The New Biodegradable Surfactant Drilling Fluid for Offshore HPHT Drilling Environment

by

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Dissertation submitted in partial fulfilment of
the requirements for the
Bachelor of Engineering (Hons)
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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
Petroleum Engineering Programme
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BACHELOR OF ENGINEERING (Hons)
(PETROLEUM ENGINEERING)

Approved by,

____

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Project Supervisor

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January 2012

CERTIFICATION OF ORIGINALITY

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

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(Thian Hui Chie)

ABSTRACT

The global growing demand for energy has driven oil and gas industry towards drilling deeper wells, many which are subjected to high pressure and high temperature (HPHT) (Burdyn and Wiener, 1956; Larsen, 2007, Godwin *et al.*, 2011). However, this development of deeper oil horizon is halted when conventional drilling fluids are unable to withstand these high temperatures (Burdyn and Wiener, 1956; Darley and Gray, 1988; Woha and Joel, 2011). Polymers (mud additives) degraded at elevated temperature and this causes unsatisfactory performances (Burdyn and Wiener, 1956; Darley and Gray, 1988).

The work was carried out to find the application of non-ionic surfactant used for Enhanced Oil Recovery (EOR)'s Polyethylene glycol (PEG) 550 based surfactant in drilling fluid. The focus will be put on the improvement of high pressure high temperature (HPHT) stability of conventional polymer, suspending agent (Xanthan Gum) and filtration reduction agent (PAC-LV) with the existence of surfactant.

The rheological and filtration properties of the drilling fluids were acquired using standard testing apparatus, viscometer and API filter press respectively. The performances were later evaluated with comparison with drilling fluids without surfactant.

It was observed that surfactant drilling fluids still exhibited slightly higher value in viscosity compared to base fluids after hot-rolling at elevated temperatures. Besides, it also showed a remarkable reduction in fluid loss by almost half even after undergone hot-rolling up to 125°C. These results showed that PEG550 had the potential to be used in offshore HPHT drilling environments.

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ABBREVIATIONS AND NOMENCLATURES

HPHT	High pressure high temperature
PEG	Polyethylene glycols
EOR	Enhanced Oil Recovery
DF	Drilling fluid
APG	Alkylpolyglucosides
RPM	Revolutions per minutes
BH	Before hot rolling
AH	After hot rolling
CMC-LV	Carboxymethyl cellulose- low viscosity
PAC-LV	Polyanionic cellulose low viscosity
XC	Xanthan Gum
PHPA	Partially-hydrolyzed polyacrylamide
OCMA	Oil Company Materials Association
API	American Petroleum Institute

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Drilling fluid or commonly known as drilling mud is a very important component in drilling operations. It performs various functions in order to ensure excellence performance throughout the operations. With drilling mud, cuttings were carried from beneath the rotary bit and transported up the annulus for separation at the surface later on. At the same time, it cooled the bit while reducing frictions between drill string and side of borehole and maintaining stability of uncased borehole sections. The formation of thin low permeable filter cake by drilling mud also prevents unwanted fluid invasion into borehole.

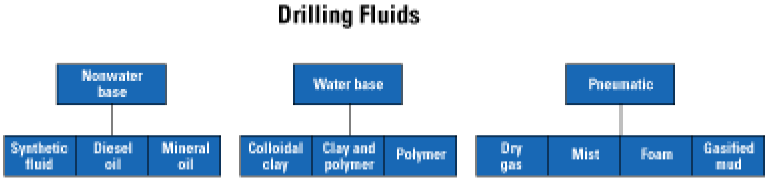


Figure 1: Classification chart for drilling fluids (*www.glossary.oilfield.slb.com*, 2012)

Generally, drilling fluids are suspensions of solid particles in an aqueous or non-aqueous suspending medium (Tehrani, 2007). Typically, there are three types of drilling fluids which are classified according to their base material. Water-based fluids are suspension of solids in water, and also contain a number of additives for the purpose of controlling mud properties (rheology, fluid loss, shale inhibition and lubricity). On the other hand, non-aqueous fluids are having organic liquid such as minerals, or synthetic oil, or diesels as the liquid carrier. Other types of drilling fluids, pneumatic fluids include dry gas (air, natural gas and nitrogen), mist, foam and gasified mud.

In the recent years, surface-active agent or better known as surfactant had been gaining its recognition due to its wide spread applications in several of areas. In drilling fluids, surfactants are mostly well known for its functions as emulsifier and wetting agents for oil based muds. Besides, its continually-growing variety of applications in water based muds had also proven that surfactants have its hidden potential to extend further. According to Lirio (2002), among the applications include:

- oil-in-water emulsifier for base fluid formulations,
- shale-swelling inhibitors to prevent wellbore instabilities,
- detergency to prevent cuttings sticking to drill bit,
- dispersants to inhibit flocculation of clay particles,
- foaming additives to generate high gas/water ratio foam used as drilling fluids for low pressure reservoirs and hard-rock drilling,
- defoaming additives to eliminate undesirable foam in water-based fluids,
- surfactant-polymer complexes for enhanced properties in fluids for low pressure reservoirs, and etc

As quoted by oilgasglossary.com (2012), surfactant drilling fluid is a drilling mud prepared by adding surfactant to a water-base mud in order to change the colloidal state of the clay from that of complete dispersion to one of controlled flocculation. This ‘controlled flocculated’ system is the resultant from research program meant to develop a thermally stable mud with a high solids carrying capacity by a major company several years ago (Hyde and James, 1957). In this system, it is believed that clays are converted to an aggregated form characterized by plate-to-plate individual stacking of clay particles which contracts to edge-to-edge attraction of clay particles in conventional mud. Flocculation of clays in a surface-to-surface stacking arrangement causes a marked reduction in plastic viscosity of mud, since small particles are combined to form fewer, more symmetrical agglomerates (Hyde and James, 1957). Thus, the controlled flocculated muds offer a number of advantages over conventional dispersed muds.

1.2 Problem Statement

The global growing demand for energy has driven oil and gas industry towards drilling deeper wells, many which are subjected to high pressure and high temperature (HPHT)

(Burdyn and Wiener, 1956; Larsen, 2007, Godwin *et al.,* 2011). As defined by United Kingdom Continental Shelf Operations Notice, HPHT wells are any well where the undisturbed bottom hole temperature is 300 °F or greater or either the pore pressure exceeds 0.8psi/ft or pressure control equipment greater than 10,000 psi rated working pressure is required (Woha and Joel, 2011).

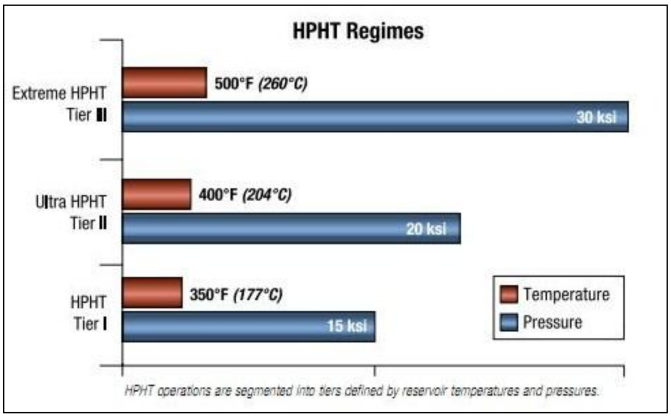


Figure 2: HPHT operations are segmented into tiers defined by reservoir temperatures and pressures (*Baker Hughes*, 2009)

Generally, several improvements in mud often resulted from the addition of single products such as polymer. These large molecules of repeating monomers are able to reduce filtration, stabilize clays, flocculate drilled solids, and increase carrying capacity (Rabia, 1985; Darley and Gray, 1988). Also, its excellent lubricating quality noticeably reduces friction between drilling fluids and hole as well as bit and rod wear. Polymers (mud additives), however, degraded at elevated temperature which caused unsatisfactory performances (Burdyn and Wiener, 1956; Darley and Gray, 1988). The development of deeper oil horizon is, therefore, halted when conventional drilling fluids are unable to withstand these high temperatures (Burdyn and Wiener, 1956; Darley and Gray, 1988; Woha and Joel, 2011).

Degraded additives can be replaced, but as the rate of degradation increases, frequent addition is required to keep the rheological properties constant, thus, costs increases and eventually become excessive (Burdyn and Wiener, 1956; Darley and Gray, 1988). Furthermore, the replacement operation can also indirectly lead to loss of drilling time.

1.3 Objectives and Scope of Study

The objectives of this research are:

i. To determine the most adequate PEG550 surfactant concentration to yield optimal drilling fluids properties.
ii. To determine the rheological and filtration performances of drilling fluids with and without PEG550 surfactant at elevated temperature.

The scope of study mainly revolves the important elements to achieve objectives stated. There are as listed:

- Conducting research on the mechanism of polymer degradation.
- Conducting research on theory and definition of terms related to surfactant
- Conducting performance test to see the effectiveness of a surfactant in exhibiting good rheology, fluid loss control and thermal stability when added to drilling fluid.

1.4 Relevance of Project

The findings from this research will enhance the applicability of PEG surfactant as additive in drilling fluid for injection wells. Through lab experiments, it is hope that the prospect of PEG surfactant will not just be limited to EOR, surfactant flooding, but also applicable in drilling fluid. The research is relevant in providing explanation on rheology performance, fluid loss control and thermal stability.

1.5 Feasibility of the Project

This project promote green environment as the non-ionic surfactant chose, PEG surfactant is biodegradable. It is derived from naturally occurring raw material (tall oil fatty acids methyl esters) which is believed to provide improved biodegradability. Also, it is an economical choice due to the ready availability of tall oil fatty acid as natural product with a relatively low price.

CHAPTER 2

LITERATURE REVIEW

This project focuses on the improvement of drilling fluid for drilling deep wells which are subjected to high temperature and high pressure (HPHT) through surfactant-induced polymer mud rheological performance modification. Therefore, the related literature is thoroughly reviewed and reported in the following sections.

2.1. Optimization through Drilling Fluid

Drilling optimization revolves around the selection of operating conditions which require the least expense in reaching the desired depth, by taking into account personnel safety, environment, protection, adequate information on penetrated formations and productivity. J. L. Lummus (1971) stated that the most essential key to optimization success is probably the drilling fluid while hydraulic comes in second (Darley and Gray, 1988). Generally, basic drilling fluid consists of three main elements which are the continuous phase water or oil, solid particles and additives. Since the first operations in US, drilling fluids went through major technological evolution using a simple mixture of water and clays to complex mixture of various specific organic and inorganic products used nowadays (Khodja *et al.*, 1999). These products improve fluid rheological properties and filtration capability, allowing the penetration of heterogeneous geological formations under the best conditions.

2.2. Polymer-based Drilling Fluid and its Thermal Stability

In drilling fluids, polymer is applied to several varied and versatile substances which are composed of a number of repeating or similar units, or groups of atoms (known as *monomers*) consisting primarily of compounds of carbon (Darley and Gray, 1988; Devereux, 1999). Polymers are intentionally added to perform very specific functions, such as rheology modification, fluid loss control, shale inhibition etc. (Van Oort, 1997; Jayanth, 2010).

Examples of polymer frequently used in drilling fluids are starch, carboxymethyl cellulose (CMC) and their derivatives, xanthan gum (XC), partially hydrolyzed polyacrylamide (PHPA). Their general properties are well known because they have been used for many years (Thomas, 1982). It is the colloidal properties that decide its role in drilling fluids. A few has strong affinity for water which developing highly swollen gels in low concentration. Also, others offer protection from flocculation by salts after strongly absorbed by clay particles. Polymers also reduce the flow of water through a filter cake using its slimy particles even though it does not swell as much as they do in fresh water. Unfortunately, these polymers pose limitations at elevated temperature mainly due to two factors: degradation of additives and chemical reaction between additives and silicate minerals in drilling fluids (Burdyn et al, 1956; Rogers, 1953).

Table 1: Thermal Stability of Common Organic Polymer

Gulf Professional Publishing- Composition and Properties of Drilling and Completion Fluids,1988

Polymer	Classification	Temperature Stability
Starch	Filtration control	Up to 200°F (93°C)
Guar gum	Filtration control, hole stability	Up to 150°F (66°C)
Xanthan gum	Suspending agent	Up to 250°F (120°C)
CMC	Filtration control	Up to 300°F (150°C)
HEC (mostly in completion fluid)	Filtration control, viscosifier	Up to 275°F (135°C)
PAC	Filtration control	Up to 300°F (150°C)

2.3.Surfactant

Surfactant is widely known as compounds, similar to short-chain fatty acids, which exhibits amphiphilic behaviour whereby one part is having affinity for nonpolar media and another one part having affinity for polar media. The polar-attractive portion is often recognized as hydrophilic part or hydrophile while the apolar part is recognized as hydrophobe or lipophilic.

