated the formation of the barite are evaporates as indicated by the occurrence of large salt ponds at Okpoma in the study area.

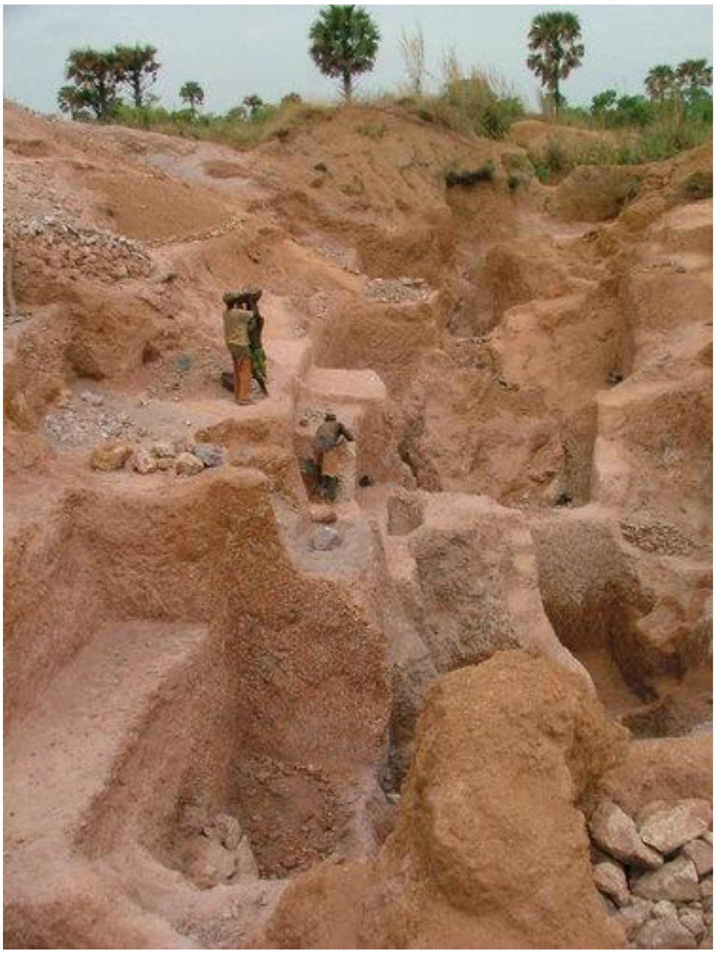

Fig. 2.8: Diagram of Osina Barite Veins.

API Standard Imported Barite obtained from an IOC operating in Nigeria was used as a control (reference) sample, and compared with barite samples procured from several Barite Veins located in Nigeria. The imported Barite has already been processed and ready for use but the locally procured Barite in this research has to be processed before use.

2.9.1 Uses of Barite

1. It is used in the oil and gas industry to increase mud density up to 21lb/gal
2. It is used to prepare solids-laden plugs for well control.
3. It is used in the paint industry as pigment
4. It is used in pharmaceuticals industry for drugs processing.

2.9.2 Physical and Chemical Characteristics of Barite

Appearance: fine beige-coloured powder. It can occur in white, beige or reddish brown variances, depending on the impurities trapped within.

Solubility: Barite is insoluble in oil and water

pH: Neutral

SG: 3.5-4.4

Bulk Density: 2160kg/m (135 lb/Cu ft)

Ayim et al(2009) in their case study discovered that the quality of the end product of Nigerian barite sold to the consumer is far below the international standard although there are barite ores in Nigeria that possess the required specific gravities and densities. They suggested that poor processing practices tend to have reduced the quality of the end product.

Nwozor K.K. and Chukwunenye E.M (2008), proposed a medium scale barite processing plant be installed in Nigeria to meet the demand of premium grade barite. Although the initial working capital is high, the plant has the advantage of quick returns on investment.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Preamble

This chapter describes the laboratory procedures, materials, apparatus and equipments used in this research work. Five (5) samples of each type of mud (WBM, OBM and SBM) were formulated with identical compositions, unweighted and then weighted with the barite samples. The rheological properties of 15 samples of weighted mud were analysed and compared to determine the effect of the varied weighting material in each mud sample.

3.2 Extraction of Base Oil

Soxhlet extraction was the process used to extract oil from the seeds of Irvingia Gabonesis. The process/set-up involves the connection of laboratory equipments assembled to have an evaporating, condensing, and collection chambers. The following apparatus and materials were used in the process.

Apparatus; Water bath, Retort Stand, Soxhlet Extractor, Measuring Cylinder, weigh balance, Rotary Evaporator, graduated beaker

Materials; Grinded Irvingia Gabonesis seeds, Solvent (Hexane), filter paper

Procedure

1. The Irvingia Gabonesis seeds were dried and grinded to remove the moisture and increase the surface area.
2. The grinded Irvingia Gabonesis seeds was weighed and recorded.
3. The weighed sample was wrapped in filter paper and placed in the thimble of the soxhlet extractor and fixed to the *condensing chamber*.

4. Hexane was poured in the distillation flask and connected to the *soxhlet extractor*.
5. The soxhlet extraction set up was immersed in the water bath and the heat was turned on.
6. The hexane evaporates and condenses at the thimble, soaks up the oil and refluxes back into the distillation flask through the siphon.
7. After the oil has been extracted from the thimble, the mixture of the oil and solvent was separated by using the rotary evaporator.

Plate 3.1: Soxhlet Extractor set up in the laboratory

Plate 3.2: Rotary Evaporator

3.3 Barite

The barite samples used were obtained from different Barite deposit locations in Nigeria. The samples were labelled B_1-B_4, sample B_0 is the imported barite sample.

3.3.1 Barite Samples Identities

Sample B_1

Osina, Yala LGA, Cross River State.

Coordinates – N06° 52’ 36.0’’ E008 45’ 53’’

Elevation; 109m

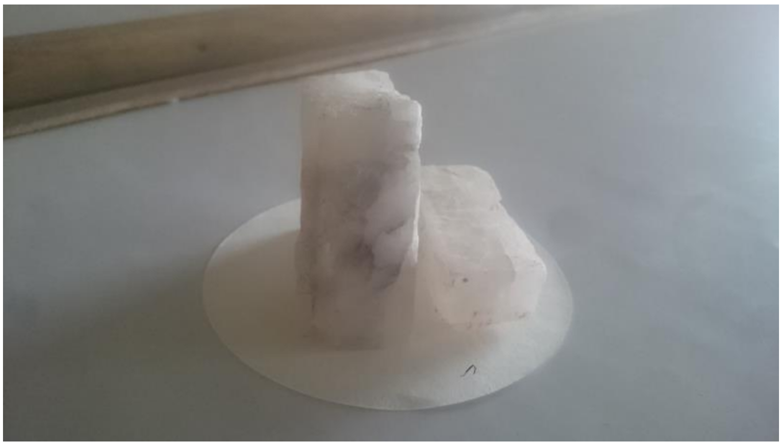

Plate 3.3: Barite Sample B_1

Sample B_2

Gabu, Yala Local Government Area, Cross River State

Coordinates - N06° 51’ 06’’ E008° 45’ 33’’

Elevation : 100m

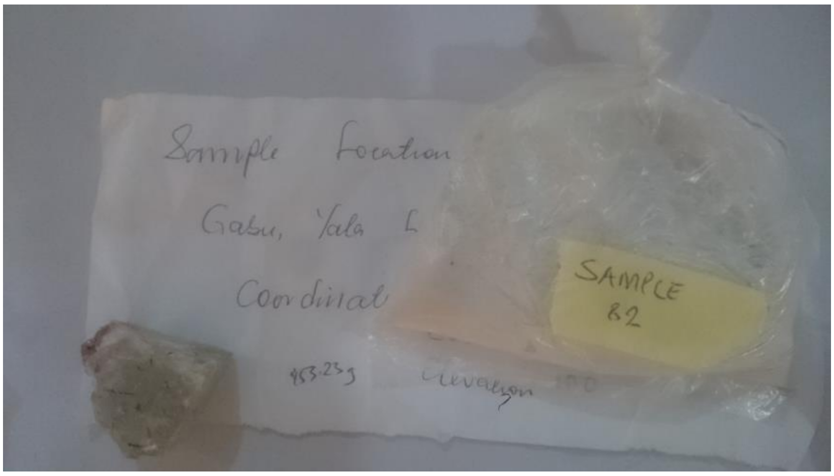

Plate 3.4: Barite Sample B_2

Sample B_3

Ochon, Obubra LGA, Cross river state

Coordinates – N05° 53’ 20.1’’ E008° 24’ 07.3’’

Elevation : 111m

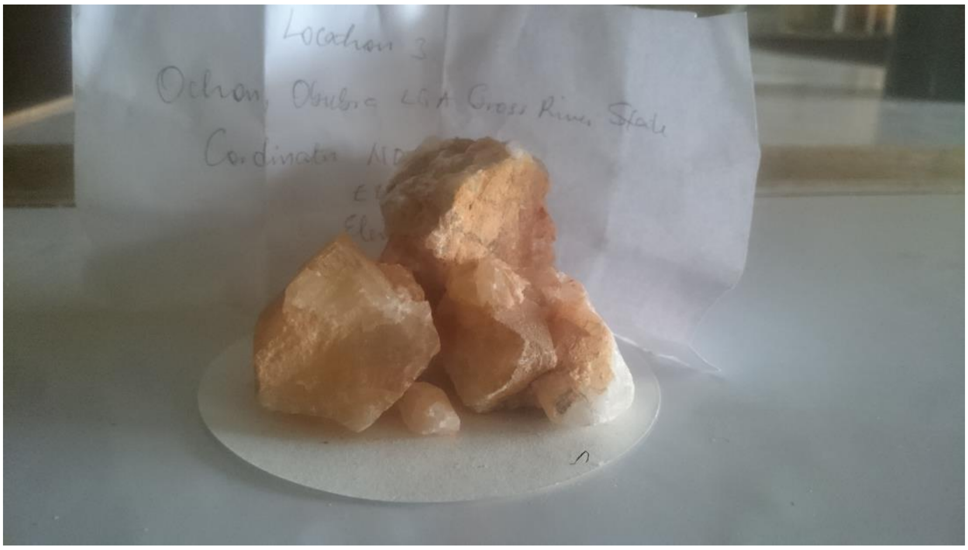

Plate 3.5: Barite sample B_3

Sample B_4

Osina, Yala LGA, Cross river state.

Coordinates - N06° 54’ 20’’ E008 46’ 38’’ Elevation : 102m

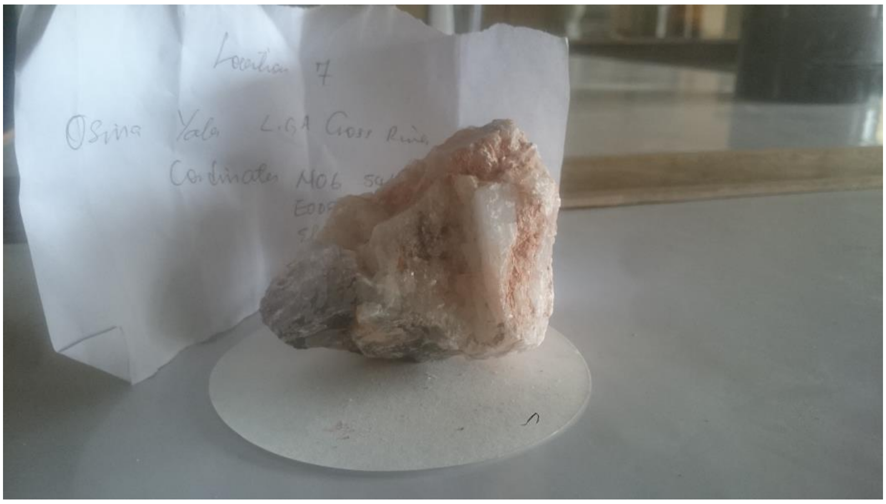

Plate 3.6: Barite Sample B_4

3.3.2 Preparation of Barite (Procedure)

The samples obtained from the Barite Veins were still in rock form and required to be micronized to be used in the laboratory. The procedure below was used in barite sample preparation.

Apparatus: Grinder, Sieves, Wire Brush, measuring cylinder, Petri dish, weigh balance

Materials: Barite rock, Fresh water

1. Each Barite Rock Sample was cleaned with distilled water and wire brush in order to remove the external impurities for instance Silicon(IV)oxide and quartz.
2. The cleaned sample was dried in the laboratory at room temperature to prevent dust and other impurities from settling on it.
3. The dried barite samples were pulverised using a mortar and pestle.
4. A sieve was used to ensure the particles size was relatively homogenous (average particle size <25µm).

Table 3.1: API specification for Barite

Specific gravity	4.2 (min)
Soluble metals or calcium:	250 ppm (max)
Wet screen analysis	
Residue on No. 200 sieve:	3% (max)
Residue on No. 325 sieve:	5% (min)

Specific Gravity of a substance is the relative density of that substance to the density of water. From the table above it can be seen that the most important property of Barite to the oil and gas industry is its specific Gravity. The specific gravity of barite is the defining property that directly affects the mud weight. Due to the limiting resource of 4.2SG barite worldwide, API has approved of a 4.1 SG barite to be used.

3.3.3 Specific Gravity of the Barite Samples

The measuring cylinder method of obtaining the specific gravity of solids was employed.

Apparatus; Measuring cylinder, weigh balance,

Materials; micronized Barite, fresh water

1. A measuring cylinder was washed, dried, cleaned and weighed empty, the mass of the measuring cylinder was recorded, $\mathbf{m_1}$.
2. Fresh water was poured into the measuring cylinder and weighed, the mass was recorded, $\mathbf{m_2}$.
3. The volume of the water was recorded,$\mathbf{v_1}$.

4. A mass of barite sample was weighed and recorded, $\mathbf{m_b}$.
5. The weighed barite is poured into the measuring cylinder containing water and weighed, $\mathbf{m_3}$.
6. The volume of water and barite was recorded, $\mathbf{v_2}$.
7. The difference between the m_2 and m_1 gives the mass of water, $\mathbf{m_w}$, $(\mathbf{m_2 - m_1 = m_w})$
8. The difference between v_2 and v_1 gives the equivalent volume of the mass of barite, $\mathbf{v_b}$. $(\mathbf{v_2 - v_1 = v_b})$

$$\text{Specific Gravity} = \frac{\text{density of substance}}{\text{density of water}} \quad \text{.....equation 5}$$

$$Density\ of\ Substance\ \left(\frac{g}{cm3}\right) = \frac{mass(g)}{volume\ cm^3} \quad \text{....equation 6}$$

3.4 Mud Formulation

A pilot test was carried out in the laboratory in order to predict the behaviour of the drilling fluid in well conditions. 350ml represents 1bbl, and 1g represents 1lb. The generic components of the basic drilling fluid types were used in the formulation of the drilling fluids. All the mud samples used in this investigation was formulated and tested following the *API Recommended practices RP-13B.*

The mud formulation involves mixing several substances to achieve a desired specification of drilling fluid. The components used in making the drilling fluid can be grouped thus – Base fluid, viscosifiers, filtration loss additive, ph control additives. The components were mixed in specific ratios and based on the mud design desired. Equipments used in the formulation of the drilling fluid include Hamilton Beach mixer, measuring cylinder, weighing balance - used for weighing chemicals- and spatula. The base fluid was measured using a measuring cylinder and poured into the cup of the Hamilton Beach mixer. Other components of the drilling fluid were added as desired and stirred.

Fig. 3.1: Hamilton Beach Mixer

3.4.1 Water Based Mud

Water based mud is usually used as spud mud or in shallow wells and thus requires less additives. Below are steps used in the formulation of water based mud.

1. 350ml of fresh water was measured and poured in a beaker.
2. 0.4g of soda ash was weighed and added to the fresh water to control hardness.
3. 0.4g of caustic soda was weighed and added to the water to make it alkaline
4. 21g of Bentonite (AQUA GEL) was measured and added to the mixture and stirred.
5. 0.3g of PolyAnionicCellulose (PAC-R) was measured and added to the mixture. This serves as a filtration loss controlling agent
6. A Hamilton Beach mixer (*Fig. 3.1*) was used to agitate the mixture for a minimum 30minutes to obtain a homogenous fluid.

7. The mud was weighed in a mud balance and readings recorded.
8. 70g of barite was added, stirred with Hamilton Beach mixer for 30minutes and weighed.
9. Readings were then recorded.
10. This process was repeated in (5) more beakers to compare the effect of the different local barite samples in each sample mud

Table 3.2: Composition of Water based mud

Components	***B0***	***B1***	***B2***	***B3***	***B4***
Water	*350ml*	*350ml*	*350ml*	*350ml*	*350ml*
Bentonite	*21g*	*21g*	*21g*	*21g*	*21g*
Caustic Soda	*0.4g*	*0.4g*	*0.4g*	*0.4g*	*0.4g*
Soda ash	*0.4g*	*0.4g*	*0.4g*	*0.4g*	*0.4g*
PAC R	*0.3g*	*0.3g*	*0.3g*	*0.3g*	*0.3g*
Unweighted Mud weight	*8.6ppg*	*8.6ppg*	*8.6ppg*	*8.6ppg*	*8.6ppg*
Barite	*70g*	*70g*	*70g*	*70g*	*70g*
Weighted Mud weight	*9.3ppg*	*9.5ppg*	*9.3ppg*	*9.4ppg*	*9.4ppg*$^{+}$

3.4.2 Oil Based Mud

The preparation process of the oil based mud is quite similar to that of the water based mud. The continuous phase is made up of oil and water mixture. In this experiment, diesel oil is mixed with water in a ratio of 80:20. API Recommended Procedures were observed. The table below gives a summary of the composition of oil based mud.

Table 3.3: Composition of (Diesel) Oil based mud

Components	***B0***	***B1***	***B2***	***B3***	***B4***
Diesel	*270ml*	*270ml*	*270ml*	*270ml*	*270ml*
Water	*67ml*	*67ml*	*67ml*	*67ml*	*67ml*
Bentonite	*21g*	*21g*	*21g*	*21g*	*21g*
Primary Emulsifier	*7ml*	*7ml*	*7ml*	*7ml*	*7ml*
Caustic Soda	*0.4g*	*0.4g*	*0.4g*	*0.4g*	*0.4g*
Soda ash	*0.4g*	*0.4g*	*0.4g*	*0.4g*	*0.4g*
PAC R	*0.2g*	*0.2g*	*0.2g*	*0.2g*	*0.2g*
Unweighted Mud weight	*7.8ppg*	*7.8ppg*	*7.8ppg*	*7.8ppg*	*7.8ppg*
Barite	*70g*	*70g*	*70g*	*70g*	*70g*
Weighted Mud weight	*9.0ppg*	*9.3ppg*	*9.0ppg*	*9.2ppg*	*9.2ppg*

3.4.3 SYNTHETIC MUD

The preparation process of the synthetic oil based mud is similar to that of the Oil based mud. The base fluid is an Olefin isomer that is non toxic and biodegradable. Due to characteristics of this base fluid certain additives such as the bridging agent and emulsifier are imperative. The continuous phase is made up of a synthetic oil and water mixture. In this experiment, synthetic oil is mixed with water in a ratio of 75:25. The table below describes the formulation used. API Recommended Procedures were observed. The table below gives explicit details of the components of the synthetic drilling fluid

Plate 3.7: Synthetic Based Fluid from Irvingia Gabonesis

Irvingia Gabonesis Oil was attempted to be used as base fluid but it was not successful. The oil was quick to change to solid form at room temperature (as shown in Fig. 3.7) but liquid in higher temperatures. The mixture obtained while using Irvingia Gabonesis as base fluid became “gelly” after about 20 seconds while stirring in the Hamilton Beach mixer. Four other attempts to formulate a mud using this oil proved futile because of its gelly characteristic. Such gelly fluid cannot be used as a drilling fluid because it will be difficult to pump downhole and will also lead to stuck pipe and maybe damage other drilling equipments.

Table 3.4: Composition of Synthetic mud

Components	***B0***	***B1***	***B2***	***B3***	***B4***
Base fluid	*207ml*	*207ml*	*207ml*	*207ml*	*207ml*
Organophilic clay	*8g*	*8g*	*8g*	*8g*	*8g*
Lime	*8g*	*8g*	*8g*	*8g*	*8g*
Primary Emulsifier	*6ml*	*6ml*	*6ml*	*6ml*	*6ml*
Water	*68ml*	*68ml*	*68ml*	*68ml*	*68ml*
Calcium Chloride	*32g*	*32g*	*32g*	*32g*	*32g*
Fluid Loss Agent	*2g*	*2g*	*2g*	*2g*	*2g*
Unweighted Mud weight	*9.8ppg*	*9.8ppg*	*9.8ppg*	*9.8ppg*	*9.8ppg*
Barite	*70g*	*70g*	*70g*	*70g*	*70g*
Weighted Mud weight	*10.5ppg*	*10.7ppg*	*10.5ppg*	*10.6ppg*	*10.7ppg*

The base fluid is an Olefin isomer that is non toxic and biodegradable. Due to characteristics of this base fluid certain additives such as the bridging agent and emulsifier are imperative.

3.5 Mud Weight

The mud weight was measured using a mud balance (fig. 3.2). The mud balance consists of a constant volume cup with a lever arm and a rider calibrated to read directly, the density of a fluid in ppg. The arm rests on a fulcrum and with the help of a level vial, an accurate balance can be obtained. The following procedure was followed.

1. The lid was removed from the mud cup and the sample mud was poured inside the cup till the cup was filled to the brim.
2. The lid was carefully replaced and firmly seated.
3. The mud cup was tapped to ensure there were no bubbles trapped inside the cup
4. A rag was used to wipe off the spilled mud outside the cup.
5. The balance arm was placed on the base, with the knife edge resting on the fulcrum
6. The rider was moved until the graduated arm was level as indicated by the level vial on the beam
7. At the left hand edge of the rider, the density of the mud was read.

Fig. 3.2: Mud Balance

3.6 Rheology Tests

Materials: Freshly prepared drilling mud samples, masking tape, recording book and pen.

The objective of rheology tests is to measure the viscosity and gel strength that relate to the flow properties of the mud. It has already been established in the literature review that the presence of solid in the drilling fluid has a role to play in the viscosity and gel strength of the fluid.

Fig. 3.3: 8-Speed OFITE 800 Viscometer (Source: OFITE 800 user manual)

The rheology test was conducted using eight rotational speeds (600, 300, 200, 100, 60, 30, 6, and 3 rpm) OFITE 800 viscometer (Figure 3.3). It is used to directly measure the viscosity of the drilling fluid. The shear stress (scale reading) was determined as a function of the shear rate (from the rotational speed). In this study, the test procedures followed the recommended practice of standard procedure for field testing drilling fluid (API Recommended Practice 13B, 2005). The plastic and apparent viscosities were obtained using these mathematical relationships:

Plastic Viscosity (PV) = 600 dial reading – 300 dial reading Equation 3.1

$$Apparent\ Viscosity\ (AV) = \frac{PV}{2} \qquad \text{Equation 3.2}$$

Yield Point (YP) = 3 dial reading Equation 3.3

The carrying capacity index CCI is calculated using parameters derived from the viscometer readings. The carrying capacity index can give us more information about the hole cleaning capability of the drilling fluid. If the CCI is equal to or less than 0.5, then the hole cleaning is poor. Where the CCI is equal to or greater than 1.0, then it indicates that hole cleaning is very good. The fluid flow index (n), also gives information about the rheology of the fluid. Where n is less than 1, the fluid is said to be shear thinning, where n is equal to 1, the fluid is a Newtonian fluid and where n is greater than 1, the fluid is said to be shear thickening.

It is a rule of thumb in any drilling fluid operation that the advisable minimum and maximum flow rates for an 8.5inch well is 355gpm and 510gpm respectively, (Ofesi et al, 2017). Hence the range of minimum and maximum annular velocity is between 214ft/min and 308.4ft/min (using equation 4). In this work, the following assumptions were made based on regular industry practice in Nigeria.

hole diameter(dh) = 8.5in

drill pipe OD (dp) = 5.5in

Annular velocity (AV) = 270ft/min

3.7 Gel Strength

The OFITE 800 Model Viscometer was also used to obtain the gel strength of the mud. The mud was stirred at 600rpm and then allowed to settle for 10 seconds before turning the dial to gel to get the 10s gel strength. Same procedure was taken for the 10 minutes gel strength but settling time was 10 minutes.

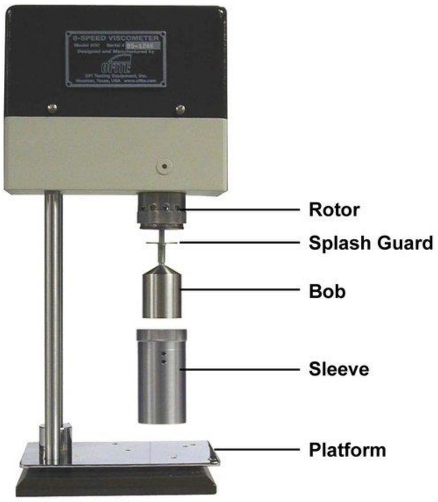

Fig 3.4: OFITE 800 Viscometer (Source: OFITE 800 user manual)

3.8 Filtration Tests

The objective of filtration tests is to simulate the fluid loss invaded through the borehole formation while hydrostatic pressure is greater than the pressure of fluid in the pore of the formation. The test indicates the rate at which permeable formations are sealed by the deposition of a mud cake after being penetrated by the bit. There are two types of filtration that occurs during a drilling program – Dynamic and Static. Static filtration occurs when the mud is not being circulated and the filter cake grows undisturbed. Dynamic filtration occurs when the mud is being circulated and the growth of filter cake is limited by erosive action of the mud stream. In this research, Static Filtration was considered.

Fig 3.5: OFITE 900 HTHP Filter Press (Source: OFITE 900 user manual)

The filtration properties of the drilling fluid samples were carried out at high temperature and high pressure conditions. An OFITE 900 HTHP filter press was used to measure the filtration properties of the drilling fluids at high temperature and pressure of 250^{o}F and 300psi. API Recommended Procedures was observed while carrying out this test.

3.9 Economic Model Parameters

The economic model comprises of input parameters, which include yearly barite production, taxes, and royalties under the various mining legislations for the country. The assumptions made are presented in the following decision rule:

Basic Decision rules for the Assumption:

(i) Cost estimates were made in US Dollars

(ii) No allowance were provided to include cost and price fluctuations in the estimate; i.e. constant dollar applied.

(iii) The yearly production was estimated using forecast values from average well consumption

(iv) The price of barite used in the analysis remained constant

(v) Estimate barite used per well is 280 tonnes (Nganje et al, 2013).

Note: The model does not account for ore loss and dilution.

