USING NATURAL RUBBER LATEX AS DRILLING FLUID ADDITIVE

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การใช้น้ำยางธรรมชาติเป็นสารเติมแต่งในโคลนเจาะ

นายธนฤทธิ์ ริยาพันธ์

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิศวกรรมศาสตรมหาบัณฑิต
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USING NATURAL RUBBER LATEX AS DRILLING FLUID ADDITIVE

Suranaree University of Technology has approved this thesis submitted in partial fulfillment of the requirements for a Master's Degree.

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ธนฤทธิ์ ริยาพันธ์ : การใช้น้ำยางธรรมชาติเป็นสารเติมแต่งในโคลนเจาะ (USING NATURAL RUBBER LATEX AS DRILLING FLUID ADDITIVE) อาจารย์ที่ปรึกษา : อาจารย์ ดร.อัฒพรรค์ วรรณโกมล, 72 หน้า.

วัตถุประสงค์ของงานวิจัยครั้งนี้คือ เพื่อศึกษาและพัฒนาน้ำโคลนที่ใช้น้ำเป็นส่วนผสมโดยใช้น้ำยางธรรมชาติเป็นสารเติมแต่ง โดยทำการเติมน้ำยางธรรมชาติที่ความเข้มข้นร้อยละ 1, 3 และ 5 โดยมวลต่อปริมาตร จากนั้นทำการทดสอบคุณสมบัติของของไหลนี้ที่อุณหภูมิ 30, 45, 60 และ 80 องศาเซลเซียสเพื่อทำการเปรียบเทียบคุณสมบัติด้านวิทยากระแสของน้ำโคลนโดยใช้แบบจำลองบิงแฮมและเพาเวอร์ลอว์ รวมทั้งทำการทดสอบคุณสมบัติการซึมผ่านและค่าความเป็นกรด-ด่างของน้ำโคลนที่ผสมน้ำยางธรรมชาติเป็นสารเติมแต่ง โดยทำการทดสอบตามขั้นตอนและวิธีการทดสอบตามมาตรฐาน API RP 13B ผลการทดสอบพบว่าเมื่อเพิ่มอัตราส่วนน้ำยางธรรมชาติในน้ำโคลนและเพิ่มอุณหภูมิที่ทำการทดสอบค่าพบว่า ความหนืด, ความหนืดพลาสติก, จุดคราก และความแข็งแรงของเจลของน้ำโคลนเพิ่มขึ้น ยกเว้นค่าความหนืดเชิงพลาสติกที่มีค่าลดลงเล็กน้อยเมื่ออุณหภูมิที่ทำการทดสอบเพิ่มขึ้น ค่าคุณสมบัติการซึมผ่านของน้ำโคลนที่อัตราส่วนน้ำยางธรรมชาติร้อยละ 3 และ 5 โดยน้ำหนักต่อปริมาตรมีค่าเพิ่มขึ้นร้อยละ 5 และ 10 ตามลำดับ และเมื่อทำการเพิ่มอุณหภูมิที่ทำการทดสอบถึง 80 องศาเซลเซียส พบว่าน้ำโคลนที่มีส่วนผสมของน้ำยางธรรมชาติมีค่าคุณสมบัติป้องกันการซึมผ่านเพิ่มขึ้นร้อยละ 10 ถึง 15 จากการทดลองแสดงให้เห็นว่าน้ำโคลนที่มีน้ำยางธรรมชาติเป็นสารเติมแต่งสามารถใช้สำหรับการเจาะหลุมที่มีอุณหภูมิก้นหลุมสูงได้ถึง 80 องศาเซลเซียส โดยไม่เกิดการย่อยสลายโดยความร้อนของสารเติมแต่งและไม่มีปัญหาการกัดกร่อนโดยสภาพความเป็นกรด

สาขาวิชา เทคโนโลยีธรณี ลายมือชื่อนักศึกษา_______________________

ปีการศึกษา 2554 ลายมือชื่ออาจารย์ที่ปรึกษา________________

THANARIT RIYAPAN : USING NATURAL RUBBER LATEX AS DRILLING FLUID ADDITIVE. THESIS ADVISOR : AKKHAPUN WANNAKOMOL, Ph.D. 72 PP.

NATURAL RUBBER LATEX/HEVEA BRASILIENSIS/DRILLING MUD/LOST CIRCULATION/STATIC FILTRATION

The objective of this study was developing water-based drilling fluid by using natural rubber latex as an additive. The objective was achieved by adding 1, 3 and 5 percent of NRL to bentonite mud. These fluids were then tested their rheological properties at 30, 45, 60 and 80^{o}C using Bingham-Plastic and Power-Law model for comparison purposes. The filtration properties and pH of mud were also tested and followed the API RP 13B. The test results indicated that the NRL containing mud exhibited pseudo-plastic flow and shear thinning behavior. The apparent viscosity, plastic viscosity, yield point and gel strength of NRL containing mud increased with increasing of NRL concentration and temperature while the plastic viscosity slightly decreased with increasing temperature. The API fluid loss values of NRL containing mud indicated a better fluid loss control properties at 3 and 5 percent NRL concentration compared to the base bentonite mud about 5 and 10 percent improvement. The NRL containing mud showed insignificant increasing in the filtration preventing properties after elevated tested temperature to 80^{o}C about 10 to 15 percent improvement without thermal degradation and corrosive problems.