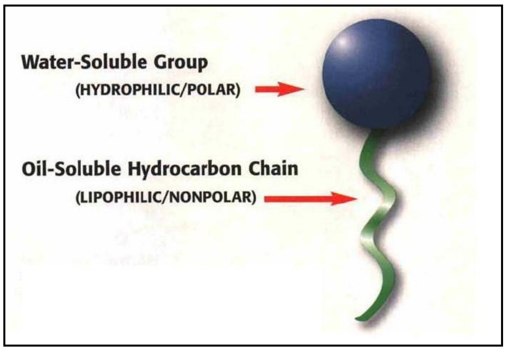


Figure 3: A typical surfactant molecule showing a hydrophilic water-attracting group and a long, oil soluble (lipophilic) hydrocarbon chain (Karnok *et al.*, 2004)

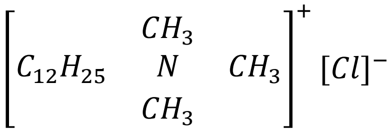
Due to their dual-affinity behaviour, amphiphilic molecules align themselves with each region of their structure is in its preferred environment. Surfactants will end up settle in interfaces between different chemical environments or phases. In this process, molecules actually cause a physical change at the surface of liquids in medium which they are dissolved by lower the interface between two liquids (interfacial tension) or between a liquid and a gas or a liquid and a solid (surface tension). Thus, oriented monolayers are formed at the interfaces which signify the surface activity.

The primary classification of surfactant is made on the basis of the charge of the polar head group. Surfactant can be classified into (Darley and Gray, 1988):

- Anionics (Negatively charged group) dissociate into large organic anion and simple inorganic cation. The classic example is soap, such as sodium oleate:

$$[C_8H_{17}CH{:}CH(CH_2)_7COO]^-[Na]^+$$

- Cationics (Positively charged group) dissociate into large organic cation and a simple inorganic anion. They are usually the salt of a fatty amine or polyamine, for example, trimethyl dodecyl ammonium chloride:



$$\begin{bmatrix} & CH_3 & \\ C_{12}H_{25} & N & CH_3 \\ & CH_3 & \end{bmatrix}^+ [Cl]^-$$

- Nonionic (No charge group) surfactants are long chain polymers which do not dissociate, for example, phenol 30-mol ethylene:

$$C_6H_5 - O - (CH_2CH_2O)_{30}H$$

which is known in the drilling industry as DMS.

2.4. Introduction to Micellesation

A colloidal aggregate of a unique number (50→100) of amphipathic molecules, which occurs at a well-defined concentration, is called the critical micelle concentration. In polar media such as water, the hydrophobic part of the amphiphiles forming the micelle tends to locate away from the polar phase while the polar parts of the molecule (head groups) tend to locate at the polar micelle solvent interface (*McGraw-Hill Encyclopedia of Science and Technology*, 2005; Garret and Grisham, 2008).

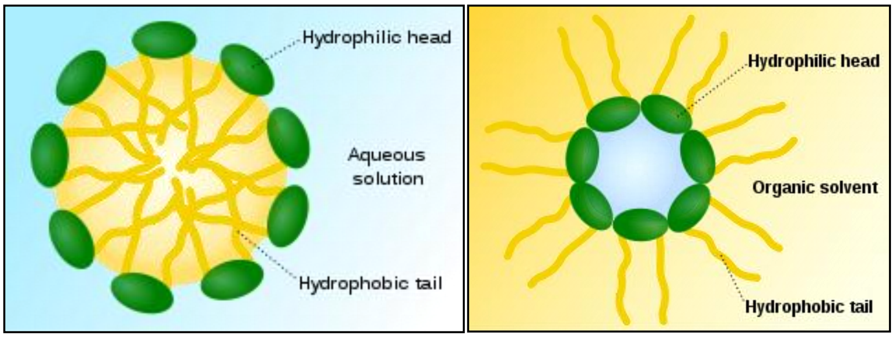


Figure 4: Micelles formation in polar medium (left) and non-polar medium (right) (*Wikibooks*, 2011)

Depends on the conditions and composition of the system, a micelle may take several forms Micelles are also formed in nonpolar media such as benzene, where the amphiphiles cluster around small water droplets in the system, forming an assembly known as a reversed micelle.

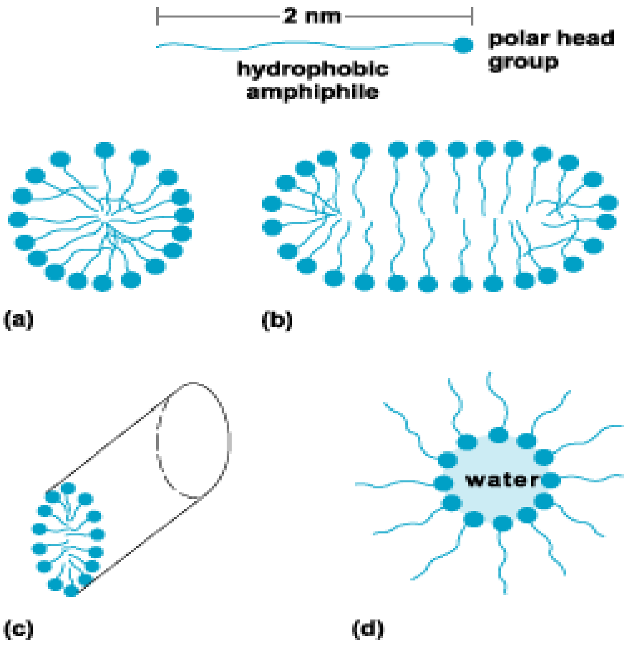


Figure 5: Form of an amphiphile and several forms of micelle: *(a)* spherical, *(b)* disk, *(c)* rod, and *(d)* reversed. (*McGraw-Hill Encyclopedia of Science and Technology*, 2005)

Surfactants are widely used and find a very large number of applications due to their remarkable ability to influence the properties of surfaces and interfaces (Schramm and Marangoni, 2000; Migahed and Al-Sabagh 2009). Among the surfactant applications in drilling fluid are listed below (Quintero, 2002):

- Oil in water emulsification in base fluid formations
- Prevention of differential sticking
- Foaming additives
- Dispersants to inhibit flocculation of clay particles
- Surfactant-polymer complexes for enhanced properties such as better rheological characteristics and reduction in fluid loss to formation in low pressure reservoirs

2.5. Polymer-Surfactant Interaction Mechanism

Nicora and William (1998) found that the addition of highly biodegradable, Alkylpolyglucosides (APG) even at very low concentrations to a polymer mud can drastically reduce the fluid loss even at high temperatures. The clusters of small APG micelles believed to be rod-shaped can attach to each polymer molecules with the APG forming hydrogen bonding and/or hydrophilic-hydrophobic interactions with the fluid loss polymer. It has been further suggested that this kind of interaction might be able to shield the polymer from oxidative degradation.

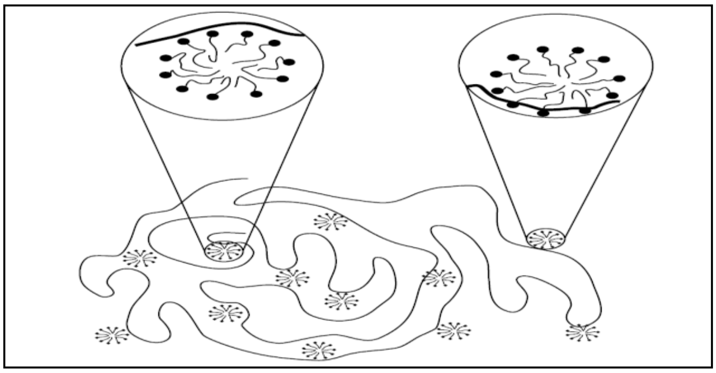


Figure 6: ‘Pearl-necklace model’ of surfactant-polymer association (*Holmberg et al.*, 2003)

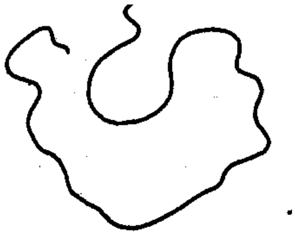
According to Holmberg *et. al.* (2003), the attractive **polymer-surfactant interactions** depend on both polymer and surfactant and there are two alternative pictures of mixed polymer-surfactant solutions:

- Association/**binding** of surfactant to the polymer (hydrophobic groups)

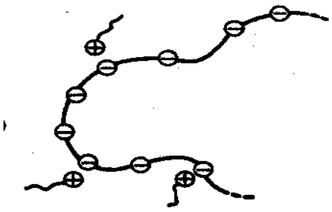
- A **micellization** of surfactant on/in the vicinity of the polymer chain (hydrophilic groups)

Another earlier research done by **Van Oort *et al.* (1997)** to exploit the interactions of polysaccharides, cellulosics and starches with polyglycols found that the hydrogen bonding and hydrophobic interactions were shielding the polymer from thermal degradation. Known as 'string-of-pearls', clusters of small micelles are attached to one polymer molecule. The forces governing the polymer-nonionic association are the hydrophobic interaction, aligning hydrophobic patches in the polymer with hydrophobic end-groups of the non-ionics, and H-bonding between more polar polymer groups and the EO or EO/PO chains of the non-ionics.

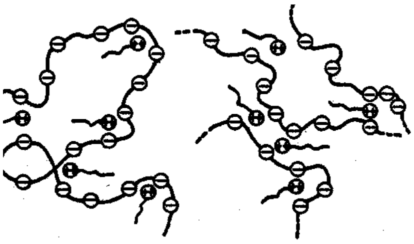
Both research works had been done to better understand the mechanism of polymer-micelle associations. Surfactant molecules contain two parts, one of which is soluble in polar medium (hydrophilic) and the other opposite end which is soluble in non-polar medium (hydrophilic). The dual nature of surfactant enables it to orient itself in various structures when immersed in polar and non-polar solvents. Furthermore, the presence of polymer molecules gives rise to changes in the solution and interfacial properties of surfactant compared to the polymer-free-systems (Srivatsa, 2010). Various possible structures can be expected through the polymer-surfactant interactions as shown in the next page (Nagarajan, 2001). The understanding of polymer-surfactant interaction will helps in the selection of suitable surfactant for HPHT drilling fluid.



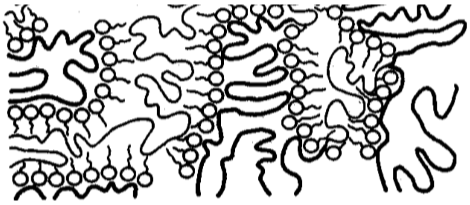
A. Polymer molecule does not interact with surfactants for electrostatic or steric reasons. No surfactant is bound to the polymer. For example, the surfactant and the polymer are both anionic or both cationic.



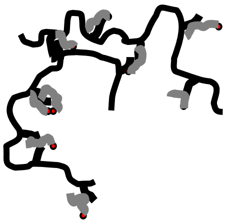
B. The polymer and the surfactant are oppositely charged. Single surfactant molecules are bound linearly along the length of the polymer molecules.



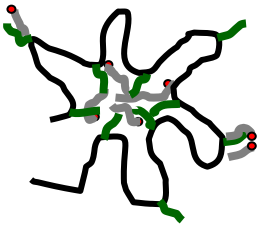
C. The polymer and the surfactant are oppositely charged. A single surfactant molecule binds at multiple sites on a single polymer molecule, giving rise to intra-molecular bridging. Alternatively, it binds to more than one polymer molecule allowing intermolecular bridging.



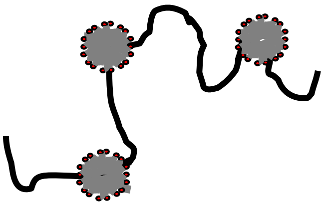
D. The polymer is an uncharged random or multiblock copolymer. The surfactant molecules orient themselves at domain boundaries separating the polymer segments of different polarities.



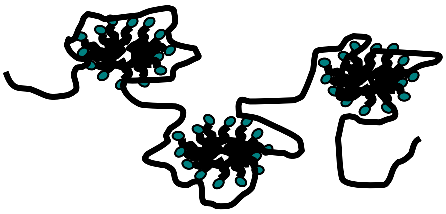
E. Polymer is hydrophobically modified. Individual surfactant molecules associate with one or more of the hydrophobic modifiers on a single polymer molecule or multiple polymer molecules.



F. Polymer is hydrophobically modified. Clusters of surfactant molecules associate with multiple hydrophobic modifiers on a single polymer molecule.



G. Polymer is hydrophobically modified. Clusters of surfactant molecules associate with each of the hydrophobic modifier on a single polymer molecule.



H. The polymer segments partially penetrate and wrap around the polar head group region of the surfactant micelles. A single polymer molecule can associate with one or more surfactant micelles.

Figure 7. Schematic visualization of various types of polymer-surfactant association structures involving nonionic polymers, charged polymers, random or multiblock copolymers, and hydrophobically modified polymers. (Nagarajan, 2001)

CHAPTER 3

METHODOLOGY

3.1 Project Approach Through Experimental Analysis

Laboratory work is carried out to investigate the interactions of common drilling fluid polymers with surfactant at elevated temperature. The polymers focused in this study are rheology modifier, Xanthan Gum (XC) and filtration control polymer, Poly Anionic Cellulose – Low Viscosity (PAC-LV). On the other hand, the surfactant used is a non ionic surfactant Polyethylene glycol (PEG) with molecular weight of 550.

In order to better understand the nature of fluid loss of common drilling fluid polymers at high temperature, experimental analysis was performed on base fluid (without surfactant) which consists of seawater as the continuous phase. The analysis carried out includes rheology test as well as API fluid loss test. The base fluid is evaluated before and after hot rolling of elevated temperature 100°C, 125°C and 150°C. The same procedures are repeated for fluid with surfactant, PEG550 added in order to understand its interactions with polymers and thus, finding its application in HPHT drilling fluid.