3.9.1 Capital Expenditure: According to Otto et al (2006) the cost components of mining capital expenditure are broken down using percentages (%) as shown in the table below;

Table 3.9: Capital Expenditure breakdown for barite mining

Parameter	**Percentage (%)**
Pre-Production Exploration Cost	3%
Mining development cost	6%
Equipment and infrastructure	20%
Processing plant	70%
Feasibility Study	1%

Source: Otto et al (2006) and Mohutsiwa (2015)

3.9.2 Operational Expenditure: Again, according to Otto et al (2006) the cost components of Barite production operations expenditure are broken down using percentages (%) as shown in the table below;

Table 3.10: Operational Expenditure breakdown for barite mining

Parameter	**Percentage (%)**
Mining operations	13%
Beneficiation	1%
Processing cost	80%
Overhead	5%
Freight	1%

Source: Otto, et al (2006) and Mohutsiwa (2015)

3.9.3 Taxes and Royalties

Type of Barite used	Income Taxes (%)	Royalties Tax %	Other taxes
Foreign Barite	3%	30%	Payment Operations levy
Nigerian Barite	5%	20%	Tertiary Education Tax 2% of Annual

CHAPTER FOUR

RESULTS AND DISCUSSION

This chapter presents and discusses the results of the experiments. Drilling fluid samples were tested and analyzed to determine the composition, physical and rheological properties and filtration properties of drilling fluid samples tested and analysed are reported in this section. The results of the experiment and analysis are discussed below.

4.1 Extraction of Irvingia Gabonesis Oil

The extraction of oil from grinded seeds of Irvingia Gabonesis was carried out using Soxhlet Extraction. After the extraction process the following results was obtained –

Table 4.1: Values obtained from the Soxhlet Extraction of Irvingia Gabonesis

Mass of dried, grounded *Irvingia Gabonesis* - m_{ig}	2132g
Mass of chaff - m_c	1404g
Mass of oil extracted - m_o	728g
Volume of oil extracted - v_o	870ml
SG of Oil	0.836 at 60°C 0.860 at 50°C
Flash point of Oil	>300°C

4.2 Specific Gravity of Barite

The quality of barite is measured based on its specific gravity. Specific gravity of 4.2 and above is ideally preferred and is rated as premium grade. Lower grade barite of 3.6-3.8 Specific gravity can also be used but will require a larger quantity of the mineral to weight up the mud as desired. Remember, a minimum amount of solids is desired in drilling mud formulation.

From the results it was observed that sample B_1 was the heaviest with a specific gravity of 4.4 and sample B_2 with the lowest specific gravity of 4.0. An error of ±0.2 was considered in the measurements.

Table 4.2: Different Barite Samples and Measurement obtained

Sample	*Mass of measuring cylinder*	*Mass of cylinder + water*	*Mass of barite + water*	*Volume of water*	*Volume of barite + water*	*Volume of barite*	*Specific gravity*
B_0	84.65	106.45g	126.54g	20ml	24.9ml	4.9	4.1
B_1	84.6g	105.88g	125.85g	20ml	24.5ml	4.5ml	4.4
B_2	84.66g	106.51g	125.56g	20ml	25ml	5ml	4.0
B_3	81.69g	101.40	121.52g	20ml	24.8ml	4.8ml	4.17
B_4	84.67g	106.67g	126.72g	20.5ml	25.2ml	4.7ml	4.26

4.3 Mud Weight

The weight of the drilling mud determines the hydrostatic head in the well and therefore must be monitored and controlled always. In this research, the formulated drilling fluid samples were measured unweighted and then weighed after being weighted up by the addition of the 5 different sample barites. 70g of barite was added to each mud sample after formulation. A graphical representation is provided for wider comparison.

Table 4.3: Mud weight of Water Based Mud samples

Sample	Weighted Mud (ppg)	Unweighted mud(ppg)
B_0	9.3	8.6
B_1	9.5	8.6
B_2	9.3	8.6
B_3	9.4	8.6
B_4	9.4	8.6

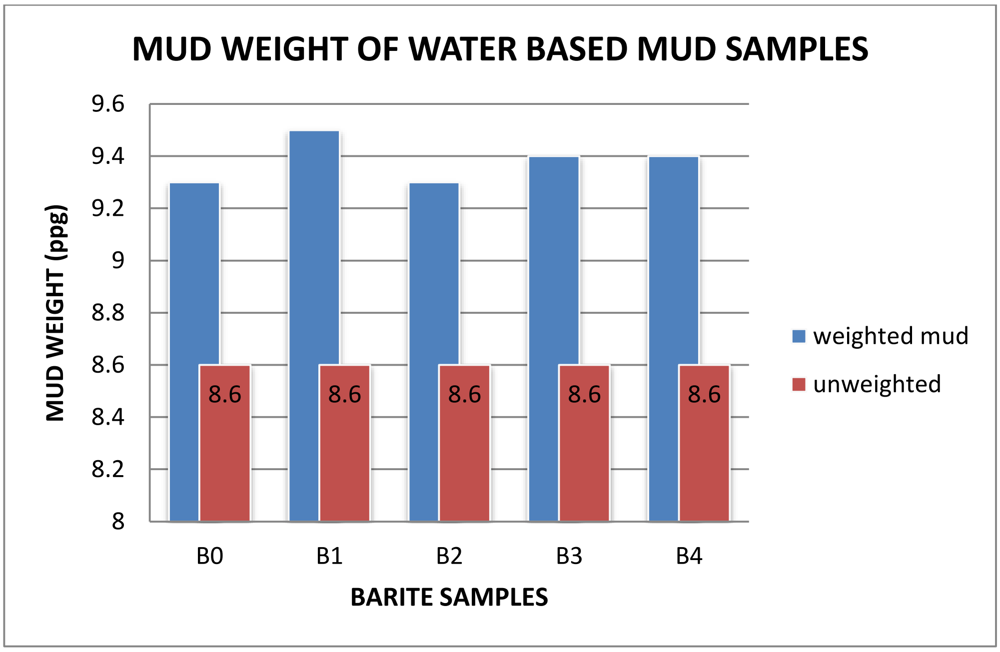

Fig. 4.1: Graphical Representation of mud weight of WBM

Table 4.4: Mud weight of Oil based Mud samples

Sample	Weighted mud (ppg)	Unweighted mud (ppg)
B_0	9	7.8
B_1	9.3	7.8
B_2	9	7.8
B_3	9.2	7.8
B_4	9.2	7.8

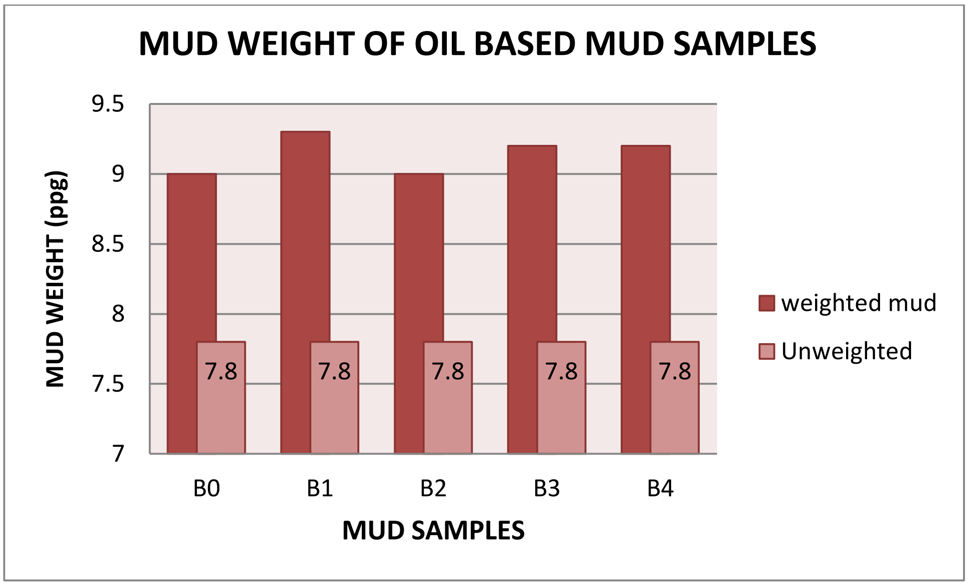

Fig. 4.2: Graphical Representation of mud weight of OBM

Table 4.5: Mud weight of the synthetic based mud samples

Sample	Weighted mud (ppg)	Unweighted mud (ppg)
B_0	10.5	9.8
B_1	10.7	9.8
B_2	10.5	9.8
B_3	10.6	9.8
B_4	10.7	9.8

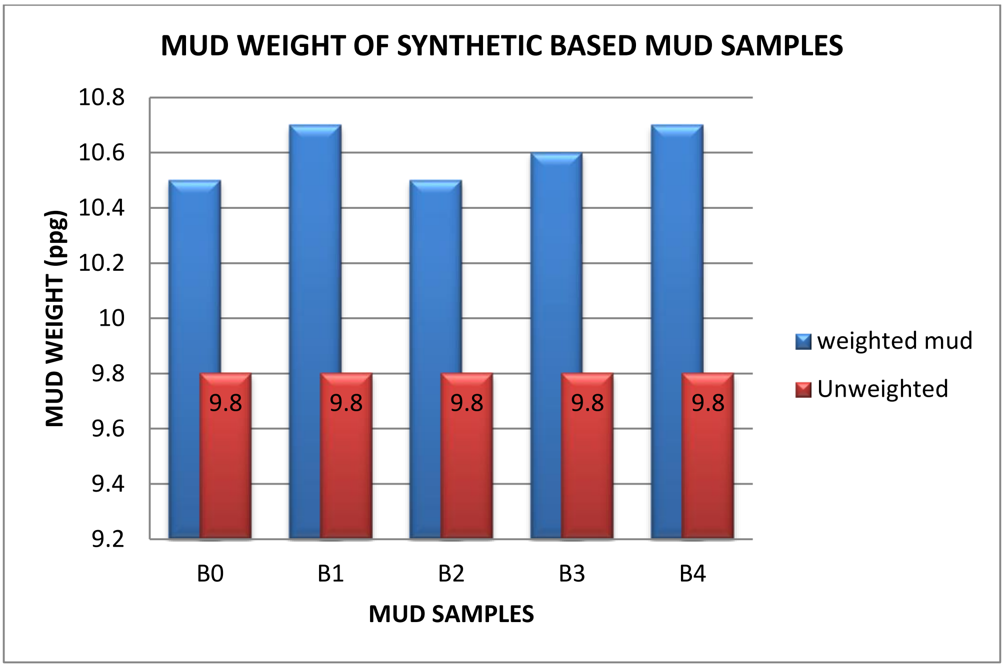

Fig. 4.3: Graphical Representation of mud weight of SBM

It is clearly observed from the graphs that sample B1 had the most effect on the mud weight in all the drilling mud types. This is desired from a weighting additive as it will reduce the amount of solids in the drilling fluid while providing the desired mud weight.

4.4 Determination of Rheological Properties and Parameters

The shear stress and shear rates values for the viscometer readings of drilling fluids are represented in the tables below. The average viscometer readings were used to calculate the shear stress and shear rates, the plastic and apparent viscosity and the yield points. The shear stresses were plotted against shear rates in order to choose the best fit curve for the Power Law or the Bingham Plastic model.

The rheological properties were measured at increasing temperatures to observe the effect of temperature on the properties of the drilling fluid. The increasing temperatures can be said to be a simulation of well conditions as drilling gets deeper.

Table 4.6: Rheology of WBM at ambient conditions

Speed (rpm)	*Dial Readings*				
	B_0	*B_1*	*B_2*	*B_3*	*B_4*
3	*52*	*33*	*51*	*50*	*50*
6	*52*	*34*	*50*	*51*	*50*
30	*54*	*37*	*54*	*53*	*52*
60	*55*	*39*	*56*	*53*	*53*
100	*57*	*40*	*57*	*56*	*55*
200	*58*	*43*	*59*	*57*	*57*
300	*60*	*46*	*61*	*60*	*60*
600	*64*	*51*	*65*	*63*	*62*

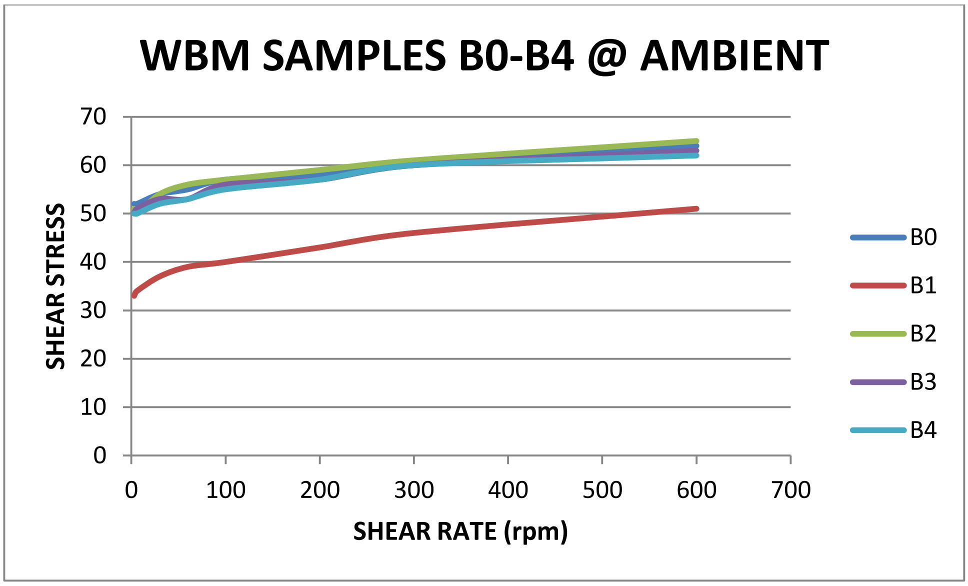

Fig. 4.4: Graph of water based mud samples at ambient conditions

Table 4.7: WBM at 120^{o}F

Speed (rpm)	*Dial Readings*				
	B_0	*B_1*	*B_2*	*B_3*	*B_4*
3	*38*	*30*	*35*	*33*	*34*
6	*38*	*30*	*36*	*34*	*34*
30	*39*	*35*	*38*	*36*	*35*
60	*40*	*36*	*40*	*39*	*38*
100	*41*	*39*	*42*	*42*	*41*
200	*46*	*42*	*45*	*44*	*43*
300	*49*	*44*	*49*	*46*	*47*
600	*52*	*46*	*52*	*50*	*51*

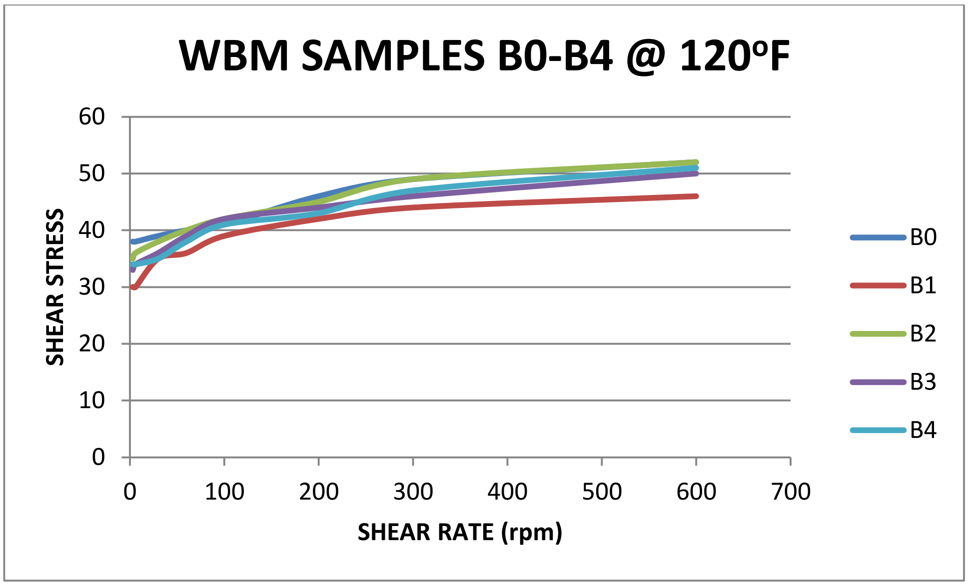

Fig. 4.5: Graph of water based samples at 120ºF

Table 4.8: WBM at 180ºF

Speed (rpm)	*Dial Readings*				
	B_0	*B_1*	*B_2*	*B_3*	*B_4*
3	*28*	*24*	*27*	*26*	*25*
6	*30*	*24*	*29*	*26*	*26*
30	*31*	*27*	*32*	*29*	*29*
60	*33*	*30*	*33*	*31*	*30*
100	*36*	*33*	*35*	*35*	*34*
200	*38*	*35*	*38*	*38*	*37*
300	*43*	*39*	*42*	*40*	*39*
600	*47*	*42*	*48*	*45*	*44*

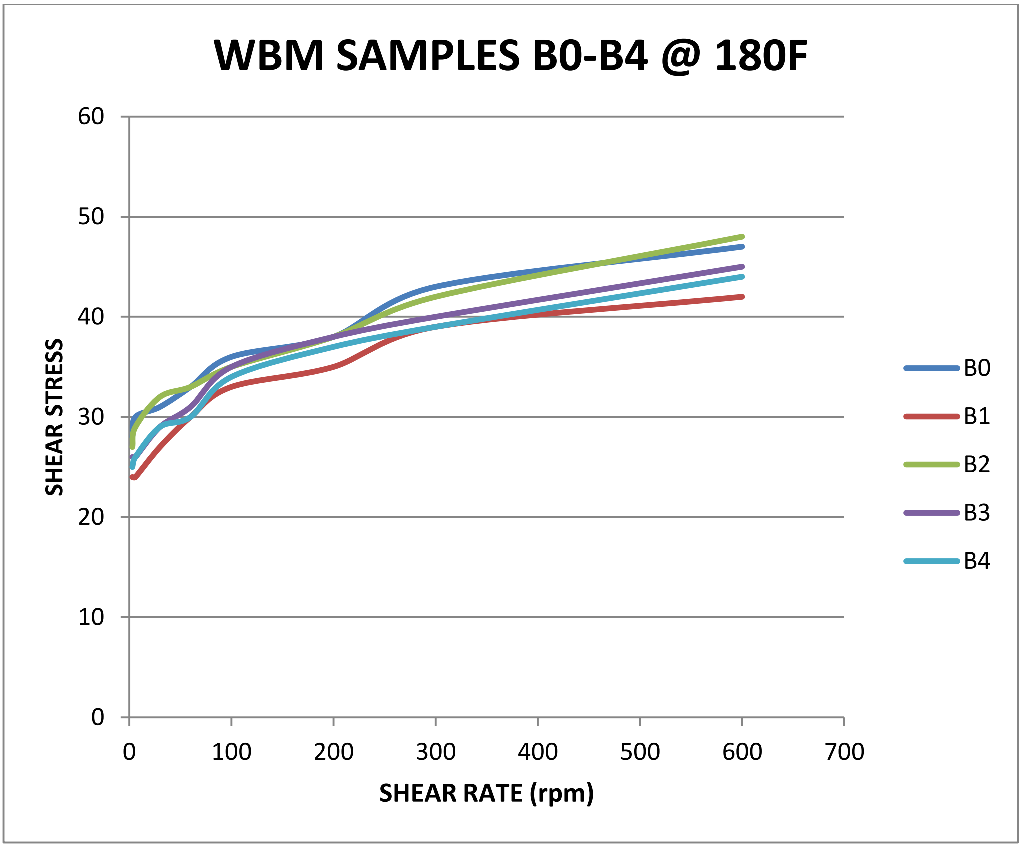

Fig 4.6: Graph of water based samples at 180°F

Table 4.9: WBM at 240°F

Speed (rpm)	*Dial Readings*				
	B_0	*B_1*	*B_2*	*B_3*	*B_4*
3	*23*	*22*	*24*	*23*	*22*
6	*27*	*23*	*27*	*23*	*24*
30	*29*	*25*	*29*	*27*	*26*
60	*31*	*27*	*32*	*30*	*28*
100	*33*	*31*	*33*	*33*	*32*
200	*35*	*33*	*36*	*35*	*34*
300	*40*	*37*	*41*	*38*	*38*
600	*44*	*41*	*44*	*42*	*42*

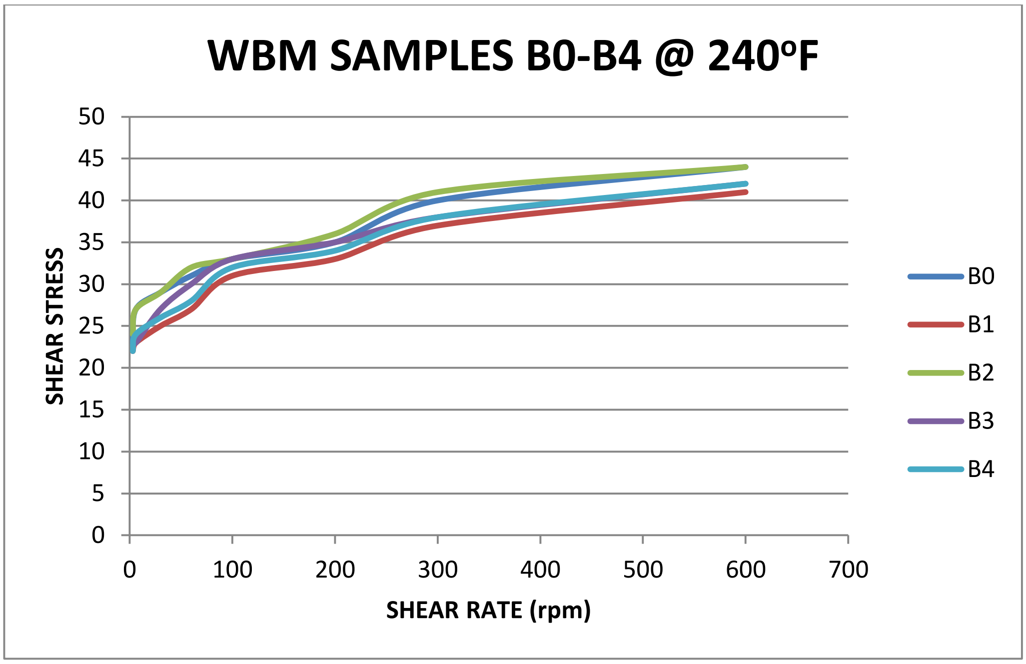

Fig. 4.7: Graph of water based samples at 240ºF

At ambient conditions, it is seen that mud sample B_1 had a lower rheology when compared to the other mud samples. However as we go deeper and encounter hotter formations, the gap in rheology difference amongst all samples thins out although it remains the lowest rheology. Sample B_0 is seen to have a higher rheology and performs better than some other samples.

The results from the rheological tests of the Diesel Oil based mud samples are as follows.

Table 4.10: Rheology of Diesel OBM at ambient condition.

Speed (rpm)	*Dial Readings*				
	B_0	*B_1*	*B_2*	*B_3*	*B_4*
3	*26*	*23*	*25*	*24*	*23*
6	*28*	*26*	*29*	*27*	*26*
30	*31*	*28*	*32*	*30*	*29*
60	*39*	*35*	*38*	*37*	*38*
100	*71*	*68*	*73*	*70*	*71*
200	*92*	*89*	*90*	*88*	*90*
300	*113*	*110*	*116*	*112*	*111*
600	*155*	*151*	*158*	*153*	*152*

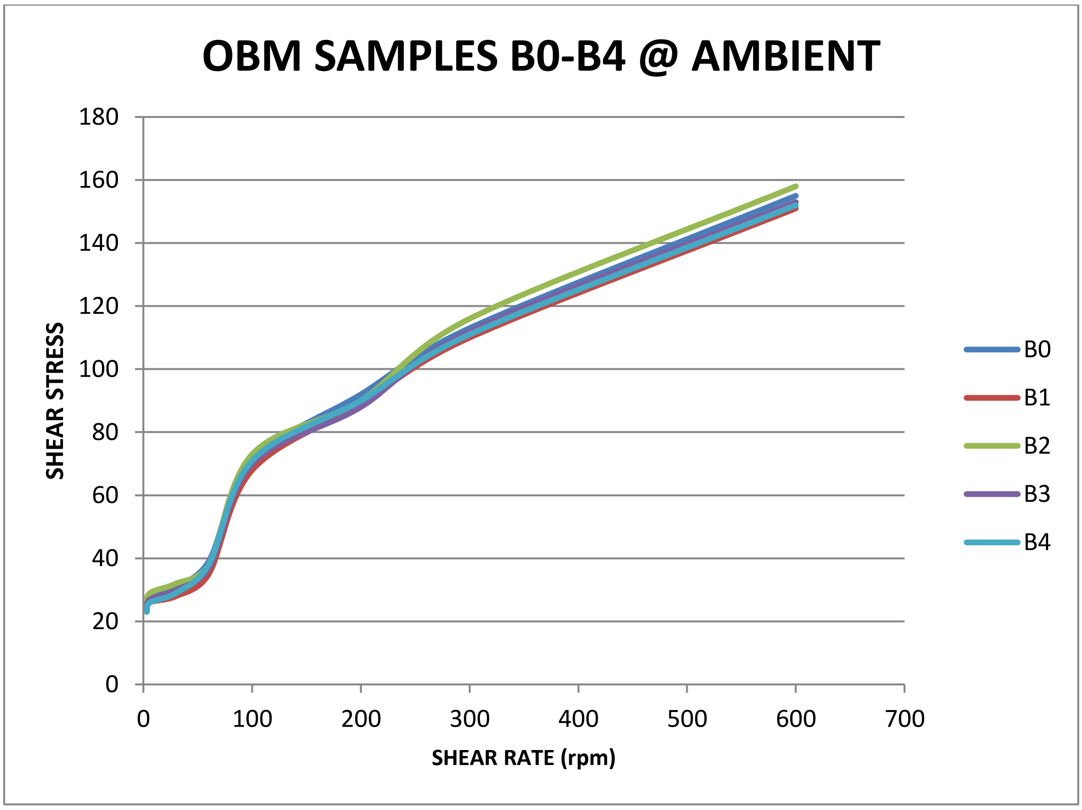

Fig 4.8: Graph of Rheology of Diesel OBM at ambient condition.

Table 4.11: Rheology of Diesel OBM at 120^{o}F.