School of Geotechnology Student Signature____________________

Academic Year 2011 Advisor Signature____________________

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Thanarit Riyapan

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SYMBOLS AND ABBREVIATIONS

τ	=	Shear stress
τ_0	=	yield stress
τ_y	=	yield stress
γ	=	shear rate
k	=	Fluid consistency index
n	=	Flow behavior index
μ_a	=	Apparent viscosity
μ_p	=	Plastic viscosity
γ_p	=	Yield point
Gel_{in}	=	Initial gel strenth
Gel_{10}	=	10 minutes gel strength
θ_i	=	Viscometer dial reading
N	=	Range extension factor of the torque spring of the VG meter
rpm	=	Rotational speed
Kg	=	Kilogram

CHAPTER I

INTRODUCTION

1.1 Background and rationale

Groundwater or petroleum wells are commonly drilled using the rotary method. In this method, losing of circulating drilling mud in unconsolidated underground formation is a major field problem, this is known as lost circulation. To reduce of losing drilling mud there are several methods have been applied. One kind of these is using of polymer additive to improve filtration properties of water-based mud because it has suitable properties. These have been proved by many researches. In abroad many kind of additive have been invented but it less study in Thailand. Therefore these should be studied and found out more potential additive for observation.

In Thailand, natural rubber latex is a good choice for use in this invention because it can be used with water-based mud and it is a biopolymer that is affable with environment. Thailand is a large natural rubber producer in the world. Therefore it is easy to provide a lot of this local material. If this invention has sufficiently performance, it may be possible to use this new application instead the expensive mud additives in well drilling activity.

1.2 Research objectives

The main aims of this research are to study the fluid loss preventing and rheological properties of drilling mud using natural rubber latex (NRL) additive. Some more objectives are comprised of (1) Study physical properties of drilling mud with NRL additive, (2) Study the effect of temperature on filtration and rheological properties, and (3) Study the effect of NRL concentration on filtration and rheological properties.

1.3 Scope and limitation of work

This research aimed to study the rheological and filtration properties of water-based drilling fluids using NRL additive. The filtration test was a static test by ignoring influence of high pressure. The study of filtration control was in a laboratory scale that was not real borehole condition. The test procedures had been followed the American Petroleum Institute Recommended Practice Standard Procedure for Field Testing Drilling Fluids (API RP 13B).

1.4 Research methodology

The research methodology comprised 5 steps as shown in Figure 1.1, including literature review, sample preparation, laboratory testing (rheology, fitration and pH test), gathering the result to discussions, conclusions, and thesis writing. Each step is described as follows;