RHEOLOGY TEST	**FLUID LOSS TEST**	**HOT-ROLLING**
FANN Model 35A is used to test the rheology performances of mud slurry	API Filter Press is used to test the filtration performances of mud slurry	Roller Oven is used to hot-rolled mud slurry at desired temperatures for minimum of 16hours

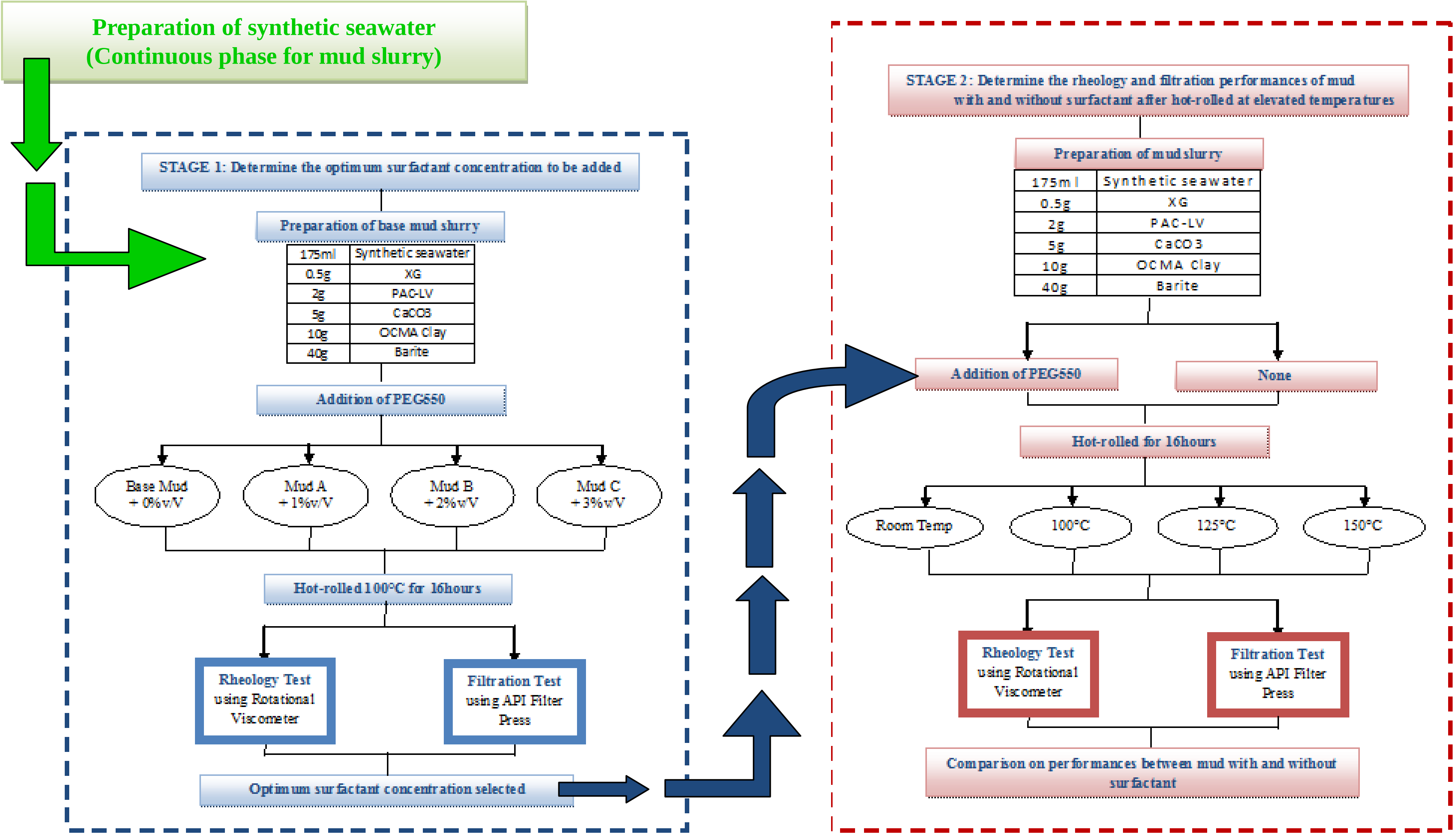


Figure 8: Project Flow Char

3.2 Raw Materials and Samples

There are two main fluid prepared for this experiment; **synthetic seawater**, the continuous phase of drilling fluid and **drilling fluid samples**. Each fluid has to be carried out in particular order to achieve consistent fluid blends for reliable results.

3.3.1 Synthetic Seawater

Synthetic seawater is prepared based on composition shown in **table 2**. To promote consistency in pH and hardness, freshly prepared synthetic seawater was used in every drilling fluid samples.

Compound		**Quantity**
Sodium Bicarbonate	$NaHCO_3$	0.2050g
Sodium Sulfate	Na_2SO_4	4.2883g
Sodium Chloride	$NaCl$	23.8333g
Calcium Chloride Dihydrate	$CaCl_2.2H_2O$	1.6433g
Magnesium Chloride Hexahydrate	$MgCl_2.6H_2O$	10.7733g
Distilled Water		1 Litre

Table 2: Compositions of synthetic seawater

Note that this synthetic seawater contains 10,550ppm sodium ions, 1693ppm combined divalent calcium and magnesium, and 33,756ppm total dissolved solids (Allan Stahl *et al.*, 1988).

3.3.2 Drilling Fluid Samples

The compositions for each mud are the same but with different additions of surfactant as shown in **table 3.**

In **stage I**, the objective is to determine the optimum concentration of PEG550 in samples which will yield the optimal rheological and filtration performances. Thus, samples in different concentration (0% v/V, 1% v/V, 2% v/V, 3% v/V) were tested.

Samples Nomenclature

Samples		Types of drilling fluid	Elements						
Stage I									
BaseMud		Blank	0ml PEG550	175ml synthetic seawater	0.5g XC	2g PAC-LV	5g CaCO3	10g OCMA Clay	40g Barite
A		+1% v/v surfactant	1.75ml PEG550						
B		+2% v/v surfactant	3.5ml PEG550						
C		+3% v/v surfactant	5.25ml PEG550						
Stage II									
Base Mud	BH	Blank	0ml PEG550	175ml synthetic seawater	0.5g XC	2g PAC-LV	5g CaCO3	10g OCMA Clay	40g Barite
	AH100C								
	AH125C								
	AH150C								
Surfactant Mud	BH	+2% v/v surfactant	3.5ml PEG550	175ml synthetic seawater	0.5g XC	2g PAC-LV	5g CaCO3	10g OCMA Clay	40g Barite
	AH100C								
	AH125C								
	AH150C								

Table 3: Drilling fluid samples

In **stage II**, the objective is to determine the rheological and filtration properties of mud with and without surfactant at elevated temperatures. Thus, samples will be hot-rolled at 4 different temperatures (room temperature, 100°C, 125°C and 150°C) before tested.

Note that the concentration of surfactant for stage II is constant and will be determined after stage I is completed.

3.3 Tools and Equipments

The laboratory equipments required for drilling fluid preparation, drilling fluid hot-rolling stages, and laboratory testing has been listed below. The primary function of the equipments is also shown.

Equipments / Tools	Primary Function
Electronic Balance	Weighting raw materials
Graduated Cylinder	Volume measurements
Multi-Mixer (Model 9B)	Mixing of drilling fluid
Roller Ovens	Aging fluid samples
Aging Cells	Contains drilling fluid for aging
Viscometer Model 35	Measures viscosity of drilling fluid
Filter Press API	Determines the filtration properties of drilling fluid
Filter Paper 3.5" (9cm)	To be used together with filter press API
Vernier Caliper	Measures mud cake thickness
Stopwatch	Accurately measures elapsed time
Digital pH Meter	Determines pH of drilling fluid

Table 4: List of tools and equipments

3.3.1 Rotational Viscometer

Figure 9: Fann Model 35A (www.fann.com, 2011)

The rotational viscometer was developed for better and accurate readings of viscosity. March Funnel was the default choice for measurement of viscosity during early days. The rotational viscometer shown at **Figure 9** is FANN Model 35A. It has fixed speeds of 3(GEL), 6, 100, 200, 300, and 600RPM that are switch selectable with RPM knob.

3.3.2 API Filter Press

Figure 10: Filter Press API (www.fann.com, 2011)

The Series 300 APT Low Pressure Low Temperature (LPLT) Filter Press consists of a mud reservoir mounted in a frame, a pressure source, a filtering medium, and a graduated cylinder for receiving and measuring filtrate. The basic unit has a cell assembly constructed of rustproof anodized aluminum and chrome plated brass, and includes the required screen and gaskets.

Working pressure is 100 psig and the filtering area is 7.1-in^2, as specified in the American Petroleum Institute, *API Recommended Practice 13B-1 and 13B-2.*

3.4 Laboratory Work Procedures

3.4.1 Preparation of Mud Samples

Multi-mixer is used in this stage. To prepare the base mud, 175ml freshly prepared seawater is poured into the multi-mixer cup and stirred well. Xanthan gum is firstly added into the cup slowly bit by bit. After all xanthan gum has been added, mixture is stirred for another 5 minutes before adding the next compounds. Then, polyacrylamide (PAC-LV) is added slowly and stirred for another 2 minutes again. The same steps are repeated for OCMA clay and barite. Calcium Carbonate ($CaCO_3$) is added after 35 minutes of stirring. The mixing of one mud sample took about 45 minutes. For mud samples with surfactant, surfactant is added into the base mud after 40 minutes of stirring.

Figure 11: Drilling fluid after mixing – base mud (left), mud with surfactant (right)

3.4.2 Mud Rheology Test

175ml of the prepared mud is taken and poured into a viscometer cup. The upper housing of viscometer is tilted back to locate the cup under the sleeve. Then, the upper housing is lowered to its normal position. Mud in the cup is stirred for about 5 seconds at 600rpm before the desired RPM is selected. Readings at 600, 300, 200, 100, 6 and 3 rpm are taken and recorded.

Another rheological parameter, gel strength measured in lb/100sqft is also obtained by noting the maximum dial deflection of viscometer turned to low rotor speed (3 rpm) after the mud is remained static for some period of time. The mud remained static for 10 seconds is recorded as 10s gel strength while 10 minutes as 10min gel strength.

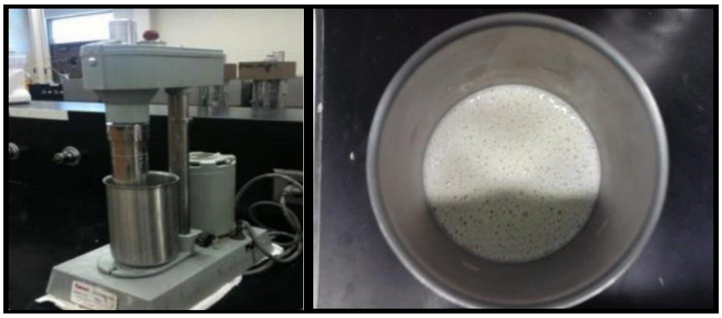


Figure 12: Rheology test in progress (left), mud samples in cup ready for test

3.4.3 Fluid Loss Test

The prepared mud is poured to a filter press cup and which is assembled as shown in **figure 14** earlier. 100psi of pressure is applied through an air supply line and the valve is opened. At the same time, timing clock is started. The volume of fluid collected in graduated cylinder is recorded every minute for duration of 30 minutes. The thickness of filter cake developed on the filter paper is also measured using a scale nearest 1/32” and observed physically.

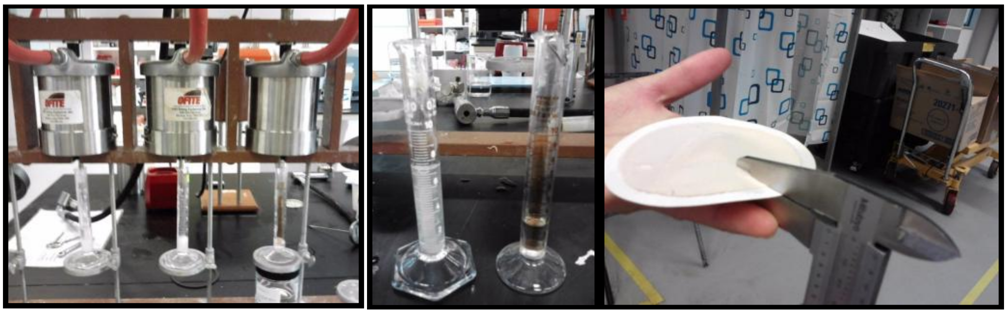


Figure 13: Fluid loss test in progress (left), filtrates collected in 10ml graduated cylinder (middle), mudcake measurement using vernier calliper (right)

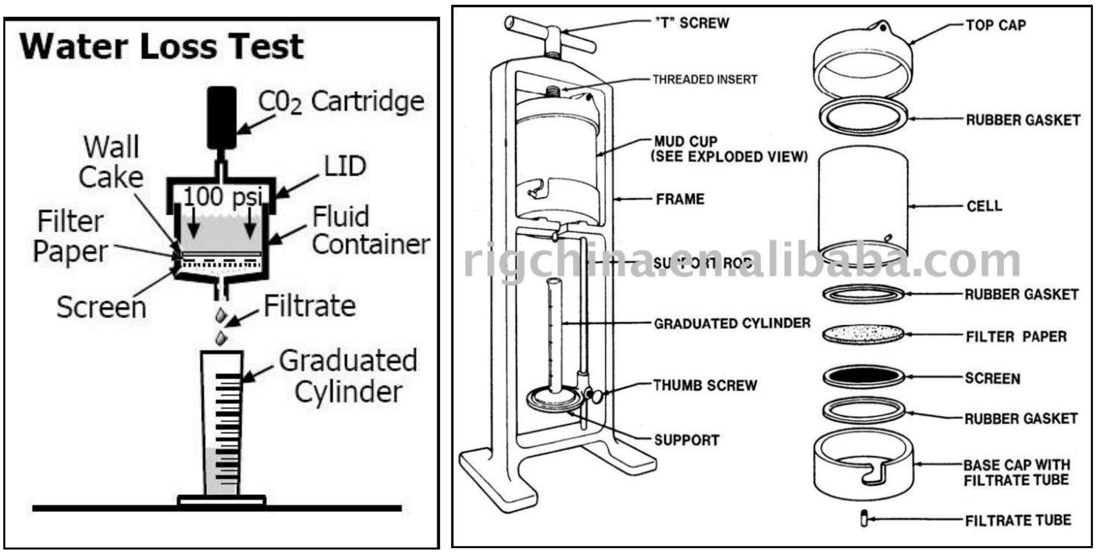


Figure 14: Arrangement of Standard API Filter Press (www.straightlinehdd.com, 2006)

3.4.4 Aging of Mud Samples at High Temperatures

Roller oven is used for this stage. 175ml of mud sample is contained in a stainless steel cell of 260ml. Then, the cell is pressurized with nitrogen to prevent boiling of the liquid phase during aging at high temperatures later. The applied pressure should be at least equal to the vapour pressure of liquid at the test temperature. Roller oven is set to be at desired test temperature and the cell is placed in it and rolled. The purpose of roller oven is to stimulate aging of mud while it is circulating in the well. The minimum time for aging is 16 hours.