Speed (rpm)	*Dial Readings*				
	B_0	B_1	B_2	B_3	B_4
3	*22*	*20*	*23*	*22*	*21*
6	*23*	*23*	*23*	*25*	*23*
30	*28*	*25*	*30*	*28*	*27*
60	*36*	*33*	*36*	*33*	*35*
100	*67*	*64*	*68*	*68*	*65*
200	*90*	*86*	*82*	*85*	*80*
300	*110*	*103*	*112*	*108*	*103*
600	*150*	*142*	*152*	*144*	*145*

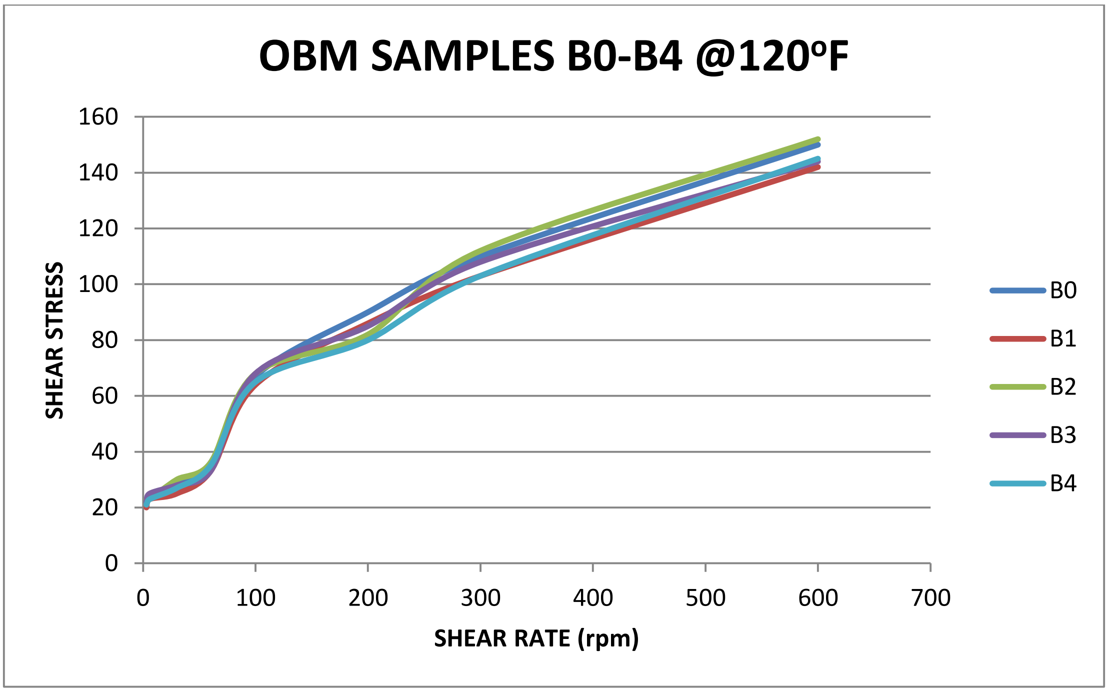

Fig 4.9: Graph of Rheology of Diesel OBM at 120^{o}F.

Table 4.12: Rheology of Diesel OBM at 180^oF.

Speed (rpm)	*Dial Readings*				
	B_0	*B_1*	*B_2*	*B_3*	*B_4*
3	*18*	*16*	*20*	*18*	*18*
6	*21*	*28*	*21*	*20*	*21*
30	*25*	*24*	*28*	*26*	*25*
60	*33*	*28*	*33*	*30*	*35*
100	*62*	*49*	*63*	*53*	*62*
200	*85*	*76*	*79*	*79*	*75*
300	*101*	*86*	*105*	*94*	*95*
600	*143*	*131*	*140*	*135*	*133*

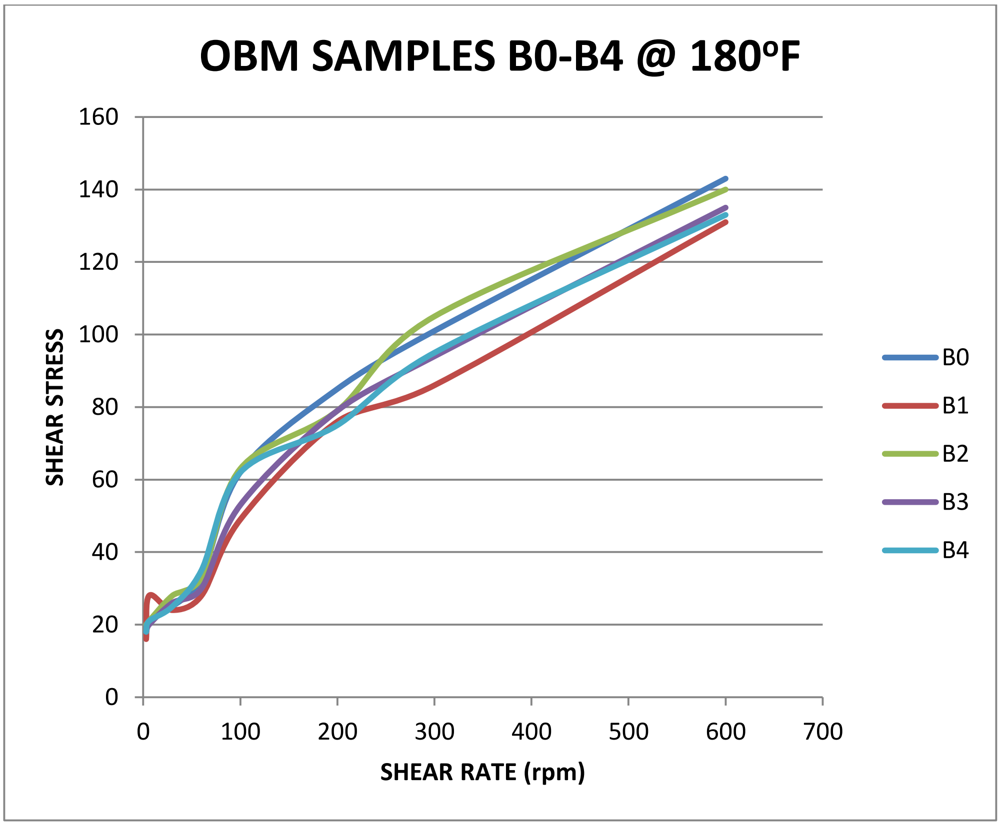

Fig 4.10: Graph of Rheology of Diesel OBM at 180°F

Table 4.13: Rheology of Diesel OBM at 240°F.

Speed (rpm)	*Dial Readings*				
	B_0	*B_1*	*B_2*	*B_3*	*B_4*
3	*13*	*11*	*15*	*13*	*16*
6	*17*	*14*	*16*	*15*	*20*
30	*20*	*17*	*22*	*20*	*23*
60	*28*	*26*	*26*	*25*	*29*
100	*57*	*45*	*56*	*45*	*52*
200	*79*	*70*	*74*	*75*	*70*
300	*95*	*81*	*98*	*89*	*89*
600	*139*	*124*	*135*	*128*	*130*

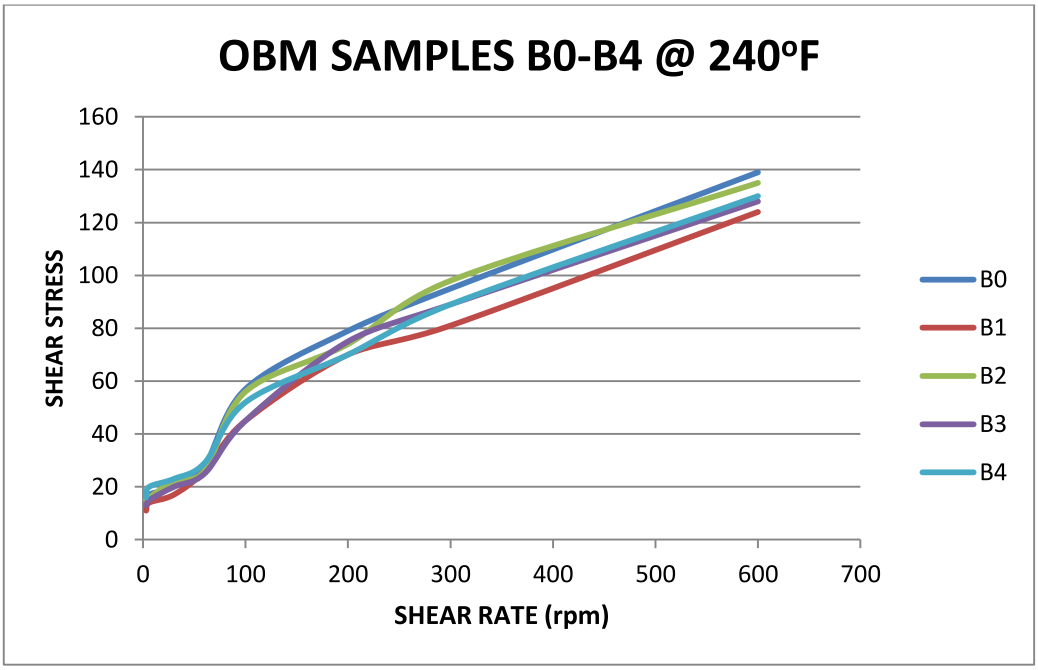

Fig 4.11: Graph of Rheology of Diesel OBM at 240°F

Generally the results from the sample muds were close to each other but as the temperature increases, their performance became a little altered. They followed the same rheological model throughout and thus can be substitutes for each other. Sample B_1 is seen to also have the lowest rheology.

The results from the rheological tests of the synthetic fluid samples are as follows.

Table 4.14: Rheology of SBM at Ambient conditions

Speed (rpm)	*Dial Readings*				
	B_0	*B_1*	*B_2*	*B_3*	*B_4*
3	*10*	*7*	*12*	*9*	*10*
6	*13*	*11*	*15*	*11*	*11*
30	*18*	*15*	*17*	*13*	*17*
60	*28*	*22*	*27*	*16*	*27*
100	*39*	*31*	*39*	*25*	*38*
200	*50*	*43*	*49*	*34*	*51*
300	*65*	*57*	*68*	*47*	*68*
600	*102*	*90*	*105*	*64*	*103*

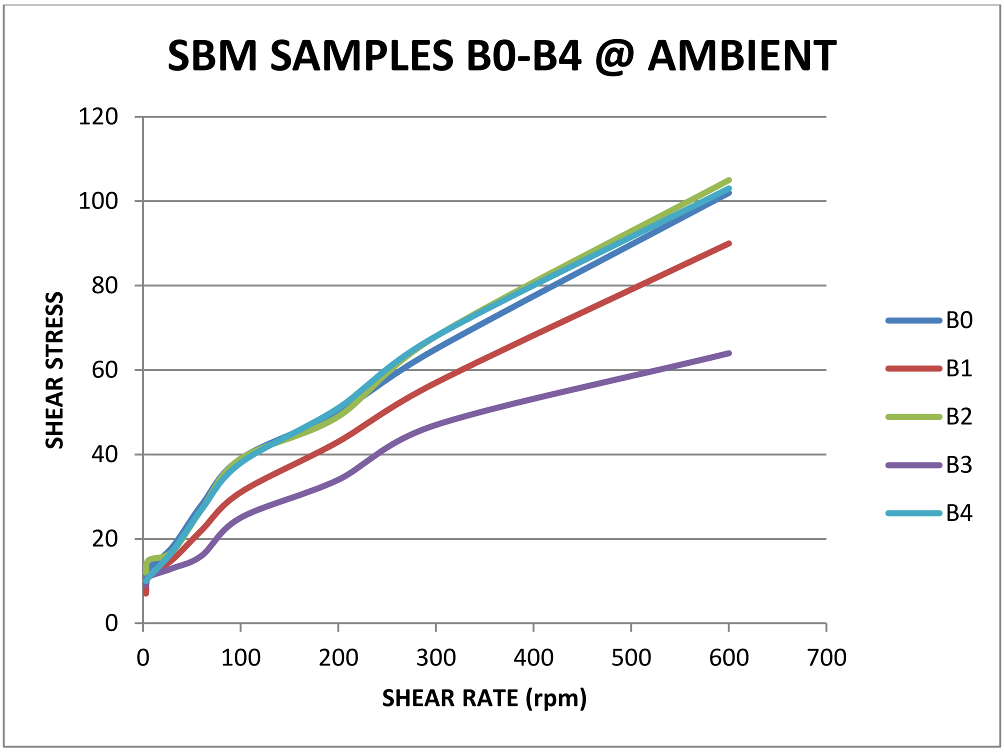

Fig 4.12: Graph of Rheology of SBM at Ambient conditions

Table 4.15: Rheology of SBM at 120°F.

Speed	*Dial Readings*				
(rpm)	*B$_O$*	*B$_1$*	*B$_2$*	*B$_3$*	*B$_4$*
3	*10*	*7*	*10*	*9*	*9*
6	*11*	*10*	*12*	*11*	*10*
30	*16*	*14*	*17*	*15*	*16*
60	*26*	*20*	*23*	*22*	*25*
100	*33*	*29*	*35*	*30*	*31*
200	*43*	*40*	*46*	*45*	*47*
300	*62*	*54*	*66*	*62*	*62*
600	*99*	*88*	*104*	*98*	*99*

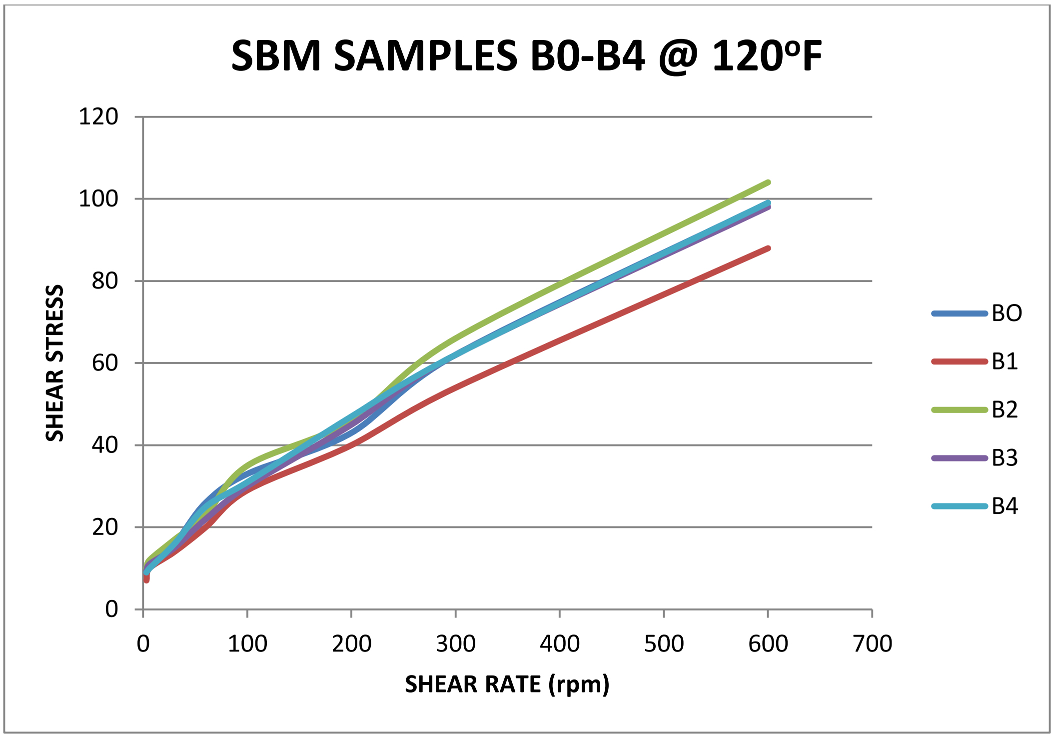

Fig 4.13: Graph of Rheology of SBM at 120°F

Table 4.16: Rheology of SBM at 180°F.

Shear Rate (rpm)	*Dial Readings*				
	B_0	*B_1*	*B_2*	*B_3*	*B_4*
3	*7*	*5*	*8*	*6*	*7*
6	*9*	*7*	*9*	*9*	*8*
30	*13*	*10*	*15*	*12*	*14*
60	*22*	*18*	*23*	*21*	*22*
100	*29*	*26*	*30*	*30*	*31*
200	*42*	*37*	*41*	*40*	*43*
300	*60*	*50*	*62*	*58*	*59*
600	*98*	*85*	*99*	*95*	*97*

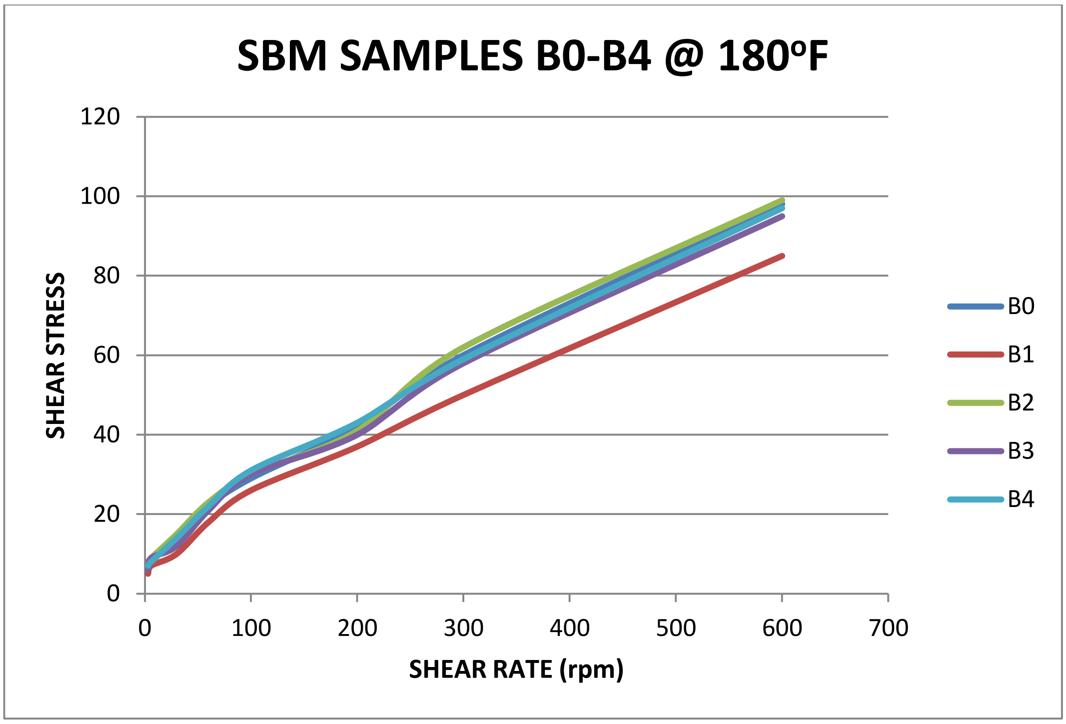

Fig 4.14: Graph of Rheology of SBM at 180°F

Table 4.17: Rheology of SBM at 240°F.

Speed (rpm)	*Dial Readings*				
	B_1	*B_2*	*B_3*	*B_4*	*B_0*
3	*7*	*4*	*7*	*6*	*5*
6	*9*	*5*	*7*	*8*	*7*
30	*12*	*9*	*14*	*11*	*14*
60	*20*	*15*	*23*	*19*	*20*
100	*27*	*23*	*30*	*30*	*29*
200	*39*	*35*	*41*	*38*	*41*
300	*57*	*45*	*61*	*58*	*56*
600	*95*	*79*	*96*	*94*	*95*

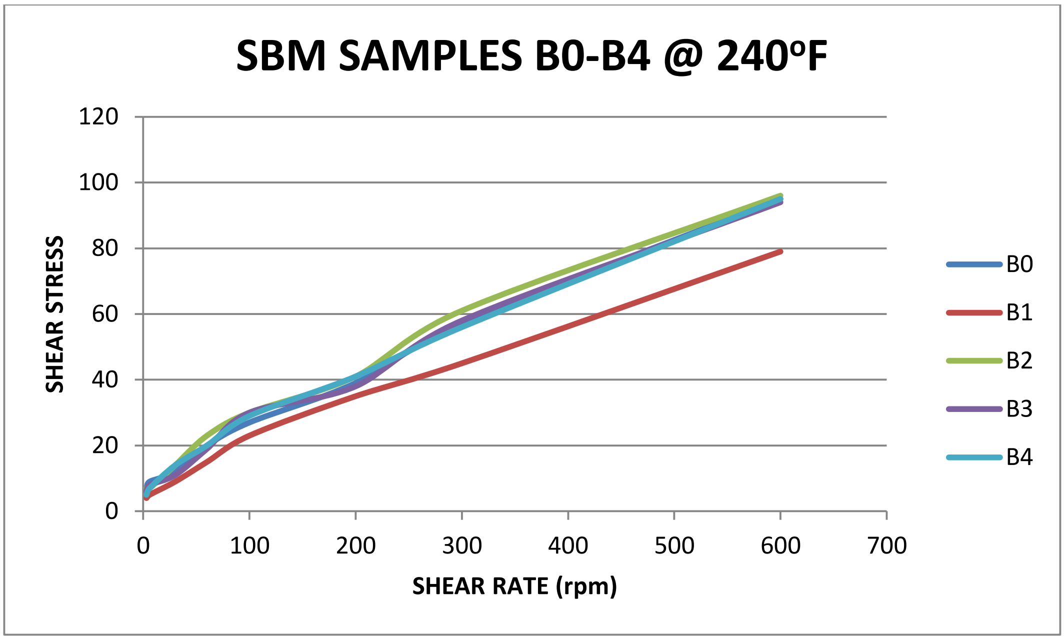

Fig 4.15: Graph of Rheology of SBM at 240^{o}F

4.6 Carrying Capacity Index (Cci)

Carrying capacity index gives information on the hole cleaning capabilities of the drilling fluid. When the CCI is less than 0.5 hole cleaning is poor, and when its greater than or equal to 1, hole cleaning is good. The CCI is calculated for each drilling fluid sample and a summary is tabulated below;

Table 4.18: Water Based Muds at Ambient Temperature

	B_0	B_1	B_2	B_3	B_4
n	*0.0976*	*0.1763*	*0.1013*	*0.0800*	*0.0538*
k	*15569.08*	*6467.10*	*14942.41*	*16444.59*	*18998.15*
CCI	*97.74*	*41.47*	*93.80*	*104.34*	*120.54*

Table 4.19: WBM at 120°F

	B_0	B_1	B_2	B_3	B_4
n	*0.1019*	*0.0875*	*0.1096*	*0.1481*	*0.1444*
k	*11097.28*	*9475.11*	*9803.06*	*7507.68*	*8098.22*
CCI	*69.66*	*60.76*	*61.54*	*47.64*	*51.38*

Table 4.20: WBM at 180°F

	B_0	B_1	B_2	B_3	B_4
n	*0.17*	*0.15*	*0.24*	*0.22*	*0.22*
k	*5664.21*	*5414.04*	*3774.93*	*4017.26*	*3887.67*
CCI	*35.56*	*34.72*	*23.7*	*25.49*	*24.67*

Table 4.21: WBM at 240°F

	B_0	B_1	B_2	B_3	B_4
n	*0.1993*	*0.2064*	*0.1519*	*0.1993*	*0.2064*
k	*3981.04*	*3667.55*	*5350.27*	*3981.04*	*3667.55*
CCI	*24.99*	*23.52*	*33.59*	*25.26*	*23.27*

Table 4.22: OBM at ambient condition.

	B_0	B_1	B_2	B_3	B_4
n	*0.6939*	*0.7142*	*0.7021*	*0.7056*	*0.7142*
k	*654.54*	*380.41*	*429.45*	*407.64*	*380.41*
CCI	*3.98*	*2.39*	*2.61*	*2.53*	*2.36*

Table 4.23: OBM at 120°C.

	B_0	B_1	B_2	B_3	B_4
n	*0.7183*	*0.7321*	*0.7092*	*0.6966*	*0.7364*
k	*359.21*	*313.64*	*386.32*	*384.74*	*326.05*
CCI	*2.18*	*1.97*	*2.35*	*2.39*	*2.02*

Table 4.24: OBM at 180°C.

	B_0	B_1	B_2	B_3	B_4
n	*0.7656*	*0.7991*	*0.7105*	*0.7612*	*0.7473*
k	*251.82*	*212.33*	*335.59*	*263.56*	*263.56*
CCI	*1.53*	*1.33*	*2.04*	*1.64*	*1.65*

Table 4.25: OBM at 240°C.

	B_0	B_1	B_2	B_3	B_4
n	*0.8253*	*0.8450*	*0.7749*	*0.8074*	*0.7818*
k	*169.45*	*141.97*	*211.67*	*172.84*	*222.26*
CCI	*1.03*	*0.89*	*1.29*	*1.07*	*1.38*

Table 4.26: SBM at Ambient conditions

	B_0	B_1	B_2	B_3	B_4
n	*0.8377*	*0.8679*	*0.8114*	*0.8244*	*0.8295*
k	*129.32*	*91.17*	*158.86*	*143.50*	*130.32*
CCI	*0.92*	*0.66*	*1.13*	*1.03*	*0.92*

Table 4.27: SBM at 120°C.

	B_0	B_1	B_2	B_3	B_4
n	*0.8377*	*0.8713*	*0.8413*	*0.8480*	*0.8515*
k	*129.32*	*91.49*	*129.14*	*116.12*	*116.13*
CCI	*0.92*	*0.66*	*0.92*	*0.83*	*0.82*

Table 4.28: SBM at 180°C.

	B_0	B_1	B_2	B_3	B_4
n	*0.8829*	*0.9069*	*0.8655*	*0.8953*	*0.8829*
k	*95.11*	*74.63*	*101.23*	*80.23*	*95.11*
CCI	*0.67*	*0.54*	*0.72*	*0.57*	*0.69*

Table 4.29: SBM at 240°C.

	B_0	B_1	B_2	B_3	B_4
n	*0.8829*	*0.9220*	*0.8745*	*0.8931*	*0.9157*
k	*93.40*	*61.81*	*91.87*	*81.80*	*74.43*
CCI	*0.66*	*0.45*	*0.65*	*0.59*	*0.54*

From the results as seen above, the CCI of all the drilling fluid formulated were above 1.0 showing good hole cleaning capabilities. Also the flow behaviour index, n was less than 1. This means the drilling fluid samples are shear thinning fluids.

4.7 Filtration Tests

The filtration tests were carried out in HP-HT conditions. The filtrate volumes and filter cake thickness were measured after 30 minutes and recorded as follows

Table 4.30: HTHP Water based mud

	B0	B1	B2	B3	B4
Filtrate	27	29	25	26	27
Filter Cake thickness	2mm	2mm	2mm	2mm	2mm

Table 4.31: HTHP Diesel OBM

	B0	B1	B2	B3	B4
Filtrate	17	15	17	17	19
Filter Cake thickness	2mm	2mm	2mm	2mm	2mm

Table 4.32: HTHP Synthetic Based Mud

	B0	B1	B2	B3	B4
Filtrate	12ml	13ml	12ml	13ml	13ml
Filter Cake thickness	3mm	4mm	4mm	4mm	3mm

4.8 Economic Analysis

The cost of barite is dependent on its grade. Low grade barites will require more volume to perform its required functions compared to premium grade barite. From this study, it is observed that Nigerian Barites meet up to API international required Standard. However, Barite processing plants are required in order to produce pristine finished product locally.

Nwozo et al 2008, showed how profitable installing Barite processing plants can be to all involved parties. Because drilling is tending towards more hostile and HTHP zones, Barite consumption has increased in recent years. In Nigeria 20,000tonnes per day is consumed, most of which are imported. Locally processed barite will curb expenses and yield more revenue.

The process of extracting Irvingia Gabonesis oil in the laboratory was relatively expensive. An industrial approach which will yield more oil will be more cost effective. In the laboratory, the extraction was not entirely done in a closed system therefore a lot of the solvent (hexane) was lost to the atmosphere. A 2litre bottle of hexane was used in extracting 750ml Irvingia Gabonesis oil. Although 850ml of hexane was recovered after the extraction, 1.15l was lost to the atmosphere by evaporation.