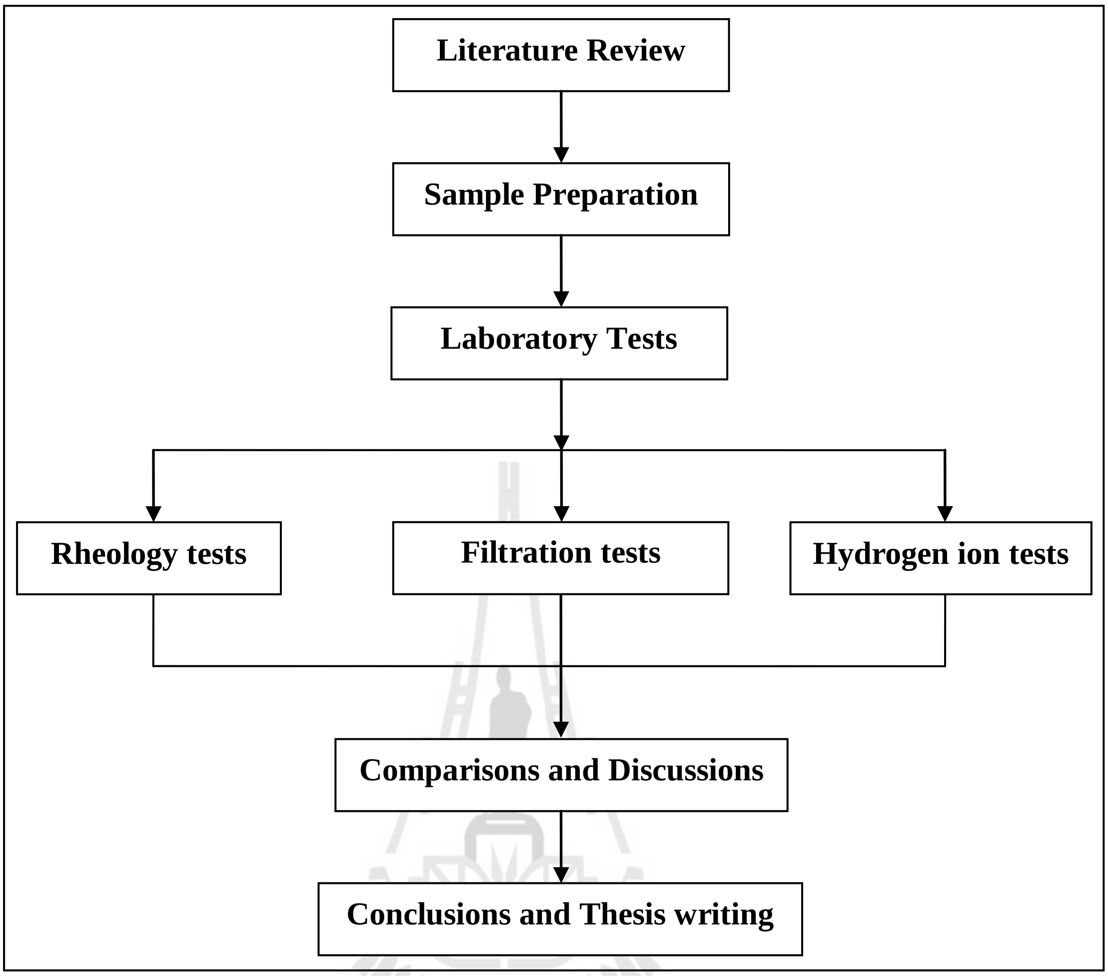

Figure 1.1 Research methodology.

1.4.1 Literature review

Literature review was carried out to improve understanding drilling mud properties. It composed of reviewing and studying water-based drilling fluids and applications, using of polymer latex in drilling mud, natural rubber latex properties and testing procedure. The sources of information were from journals, researches, dissertation and books concerned.

1.4.2 Sample preparation

A base bentonite-water suspension was prepared using 60 grams of bentonite per liter of water and 120 grams of barite per liter of water were added to control density. The testing mud samples were weighted of 1.2 grams per cubic-centimeter containing 6 percent bentonite weight by volume as a base composition. Various NRL concentrations were added to test mud to perform as viscosifier and fluid loss additive. The experiments were carried out in the laboratory at the Suranaree University of Technology.

1.4.3 Laboratory test

The laboratory testing was divided into three groups; rheology test, filtration test and pH test. The properties were determined in the laboratory under temperature at 30, 45, 60 and 80^{o}C respectively. Three samples were tested for each condition. The test methods had been followed the relevant API standard practice.

1.4.3.1 Rheology tests

The objective of rheology tests was to measure rheological characteristics of drilling fluid with various shear rates. The test procedures had been followed API RP 13B standard practice. The test was performed by rotary viscometer (Fann VG) which had a geometry that gave the following expression for a fit of the data to the Bingham Plastic model (API RP 13D). Three mud samples were prepared and tested under each designed conditions. Consequently, the drilling fluid rheological parameters were observed and recorded.

1.4.3.2 Filtration tests

The objective of filtration tests was to measure the fluid loss that invaded to permeable formation while drilling mud was circulating. The test procedures had been followed API RP 13B standard practice. The API Filter Press was used to determine the filtration rate through a standard filter paper and the rate which the mudcake thickness increases on the standard filter paper under tested condition. The filter press was operated at pressure of 100 psig and filtrate volume collected in a 30 minute time period was reported as the standard water loss. A quality of mud filtrate cake could be estimated by its thickness and its other properties such as lubricity, erodibility and texture.

1.4.3.3 Hydrogen ion tests

The objective of filtration of pH test was to measure acidity or alkalinity of tested mud by determining hydrogen ion concentration of drilling mud. The procedure employed a pH meter with a glass electrode that gave more accuracy than pHydrion paper.

1.4.4 Comparisons and discussions

Results from laboratory measurements in term of plastic viscosity, yield point, gel strength, filtrate volume, mudcake thickness and pH, were compared between those resulted from base bentonite mud and NRL containing mud. Similarity and discrepancy of results had been discussed. An influence of temperature that affected to drilling mud properties parameters were described and the feasibility of using NRL drilling mud in onshore and offshore well in Thailand was also considered.

1.4.5 Conclusions and thesis writing

All research activities, methods and results were documented and complied in the thesis.

1.5 Thesis contents

Chapter I introduces the thesis by briefly describing the background of problem and significance of the study. The research objectives, methodology, scope and limitation are identified. **Chapter II** summarizes results of the literature review to improve an understanding of drilling mud characteristics and the factor that affects to mud properties. **Chapter III** describes the sample preparation and experiment procedure for laboratory testing. **Chapter IV** presents the result obtained from the laboratory testing and comparison the result between two mud formulas. **Chapter V** concludes the research results and recommendations for future studies.