Figure 15: Roller oven (left), Mud sample after aging at high temperature (right)

3.5 Project Schedule

ACTIVITIES	FYP I				FYP II			
	S	O	N	D	J	F	M	A
Literature review and understanding of theory	■	■						
Research ethodology and preparation of materials and apparatus			■	■				
Measurement of Polyethylene gylcol (PEG550) surfactant physical properties					■			
Formulation of drilling mud based on spe paper					■			
Rheological and filtration properties test on base drilling mud						■	■	
Rheological and filtration properties test on PEG550 surfactant added drilling mud						■	■	
Comparison for effect of PEG550 surfactant and analysis of results							■	■
Documentation of PEG550 surfactant drilling fluid								■

MILESTONES	FYP I				FYP II			
	S	O	N	D	J	F	M	A
Completion of theory understanding and research methodology				■				
Documentation of PEG550 surfactant physical properties					■			
Formulation of drilling mud ready for experiments					■			
Documentation of rheological and filtration properties of base mud (polymer-based mud)							■	
Documentation of rheological and filtration properties of PEG550 surfactant drilling mud							■	
Documentation of improvement done by PEG550 surfactant drilling mud								■
Project completion								■

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Data Gathering and Analysis

Generally, the laboratory work is divided into two (2) stages:

Stage	Objectives
Stage I	To determine the optimum addition (concentration) of surfactant in drilling mud before and after hot rolling
Stage II	To determine the rheological and fluid loss performances of drilling mud with and without surfactant at elevated temperature.

Firstly, evaluation on the effect of various surfactant concentrations on mud has been carried out. The purpose is to determine the sufficient concentration of surfactant in polymer based drilling fluid in order to yield optimal rheological and filtration performances when exposed to high temperatures (after hot-rolling). These performances will reflect mud thermal stability and therefore, optimum concentration is then selected.

Next, experimental analysis is proceeded to stage II whereby hot rolling temperature is increased by the factor of 25°C each time and the effect of various temperatures on surfactant mud are observed. Rheological and filtration performances reflect its thermal stability. To determine whether there is any improvement after addition, the performances of mud samples without surfactant are used as benchmark.

All the stages of laboratory work were similar and the steps are shown in **figure 16** below. Generally, the main parameters observed and focused are the rheological and fluid loss properties.

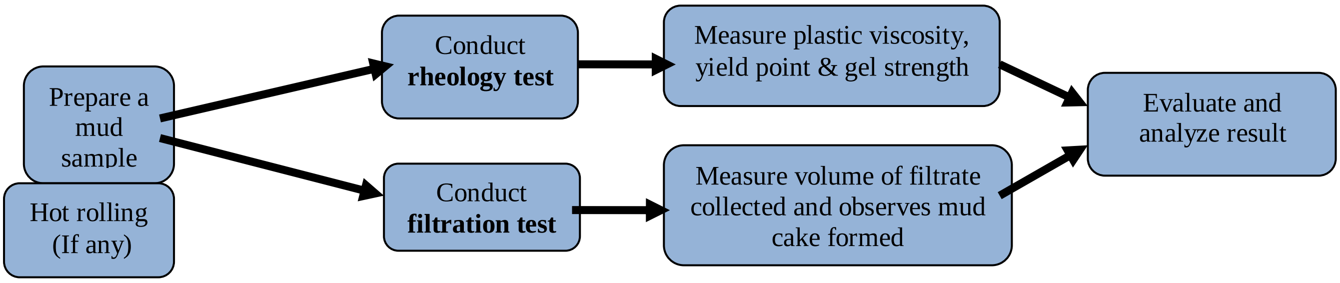


Figure 16: Flow sheet of experimental procedure

4.2 Rheology Measurements

The Fann 35 viscometer was used to measure the shear characteristic of the drilling fluid at six (6) different speeds; 600rpm, 300rpm, 200rpm, 100rpm, 6rpm and 3rpm. The 10s and 10min gel strength were also measured.

4.2.1 Samples After Addition of Surfactant

Table 5 shows the shear rate and shear stress values for polymer mud and polymer-surfactant mud.

Parameters		Shear rate	Shear stress	Parameters		Shear rate	Shear stress
Mud	RPM			Mud Samples	RPM		
Polymer mud	600	1057	57337	Polymer-surfactant mud	600	1076	82898
	300	528	36487		300	538	56665
	200	352	28009		200	359	45357
	100	176	17823		100	179	31003
	6	11	2846		6	11	6617
	3	5	1811		3	5	4523

Table 5: Calculated shear rate and shear stress values for polymer mud and polymer-surfactant mud

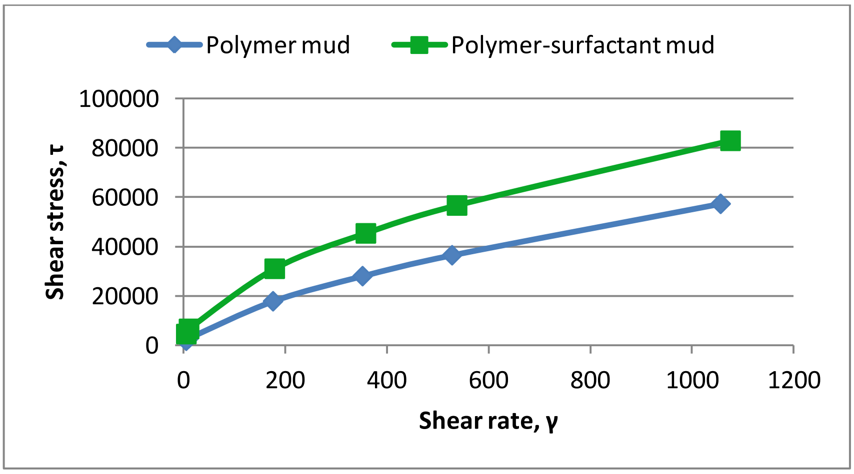


Figure 17: Shear stress vs shear rate polymer mud and polymer-surfactant mud

Water-based mud with polymer additives exhibits pseudo-plastic characteristic. The curve shown is non-linear with no definite yield point approaching linearity at high shear rate. After addition of surfactant, mud sample also exhibiting the non-linear curve shape as shown in **figure 17**. The mixture of polymer-surfactant mud matches the performance of polymer fluid system.

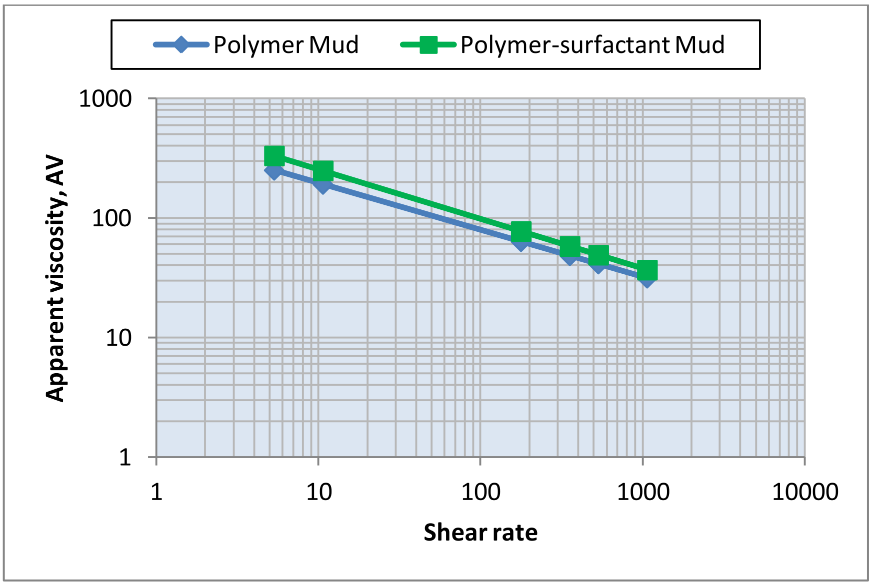
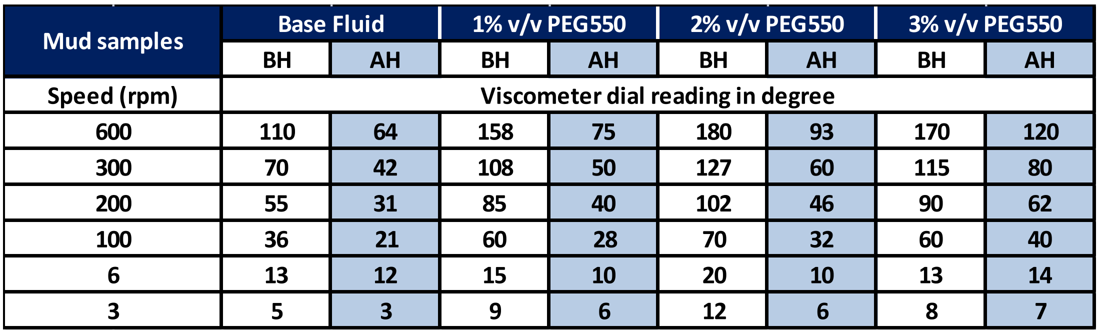


Figure 18: Apparent viscosity vs shear rate polymer mud and polymer-surfactant mud

Figure 18 showed that both mud displayed high viscosity during static condition (tripping operation) and low viscosity during dynamic condition (drilling operation). At static condition, long chain of polymer are randomly entangled, however, they do not set up a structure due to predominately repulsive electrostatic forces. At dynamic condition, the chains tend to align themselves parallel to the direction of flow. As shear rate increases, this tendency also increases which causes the effective viscosity of fluid to decrease. This type of fluid is favourable. Therefore, addition of surfactant does not affect the performances of mud to act as pseudo-plastic fluid.

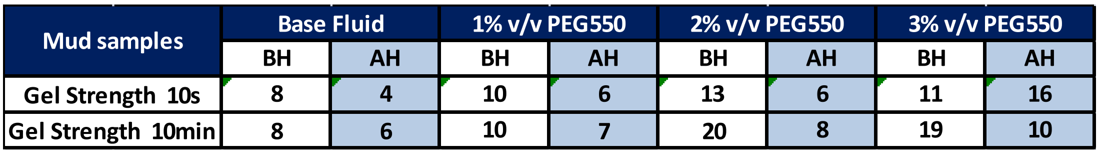
4.2.2 Stage I: Effect of Various Addition of Surfactant

Table 6 & 7 shows the result before hot rolling and after hot rolling of mud samples at 100°C for various addition of surfactant.



Mud samples	Base Fluid		1% v/v PEG550		2% v/v PEG550		3% v/v PEG550	
	BH	AH	BH	AH	BH	AH	BH	AH
Speed (rpm)	Viscometer dial reading in degree							
600	110	64	158	75	180	93	170	120
300	70	42	108	50	127	60	115	80
200	55	31	85	40	102	46	90	62
100	36	21	60	28	70	32	60	40
6	13	12	15	10	20	10	13	14
3	5	3	9	6	12	6	8	7

Table 6: Viscometer reading for mud samples (Stage I)



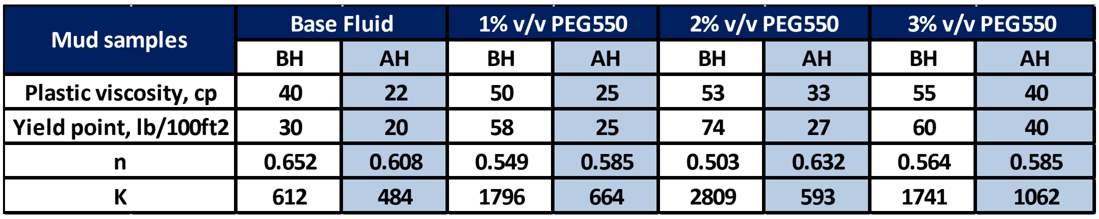
Mud samples	Base Fluid		1% v/v PEG550		2% v/v PEG550		3% v/v PEG550	
	BH	AH	BH	AH	BH	AH	BH	AH
Gel Strength 10s	8	4	10	6	13	6	11	16
Gel Strength 10min	8	6	10	7	20	8	19	10

Table 7: 10s and 10min gel strength (Stage I)

The flow behaviour of pseudoplastic fluids is illustrated using power law model:

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

Where K is the consistency index and n is the flow behaviour index. For pseudoplastic fluids, n <1.