When materials are procured locally within the operational environment, it can be agreed that it should be cheaper having knocked off importation and other logistics cost. The use of Nigerian Barite in drilling operations is not only going to save cost for the operator but will benefit the nation economically.

Actual Production (Tonnes); is the product of percentage composition of barite and the raw production. Assumption per well, that is, 280 tonnes per figures as reported in Nganje (2013).

Operating Cost ($/Unit); is defined as the rate of total cost of operations to the total production.

Gross Revenue (GR); For a viable mining project, GR must be greater than operating cost and other tax deduction.

Annual Barite revenue is estimated by

$GR = R - (T) * (G) * (P)$ Equation (4.1)

Where;

R is Revenue;

T is tonnage of Ore produced per year (t/year);

G is the Grade of Ore (Assumed 0.88); and

P is the unit price of barite (assumed US 1$ to N400).

4.7.1 Profitability Indicators:

Net Present Values (NPV), Internal Rate of Return (IRR) and Payout were used.

Table 4.33 CAPEX:

Parameters	**Imported Barite Used**	**Nigerian Barite Used**
Average Annual Barite Sales (tonnes)	56,000	32,000
Development Period (years)	1	1
Pre-Production Mine Exploration (‘000 USD)	601.5	411.75
Mining development cost (‘000 USD)	823.5	1203
Equipment and infrastructure (‘000 USD)	845	2745
Processing plant Cost (‘000 USD)	607.5	200.5
Feasibility Study (‘000 USD)	137.25	22
Total CAPEX (Million $)	13.7	20.1

Table 4.34 OPEX:

Parameters	**Imported Barite Used**	**Nigerian Barite Used**
Mining operations (‘000 USD)	767	520
Beneficiation (‘000 USD)	59	40
Processing cost (‘000 USD)	4720	3200
Overhead (‘000 USD)	295	200
Freight (‘000 USD)	59	40
Total CAPEX (Million $)	5.9	4.0
Permit for Mining (‘000 USD)	400	250
Exploration Permit for Lease	9	9

Comparison: The cost per tonne of barite in a year for imported case is $118.20, while Nigerian barite case is $124.25.

Table 4.35: Operational Cost Per Tonnage for Year 1

Parameters	**Imported Barite Used**	**Nigerian Barite Used**
Mining operations ($/tonne)	15.11	16.19
Beneficiation ($/tonne)	1.16	1.25
Processing cost ($/tonne)	92.97	99.63
Overhead ($/tonne)	5.83	6.23
Freight ($/tonne)	0.99	1.26
Total Cost ($/tonne)	118.20	124.25
Selling Price per Unit	400.00	400.00

Table 4.36 Profitability Indicators

Type of Barite Used	**IRR**	**NPV @ 15% (Million $)**	**Payout Period**
Imported Barite	43%	29.6	3.2 years
Nigerian Barite	34%	15.2	4.0 years

IRR – Imported Barite Used is 43% and Nigerian Barite used is 34%

Imported Barite Used; NPV – $29.6 M; Payout – 3.2 years

Nigerian Barite Used; NPV – $15.2 M ; Payout – 4.2 years.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The analysis and the discussion of the results made the following conclusions;

Generally the mud weights of the various barite weighted samples in the OBM, WBM and SBM were relatively close. It was clearly seen that barite sample B_1, having the highest specific gravity always had the highest mud weight in every type of drilling fluid. This also reflected in the rheological properties as its plastic viscosity and gel strength came out more favourable.

It was observed that there was a reduction in the mud weight and viscosities as the temperature is increased. As the temperature was increased the rheological model was maintained showing that the mud samples could also be functional in hostile high pressure high temperature environment.

With these results when compared with the API Barite (B_0), it can be seen that Nigerian barites perform favourably as weighting materials, even in high temperatures.

There are organic biodegradable synthetic based fluids that are being used in the industry, sadly an attempt to use Irvingia Gabonesis oil as a substitute base fluid in this study did not work out. More research is required to make this a success.

Nigeria is replete with so many varied raw materials which can be used for a variety of purposes which will improve the economic situation of the country and also encourage indigenous technology development, thus support and encouragement of purposeful research is necessary.

The Barites used for this experiment is readily available in commercial quantities but in its unprocessed form, thus some errors and problems encountered are as a result of its crude and unprocessed state. Pristine processing techniques and equipment should be used to achieve industrial premium grade finished products. This will make it easy to use and would improve the export value.

5.2 Recommendations

From the experience of other barite mines, it was discovered that as the veins are being exploited, the quality of the mineral reduces, i.e the specific gravity may reduce as the vein is being depleted. Due to continuous mining and increase in the demand for barite, there is a possibility of the world lacking enough quantities of High grade Premium barite of 4.2 SG. In that light, a beneficiation process will be recommended, to yield more quantities. The process may involve mixing low grade barite and high grade barite at a pre-determined proportion to achieve the approved standard.

Barite should be micronized to have a maximum particle size of at least 3% <45µm. An average particle size of 1µm is preferable. Adequate machinery should be provided for this measure to be achieved. Impurities like quartz and silicon IV oxide should be reduced to as low as reasonably possible.

The Nigerian government should issue import wavers on Barite processing equipments and tax holidays to individuals or companies that choose to venture into Processing of Local Barites to encourage the growth of the industry in Nigeria.

Although Irvingia Gabonesis is relatively expensive and is categorised as edible vegetable plant, extracting its oil for industrial use will be an economical challenge but its results is worth it. However, plantations can be set up strictly for production of industrial use of Irvingia Gabonesis. More research can be carried out on its usability for oil in water emulsion; this will reduce the amount of oil being used and reduce cost also. Irvingia Gabonesis is environmentally friendly, biodegradable and requires very low disposal cost. Due to certain setbacks in this research such as time restrictions and financial demands, experiments to ensure the usability of Irvingia Gabonesis oil was impaired. Further research would be required to discover the appropriate bridging agent or emulsifying agent required to create a homogenous fluid.

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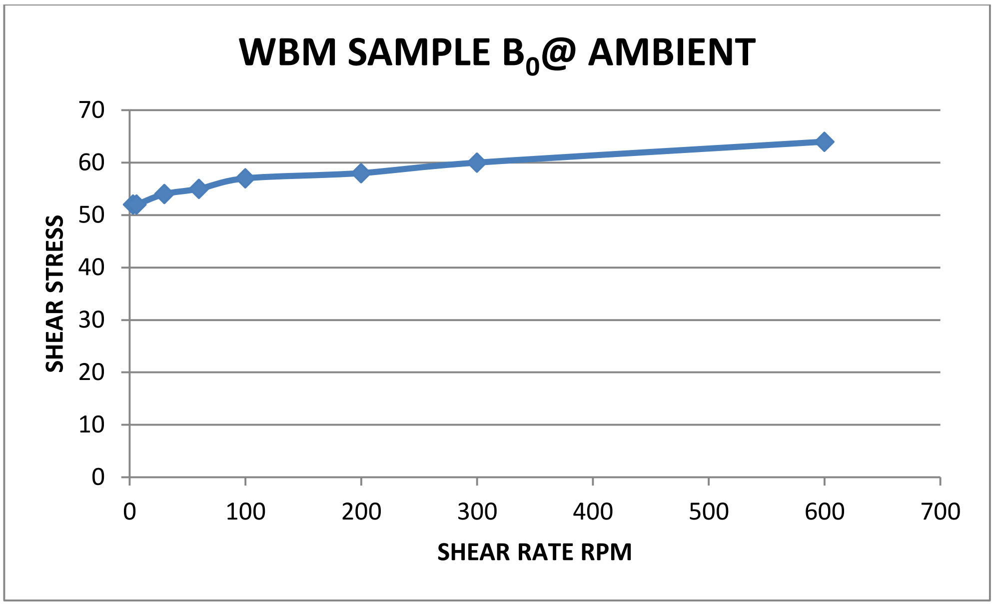
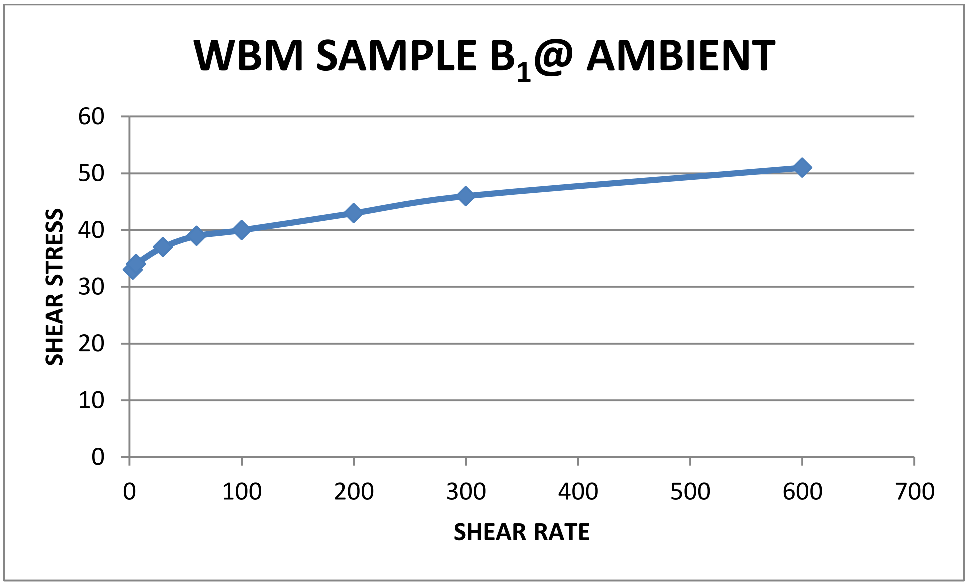
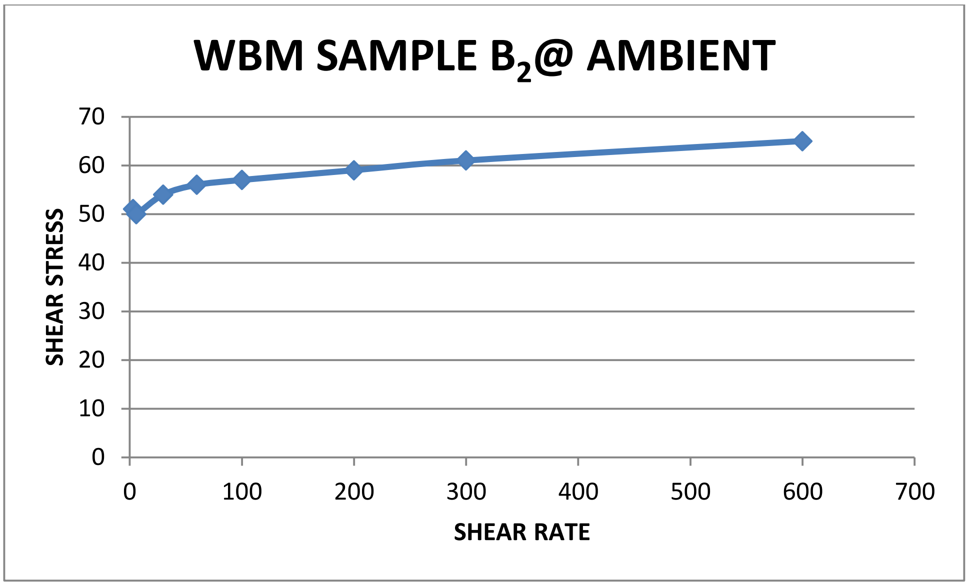
APPENDIX

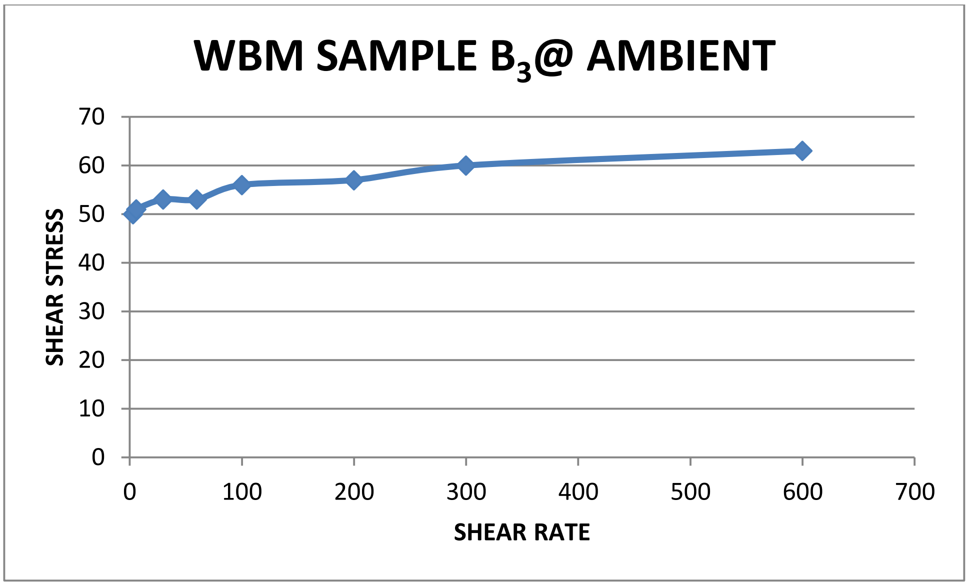
WATER BASED MUDS AT AMBIENT TEMPERATURE

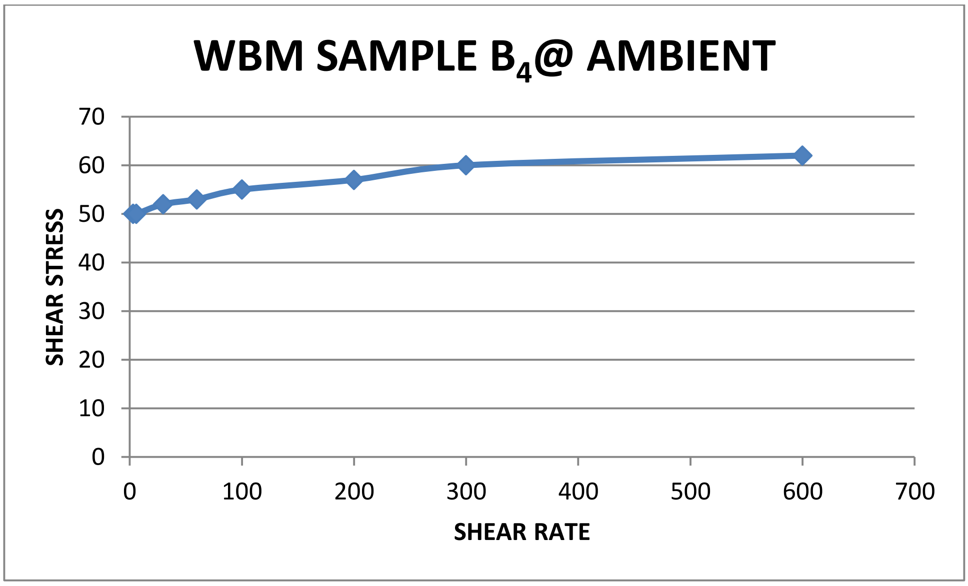
Speed (rpm)	*Readings*				
	B0	*B1*	*B2*	*B3*	*B4*
3	*52*	*33*	*51*	*50*	*50*
6	*52*	*34*	*50*	*51*	*50*
30	*54*	*37*	*54*	*53*	*52*
60	*55*	*39*	*56*	*53*	*53*
100	*57*	*40*	*57*	*56*	*55*
200	*58*	*43*	*59*	*57*	*57*
300	*60*	*46*	*61*	*60*	*60*
600	*64*	*51*	*65*	*63*	*62*
10s Gel Strength (lb/100ft^2)	*54*	*33*	*53*	*51*	*53*
10mins Gel Strength (lb/100ft^2)	*61*	*51*	*64*	*59*	*62*
Plastic Viscosity (cp)	*4*	*5*	*4*	*3*	*2*
Apparent Viscosity (cp)	*32*	*25.5*	*32.5*	*31.5*	*31*
Yield point (lb/100ft^2)	*56*	*41*	*57*	*57*	*58*
N	*0.0976*	*0.1763*	*0.1013*	*0.0800*	*0.0538*
K	*15569.08*	*6467.10*	*14942.41*	*16444.59*	*18998.15*
CCI	*97.74*	*41.47*	*93.80*	*104.34*	*120.54*


WBM SAMPLE B_0@ AMBIENT
SHEAR STRESS
70
60
50
40
30
20
10
0
0
100
200
300
400
500
600
700
SHEAR RATE RPM


WBM SAMPLE B_1@ AMBIENT
SHEAR STRESS
60
50
40
30
20
10
0
0
100
200
300
400
500
600
700
SHEAR RATE

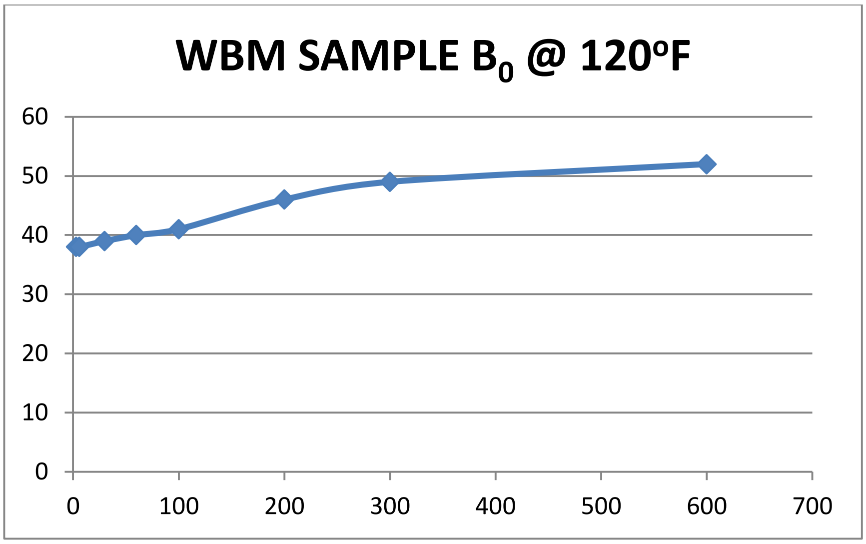

WBM SAMPLE B_2@ AMBIENT
SHEAR STRESS
0
10
20
30
40
50
60
70
SHEAR RATE
0
100
200
300
400
500
600
700

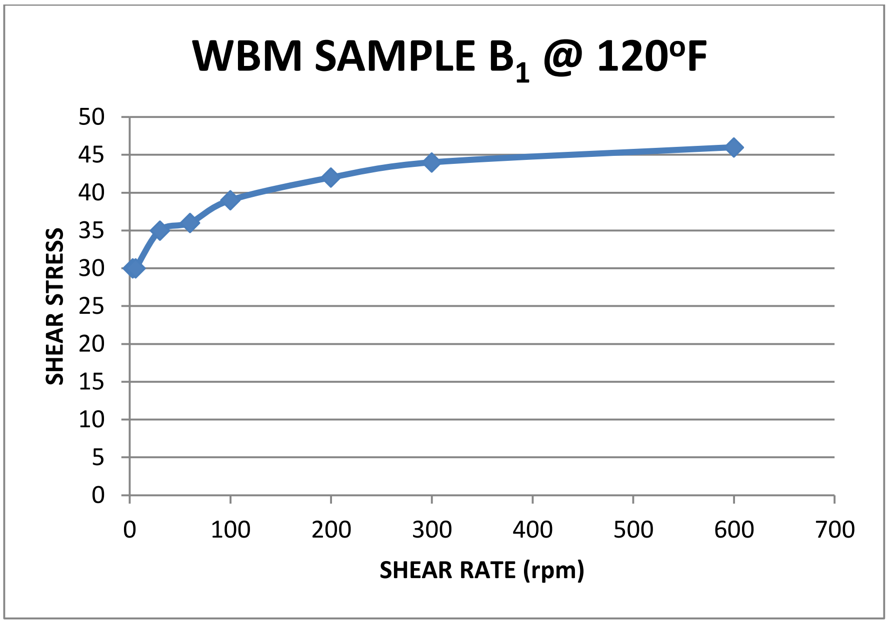

WBM SAMPLE B_3@ AMBIENT
SHEAR STRESS
0
10
20
30
40
50
60
70
SHEAR RATE
0
100
200
300
400
500
600
700

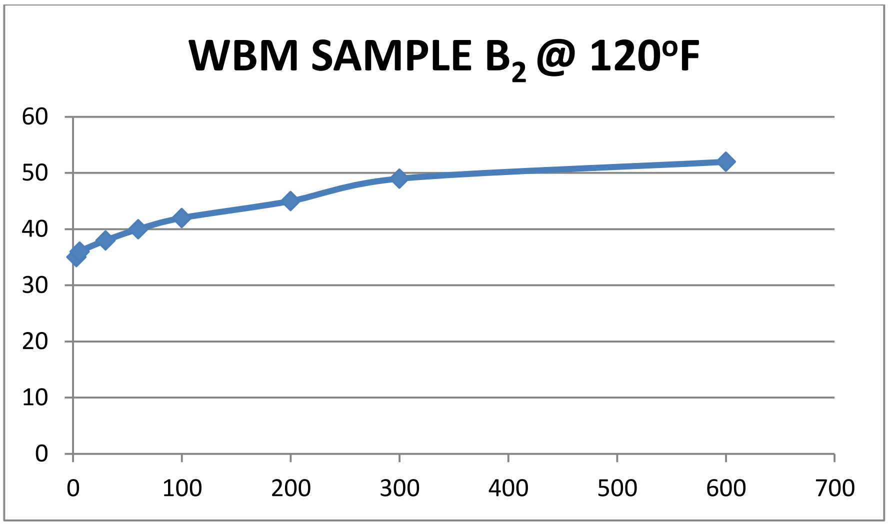

WBM SAMPLE B_4@ AMBIENT
SHEAR STRESS
0
10
20
30
40
50
60
70
SHEAR RATE
0
100
200
300
400
500
600
700

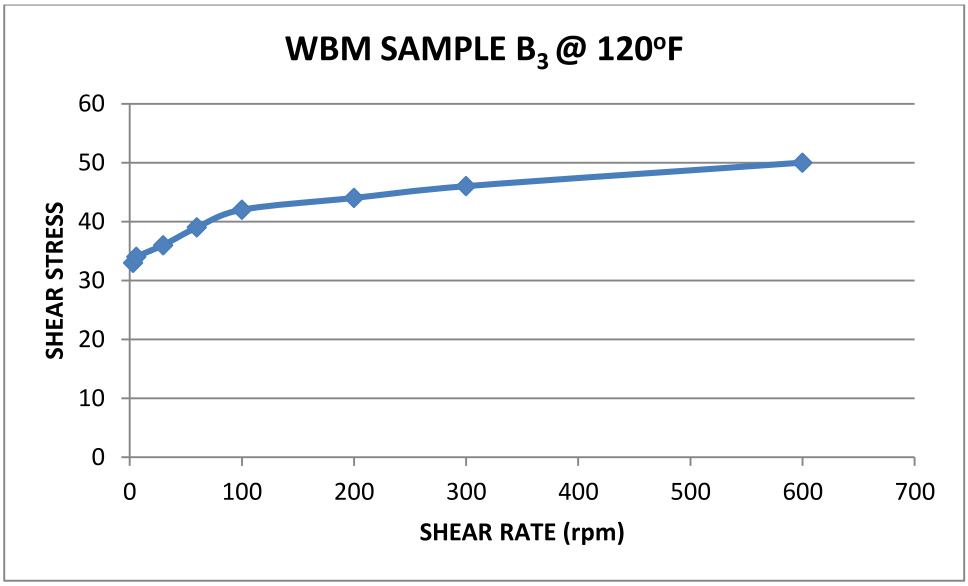
WBM at 120ºF

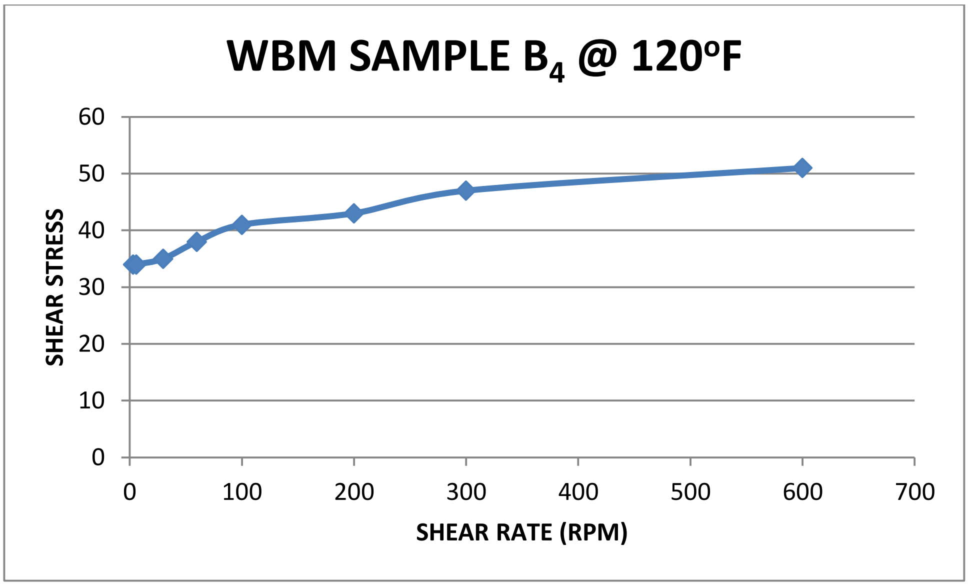
Speed (rpm)	*Readings*				
	B0	*B1*	*B2*	*B3*	*B4*
3	*38*	*30*	*35*	*33*	*34*
6	*38*	*30*	*36*	*34*	*34*
30	*39*	*35*	*38*	*36*	*35*
60	*40*	*36*	*40*	*39*	*38*
100	*41*	*39*	*42*	*42*	*41*
200	*46*	*42*	*45*	*44*	*43*
300	*49*	*44*	*49*	*46*	*47*
600	*52*	*46*	*52*	*50*	*51*
10s Gel Strength (lb/100ft^2)	*38*	*30*	*37*	*34*	*33*
10mins Gel Strength (lb/100ft^2)	*43*	*42*	*46*	*45*	*46*
Plastic Viscosity (cp)	*3*	*2*	*3*	*4*	*4*
Apparent Viscosity (cp)	*26*	*23*	*26*	*25*	*25.5*
Yield point (lb/100ft^2)	*46*	*42*	*46*	*42*	*43*
n	*0.1019*	*0.0875*	*0.1096*	*0.1481*	*0.1444*
k	*11097.28*	*9475.11*	*9803.06*	*7507.68*	*8098.22*
CCI	*69.66*	*60.76*	*61.54*	*47.64*	*51.38*


WBM SAMPLE B_0 @ 120ºF
60
50
40
30
20
10
0
0
100
200
300
400
500
600
700


WBM SAMPLE B_1 @ 120ºF
SHEAR STRESS
50
45
40
35
30
25
20
15
10
5
0
0
100
200
300
400
500
600
700
SHEAR RATE (rpm)