CHAPTER II

LITERATURE REVIEW

2.1 Introduction

Relevant topics and previous research results were reviewed to improve understanding of water-based drilling fluids and applications, using of polymer latex in drilling mud, natural rubber latex properties, and API standard practice. This chapter also describes the drilling fluid rheology which is plays important role for mud characteristic. The sources of information were from journals, researches, dissertation and books. Results from the review are summarized as follows.

2.2 Functions of drilling fluid

In rotary drilling there are a variety of functions and characteristics that are expected of drilling fluids. The drilling fluid is used in the process to (1) clean the rock fragments from beneath the bit and carry them to separating at 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, and (4) cool and lubricate the rotating drillstring and bit (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 of the drilling equipment and subsurface tubulars. The bentonite used in drilling fluid is monmorillonite 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. The added bentonite is sometimes unable to provide satisfactory those properties that required for optimum performance in an oil well drilling. Therefore the polymers are added to achieve desired result.

2.3 Polymer used in drilling fluid

Polymers have been used in drilling fluids since the 1930s (MI-Swaco, 1998), when cornstarch was introduced as a fluid-loss-control additive. Since that time, polymers have become more specialized and their acceptance has increased accordingly. Polymers are part of practically every water-base system in use today. Indeed, some systems are totally polymer-dependent and are termed broadly as polymer systems. A wide array of polymers is available today. Some polymers like starch, for instance originate from natural.

Stowe *et al*. (2004) described the effectiveness of polymer that used in drilling mud. It has been discovered that a polymer latex added to a water-based drilling fluid can reduce the rate the drilling fluid pressure invades the borehole wall of a subterranean formation during drilling operation. The polymer latex preferably is capable of providing a deformable latex film or seal on at least a portion of a subterranean formation. Within the context of this invention, the terms "film" or "seal" are not intended to mean a completely impermeable layer. The seal is considered to be semi-permeable, but nevertheless at least partially blocking of fluid transmission sufficient to result in a great improvement in osmotic efficiency. The pressure blockage, reliability, magnitude and pore size that can be blocked are all increased by the latex addition. Inhibiting drilling fluid pressure invasion into the wall of a borehole is one of the most important factors in maintaining wellbore stability.

Chesser *et al*. (2008) reviewed performance of using nonionic water soluble polymers as fluid loss control agent. There are starches, derivative starches, gums, derivative gums, and cellulosic. These polymers have certain advantages, but suffer from the disadvantage that they have limited temperature stability. As wells are drilled deeper, higher bottom hole temperature are encountered. Drilling fluids need to maintain stable rheology and low filtration at temperatures above 300°F. Unfortunately, the nonionic water soluble polymers currently in use are not stable at exceeding about 225°F with extended aging times. Filtration control additives are needed which will quickly form a thin, dispersible filter cake, and which also have high temperature stability for prolonged period of time.

Chilingarian *et al*. (1983) reported on the results of water-soluble xanthan gum biopolymer which is produced from the bacterial action on carbohydrates and is sometime called an XC polymer. Some advantages of the biopolymer drilling fluid system include: (1) ease of mixing and maintenance, (2) compatibility with all presently-used drilling fluid materials and chemicals, (3) relative insensitivity to salt and gypsum contamination, (4) retainment of original viscosity after repeated exposure to high shear rates, and (5) excellent suspension properties for weighting agents.

Stowe *et al*. (2004) provided results of filtration tests, the latex polymer can provide excellent bridging and sealing ability to reduce the permeability of formation where the lost circulation of drilling fluids may encounter. Two latexes, carboxylated styrene-butadiene and sulfonated styrene polymer are used for water-based applications. At 300^{o}F without latex polymer, the fluid loss of this mud is out of control. However, addition 3% latex by volume of polymer latex in to mud, the fluid loss decreases sharply with time.

Bailey (2001) studied effect of temperature on fluids loss in latex systems using a barite and xanthan composition as drilling fluid. Polymer base fluid consisted 4 grams per liter of xanthan gum and 160 grams per liter of API barite. The fluid shows rapid loss of filtration control at 80^{o}C. Xanthan gum has a limited temperature stability, it begins lose performance around 105-110^{o}C. It generally found that loss increases with increasing temperature. In addition the bio-polymeric additive will degrade at high temperature (Caenn *et al*., 1996).

Mahto and Sharma (2004) studied rheology of water-based drilling fluid using tamarind gum and polyanionic cellulose (PAC). The tamarind drilling fluids gum are economical than guar gum drilling fluids and tamarind gum is readily available in India, thus is a more suitable drilling fluid. Combinations of tamarind gum, PAC, and bentonite clay produce favorable rheological properties and optimum fluid loss at very low concentrations. In addition, its effect on formation damage is less than guar gum drilling fluids.