Mud samples	Base Fluid		1% v/v PEG550		2% v/v PEG550		3% v/v PEG550	
	BH	AH	BH	AH	BH	AH	BH	AH
Plastic viscosity, cp	40	22	50	25	53	33	55	40
Yield point, lb/100ft2	30	20	58	25	74	27	60	40
n	0.652	0.608	0.549	0.585	0.503	0.632	0.564	0.585
K	612	484	1796	664	2809	593	1741	1062

Table 8: Power law model calculation (Stage I)

Based on **table 8**, all mud samples exhibits pseudoplastic fluids behaviour as all calculated n values are smaller than 1. All rheology were lost after 16 hours of hot-rolling of the base solution, polymer mud without addition of surfactant. Xanthan gum (polymer additive) used to provide pseudoplastic behaviour for the mud is thermally stable up to 120°C only. Therefore, it had slowly degraded when exposed to high temperature. However, with addition of increasing surfactant into polymer mud, rheology was retained. It can also be observed that the more surfactant is added, the lesser affected plastic viscosity and yield point by high temperature. This behaviour shows that increasing surfactant concentration will more increases the thermal stability of mud.

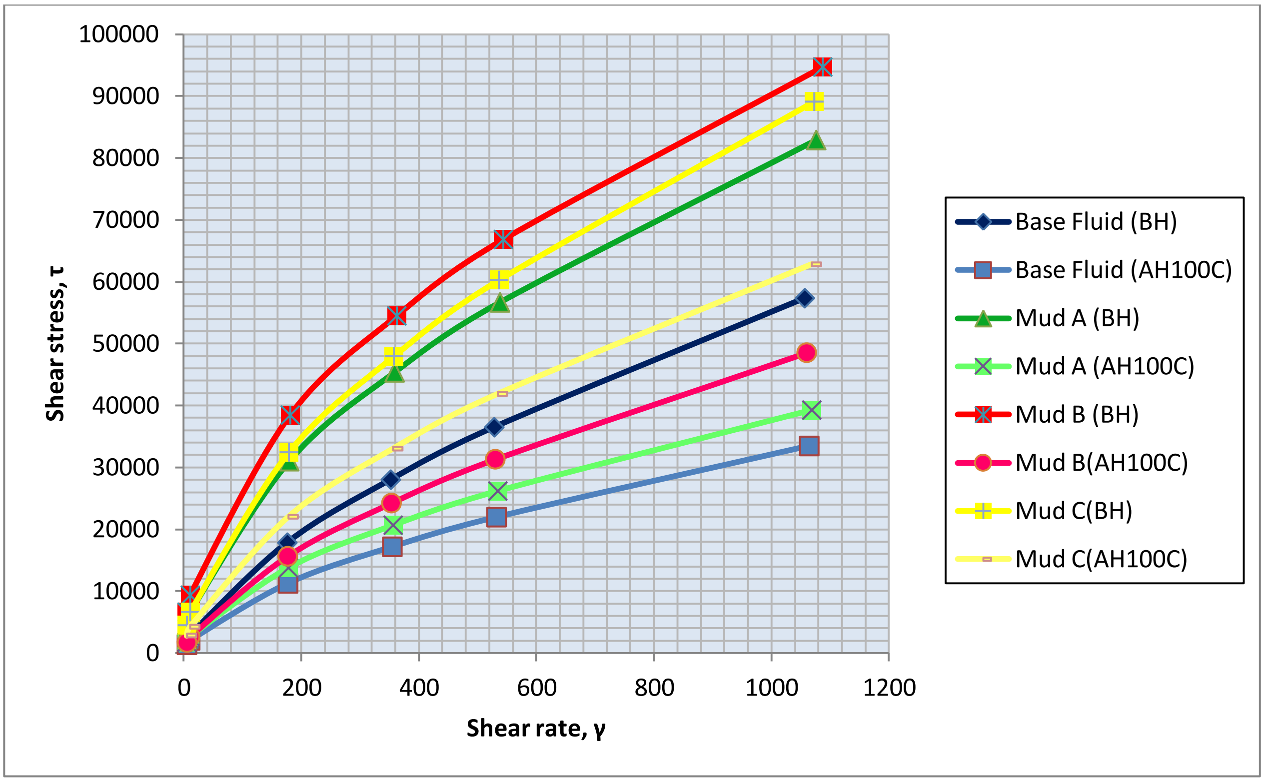


Figure 19: Shear stress vs shear rate for all mud samples (Stage I)

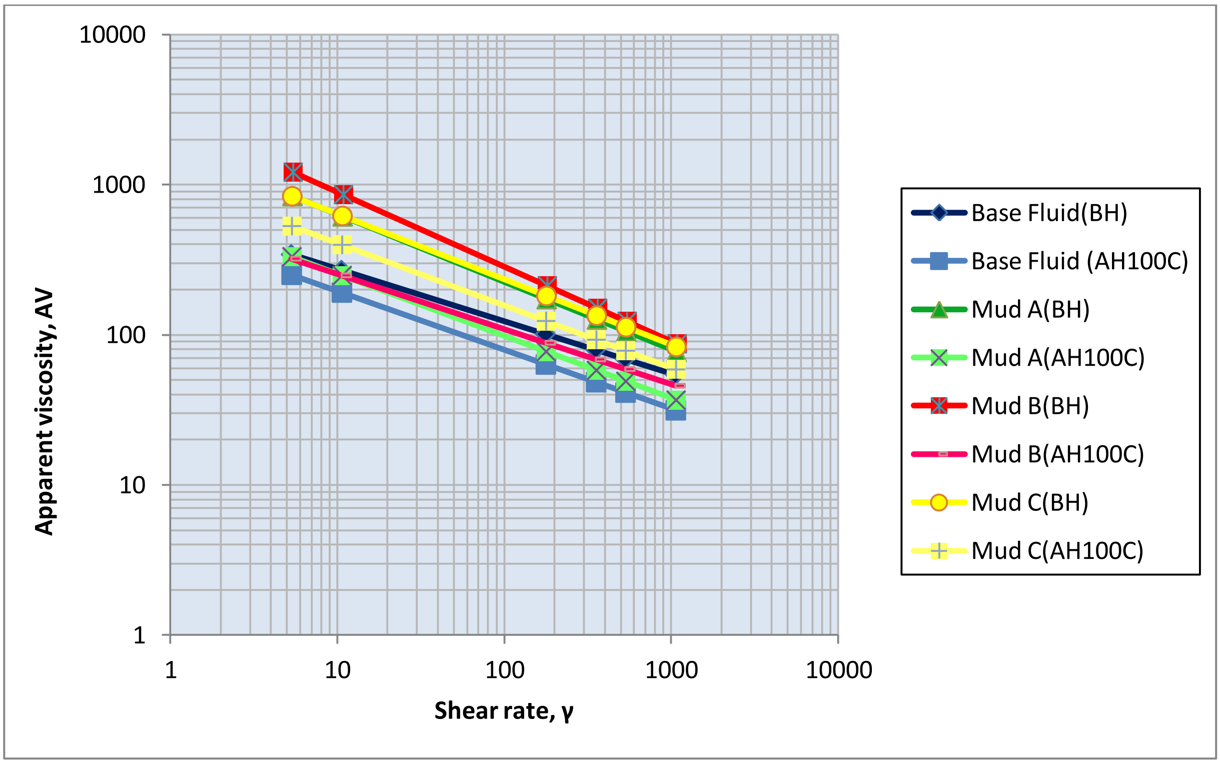


Figure 20: Apparent viscosity vs shear rate for all mud samples (Stage I)

Figure 20 shows the apparent viscosity vs shear rate for all mud samples before and after hot-rolling. The results show that the apparent viscosity decreases after they were exposed to high temperature of 100°C. For base fluid, rapid decrease was noticed at high shear. However, the rate of decrease for muds with surfactant was mostly constant. Surprisingly, mud B shows a remarkable reverse rate of apparent viscosity decrease at high temperature. Its apparent viscosity does not decrease much as when compared to lower shear rate. As a result, sufficient viscosity for hole cleaning can be maintained when drilling goes deeper with higher temperature. Thus, 2%v/V of surfactant addition into base mud is chosen to be the optimum choice.

4.2.3 Stage II: Effects of Elevated Temperatures

Table 9 & 10 shows the results of mud with and without surfactant at elevated temperatures.

Mud samples	Without PEG550				With PEG550			
	BH	AH 100°C	AH 125°C	AH 150°C	BH	AH 100°C	AH 125°C	AH 150°C
Speed (rpm)	Viscometer dial reading in degree							
600	110	64	29	8	180	93	55	11
300	70	42	19	6	127	60	35	7
200	55	31	14	4	102	46	26	5
100	36	21	10	3	70	32	18	4
6	13	12	2	1	20	10	7	1
3	5	3	1	0	12	6	3	0

Table 9: Viscometer reading for mud samples (Stage II)

Mud samples	Without PEG550				With PEG550			
	BH	AH 100°C	AH 125°C	AH 150°C	BH	AH 100°C	AH 125°C	AH 150°C
Gel strength 10s	8	4	1	1	13	6	3	1
Gel strength 10min	8	6	1	1	20	8	4	1

Table 10: 10s and 10 min gel strength (Stage II)

Based on rough observation of the above results, rheology for all muds decreased every time when temperature increased by a factor of 25°C. Also, it is clearly shown that values are higher for surfactant-polymer mud compared to polymer mud. Rheological performance for polymer-surfactant mud still remains high even until AH125°C. However, all rheology for both mud were lost after hot-rolling at 125°C.

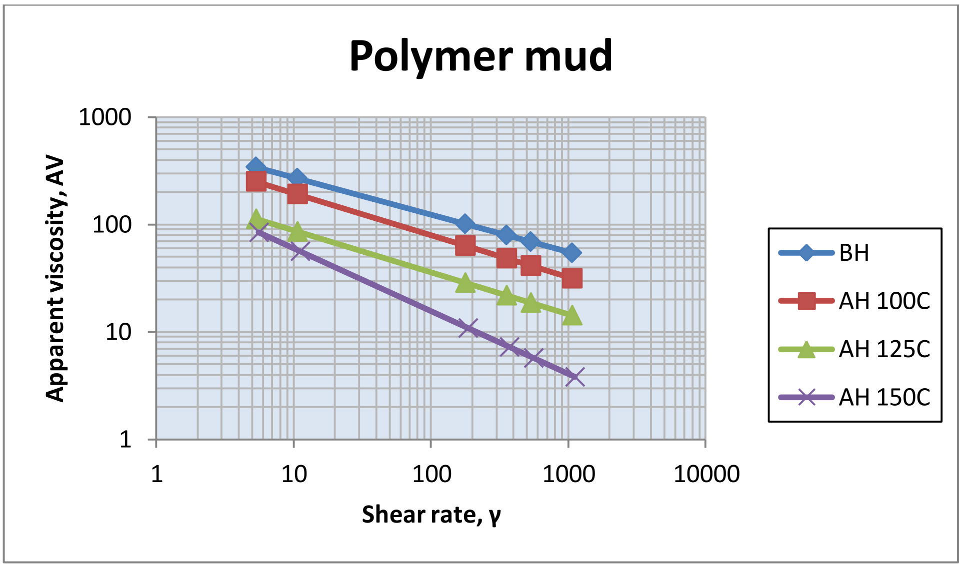
For comparison purpose, data such as plastic viscosity, yield point, n and K value were calculated and tabulated in **table 11**.

Mud samples	Without PEG550				With PEG550			
Parameters	BH	AH 100°C	AH 125°C	AH 150°C	BH	AH 100°C	AH 125°C	AH 150°C
Plastic viscosity, cp	40	22	10	2	53	33	20	4
Yield point, lb/100ft2	30	20	9	4	74	27	15	3
n	0.652	0.608	0.610	0.415	0.503	0.632	0.652	0.652
K	612	484	216	230	2809	593	306	61

Table 11: Power law model calculation (Stage II)

The rheological performances of both mud with and without surfactant decreases as temperature increases, indicating performances deterioration of xanthan gum (polymer additive) is becoming more significant. This deterioriation occurs due to the nature degradation of xanthan gum as temperature increases. The components of the long chain backbone of polymer begin to separate (molecular scisson) and react with one another to change the properties of the polymer at high temperature. However, the rheology of mud with surfactant remains higher even at elevated temperatures. The polymer-polyglcol association formed probably shields the polymer from oxidation (perhaps polyglcol acts as sacrificial agent), thereby reducing the degradation rate (Van Oort *et al.*, 1997).

The apparent viscosity versus shear rate for both mud with and without surfactant under elevated temperatures were also plotted in log log graphs and presented in **figure 21**.