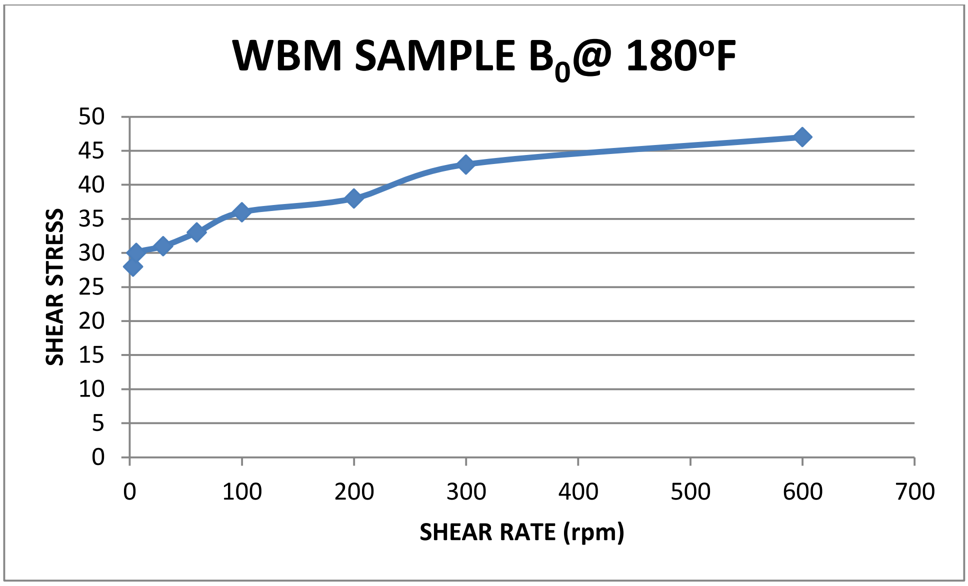

WBM SAMPLE B_2 @ 120ºF
60
50
40
30
20
10
0
0
100
200
300
400
500
600
700

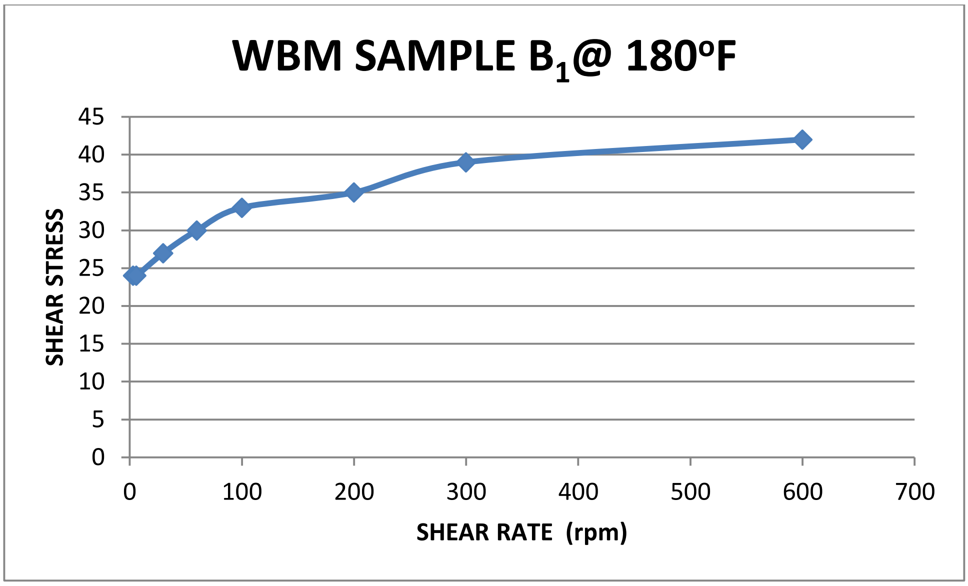

WBM SAMPLE B_3 @ 120ºF
SHEAR STRESS
60
50
40
30
20
10
0
0
100
200
300
400
500
600
700
SHEAR RATE (rpm)

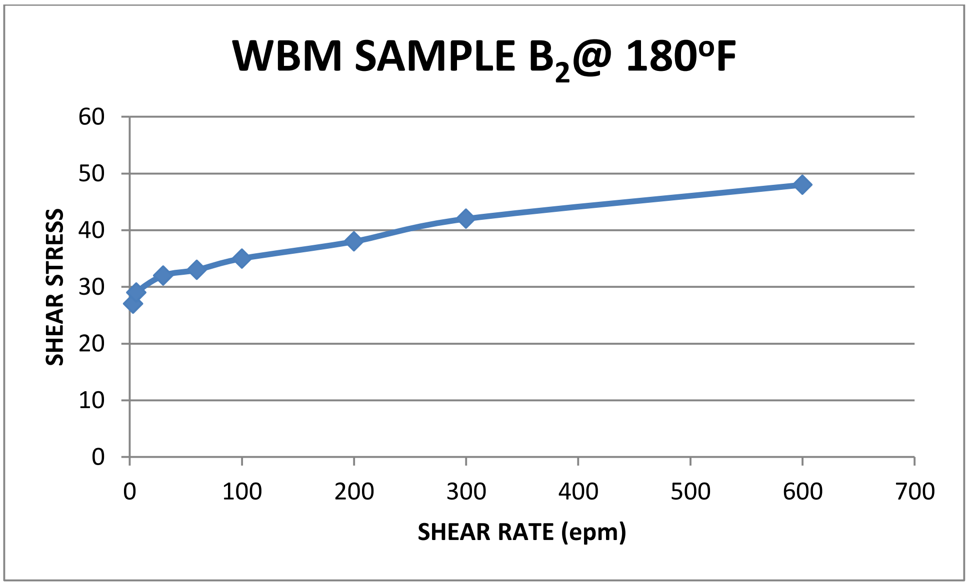

WBM SAMPLE B_4 @ 120ºF
SHEAR STRESS
60
50
40
30
20
10
0
0
100
200
300
400
500
600
700
SHEAR RATE (RPM)

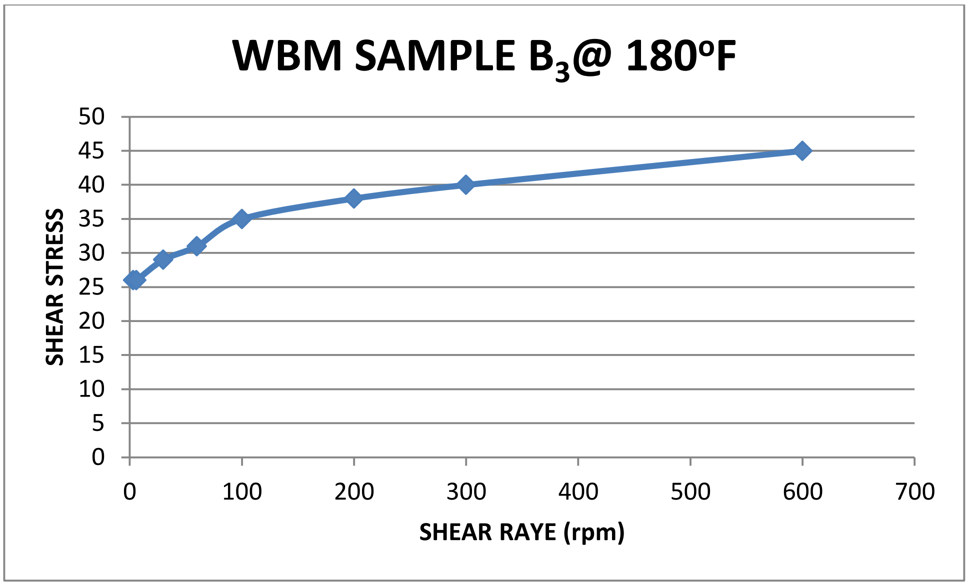
WBM at 180°F

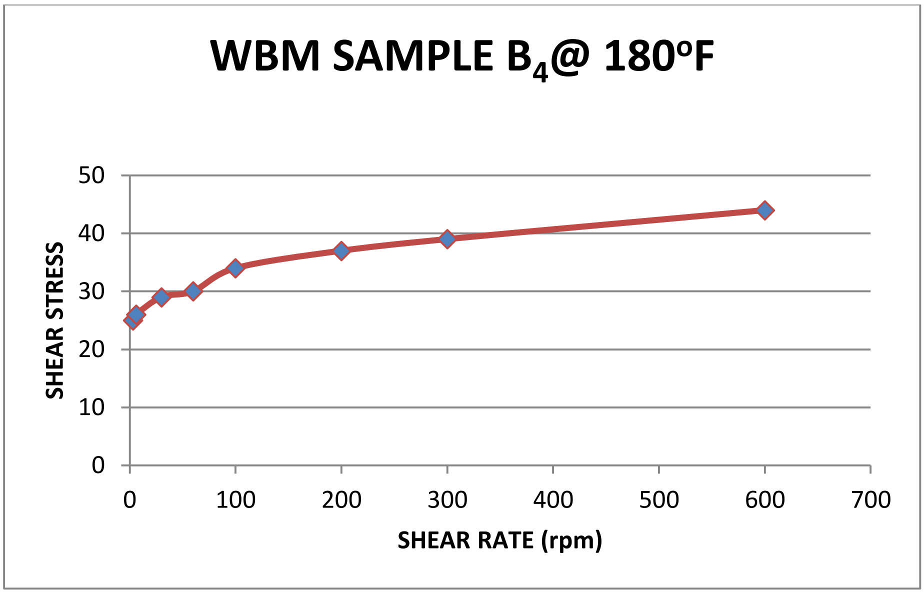
Speed (rpm)	*Readings*				
	B0	*B1*	*B2*	*B3*	*B4*
3	*28*	*24*	*27*	*26*	*25*
6	*30*	*24*	*29*	*26*	*26*
30	*31*	*27*	*32*	*29*	*29*
60	*33*	*30*	*33*	*31*	*30*
100	*36*	*33*	*35*	*35*	*34*
200	*38*	*35*	*38*	*38*	*37*
300	*43*	*39*	*42*	*40*	*39*
600	*47*	*42*	*48*	*45*	*44*
10s Gel Strength (lb/100ft^2)	*29*	*23*	*38*	*26*	*25*
10mins Gel Strength (lb/100ft^2)	*38*	*31*	*46*	*34*	*33*
Plastic Viscosity (cp)	*4*	*3*	*6*	*5*	*5*
Apparent Viscosity (cp)	*23.5*	*21*	*24*	*22.5*	*22*
Yield point (lb/100ft^2)	*39*	*36*	*36*	*35*	*34*
N	*0.17*	*0.15*	*0.24*	*0.22*	*0.22*
K	*5664.21*	*5414.04*	*3774.93*	*4017.26*	*3887.67*
CCI	*35.56*	*34.72*	*23.7*	*25.49*	*24.67*


WBM SAMPLE B_0@ 180°F
SHEAR STRESS
50
45
40
35
30
25
20
15
10
5
0
0
100
200
300
400
500
600
700
SHEAR RATE (rpm)


WBM SAMPLE B_1@ 180°F
SHEAR STRESS
45
40
35
30
25
20
15
10
5
0
0
100
200
300
400
500
600
700
SHEAR RATE (rpm)

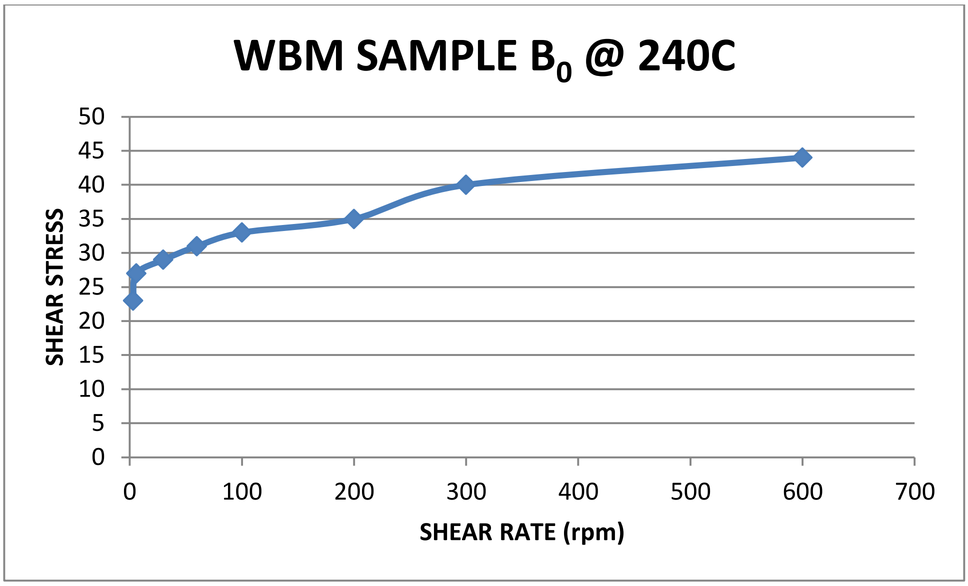

WBM SAMPLE B_2@ 180°F
SHEAR STRESS
60
50
40
30
20
10
0
0
100
200
300
400
500
600
700
SHEAR RATE (epm)

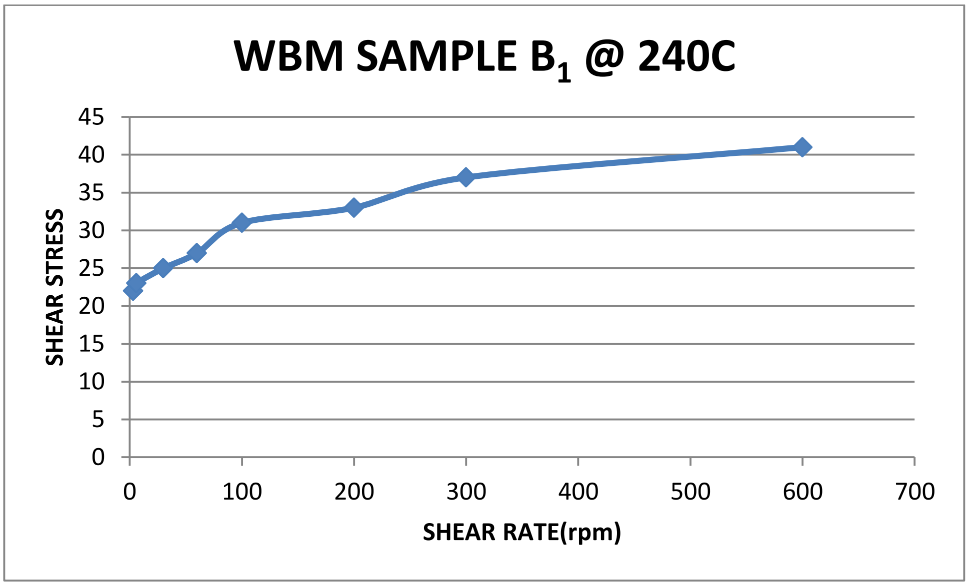

WBM SAMPLE B3@ 180oF
SHEAR STRESS
50
45
40
35
30
25
20
15
10
5
0
0
100
200
300
400
500
600
700
SHEAR RAYE (rpm)

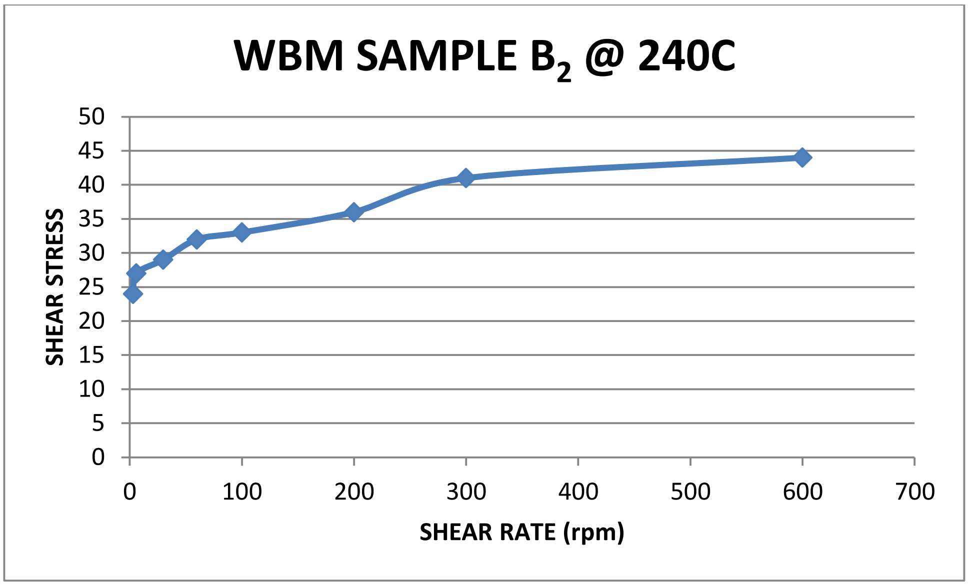

WBM SAMPLE B4@ 180oF
SHEAR STRESS
50
40
30
20
10
0
0
100
200
300
400
500
600
700
SHEAR RATE (rpm)

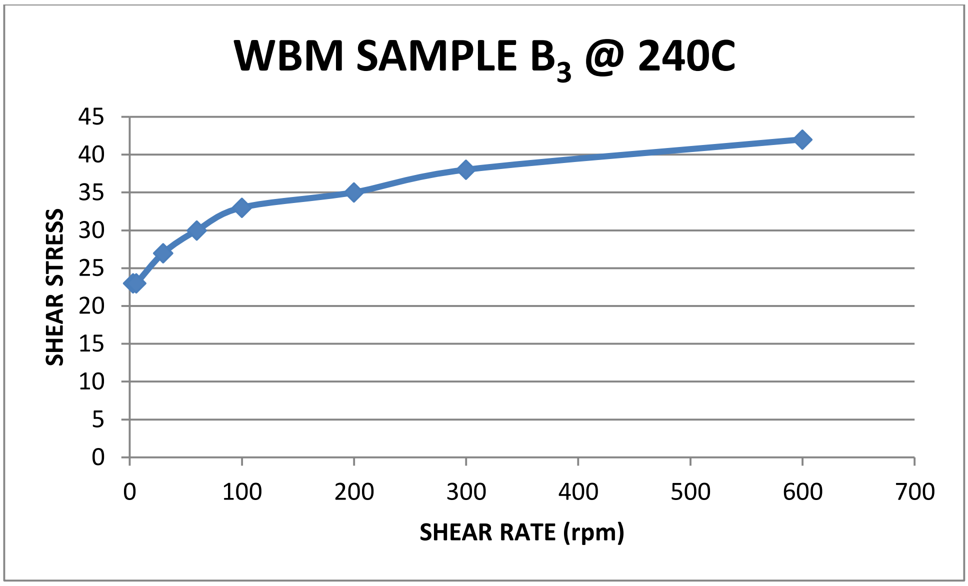
WBM at 240°F

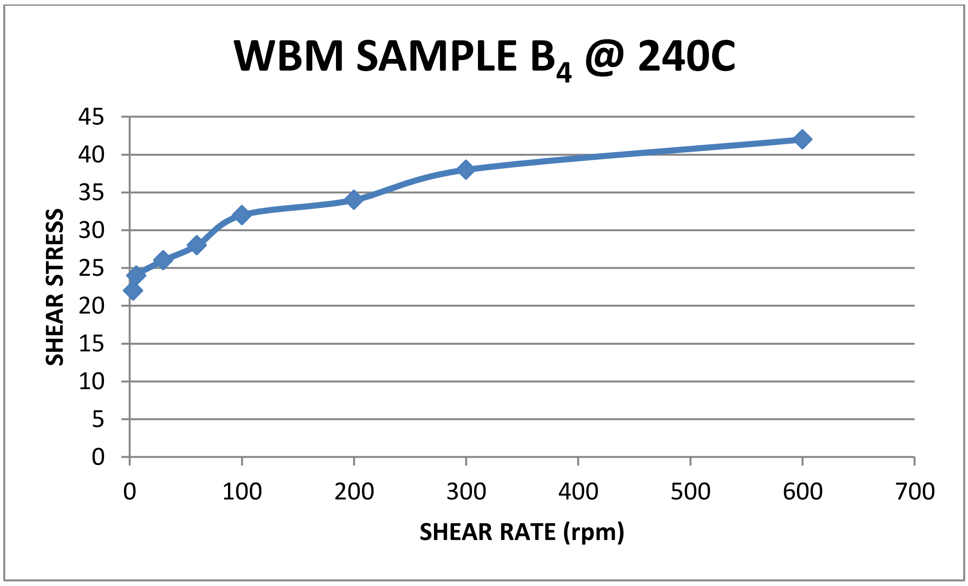
Speed (rpm)	*Readings*				
	B0	*B1*	*B2*	*B3*	*B4*
3	*23*	*22*	*24*	*23*	*22*
6	*27*	*23*	*27*	*23*	*24*
30	*29*	*25*	*29*	*27*	*26*
60	*31*	*27*	*32*	*30*	*28*
100	*33*	*31*	*33*	*33*	*32*
200	*35*	*33*	*36*	*35*	*34*
300	*40*	*37*	*41*	*38*	*38*
600	*44*	*41*	*44*	*42*	*42*
10sGel Strength (lb/100ft^2)	*21*	*20*	*22*	*21*	*20*
10mins Gel Strength (lb/100ft^2)	*29*	*24*	*30*	*28*	*26*
Plastic Viscosity (cp)	*4*	*4*	*3*	*4*	*4*
Apparent Viscosity (cp)	*22*	*20.5*	*22*	*21*	*21*
Yield point (lb/100ft^2)	*36*	*33*	*38*	*34*	*34*
n	*0.1993*	*0.2064*	*0.1519*	*0.1993*	*0.2064*
k	*3981.04*	*3667.55*	*5350.27*	*3981.04*	*3667.55*
CCI	*24.99*	*23.52*	*33.59*	*25.26*	*23.27*


WBM SAMPLE B_0 @ 240C
SHEAR STRESS
50
45
40
35
30
25
20
15
10
5
0
0
100
200
300
400
500
600
700
SHEAR RATE (rpm)


WBM SAMPLE B_1 @ 240C
SHEAR STRESS
45
40
35
30
25
20
15
10
5
0
0
100
200
300
400
500
600
700
SHEAR RATE(rpm)

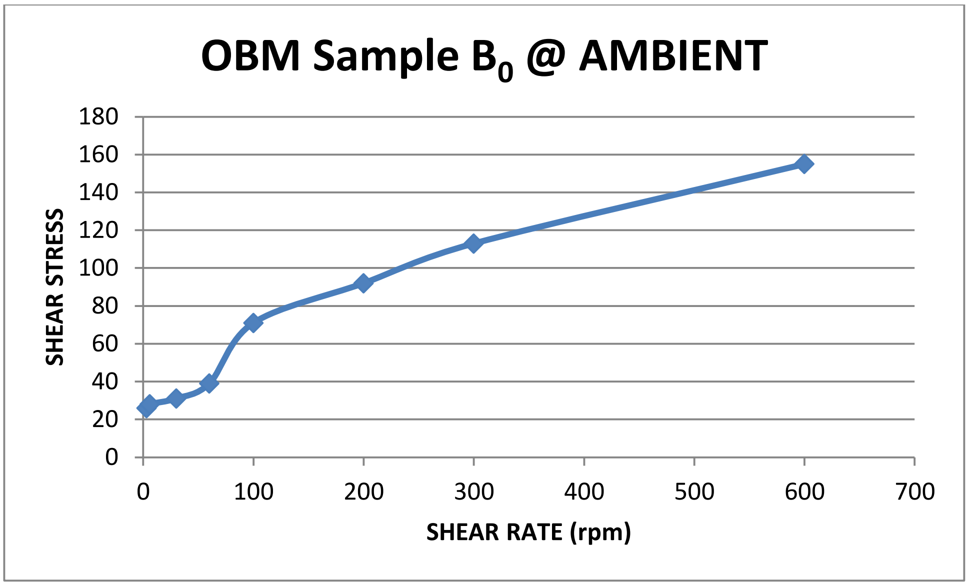

WBM SAMPLE B2 @ 240C
SHEAR STRESS
50
45
40
35
30
25
20
15
10
5
0
0
100
200
300
400
500
600
700
SHEAR RATE (rpm)

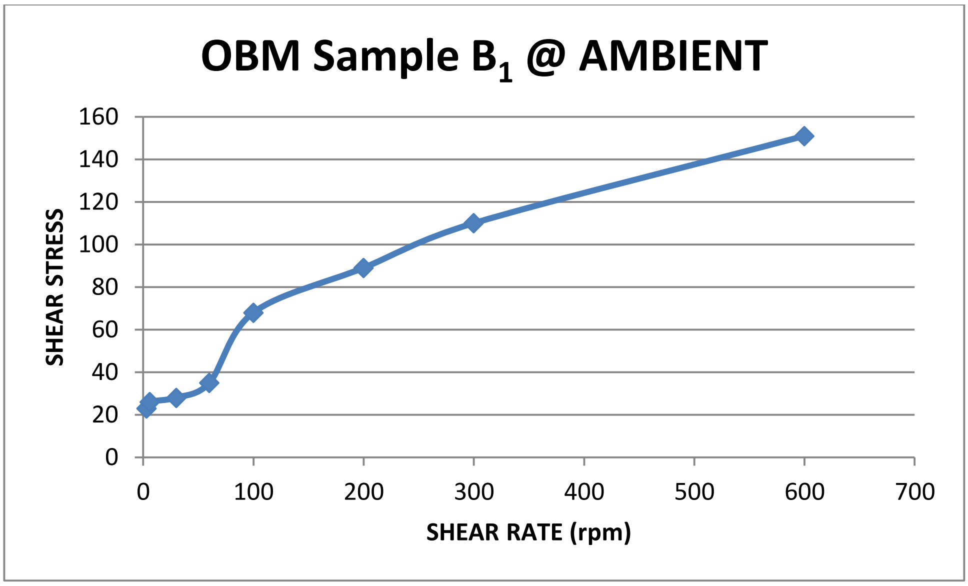

WBM SAMPLE B3 @ 240C
SHEAR STRESS
45
40
35
30
25
20
15
10
5
0
0
100
200
300
400
500
600
700
SHEAR RATE (rpm)

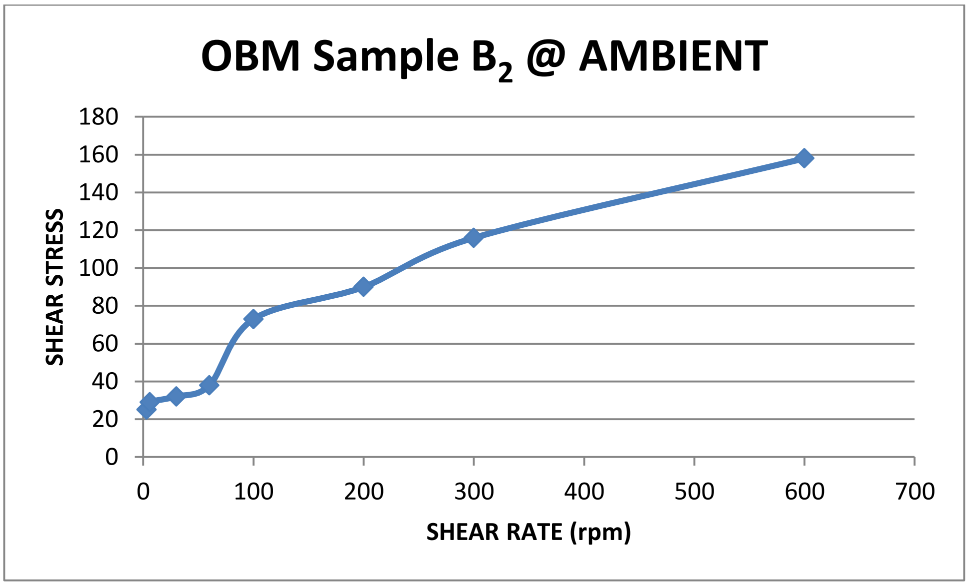

WBM SAMPLE B4 @ 240C
SHEAR STRESS
45
40
35
30
25
20
15
10
5
0
0
100
200
300
400
500
600
700
SHEAR RATE (rpm)

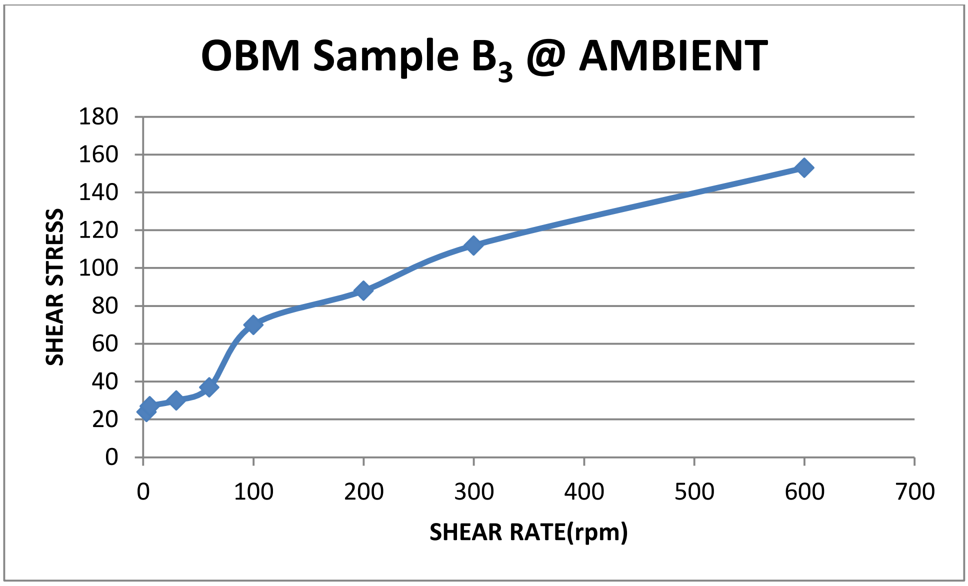
Rheology of Diesel OBM at ambient condition.