2.4 Natural rubber latex

Blackley (1997) detailed about natural rubber latex and its classification. The Latex is commonly used to denote a stable colloidal dispersion of a polymeric substance in an aqueous medium. It has sometimes been extended to include stable colloidal dispersions of polymers in non-aqueous media in which the polymer is insoluble Rubber latex system can be classified into two classes. The synthetic latex is normally obtained from emulsion addition polymerization and condensation polymerization. Natural latex is obtained from plants. Natural rubber latex may be tapped off from part of plants, such as bark, roots, leaves, stems, tubers and fruits. Nowadays most natural rubber latex is derived from the species Hevea brasiliensis of the family Euphorbiaceae.

Cacioli (1997) described the rubber component from Hevea rubber tree. It is an entirely more than 98 percent of cis-1,4-polyisoprene (Figure 2.1) which is unable to crystallize under normal conditions. Therefore it exists as an amorphous, rubbery material. Natural rubber latex (NRL) typically contains 34 percent (by weight) of rubber, 2 to 3 percent proteins, 1.5 to 3.5 percent resins, 0.5 to 1 percent ashes, 1.0 to 2.0 percent sugar, 0.1 to 0.5 percent sterol glycosides, and 55 to 60 percent of water.

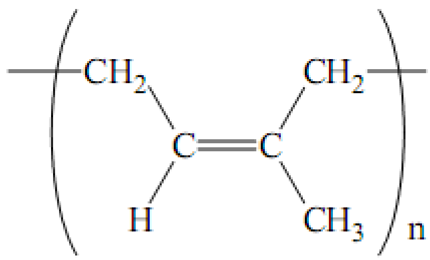

Figure 2.1 Chemical structure of cis-1,4-polyisoprene in Hevea latex.

Sridee (2006) investigated the influence of temperature on the viscosity of NRL samples with different total solid content. Temperature range of 10 to 40°C with the increment of 5°C was used. The result indicated that the latex viscosity decreased when temperature is increased at all shear rates. As for all liquids, latex viscosity decreases with increasing temperature.

2.5 API Recommended Practices

The American Petroleum Institute has set forth numerous recommended practices designed to standardize various procedures associated with the petroleum industry. The practices are subject to revision from time-to-time to keep pace with current accepted technology. One such standard is API Bulletin RP 13B, "Recommended Practice Standard Procedure for Field Testing Water-Based Drilling Fluids". This Bulletin described the drilling fluid measurements of the primary characteristics of a drilling fluid. This research is focused to the section of (1) viscosity and gel strength that measurement of mud related flow properties, (2) filtration that measurement of liquid phase loss that exposed to permeable formations, and (3) pH that measurement of the alkaline and acid relationship in the mud.

2.6 Drilling Fluid Rheology

Numerous books have described about rheology of drilling fluid and models that used to explain fluid flow behavior. Rheology is the science of flow and deformation of matter. It describes the interrelation between force, deformation and time. There is a rheological model describes the flow behavior of a fluid by developing a mathematical relationship between shear stress and shear rate. In general, drilling fluid rheology is described by two widely used models, namely: Bingham Plastic Model and the Power

Law Model. Another model that important is the Herschel-Buckley Model. These three models are discussed in this study.

2.6.1 Bingham Plastic Model

This model is defined by the relationship:

$$\tau = \tau_0 + \mu_p \gamma \tag{2.1}$$

Where, τ = shear stress

τ_0 = yield stress

μ_p = plastic viscosity

γ = shear rate

Bingham Plastic fluid will not flow until the applied shear stress exceeds the minimum yield stress. Once the yield stress has been exceeded, changes in shear stress are proportional to changes in shear rate and the constant of proportionality is called the plastic viscosity. Figure 2.2 shows a graphical representation of this model. The plastic viscosity is the slope of the Bingham Plastic line. The plastic viscosity decreased with increased shear rate due to a phenomenon called “shear thinning”.