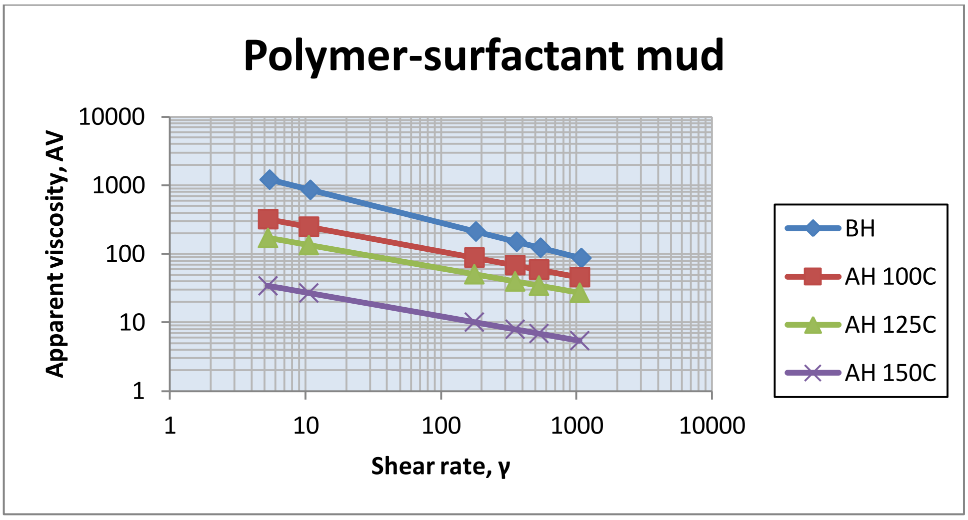


Figure 21: Apparent viscosity vs shear rate at elevated temperatures for polymer mud (top) and polymer-surfactant mud (bottom) - Stage II

It is known earlier (stage I) that apparent viscosity of all muds decreased when exposed to high temperature of 100°C. In stage II, it was observed that as temperature goes higher, decrease of its apparent viscosity goes on. For polymer mud, the rates of decrease at elevated temperatures mostly are not constant. The decrease was found to be more pronounced at higher shear rate. On the other hand, the apparent viscosities of polymer-surfactant mud at elevated temperatures decreased constantly throughout different shear rates. Its final apparent viscosity after hot-rolling of 150°C is still maintained higher than polymer mud.

4.3 Filtration Measurements

The API Filter Press was used to evaluate the filtration properties of the drilling fluid after hot-rolling at elevated temperatures; AH100°C, AH125°C, and AH150°C.

The conditions recommended by the API are as follows:

Time: 30 minutes

Pressure: 100psi

Area of cake: $7in^2$

The thickness of mud cakes were also measured and observed.

4.3.1 *Filtrate Volume As A Function of Surfactant Concentration*

Table 12 shows the fluid loss over a period of 30 minutes for mud with various additions of surfactant; 0%v/V, 1%v/V, 2%v/V and 3%v/V

Mud samples	**Base Fluid**		**1% v/v PEG550**		**2% v/v PEG550**		**3% v/v PEG550**	
	BH	**AH**	**BH**	**AH**	**BH**	**AH**	**BH**	**AH**
Time (min)	**Volume of filtrate (ml)**							
5	**1.3**	**8.7**	**1.4**	**4.1**	**1.5**	**2.6**	**1.5**	**3.2**
10	**1.9**	**9.3**	**1.9**	**5.0**	**2.1**	**3.5**	**2.3**	**4.1**
15	**2.4**	**9.9**	**2.4**	**5.7**	**2.7**	**4.1**	**2.9**	**4.6**
20	**2.9**	**10.5**	**2.9**	**6.4**	**3.4**	**4.6**	**3.5**	**5.2**
25	**3.2**	**11.0**	**3.2**	**7.0**	**3.7**	**5.1**	**3.9**	**5.7**
30	**3.6**	**11.5**	**3.7**	**7.4**	**4.0**	**5.8**	**4.3**	**6.1**
Fluid Loss (ml)	**3.6**	**11.5**	**3.7**	**7.4**	**4.0**	**5.8**	**4.3**	**6.1**

Table 12: API fluid loss after hot-rolling 100°C for different surfactant concentration (Stage I)

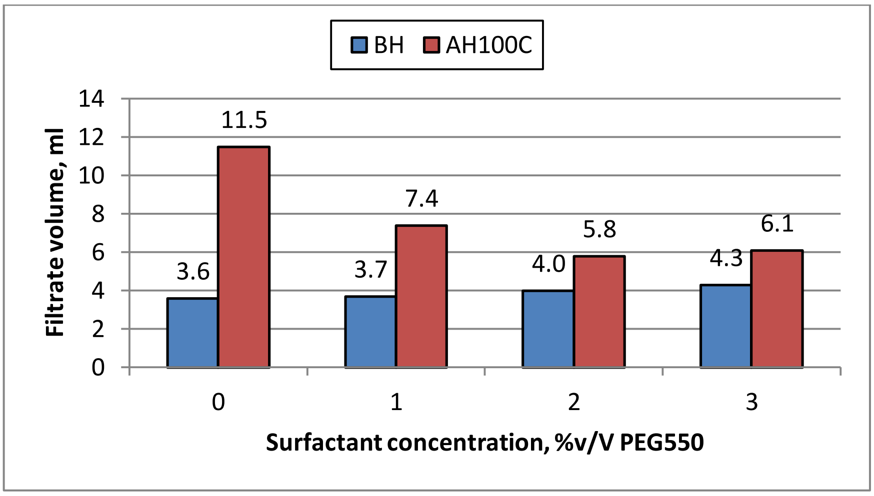


Figure 22: API fluid loss after hot-rolling 100°C for different surfactant concentration (Stage I)

The API fluid loss for all mud before hot-rolling is approximately the same ranging from 3.6 – 4.3ml. Mud samples with added surfactant seem to experience slightly higher fluid loss compared to base mud. After hot-rolling at 100°C, on the other hand, base mud experienced the highest fluid loss. As surfactant concentration increases, fluid loss decreases. Mud with 2%v/V PEG550 was found to experience the lowest fluid loss among all AH mud samples. Thus, an addition of PEG550 into the base mud did decrease the degradation of fluid loss polymer and 2%v/V is sufficient enough.

4.3.2 Filtrate Volume As A Function of Elevated Temperatures

Table 13 shows the results for mud with and without the addition of surfactant at elevated temperatures of 100°C, 125°C, and 150°C.

Mud samples	Without PEG550				With PEG550			
	BH	AH 100°C	AH 125°C	AH 150°C	BH	AH 100°C	AH 125°C	AH 150°C
Time, s	Volume of filtrate, ml							
5	1.3	7.4	27.40	TLC	1.4	2.6	18.90	TLC
10	1.9	8.4	38.50		2.3	3.5	24.60	
15	2.4	9.0	45.70		2.9	4.1	27.20	
20	2.9	9.6	59.80		3.5	4.6	28.70	
25	3.2	10.1	63.40		3.8	5.3	30.10	
30	3.6	10.5	66.10		4.0	5.8	30.70	
Fluid Loss (ml)	3.6	10.5	66.1		4.0	5.8	30.7	

Table 13: API fluid loss at elevated temperatures (Stage II)

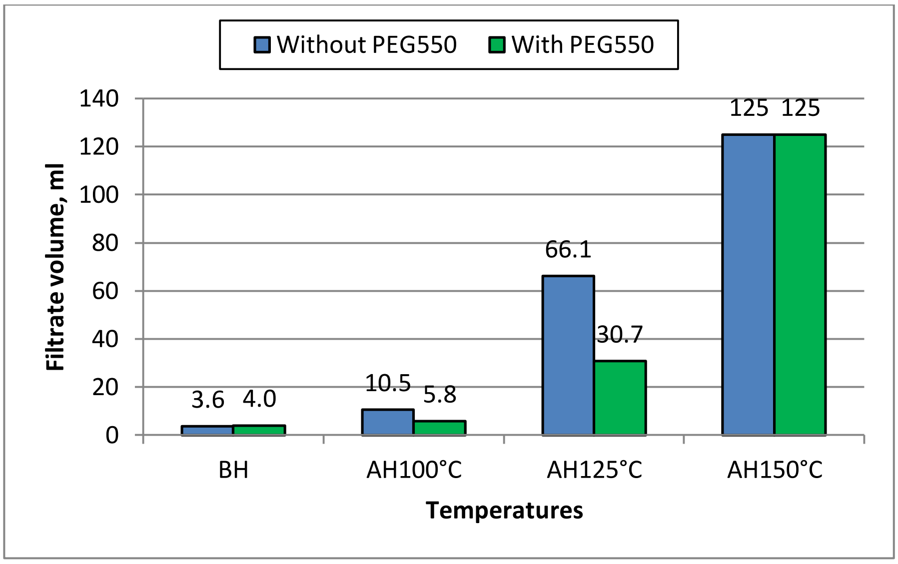


Figure 23: API fluid loss at elevated temperatures (Stage II)

Figure 23 shows that the fluid loss for all mud increases as temperature increases. The increase in temperature reduces the viscosity of the filtrate and thus, filtrate volume increases. The viscosity deterioration at elevated temperature was caused by the thermal degradation of polymer (viscosifier), xanthan gum which is only thermally stabilized up to 120°C as proven and shown earlier. So, it is evident that changes in temperature may have substantial effect on filtrate volume due to the changes in filtrate viscosity.

With added surfactant, however, it was found that the rate of increase in fluid loss is lower by approximately half compared to the mud without surfactant. This behaviour continued for temperature up to 125°C. At 150°C, total lost control (TLC) was observed for both mud with and without surfactant. All filtration properties were lost at this stage.

4.4 pH Measurement

Mud samples	Base Fluid		1% v/v PEG550		2% v/v PEG550		3% v/v PEG550	
	BH	AH	BH	AH	BH	AH	BH	AH
pH	8.06	7.36	7.97	7.13	7.94	6.92	7.73	6.93
Temperature (°C)	28.2	47.8	28.2	53.6	28.2	50.8	28.7	36.8

Table 14: pH measurements and temperature (Stage I)

Table 14 shows the pH measurements of all mud with increasing surfactant concentration and their ambient mud temperature. A decrease on pH was observed on all mud samples with added surfactant. This decrease in pH measurement is due to the raw material of surfactant. Its fatty acid methyl esters are usually opoxidized either from peracetic acids or from hydrogen peroxide and a suitable catalyst. Therefore, it gives a drop in mud pH measurement after addition. Also, as the concentration of surfactant in mud increased, its pH also decreases and mud sample becomes more acidic.

Mud samples	Without PEG550				With PEG550			
	BH	AH 100°C	AH 125°C	AH 150°C	BH	AH 100°C	AH 125°C	AH 150°C
pH	8.06	7.36	7.45	7.65	7.94	6.92	6.98	7.25
Temperature (°C)	28.2	47.8	57.4	47.8	28.2	50.8	51.8	61.3

Table 15: pH measurements and temperature (Stage II)

Table 15 shows the pH measurements of mud samples after hot-rolling at elevated temperatures. The polymer-surfactant mud (BH) had a decrease in pH after the addition of surfactant as explained earlier. After hot-rolling, however, an increase in mud pH was observed. As temperature of hot-rolling increases, pH of polymer-surfactant mud increases which indicates the vanishing of surfactant from mud system and mud becomes less acidic. This behaviour may indicate the sacrificial of surfactant in the process of preventing polymer from thermal degradation.

4.5 Performance Improvement of Mud After Addition of Surfactant

Figure 24 shows a plot of mud without and with surfactant after hot-rolling at elevated temperatures. For easy comparison, noted that the results of mud with surfactant were plotted in black lines and were also indicated with double star (**) in the legend. After addition, it was found that the viscosity of mud was retained and deterioration of rheological performances is lessened even at elevated temperatures.

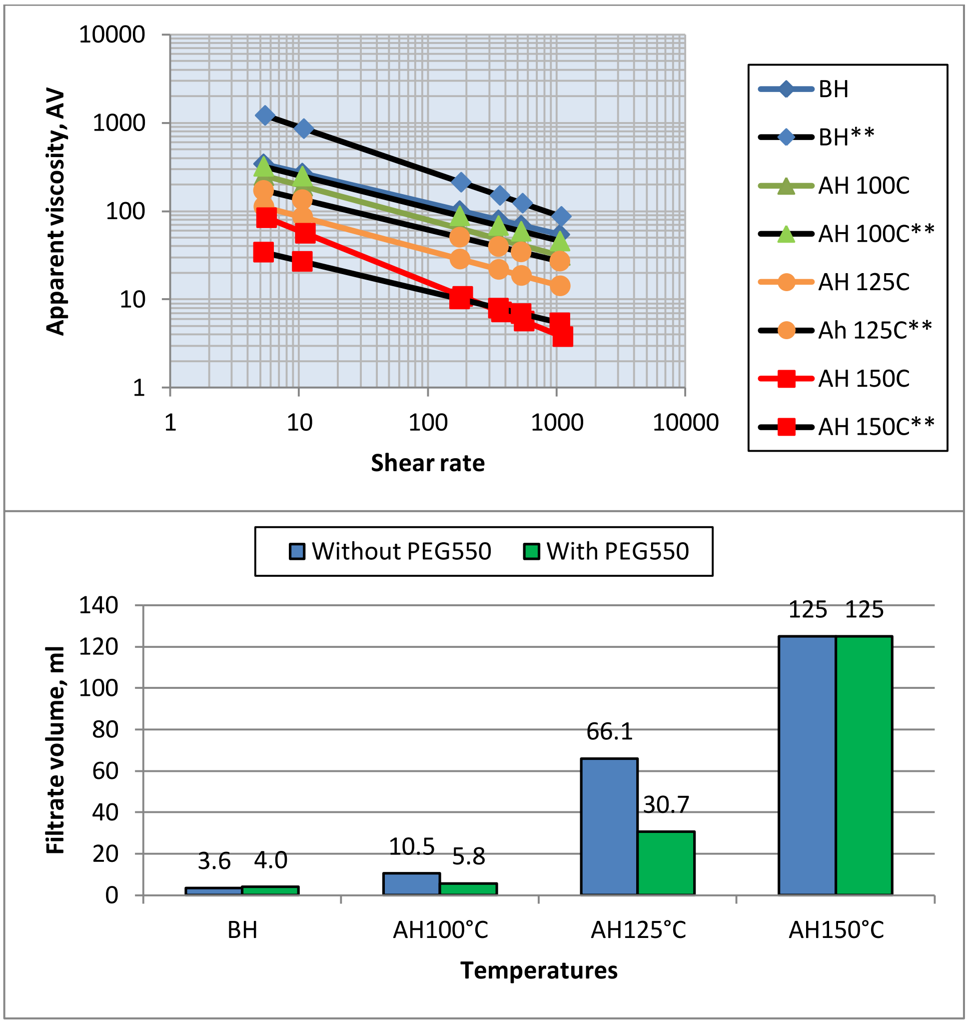


Figure 24: Performance improvement after addition of surfactant on rheological properties (top) and filtration properties (bottom)

It was also found that addition of surfactant remarkably slowed down the rate of fluid loss by half when mud was exposed to temperatures up to 125°C. Thus, this maintains a stabilized viscosity for optimum mud performances.