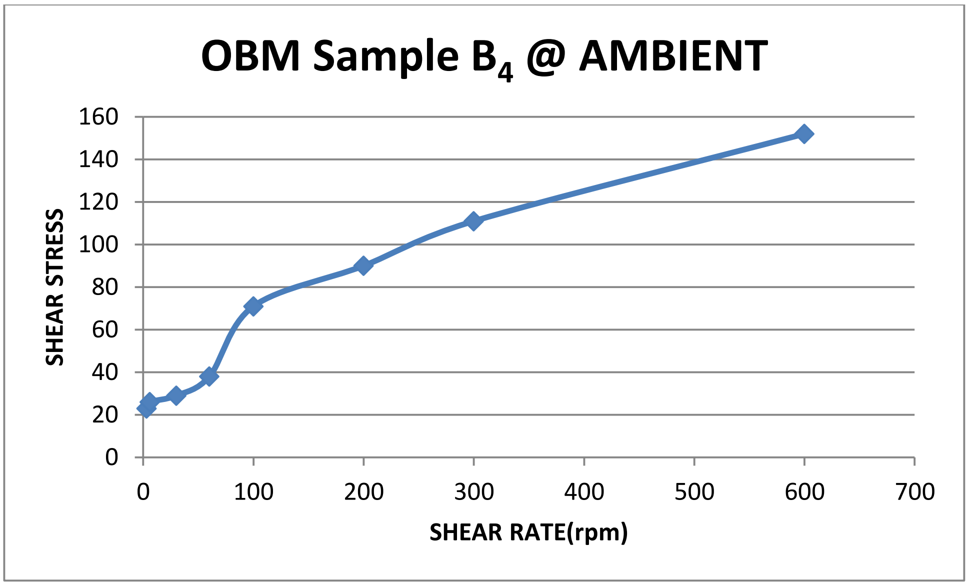
Speed (rpm)	Readings				
	B0	B1	B2	B3	B4
3	26	23	25	24	23
6	28	26	29	27	26
30	31	28	32	30	29
60	39	35	38	37	38
100	71	68	73	70	71
200	92	89	90	88	90
300	113	110	116	112	111
600	155	151	158	153	152
10s Gel (lb/100ft^2)	27	24	24	25	25
10mins Gel Strength (lb/100ft^2)	39	33	40	35	34
Plastic Viscosity (cp)	42	41	42	41	41
Apparent Viscosity (cp)	77.5	75.5	79	76.5	76
Yield point (lb/100ft^2)	71	69	74	71	70
n	0.6939	0.7142	0.7021	0.7056	0.7142
k	654.54	380.41	429.45	407.64	380.41
CCI	3.98	2.39	2.61	2.53	2.36


OBM Sample B_0 @ AMBIENT
SHEAR STRESS
180
160
140
120
100
80
60
40
20
0
0
100
200
300
400
500
600
700
SHEAR RATE (rpm)


OBM Sample B_1 @ AMBIENT
SHEAR STRESS
160
140
120
100
80
60
40
20
0
0
100
200
300
400
500
600
700
SHEAR RATE (rpm)


OBM Sample B_2 @ AMBIENT
SHEAR STRESS
180
160
140
120
100
80
60
40
20
0
0
100
200
300
400
500
600
700
SHEAR RATE (rpm)

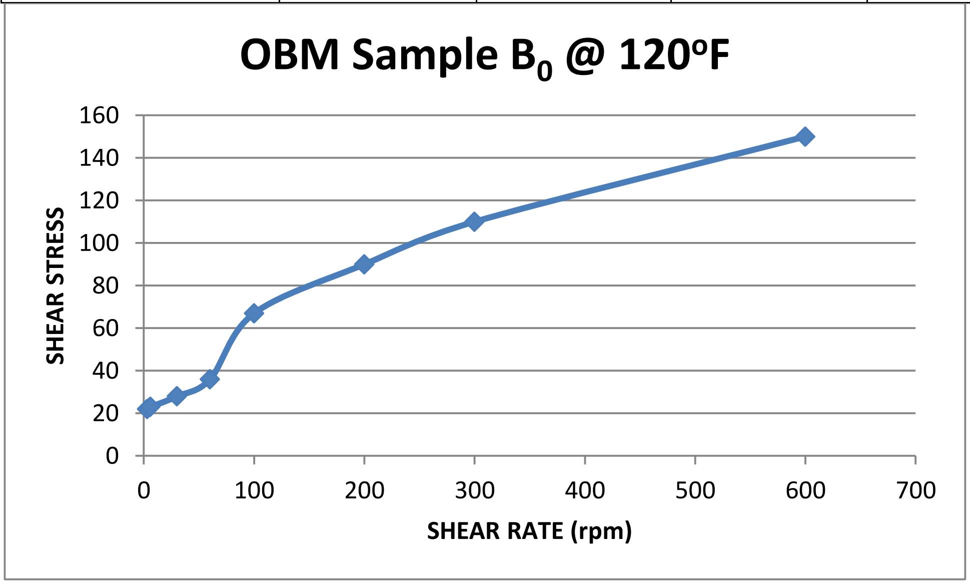


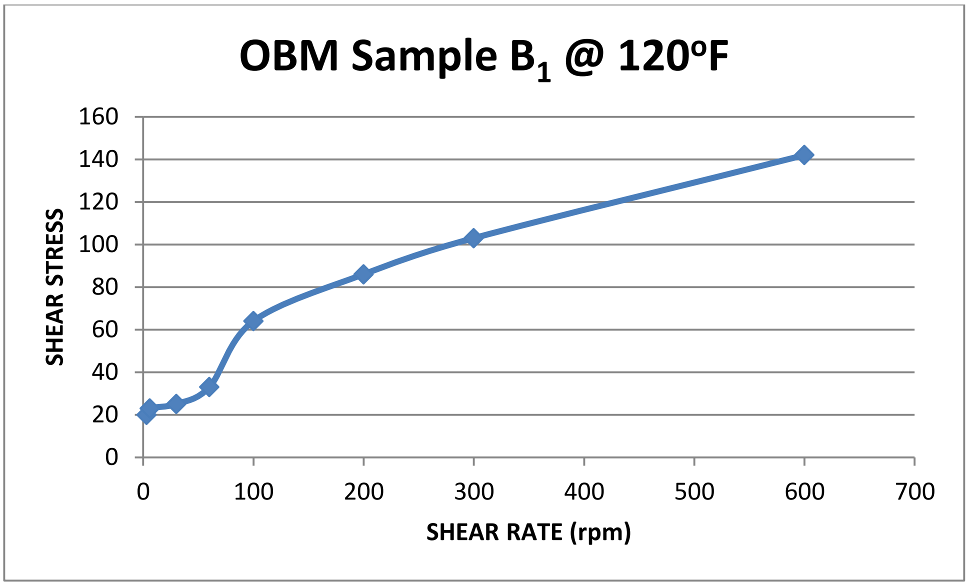


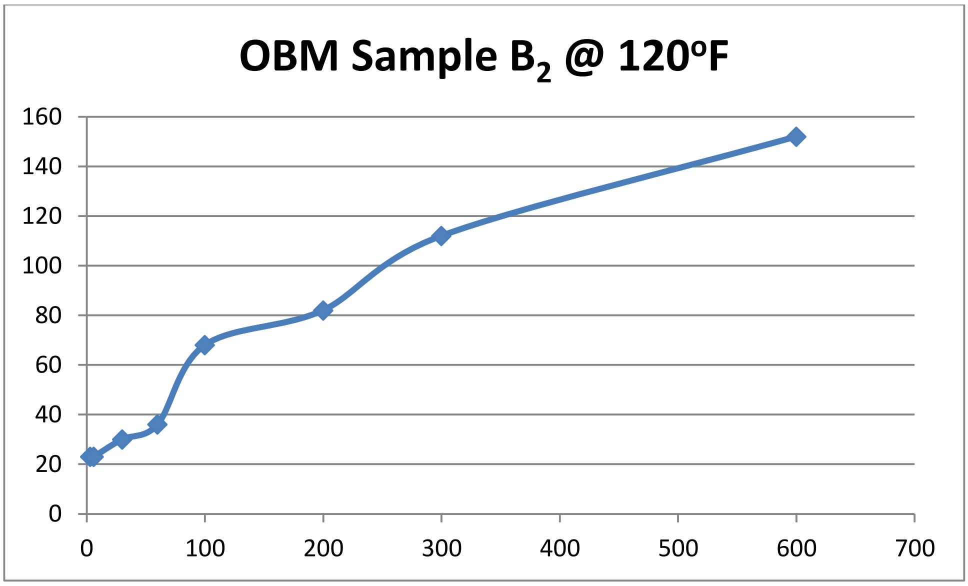
Rheology of Diesel OBM at 120^{o}C.

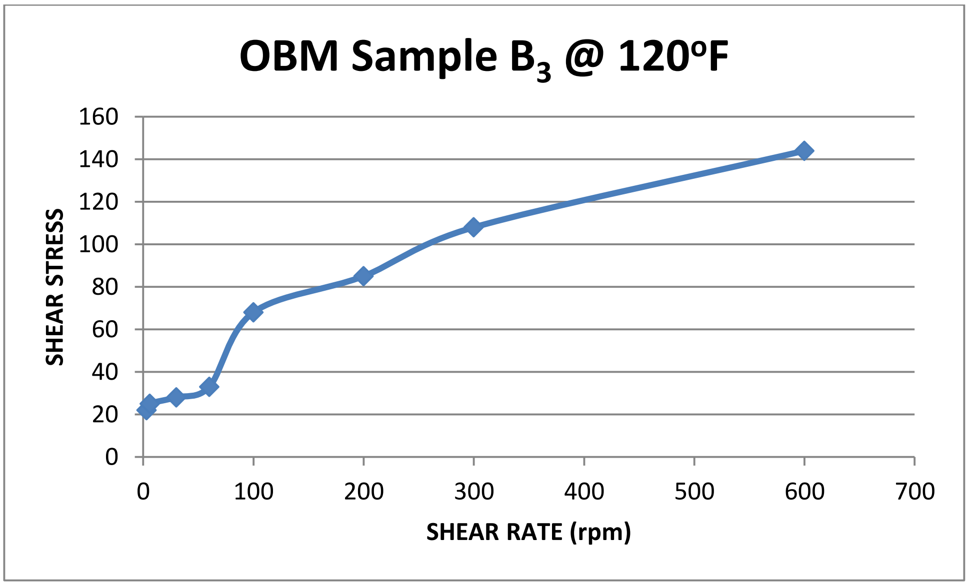
Speed (rpm)	*Readings*				
	B0	*B1*	*B2*	*B3*	*B4*
3	*22*	*20*	*23*	*22*	*21*
6	*23*	*23*	*23*	*25*	*23*
30	*28*	*25*	*30*	*28*	*27*
60	*36*	*33*	*36*	*335*	*35*

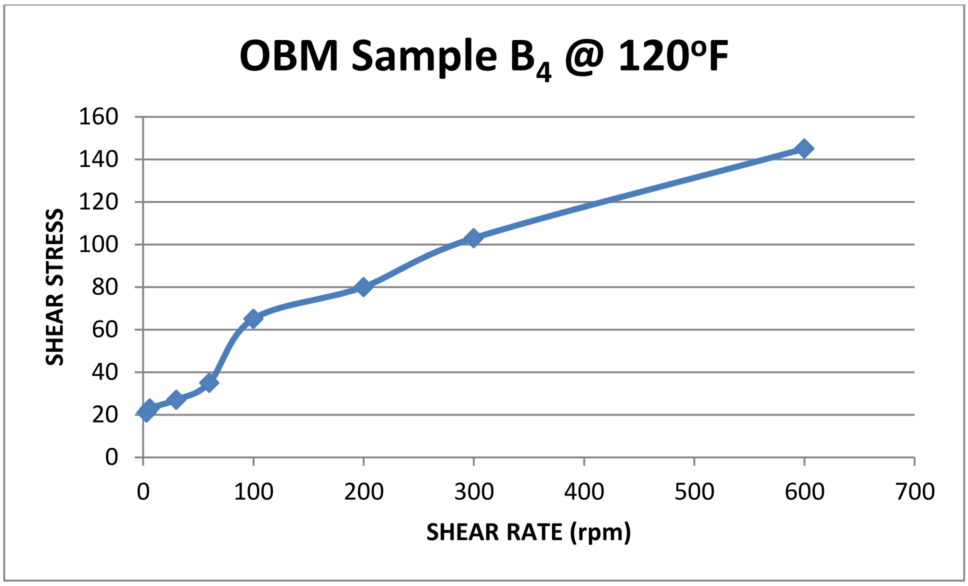
100	*67*	*64*	*68*	*68*	*65*
200	*90*	*86*	*82*	*85*	*80*
300	*110*	*103*	*112*	*108*	*103*
600	*150*	*142*	*152*	*144*	*145*
10s Gel Strength (lb/100ft^2)	*25*	*22*	*25*	*21*	*22*
10mins Gel Stnt (lb/100ft^2)	*38*	*30*	*40*	*32*	*34*
Plastic Viscosity (cp)	*40*	*39*	*40*	*36*	*42*
Apparent Viscosity (cp)	*75*	*71*	*76*	*72*	*72.5*
Yield point (lb/100ft^2)	*70*	*64*	*72*	*72*	*61*
n	*0.7183*	*0.7321*	*0.7092*	*0.6966*	*0.7364*
k	*359.21*	*313.64*	*386.32*	*384.74*	*326.05*
CCI	*2.18*	*1.97*	*2.35*	*2.39*	*2.02*




OBM Sample B_1 @ 120°F
SHEAR STRESS
0
20
40
60
80
100
120
140
160
0
100
200
300
400
500
600
700
SHEAR RATE (rpm)

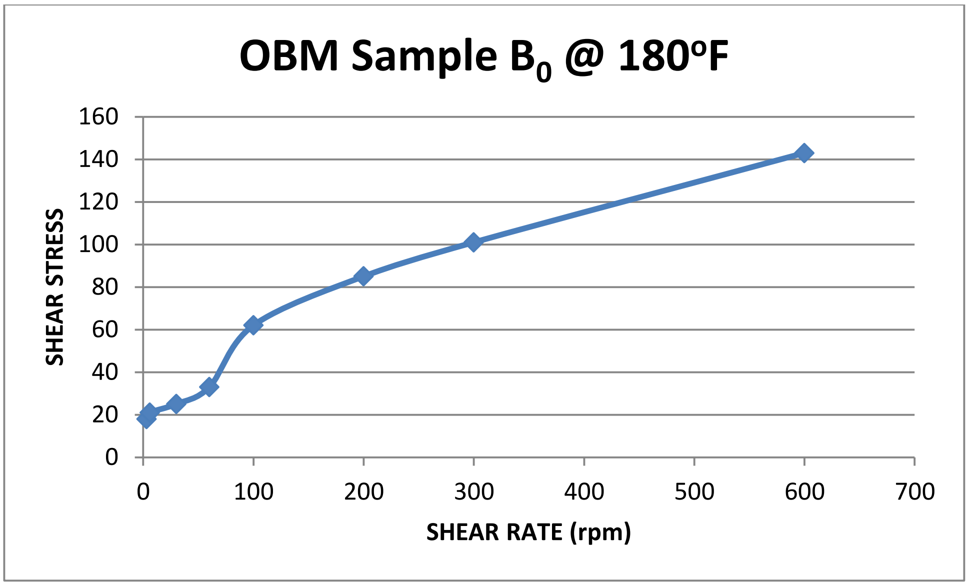

OBM Sample B_2 @ 120°F
0
20
40
60
80
100
120
140
160
0
100
200
300
400
500
600
700


OBM Sample B_3 @ 120°F
SHEAR STRESS
0
20
40
60
80
100
120
140
160
0
100
200
300
400
500
600
700
SHEAR RATE (rpm)

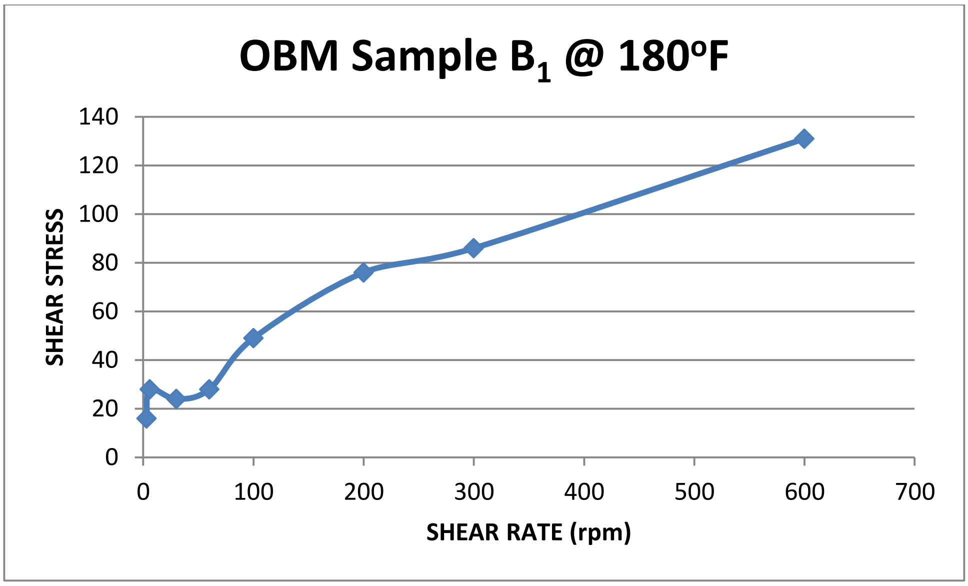


Rheology of Diesel OBM at 180°C.

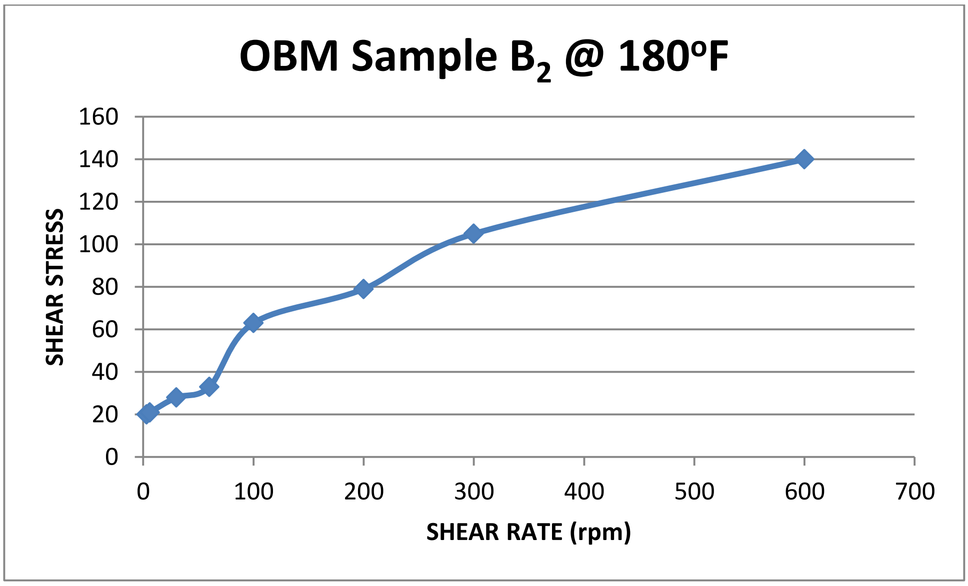
Speed (rpm)	*Readings*				
	B0	*B1*	*B2*	*B3*	*B4*
3	*18*	*16*	*20*	*18*	*18*
6	*21*	*20*	*21*	*20*	*21*
30	*25*	*24*	*28*	*26*	*25*
60	*33*	*28*	*33*	*30*	*35*
100	*62*	*49*	*63*	*53*	*62*
200	*85*	*76*	*79*	*79*	*75*
300	*101*	*86*	*105*	*94*	*95*
600	*143*	*131*	*140*	*135*	*133*
10s Gel Strength (lb/100ft^2)	*20*	*18*	*21*	*19*	*19*
10mins Gel Strength (lb/100ft^2)	*36*	*29*	*35*	*30*	*28*
Plastic Viscosity (cp)	*42*	*45*	*35*	*41*	*38*
Apparent Viscosity (cp)	*71.5*	*65.5*	*70*	*67.5*	*66.5*
Yield point (lb/100ft^2)	*59*	*21*	*70*	*53*	*57*
n	*0.7656*	*0.7991*	*0.7105*	*0.7612*	*0.7473*
k	*251.82*	*212.33*	*335.59*	*263.56*	*263.56*
CCI	*1.53*	*1.33*	*2.04*	*1.64*	*1.65*