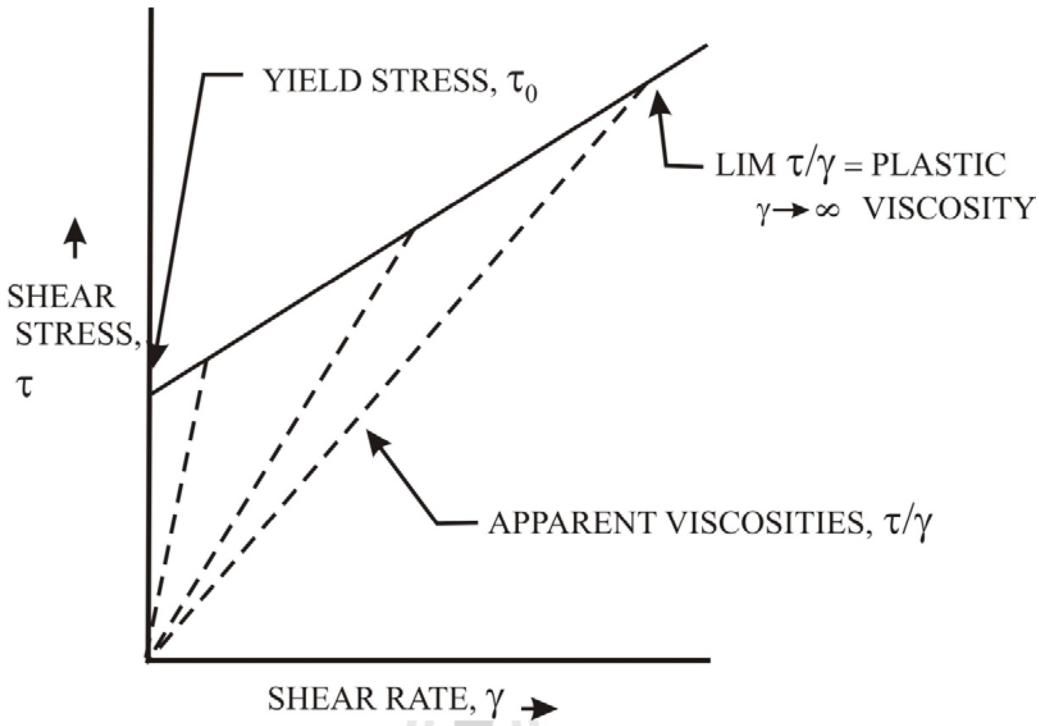

Figure 2.2 Flow curve for Bingham plastic model.

2.6.2 Power Law Model

The power-law model is defined by the equation

$$\tau = k\gamma^{n} \tag{2.2}$$

Where, τ = Shear stress

k = Fluid consistency index

γ = Shear rate

n = Flow behavior index

The parameter, k and n are constants characteristic of a particular fluid. k is a measure of the consistency of the fluid, the higher the value of k the more viscous the fluid; n is a measure of the degree of non-Newtonian behavior of the fluid.

Both parameters, *n* and *k*, are obtained from the log-log plot of shear stress versus shear rate. When *n* = 1, the fluid behaves as a Newtonian fluid and the Power-Law equation is identical to the Newtonian fluid equation. For n greater than 1, the fluid is classified as dilatant. Dilatant fluids are shear rate dependent. Their apparent viscosities increase with increase in shear rate. If n is less than 1, then the fluid is referred as pseudoplastic. Pseudoplastic fluids are also shear rate dependent with their apparent viscosities decreasing as shear rate decreases. Figure 2.3 shows the graphical representation of Power Law fluids and Figure 2.4 shows a graphical comparison of the Newtonian model, Bingham Plastic model and the Power-Law model.

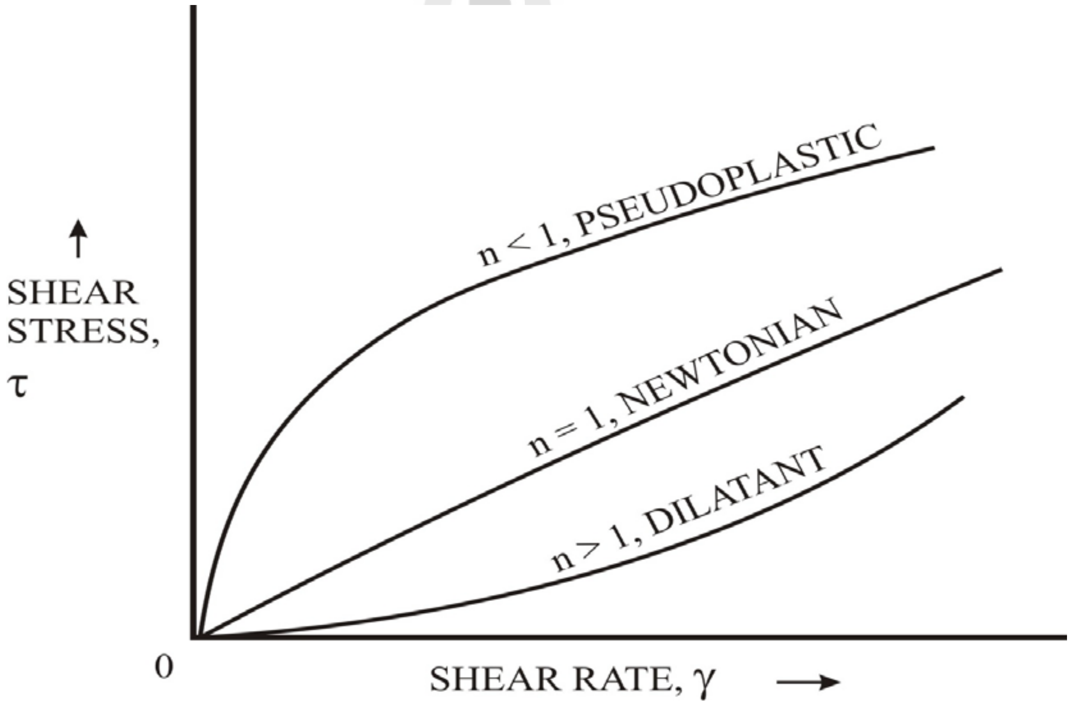

Figure 2.3 Flow curve for Power law model.