4.6 Performance Improvement of Mud After Addition of Increasing Surfactant Concentration

Figure 25 shows a plot of apparent viscosity versus shear rate of mud with increasing surfactant concentration. For easy comparison and relation to high temperature, noted that only the results of mud which undergone hot-rolling at 100°C were shown. It was found that as surfactant concentration increases, viscosity of mud would also increases. This behaviour is favourable as sufficient viscosity of mud can be retained at even higher temperatures by increasing concentration.

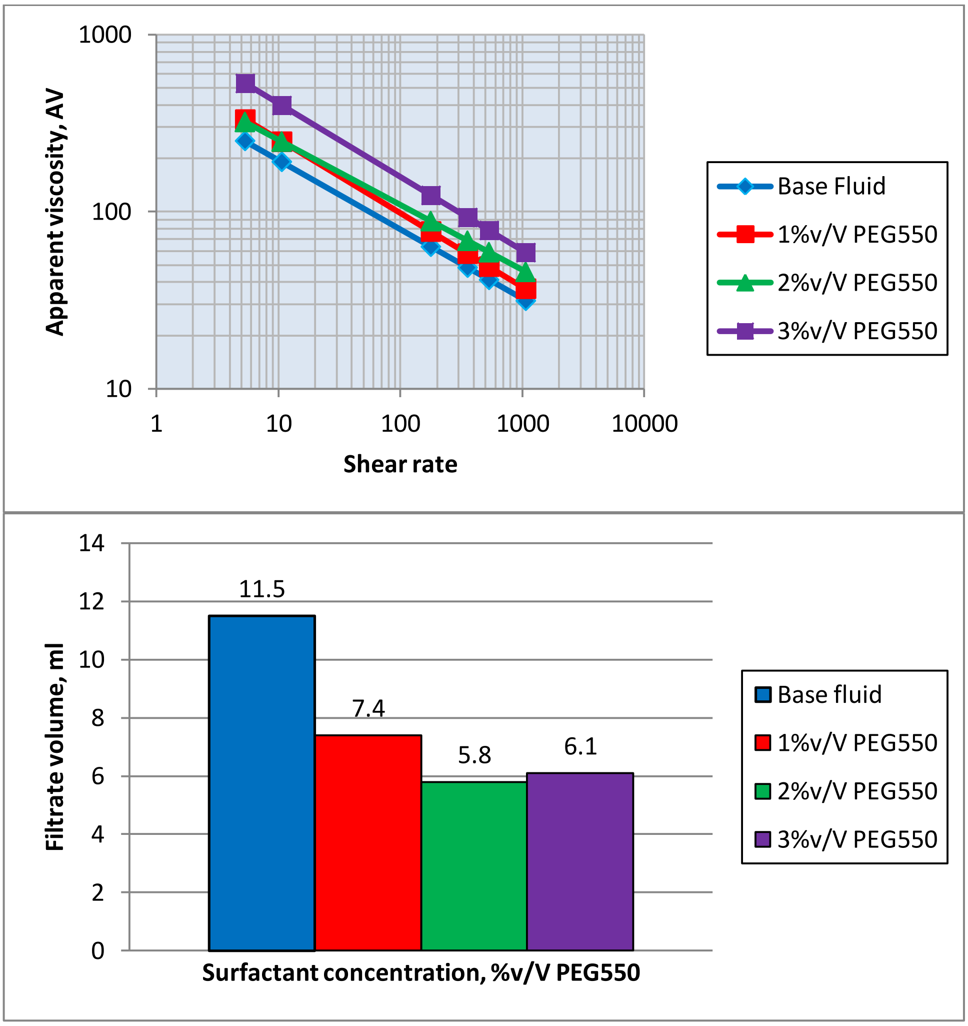


Figure 25: Performance improvement after addition of increasing surfactant concentration on rheological properties (top) and filtration properties (bottom)

Also, it was proven that increasing surfactant concentration can further reduces mud fluid loss when exposed to higher temperatures. Thus, lesser mud filtrate will invade into the formation during drilling operation and excellent rheological performances can be retained.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Based on the research done, the following conclusions can be made:

- The addition of PEG550 helps in improving the thermal stability of mud based on the evaluation of its rheological and filtration performances.
- 2% v/V was chosen as the sufficient surfactant concentration to yield optimal mud performances.
- After hot rolling at elevated temperatures, mud with added surfactant still maintaining high viscosity although it is not that much obvious.
- Remarkable reduction on fluid loss by half (50%) was observed on mud with surfactant after hot-rolling at elevated temperatures. This improvement on fluid loss control will eventually helps in retaining mud viscosity at high temperatures.
- The finding of the project will be significant and beneficial to the industry in the aspect of deeper drilling operations.

5.2 Recommendations

Based on the research done, the following recommendations are also made:

- For evaluating such works, both temperature and time of exposure to that temperature are relevant factors and must be taken into account. As only temperature effect is able carried out this time due to time constraint, this research can be further extended for the effect of exposure time in the next stage.
- For mud rheology test, scleroglucan which is another type of rheology modifier can also be tested to support the obtained result for xanthan gum. Same goes for filtration test, other similar polymer additives such as starch, or carboxy methyl cellulose can be used.

REFERENCES

Burdyn, R.F. and Wiener L.D. October 1956, “Calcium Surfactant Drilling Fluids,”*Petroleum Branch, American Institute of Mining, Metallurgical, and Petroleum Engineers*.

Darley H.C.H. and Gray G.R. 1988, *Composition and Properties of Drilling and Completion Fluids*, **(5)**, Gulf Professional Publishing.

Garret H.R. and Grisham C.M. December 2008, *Biochemistry*,**(4)**, Brooks Cole.

Godwin W., Ogbonna J., and Boniface O. 2011, “Advances in Mud Design and Challenges,” *SPE 150737, Nigeria Annual International Conference and Exhibition,* Abuja, Nigeria

Holmberg K., Jonsson B., Kronberg B., and Lindman B. 2003, *Surfactant and Polymer in Aqueous Solution* **(2)**, John Willey & Sons, LTD.

Khodja M., Saber M.K., Canselier J.P., Cohaut N., and Bergaya F.,”Drilling Fluid Technology: Performances and Environment Considerations,” *Drilling Technology in Non-Technical Language*. (November 1, 1999). p. 227

Larsen H. Summer 2007, “Behaviour of mud under HPHT conditions,” *Master Thesis at IPT, Norwegian University of Science and Technology,* Trondheim, Norway.

Migahed M.A. and Al-Sabagh A.M. 2009, “Beneficial Role of Surfactant as Corossion Inhibitors in Petroleum Industry: A Review Article,” *Chemical Engineering Communication* **196 (9)**: 1054-1075

Quintero L. 2002, “An Overview of Surfactant Applications in Drilling Fluids for Petroleum Industry,” *Journal of Dispersion Science and Technology* **23**: 393-404

Rogers W.F. 1953, “Composition and Properties of Oil Well Drilling Fluids,” *Gulf Publishing Company,* p.437-461

Schramm L.L. and Marangoni D.G. 2000, *Surfactant: Fundamentals and Applications in the Petroleum Industry,* The Press Syndicate of the University of Cambridge, United Kingdom

Srifvatsa J.T. August 2010, “An Experimental Investigation on Use of Nanoparticle as Fluid Loss Additives in a Surfactant-Polymer Based Drilling Fluid,” *Master Thesis at Texas Tech University,* United States

Thomas D.C April 1982, “Thermal Stability of Starch- and Carboxymetyl Cellulose- Based Polymers Used in Drilling Fluid,” *SPE 8463, SPE 54th Annual Technical Conference and Exhibition,* Las Vegas

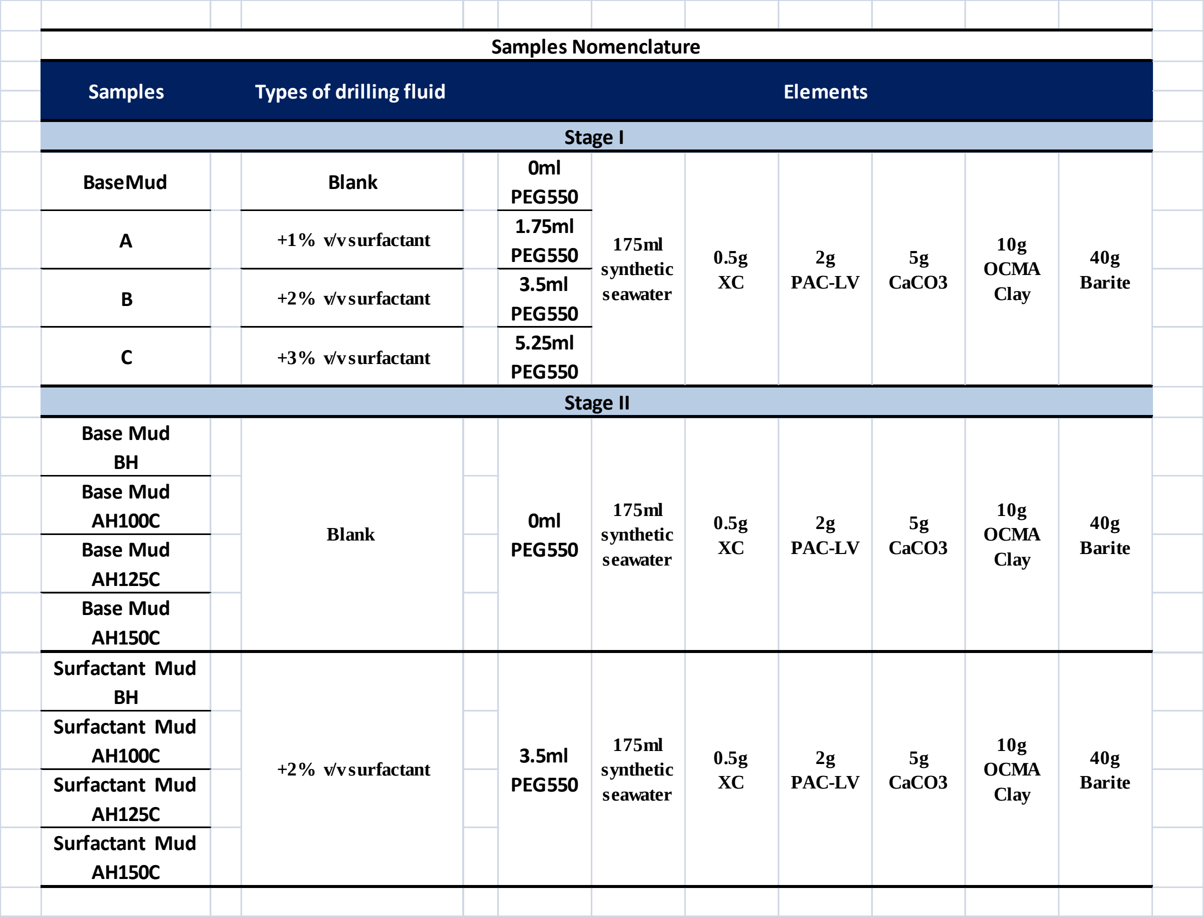
Van Oort E., Bland R.G., and Howard S.K. 1997, “Improving HPHT Stability of Water Based Drilling Fluids,” *SPE/IADC Drilling Conference*, Armsterdam.

Wunderlich R.W. 1991, “ Obtaining Samples with Preserved Wettability,” in *Interfacial Phenomenon in Petroleum Recovery, Surfactant Science Series* **36**: 289-317

Nicora L. F. and McGregor W. M. 1998, “Biodegradable Surfactant for Cosmetics Find Application in Drilling Fluids,” *IADC/SPE Drilling Conference,* Dallas, Texas.