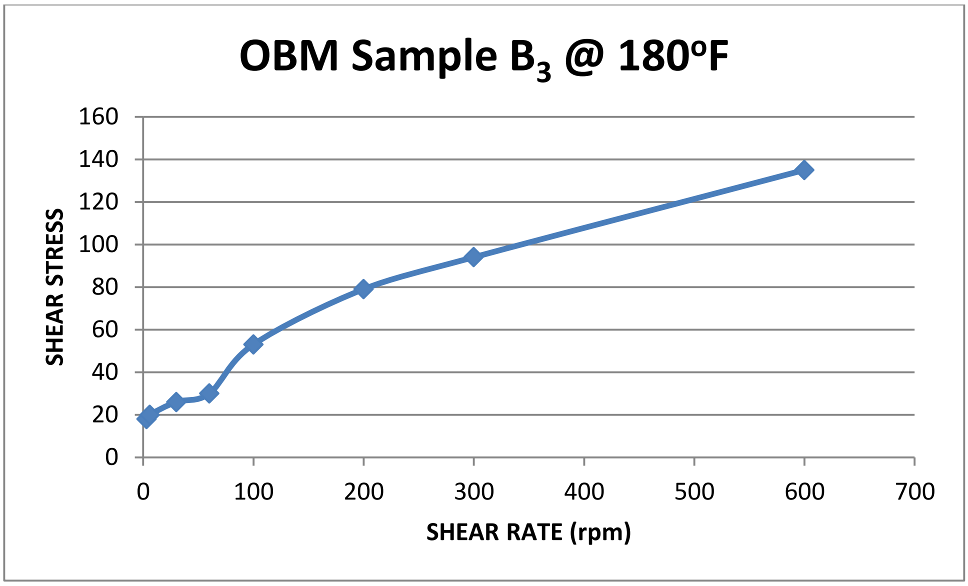
OBM Sample B_0 @ 180°F

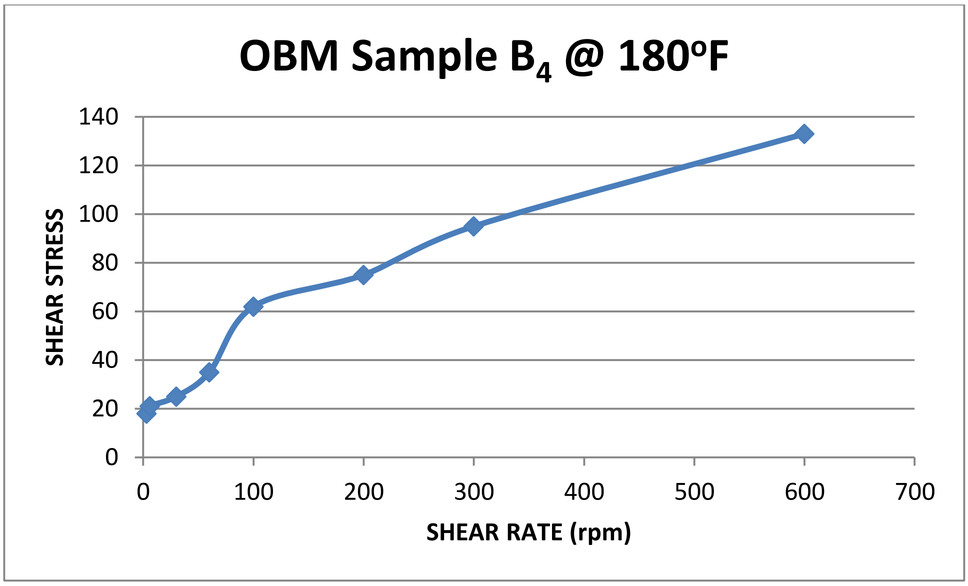


OBM Sample B_1 @ 180°F



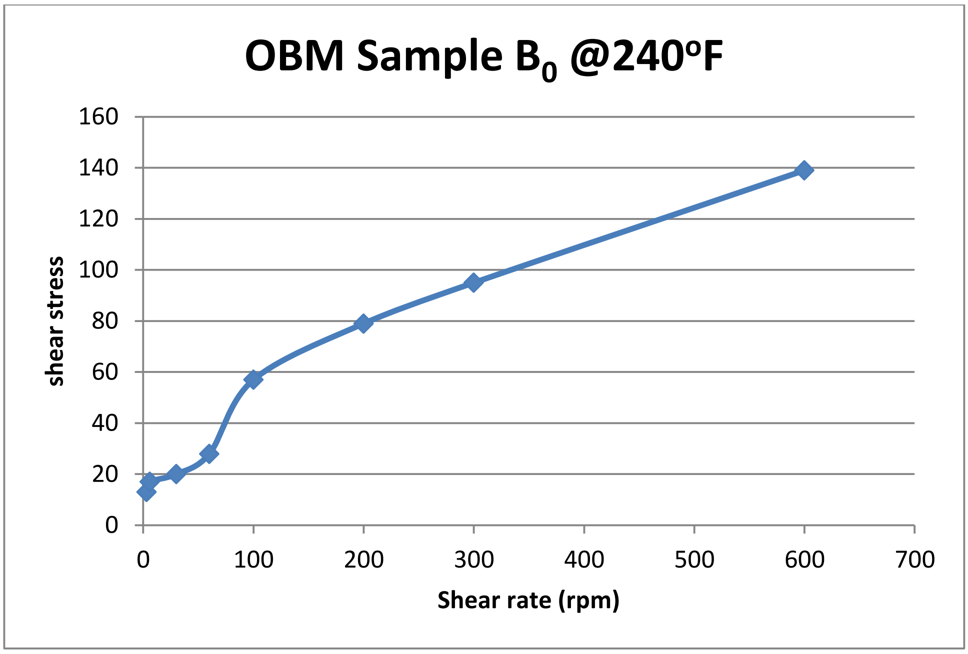
OBM Sample B_2 @ 180°F

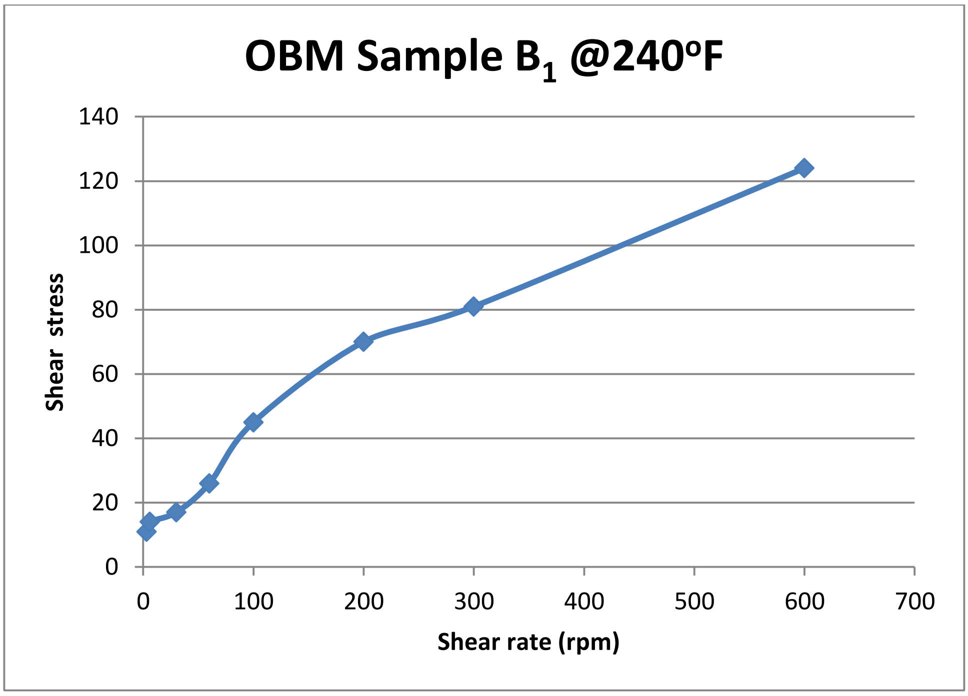

OBM Sample B_3 @ 180°F
SHEAR STRESS
SHEAR RATE (rpm)
0
20
40
60
80
100
120
140
160
0
100
200
300
400
500
600
700

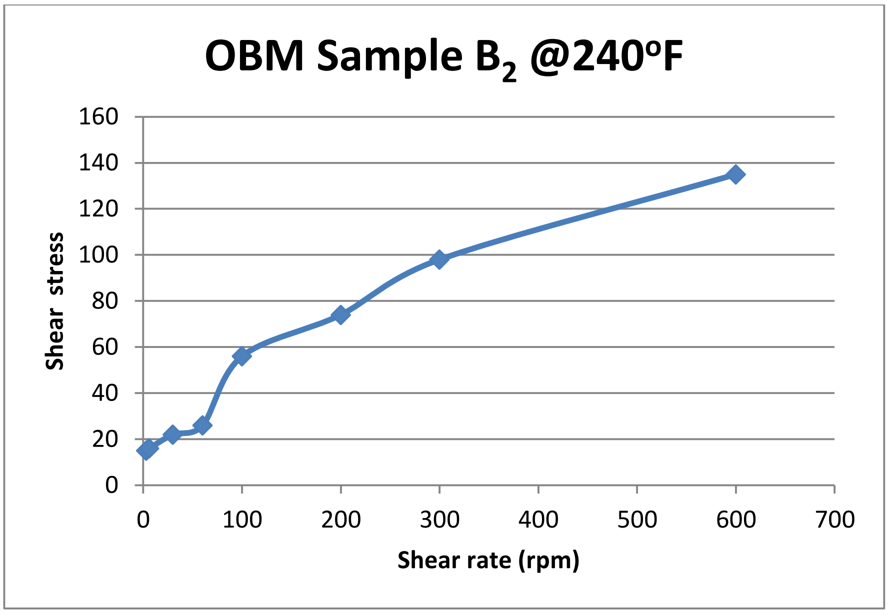

OBM Sample B_4 @ 180°F
SHEAR STRESS
SHEAR RATE (rpm)
0
20
40
60
80
100
120
140
0
100
200
300
400
500
600
700

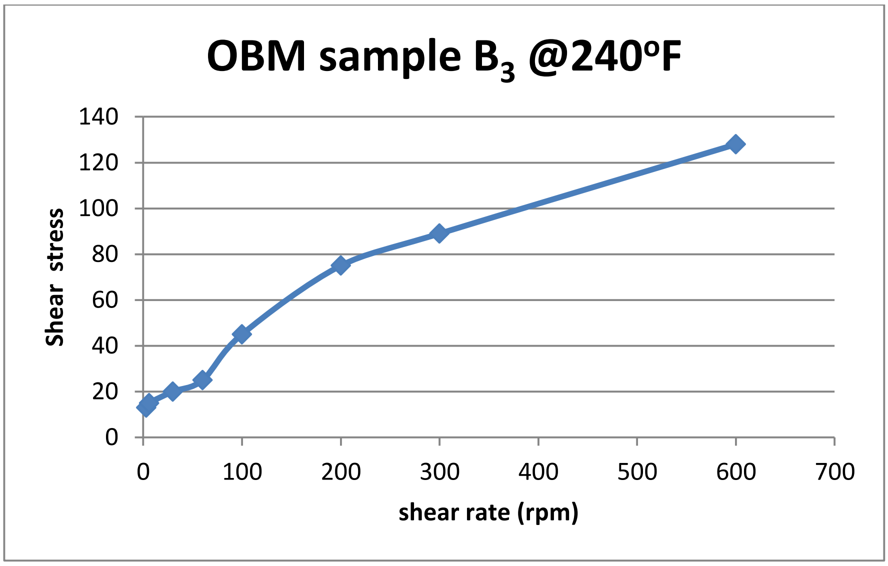
Rheology of Diesel OBM at 240^{o}C.

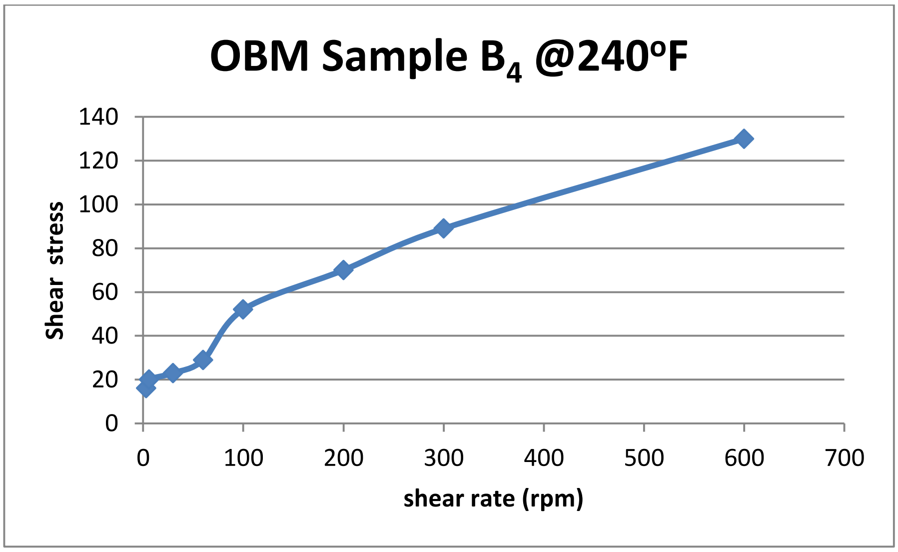
Speed (rpm)	*Readings*				
	B0	*B1*	*B2*	*B3*	*B4*
3	*13*	*11*	*15*	*13*	*16*
6	*17*	*14*	*16*	*15*	*20*
30	*20*	*17*	*22*	*20*	*23*
60	*28*	*26*	*26*	*25*	*29*
100	*57*	*45*	*56*	*45*	*52*
200	*79*	*70*	*74*	*75*	*70*
300	*95*	*81*	*98*	*89*	*89*
600	*139*	*124*	*135*	*128*	*130*
10s Gel Strength (lb/100ft^2)	*15*	*13*	*16*	*18*	*15*
10mins Gel Strength (lb/100ft^2)	*31*	*27*	*32*	*28*	*28*
Plastic Viscosity (cp)	*44*	*43*	*37*	*39*	*41*
Apparent Viscosity (cp)	*69.5*	*62*	*67.5*	*64*	*65*
Yield point (lb/100ft^2)	*51*	*38*	*61*	*50*	*48*
n	*0.8253*	*0.8450*	*0.7749*	*0.8074*	*0.7818*
k	*169.45*	*141.97*	*211.67*	*172.84*	*222.26*
CCI	*1.03*	*0.89*	*1.29*	*1.07*	*1.38*


OBM Sample B_0 @240°F
shear stress
160
140
120
100
80
60
40
20
0
0
100
200
300
400
500
600
700
Shear rate (rpm)


OBM Sample B_1 @240°F
Shear stress
140
120
100
80
60
40
20
0
0
100
200
300
400
500
600
700
Shear rate (rpm)

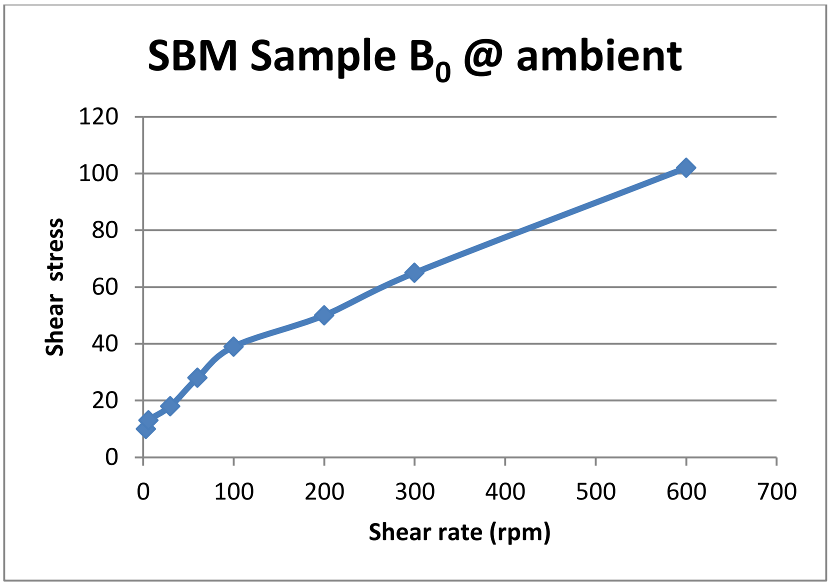

OBM Sample B_2 @240°F
Shear stress
160
140
120
100
80
60
40
20
0
0
100
200
300
400
500
600
700
Shear rate (rpm)

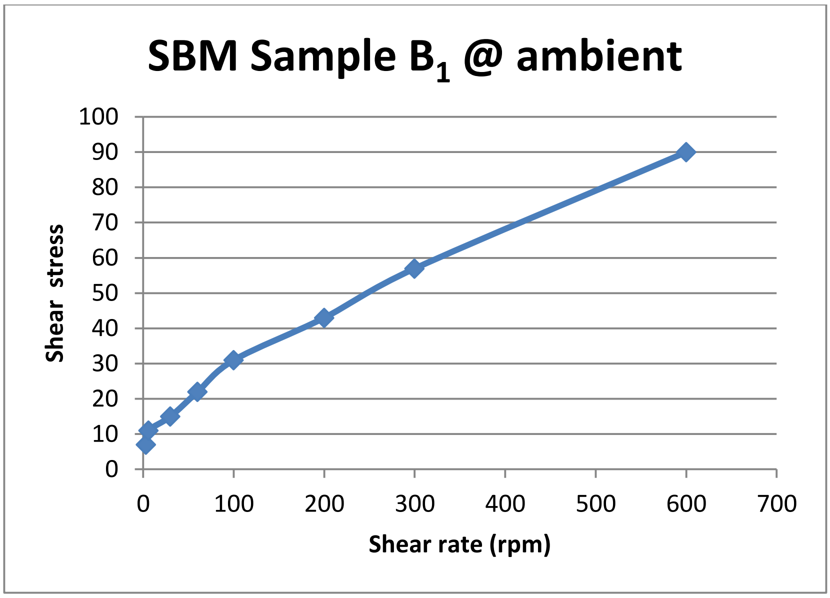

OBM sample B_3 @240°F
Shear stress
140
120
100
80
60
40
20
0
0
100
200
300
400
500
600
700
shear rate (rpm)

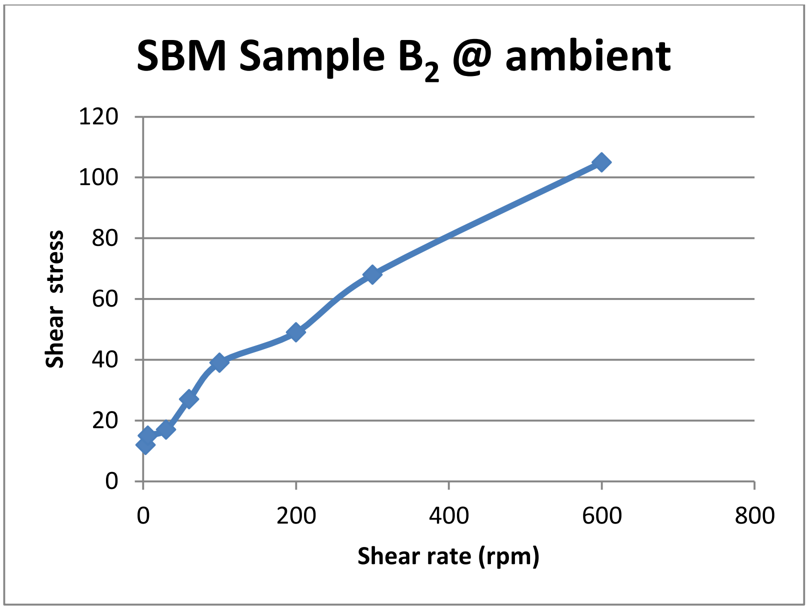

OBM Sample B_4 @240°F
Shear stress
140
120
100
80
60
40
20
0
0
100
200
300
400
500
600
700
shear rate (rpm)

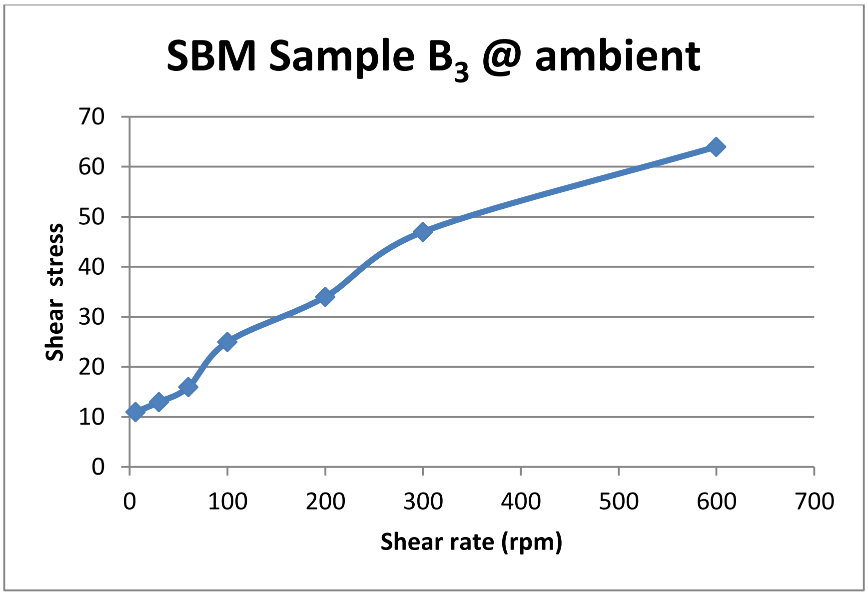
Rheology of SBM at Ambient conditions

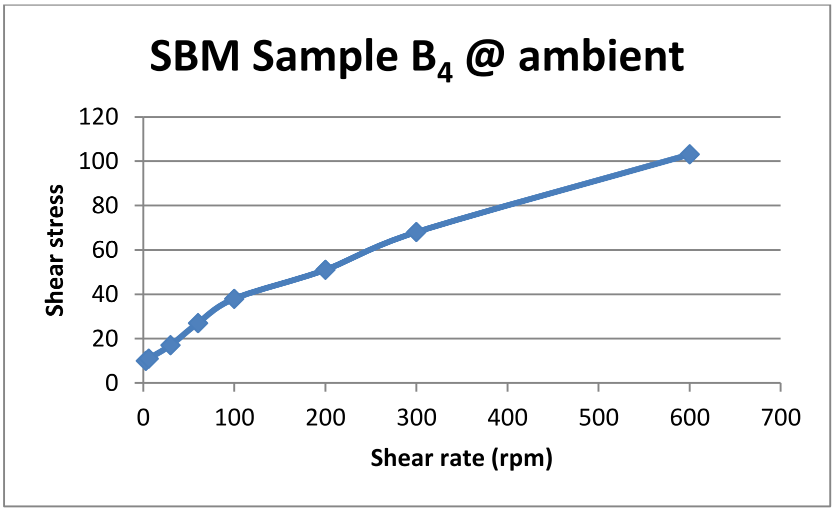
Speed (rpm)	*Readings*				
	B0	*B1*	*B2*	*B3*	*B4*
3	*10*	*7*	*12*	*11*	*10*
6	*13*	*11*	*15*	*13*	*11*
30	*18*	*15*	*17*	*16*	*17*
60	*28*	*22*	*27*	*25*	*27*
100	*39*	*31*	*39*	*34*	*38*
200	*50*	*43*	*49*	*47*	*51*
300	*65*	*57*	*68*	*64*	*68*
600	*102*	*90*	*105*	*101*	*103*
10s Gel Strength (lb/100ft^2)	*9*	*8*	*14*	*12*	*11*
10mins Gel Strength (lb/100ft^2)	*21*	*17*	*23*	*19*	*20*
Plastic Viscosity (cp)	*37*	*33*	*37*	*37*	*35*
Apparent Viscosity (cp)	*51*	*45*	*52.5*	*50.5*	*51.5*
Yield point (lb/100ft^2)	*28*	*25*	*31*	*27*	*33*
n	*0.8377*	*0.8679*	*0.8114*	*0.8244*	*0.8295*
k	*129.32*	*91.17*	*158.86*	*143.50*	*130.32*
CCI	*0.92*	*0.66*	*1.13*	*1.03*	*0.92*


SBM Sample B_0 @ ambient
Shear stress
Shear rate (rpm)
0
20
40
60
80
100
120
0
100
200
300
400
500
600
700


SBM Sample B_1 @ ambient
Shear stress
Shear rate (rpm)
0
10
20
30
40
50
60
70
80
90
100
0
100
200
300
400
500
600
700

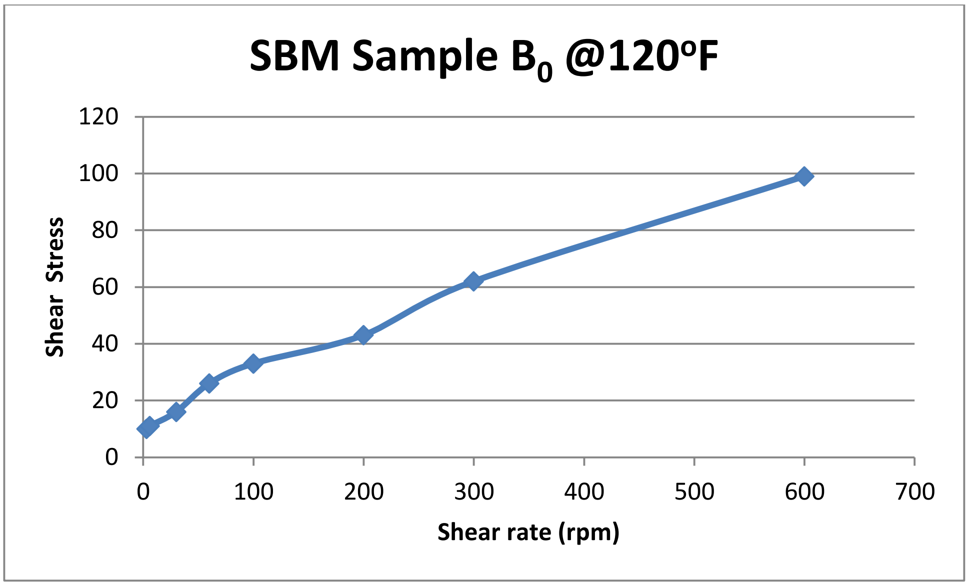

SBM Sample B_2 @ ambient
Shear stress
120
100
80
60
40
20
0
0
200
400
600
800
Shear rate (rpm)

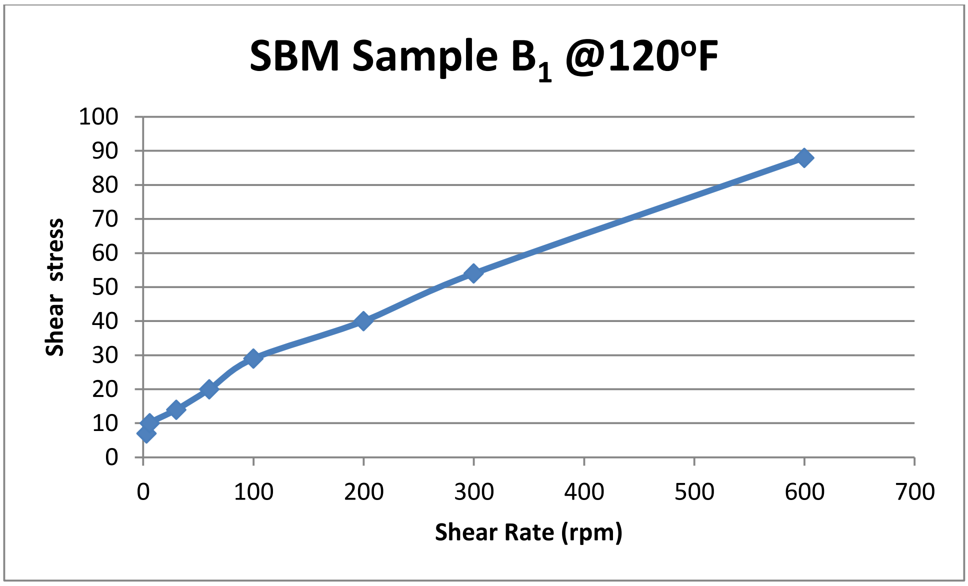

SBM Sample B_3 @ ambient
Shear stress
70
60
50
40
30
20
10
0
0
100
200
300
400
500
600
700
Shear rate (rpm)

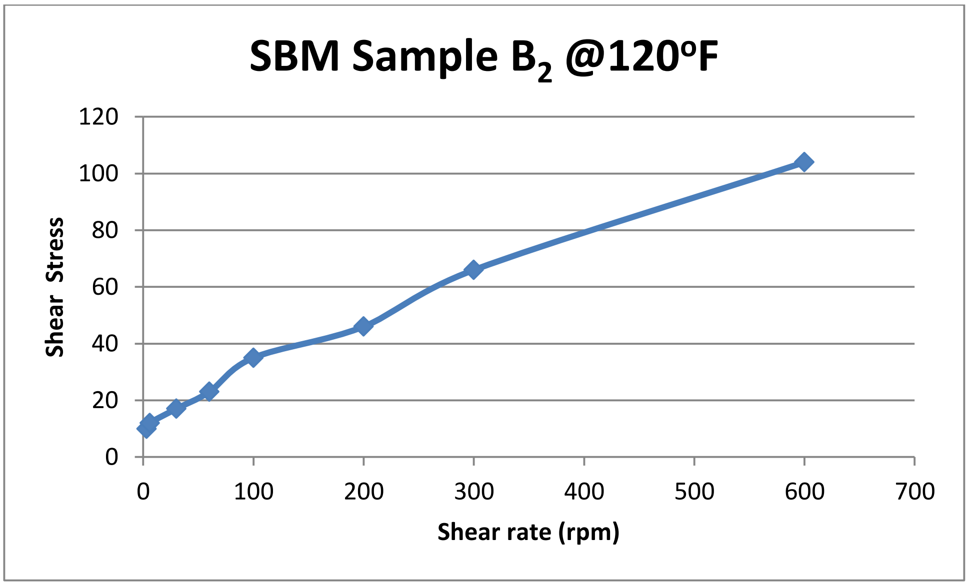

SBM Sample B_4 @ ambient
Shear stress
120
100
80
60
40
20
0
0
100
200
300
400
500
600
700
Shear rate (rpm)

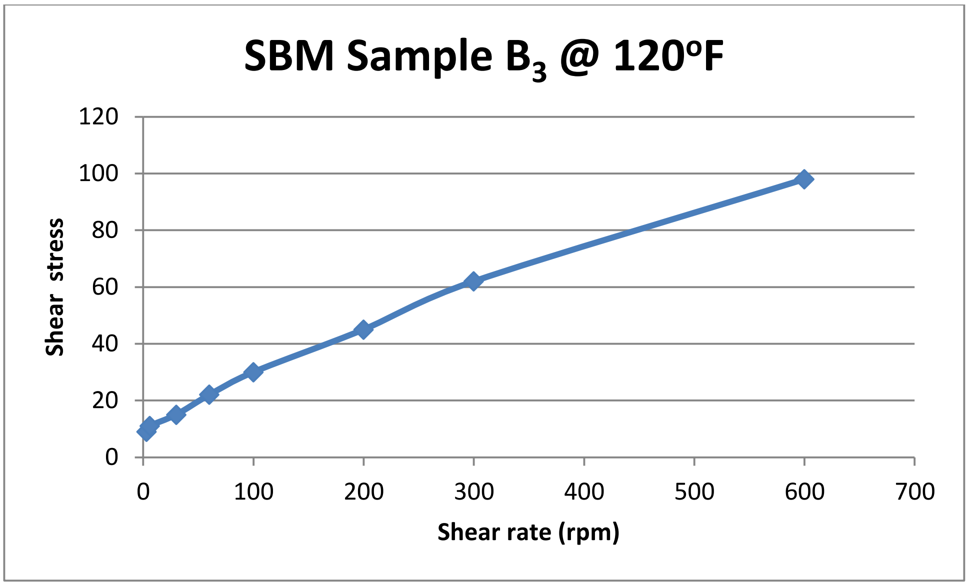
Rheology of SBM at 120^oC.