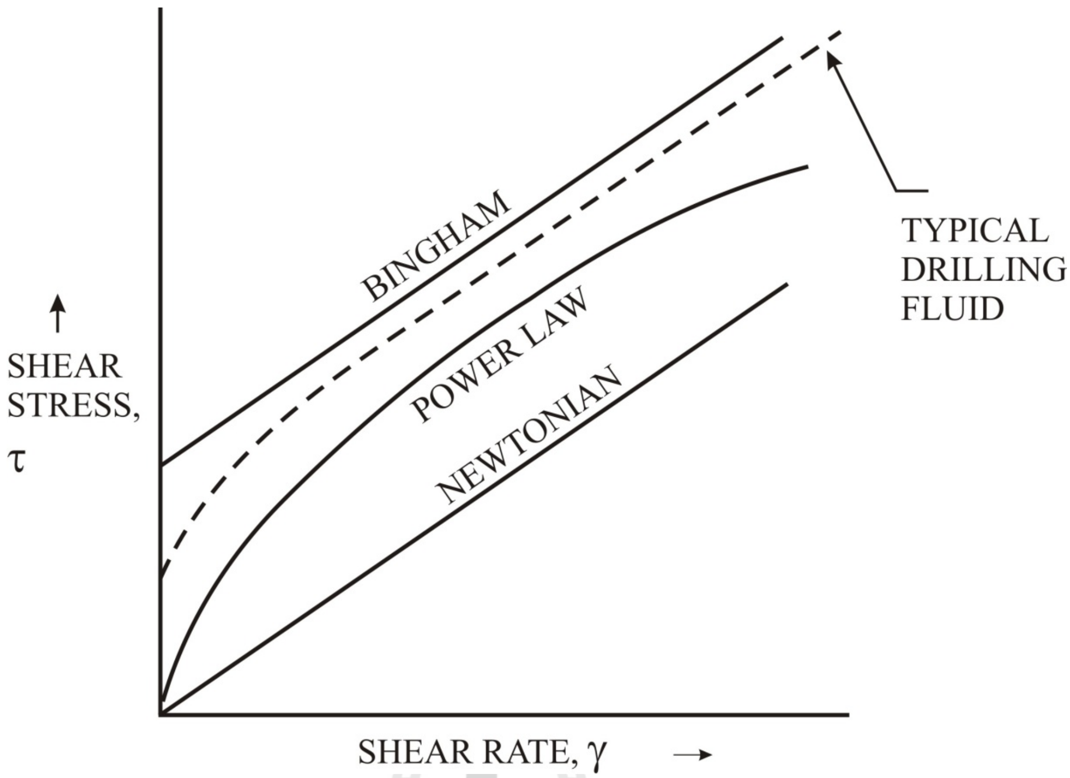

Figure 2.4 Flow curve for typical drilling fluid in comparison with Newtonian, Bingham plastic, and Power law model.

2.6.3 Herschel-Bulkley Model

Herschel-Bulkley model is defined by the equation

$$\tau = \tau_y + k\gamma^n \qquad (2.3)$$

Where,

τ = Shear stress

τ_y = yield stress

k = Fluid consistency index

γ = Shear rate

n = Flow behavior index

This model also called the modified power law model and yield-pseudoplastic model. The model is used to describe the flow of pseudoplastic drilling fluids which require a yield stress to initiate flow. A rheogram of shear stress minus yield stress versus shear rate is straight line on log-log coordinates. This model is widely used because it (1) describes the flow behavior of most drilling fluid, (2) includes a yield stress value that important for several hydraulic issues, and (3) includes the Bingham plastic and Power law model as special cases. The rheological parameters recorded in an API Drilling Fluid report are plastic viscosity and yield point from Bingham plastic model. These two terms can be used to calculate key parameters for other rheological models.

CHAPTER III

LABORATORY EXPERIMENTS

3.1 Introduction

The objective of the laboratory experiments is to assess the effects of NRL concentration and temperature on rheological and filtration property of bentonite mud samples. This chapter includes the sample preparation, testing instruments and experiments method. The tests were divided in to three groups; theology tests, filtration tests and pH tests.

3.2 Sample preparation

The bentonite clay was obtained from MI-Swaco Company, Indonesia. The barite for soil analysis was obtained from Ajax Finechem Pty Ltd, Australia, and high concentration natural rubber latex was produced from Thaihua rubber public company, Sakonnakorn, Thailand.