APPENDICES

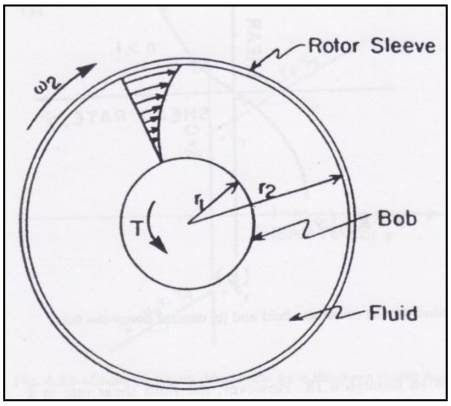
Samples Nomenclature

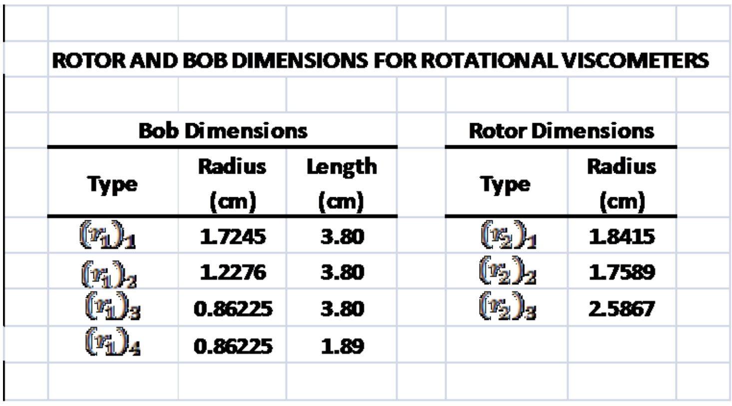


Samples Nomenclature

Samples	Types of drilling fluid	Elements						
Stage I								
BaseMud	Blank	0ml PEG550	175ml synthetic seawater	0.5g XC	2g PAC-LV	5g CaCO3	10g OCMA Clay	40g Barite
A	+1% v/v surfactant	1.75ml PEG550						
B	+2% v/v surfactant	3.5ml PEG550						
C	+3% v/v surfactant	5.25ml PEG550						
Stage II								
Base Mud BH	Blank	0ml PEG550	175ml synthetic seawater	0.5g XC	2g PAC-LV	5g CaCO3	10g OCMA Clay	40g Barite
Base Mud AH100C								
Base Mud AH125C								
Base Mud AH150C								
Surfactant Mud BH	+2% v/v surfactant	3.5ml PEG550	175ml synthetic seawater	0.5g XC	2g PAC-LV	5g CaCO3	10g OCMA Clay	40g Barite
Surfactant Mud AH100C								
Surfactant Mud AH125C								
Surfactant Mud AH150C								

Rotational Viscometer Calculation





ROTOR AND BOB DIMENSIONS FOR ROTATIONAL VISCOMETERS

Bob Dimensions				Rotor Dimensions	
Type	Radius (cm)	Length (cm)		Type	Radius (cm)
$(r_1)_1$	1.7245	3.80		$(r_2)_1$	1.8415
$(r_1)_2$	1.2276	3.80		$(r_2)_2$	1.7589
$(r_1)_3$	0.86225	3.80		$(r_2)_3$	2.5867
$(r_1)_4$	0.86225	1.89			

Bottom view of rotational viscometer (*Sources: Society of Petroleum Engineers, 1991*)

Power-Law Model

$$\boxed{\boldsymbol{\tau = K(\gamma)^n}}$$

Where

1) Flow Behavior Index, *n*

$$n = 3.322\log\left(\frac{\theta_{600}}{\theta_{300}}\right)$$

Or

$$n = \frac{\log\left(\frac{\theta_{N2}}{\theta_{N1}}\right)}{\log\left(\frac{N_2}{N_1}\right)}$$

2) Flow Consistency Index, *K*

$$K = \frac{510\ \theta_N}{(511)^n}$$

Or

$$K = \frac{510\ \theta_{300}}{(1.703N)^n}$$

Calculation of shear rate

$$\gamma = 0.2094N \frac{\frac{1}{r^{\left(\frac{2}{n}\right)}}}{n\left[\frac{1}{r_1^{\left(\frac{2}{n}\right)}} - \frac{1}{r_2^{\left(\frac{2}{n}\right)}}\right]}$$

Calculation of apparent viscosity (AV)

Most drilling fluids are too complex to be characterized by a single value of viscosity. The apparent viscosity is measured depends on the shear rate at which measurement is made and the prior shear rate history of the fluid.

$$\mathrm{AV} = \mathrm{K}(\gamma)^{\mathrm{n}-1}$$

Results of Stage I

Mud samples	**Base Fluid**		**1% v/v PEG550**		**2% v/v PEG550**		**3% v/v PEG550**	
	BH	**AH**	**BH**	**AH**	**BH**	**AH**	**BH**	**AH**
Speed (rpm)	**Viscometer dial reading in degree**							
600	**110**	**64**	**158**	**75**	**180**	**93**	**170**	**120**
300	**70**	**42**	**108**	**50**	**127**	**60**	**115**	**80**
200	**55**	**31**	**85**	**40**	**102**	**46**	**90**	**62**
100	**36**	**21**	**60**	**28**	**70**	**32**	**60**	**40**
6	**13**	**12**	**15**	**10**	**20**	**10**	**13**	**14**
3	**5**	**3**	**9**	**6**	**12**	**6**	**8**	**7**

Mud Samples		**Base Fluid**		**1% v/v PEG550**		**2% v/v PEG550**		**3% v/v PEG550**	
RPM	**Parameters**	**BH**	**AH**	**BH**	**AH**	**BH**	**AH**	**BH**	**AH**
600	AV	**54**	**31**	**77**	**37**	**87**	**46**	**83**	**59**
	γ	1057	1064	1076	1068	1087	1060	1073	1068
	τ	57337	33454	82898	39261	94713	48537	89110	62817
300	AV	69	41	105	49	123	59	112	78
	γ	528	532	538	534	544	530	536	534
	τ	36487	21954	56665	26174	66825	31314	60280	41878
200	AV	80	48	126	58	150	69	134	93
	γ	352	355	359	356	362	353	358	356
	τ	28009	17159	45357	20647	54492	24232	47959	33035
100	AV	101	63	173	77	212	89	181	124
	γ	176	177	179	178	181	177	179	178
	τ	17823	11260	31003	13764	38446	15633	32441	22022
6	AV	269	191	615	248	858	249	619	397
	γ	11	11	11	11	11	11	11	11
	τ	2846	2037	6617	2654	9332	2639	6638	4247
3	AV	343	251	841	331	1211	321	837	530
	γ	5	5	5	5	5	5	5	5
	τ	1811	1337	4523	1769	6584	1702	4490	2831

Mud samples	**Base Fluid**		**1% v/v PEG550**		**2% v/v PEG550**		**3% v/v PEG550**	
	BH	**AH**	**BH**	**AH**	**BH**	**AH**	**BH**	**AH**
n	**0.652**	**0.608**	**0.549**	**0.585**	**0.503**	**0.632**	**0.564**	**0.585**
K	**612**	**484**	**1796**	**664**	**2809**	**593**	**1741**	**1062**

Results of Stage II

Mud samples	Without PEG550				With PEG550			
	BH	AH 100°C	AH 125°C	AH 150°C	BH	AH 100°C	AH 125°C	AH 150°C
Speed (rpm)	Viscometer dial reading in degree							
600	110	64	29	8	180	93	55	11
300	70	42	19	6	127	60	35	7
200	55	31	14	4	102	46	26	5
100	36	21	10	3	70	32	18	4
6	13	12	2	1	20	10	7	1
3	5	3	1	0	12	6	3	0

Mud Samples		Without PEG550				With PEG550			
RPM	Parameters	BH	AH 100°C	AH 125°C	AH 150°C	BH	AH 100°C	AH 125°C	AH 150°C
600	AV	54	31	14	4	87	46	27	5
	γ	1057	1064	1064	1116	1087	1060	1057	1057
	τ	57340	33456	15157	4233	94717	48539	28670	5734
300	AV	69	41	19	6	123	59	35	7
	γ	528	532	532	558	544	530	528	528
	τ	36487	21954	9930	3174	66825	31314	18244	3649
200	AV	80	48	22	7	150	69	40	8
	γ	352	355	355	372	362	353	352	352
	τ	28009	17159	7754	2683	54492	24232	14005	2801
100	AV	101	63	29	11	212	89	51	10
	γ	176	177	177	186	181	177	176	176
	τ	17823	11260	5080	2012	38446	15633	8912	1782
6	AV	269	191	86	56	858	249	135	27
	γ	11	11	11	11	11	11	11	11
	τ	2846	2037	913	626	9332	2639	1423	285
3	AV	343	251	112	84	1211	321	171	34
	γ	5	5	5	6	5	5	5	5
	τ	1811	1337	598	469	6584	1702	905	181

Mud samples	Without PEG550				With PEG550			
Parameters	BH	AH 100°C	AH 125°C	AH 150°C	BH	AH 100°C	AH 125°C	AH 150°C
n	0.652	0.608	0.610	0.415	0.503	0.632	0.652	0.652
K	612	484	216	230	2809	593	306	61

Filtration Measurements

Results of Stage I

Time	Base Fluid		1% v/v PEG550		2% v/v PEG550		3% v/v PEG550	
	BH	AH	BH	AH	BH	AH	BH	AH
1	0.2	6.9	0.1	2.8	0.2	1.5	0.6	2.0
2	0.4	7.5	0.3	3.1	0.5	2.0	0.8	2.5
3	0.7	7.9	0.6	3.6	0.7	2.2	1.0	2.7
4	1.0	8.4	1.2	3.8	0.9	2.4	1.4	3.0
5	1.3	8.7	1.4	4.1	1.5	2.6	1.5	3.2
6	1.5	8.9	1.5	4.4	1.5	2.8	1.6	3.4
7	1.6	9.1	1.6	4.5	1.6	3.0	1.8	3.6
8	1.7	9.2	1.7	4.6	1.7	3.1	1.9	3.8
9	1.8	9.3	1.8	4.8	1.8	3.3	2.1	3.9
10	1.9	9.3	1.9	5.0	2.1	3.5	2.3	4.1
11	2.0	9.5	2.0	5.2	2.1	3.6	2.4	4.2
12	2.1	9.6	2.1	5.3	2.3	3.7	2.6	4.3
13	2.2	9.7	2.2	5.5	2.5	3.9	2.7	4.4
14	2.3	9.8	2.3	5.6	2.6	1.0	2.8	4.5
15	2.4	9.9	2.4	5.7	2.7	4.1	2.9	4.6
16	2.5	10.0	2.5	5.8	2.9	4.2	3.0	4.8
17	2.6	10.2	2.6	6.0	3.0	4.3	3.2	4.9
18	2.7	10.3	2.7	6.1	3.1	4.4	3.3	5.0
19	2.8	10.4	2.8	6.2	3.3	4.5	3.4	5.1
20	2.9	10.5	2.9	6.4	3.4	4.6	3.5	5.2
21	3.0	10.6	3.0	6.5	3.4	4.7	3.5	5.3
22	3.1	10.8	3.1	6.6	3.5	4.8	3.6	5.4
23	3.1	10.9	3.1	6.7	3.5	5.0	3.7	5.5
24	3.2	10.9	3.2	6.8	3.6	5.0	3.8	5.6
25	3.2	11.0	3.2	7.0	3.7	5.1	3.9	5.7
26	3.3	11.2	3.3	7.1	3.7	5.2	3.9	5.8
27	3.4	11.3	3.4	7.2	3.8	5.4	4.0	5.8
28	3.4	11.4	3.5	7.2	3.9	5.6	4.1	5.9
29	3.5	11.5	3.6	7.3	4.0	5.7	4.2	6.0
30	3.6	11.5	3.7	7.4	4.0	5.8	4.3	6.1

Results of Stage II

Time	Without PEG550				With PEG550			
	BH	AH 100°C	AH 125°C	AH 150°C	BH	AH 100°C	AH 125°C	AH 150°C
1	0.2	5.4	13.3	TLC	0.5	1.5	7.4	TLC
2	0.4	6.2	17.1		0.7	2.0	9.5	
3	0.7	6.8	20.7		0.9	2.2	14.0	
4	1.0	7.0	24.2		1.3	2.4	16.6	
5	1.3	7.4	27.4		1.4	2.6	18.9	
6	1.5	7.6	30.0		1.6	2.8	19.9	
7	1.6	7.9	32.6		1.8	3.0	21.6	
8	1.7	8.0	34.9		1.9	3.1	22.8	
9	1.8	8.2	36.7		2.1	3.3	23.8	
10	1.9	8.4	38.5		2.3	3.5	24.6	
11	2.0	8.5	40.3		2.4	3.6	25.2	
12	2.1	8.6	41.9		2.6	3.7	25.8	
13	2.2	8.8	43.3		2.7	3.9	26.3	
14	2.3	8.9	44.5		2.8	1.0	26.8	
15	2.4	9.0	45.7		2.9	4.1	27.2	
16	2.5	9.2	46.9		3.0	4.2	27.6	
17	2.6	9.3	48.0		3.2	4.3	27.8	
18	2.7	9.4	49.0		3.3	4.4	28.2	
19	2.8	9.5	59.0		3.4	4.5	28.4	
20	2.9	9.6	59.8		3.5	4.6	28.7	
21	3.0	9.7	60.6		3.5	4.7	29.1	
22	3.1	9.8	61.5		3.6	4.8	29.4	
23	3.1	9.9	62.1		3.7	5.0	29.7	
24	3.2	10.0	62.8		3.8	5.0	29.9	
25	3.2	10.1	63.4		3.8	5.3	30.1	
26	3.3	10.20	64.0		3.9	5.2	30.2	
27	3.4	10.3	64.6		4.0	5.3	30.4	
28	3.4	10.4	65.2		4.1	5.4	30.5	
29	3.5	10.5	65.8		4.2	5.5	30.6	
30	3.6	10.5	66.1		4.0	5.8	30.7	