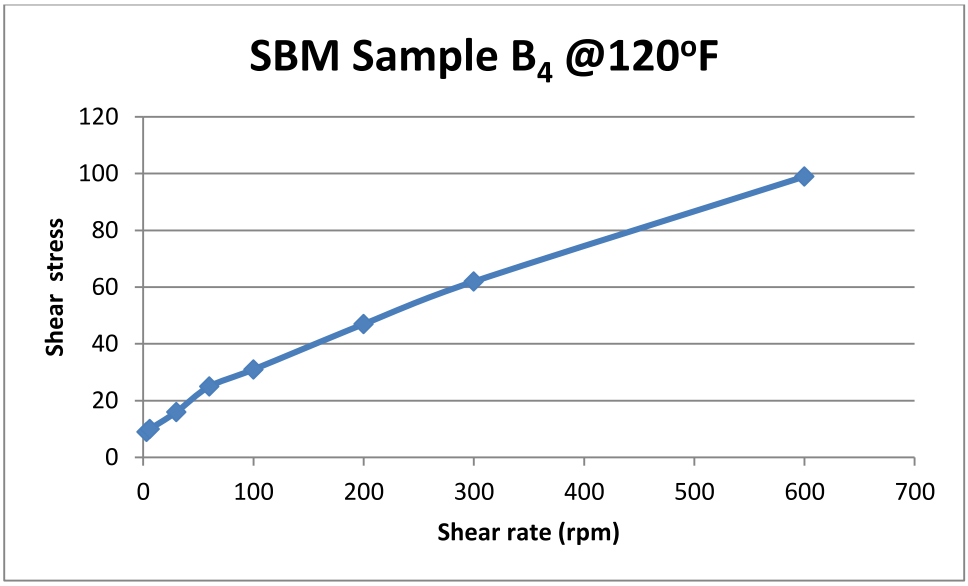
Speed (rpm)	*Readings*				
	B0	*B1*	*B2*	*B3*	*B4*
3	*10*	*7*	*10*	*9*	*9*
6	*11*	*10*	*12*	*11*	*10*
30	*16*	*14*	*17*	*15*	*16*
60	*26*	*20*	*23*	*22*	*25*
100	*33*	*29*	*35*	*30*	*31*
200	*43*	*40*	*46*	*45*	*47*
300	*62*	*54*	*66*	*62*	*62*
600	*99*	*88*	*104*	*98*	*99*
10s Gel Strength (lb/100ft^2)	*10*	*9*	*14*	*11*	*10*
10mins Gel Strength (lb/100ft^2)	*21*	*18*	*21*	*19*	*18*
Plastic Viscosity (cp)	*37*	*34*	*38*	*36*	*37*
Apparent Viscosity (cp)	*49.5*	*44*	*52*	*49*	*49.5*
Yield point (lb/100ft^2)	*25*	*20*	*28*	*26*	*25*
n	*0.8377*	*0.8713*	*0.8413*	*0.8480*	*0.8515*
k	*129.32*	*91.49*	*129.14*	*116.12*	*116.13*
CCI	*0.92*	*0.66*	*0.92*	*0.83*	*0.82*


SBM Sample B_0 @120ºF
Shear Stress
0
20
40
60
80
100
120
0
100
200
300
400
500
600
700
Shear rate (rpm)


SBM Sample B_1 @120ºF
Shear stress
0
10
20
30
40
50
60
70
80
90
100
0
100
200
300
400
500
600
700
Shear Rate (rpm)

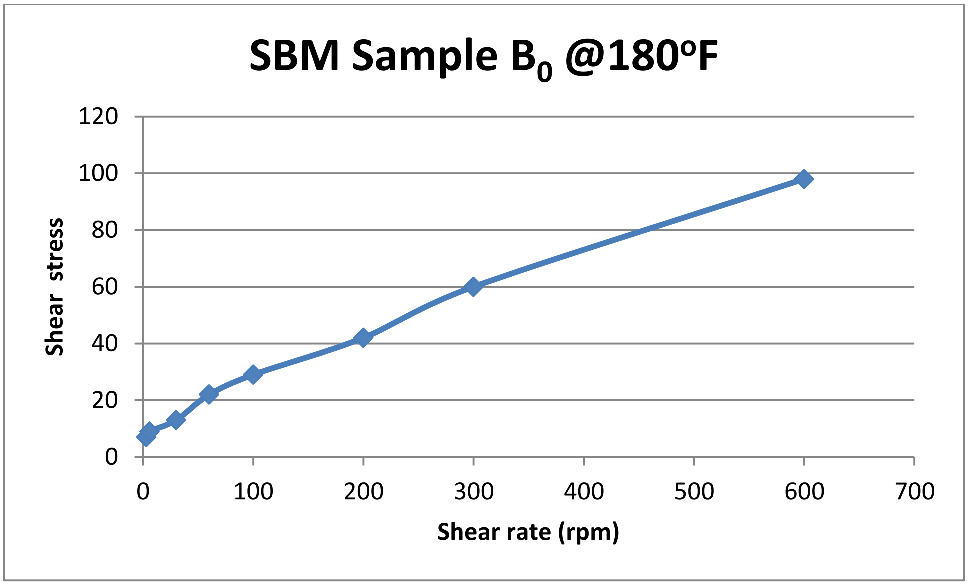

SBM Sample B_2 @120ºF
Shear Stress
0
20
40
60
80
100
120
0
100
200
300
400
500
600
700
Shear rate (rpm)

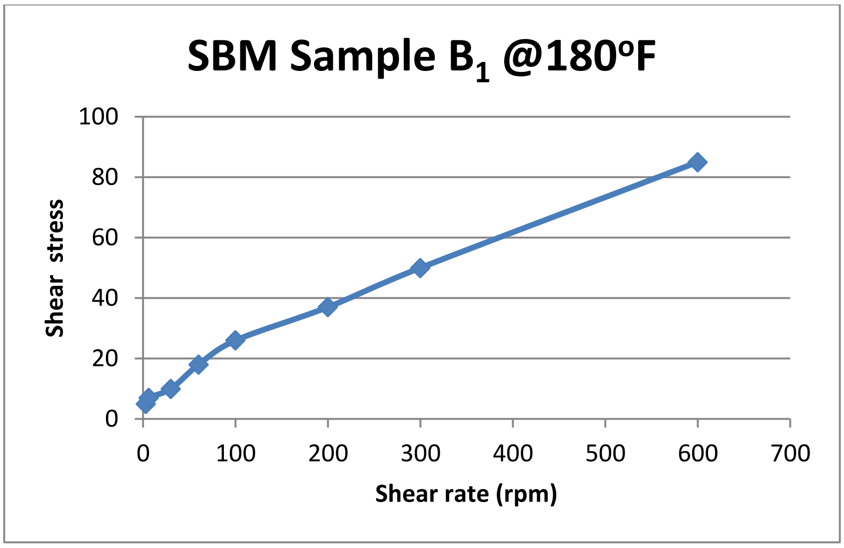

SBM Sample B_3 @ 120°F
Shear stress
120
100
80
60
40
20
0
0
100
200
300
400
500
600
700
Shear rate (rpm)

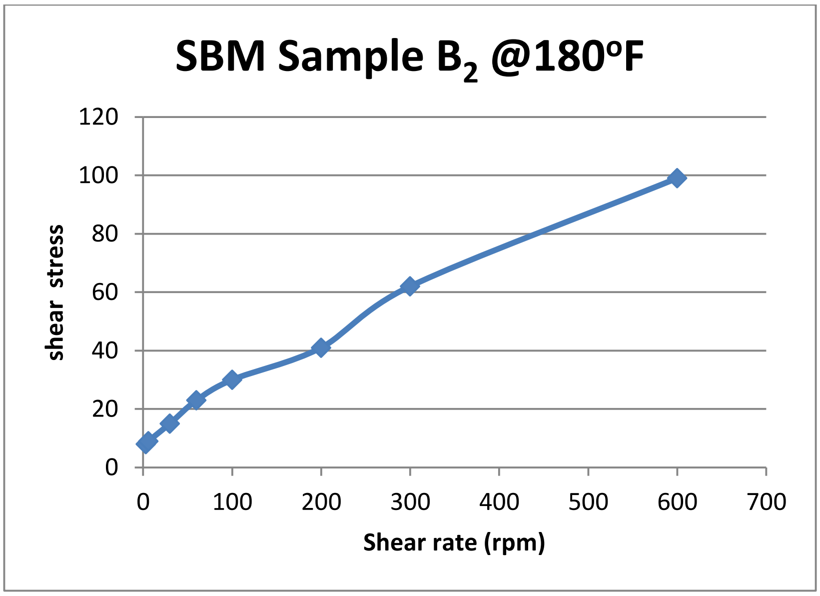

SBM Sample B_4 @120°F
Shear stress
120
100
80
60
40
20
0
0
100
200
300
400
500
600
700
Shear rate (rpm)

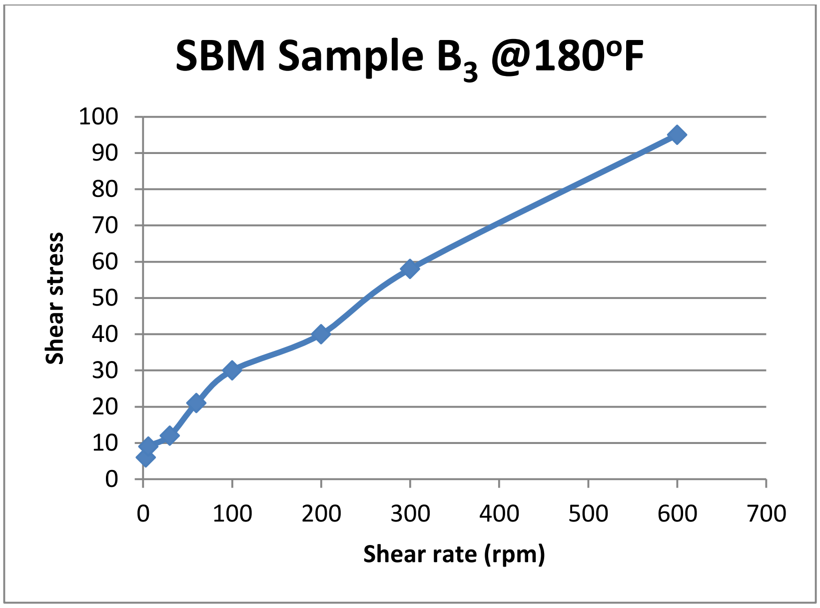
Rheology of SBM at 180°C.

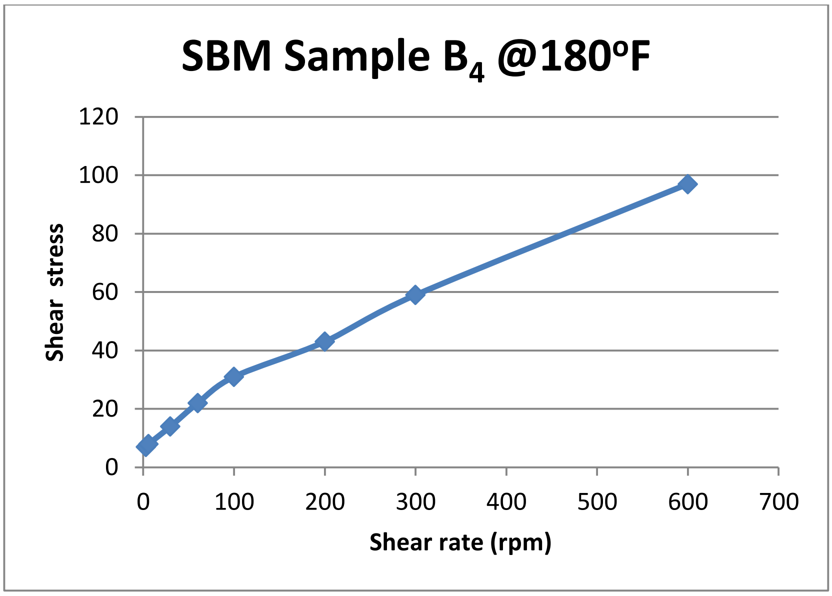
Speed (rpm)	*Readings*				
	B0	*B1*	*B2*	*B3*	*B4*
3	*7*	*5*	*8*	*6*	*7*
6	*9*	*7*	*9*	*9*	*8*
30	*13*	*10*	*15*	*12*	*14*
60	*22*	*18*	*23*	*21*	*22*
100	*29*	*26*	*30*	*30*	*31*
200	*42*	*37*	*41*	*40*	*43*
300	*60*	*50*	*62*	*58*	*59*
600	*98*	*85*	*99*	*95*	*97*
10s Gel Strength (lb/100ft^2)	*7*	*6*	*8*	*6*	*7*
10mins Gel Strength (lb/100ft^2)	*14*	*13*	*18*	*15*	*14*
Plastic Viscosity (cp)	*38*	*35*	*37*	*37*	*38*
Apparent Viscosity (cp)	*49*	*42.5*	*49.5*	*47.5*	*48.5*
Yield point (lb/100ft^2)	*22*	*15*	*25*	*21*	*21*
n	*0.8829*	*0.9069*	*0.8655*	*0.8953*	*0.8829*
k	*95.11*	*74.63*	*101.23*	*80.23*	*95.11*
CCI	*0.67*	*0.54*	*0.72*	*0.57*	*0.69*


SBM Sample B_0 @180°F
Shear stress
120
100
80
60
40
20
0
0
100
200
300
400
500
600
700
Shear rate (rpm)


SBM Sample B_1 @180°F
Shear stress
100
80
60
40
20
0
0
100
200
300
400
500
600
700
Shear rate (rpm)

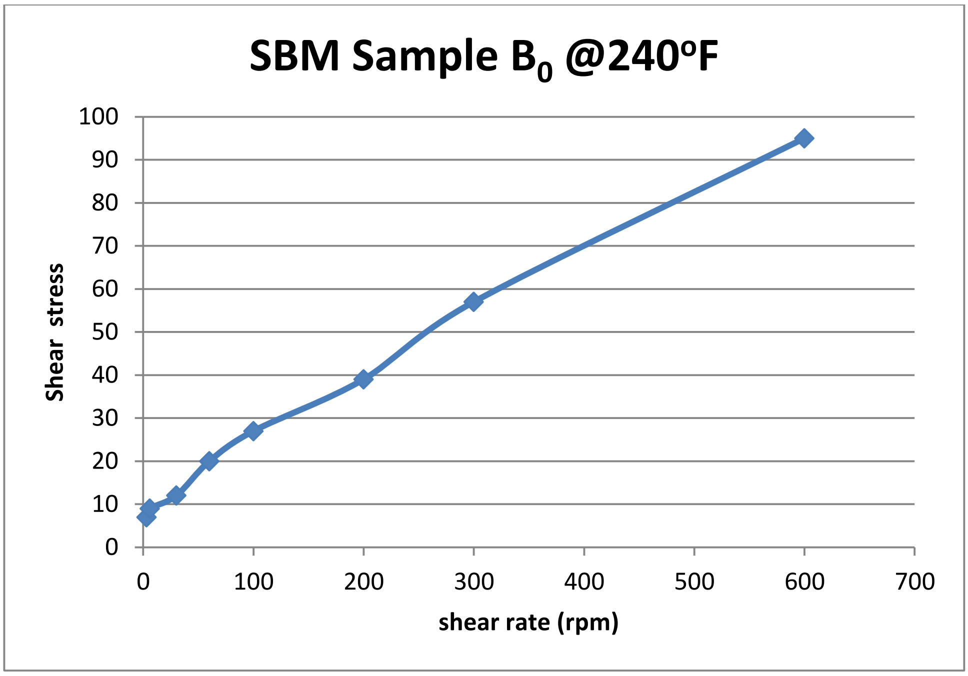

SBM Sample B_2 @180°F
shear stress
120
100
80
60
40
20
0
0
100
200
300
400
500
600
700
Shear rate (rpm)

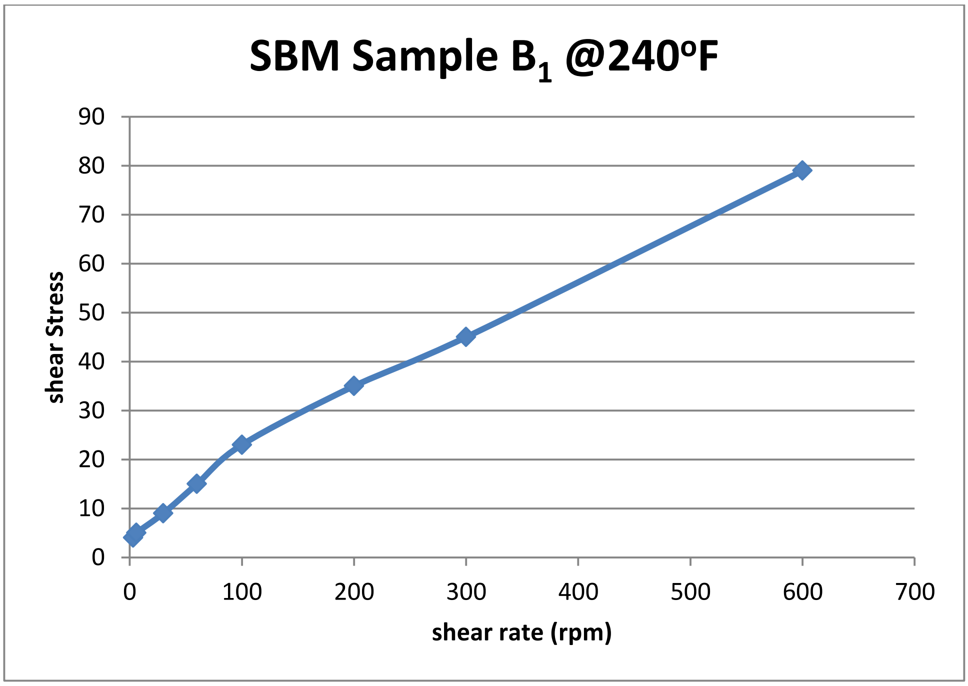

SBM Sample B_3 @180ºF
Shear stress
100
90
80
70
60
50
40
30
20
10
0
0
100
200
300
400
500
600
700
Shear rate (rpm)

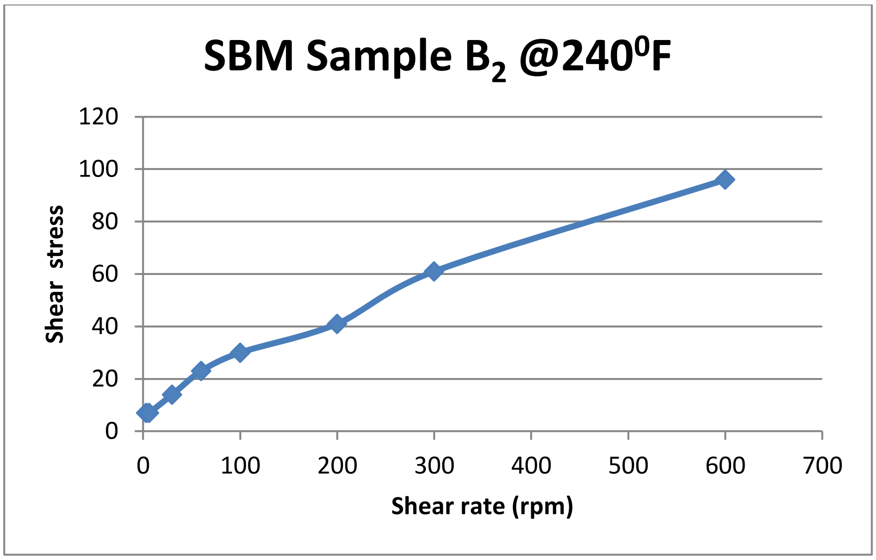

SBM Sample B_4 @180ºF
Shear stress
120
100
80
60
40
20
0
0
100
200
300
400
500
600
700
Shear rate (rpm)

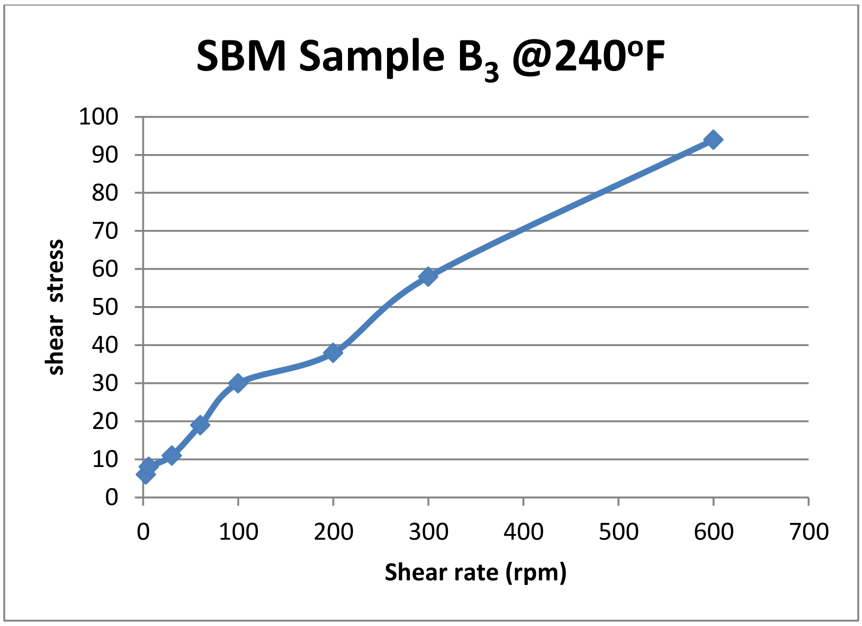
Rheology of SBM at 240°C.

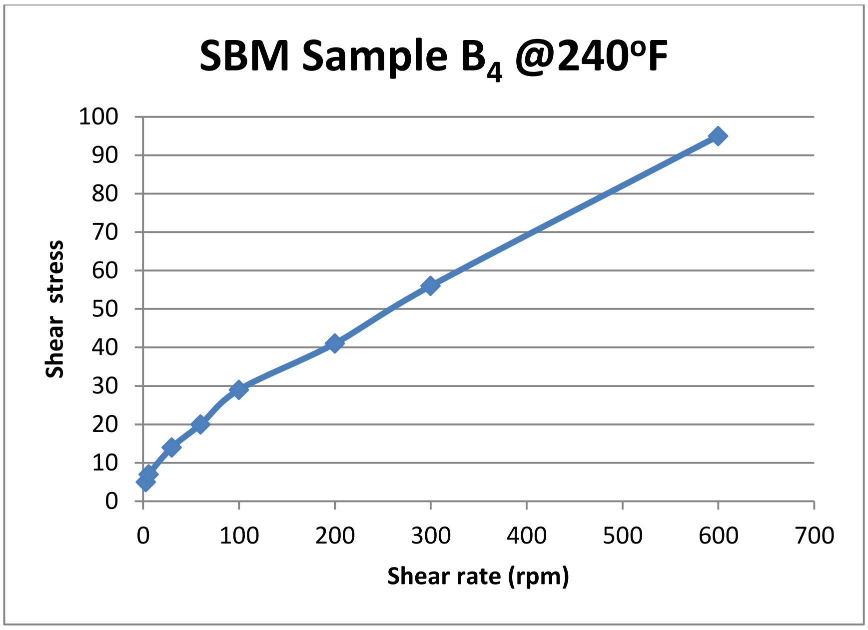
Speed (rpm)	*Readings*				
	B0	*B1*	*B2*	*B3*	*B4*
3	*7*	*4*	*7*	*6*	*5*
6	*9*	*5*	*7*	*8*	*7*
30	*12*	*9*	*14*	*11*	*14*
60	*20*	*15*	*23*	*19*	*20*
100	*27*	*23*	*30*	*30*	*29*
200	*39*	*35*	*41*	*38*	*41*
300	*57*	*45*	*61*	*58*	*56*
600	*95*	*79*	*96*	*94*	*95*
10s Gel Strength (lb/100ft^2)	*7*	*5*	*7*	*8*	*7*
10mins Gel Streng(lb/100ft^2)	*13*	*11*	*14*	*15*	*13*
Plastic Viscosity (cp)	*38*	*34*	*35*	*36*	*39*
Apparent Viscosity (cp)	*47.5*	*39.5*	*48*	*47*	*47.5*
Yield point (lb/100ft^2)	*19*	*11*	*26*	*22*	*17*
n	*0.8829*	*0.9220*	*0.8745*	*0.8931*	*0.9157*
k	*93.40*	*61.81*	*91.87*	*81.80*	*74.43*
CCI	*0.66*	*0.45*	*0.65*	*0.59*	*0.54*


SBM Sample B_0 @240°F
Shear stress
shear rate (rpm)
0
10
20
30
40
50
60
70
80
90
100
0
100
200
300
400
500
600
700


SBM Sample B_1 @240°F
shear Stress
shear rate (rpm)
0
10
20
30
40
50
60
70
80
90
0
100
200
300
400
500
600
700


SBM Sample B_2 @240^0F
Shear stress
120
100
80
60
40
20
0
0
100
200
300
400
500
600
700
Shear rate (rpm)


SBM Sample B_3 @240^oF
shear stress
100
90
80
70
60
50
40
30
20
10
0
0
100
200
300
400
500
600
700
Shear rate (rpm)


SBM Sample B4 @240ºF
Shear stress
0
10
20
30
40
50
60
70
80
90
100
0
100
200
300
400
500
600
700
Shear rate (rpm)