Generally, a ranges of drilling fluids density for typical well drilling is 1.5 to 8.5 percent bentonite weight by volume, mud weight vary around 8.85 to 18 pound per gallon depend on graded bentonite and drilled formations (MI-Swaco, 1998). Figure 3.1 demonstrates the composition and nature of common drilling muds. The curves show the increasing of viscosity with percentage of bentonite solids.

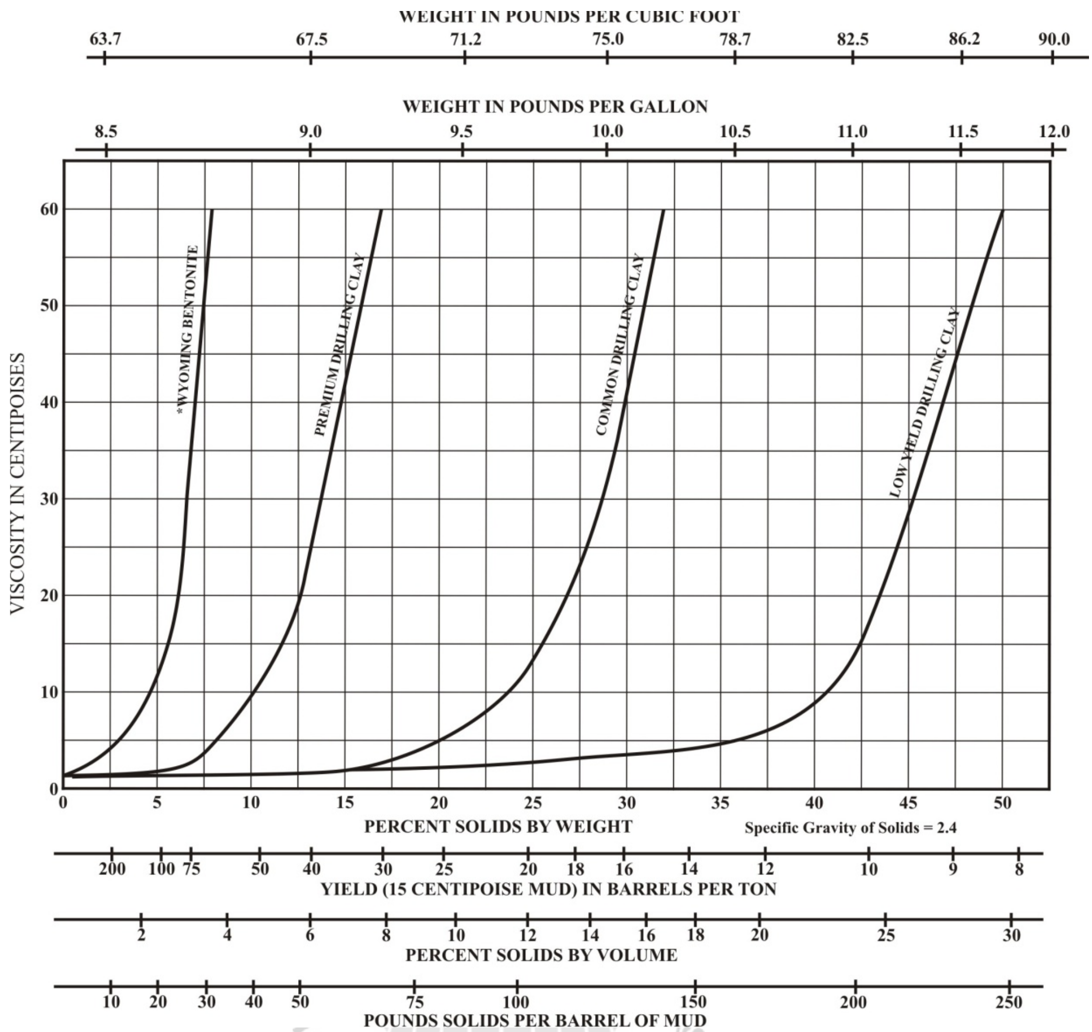

Figure 3.1 Composition and nature of common drilling muds (modified from Gatlin, 1960).

Since the grade of bentonite clay that use in the experiment is not Wyoming grade. It is necessary to find appropriate amount of bentonite that meet the viscosity requirement for typical well drilling. Table 3.1 shows bentonite water-base suspension at 2, 4, 6, and 8 percent bentonite weight by volume at 30^{o}C. It shows that bentonite mud suspension at 6 percent of bentonite weight by volume meet a minimum required viscosity for typical well drilling. Therefore the experiment had been selected 6 percent of bentonite weight by volume as a base composition.

Table 3.1 Bentonite water-base suspension.

%Bentonite (weight by volume)	Average apparent viscosity (cP)
2%	0.5
4%	3
6%	11
8%	33

A base bentonite-water suspension was prepared using 30 grams of bentonite per 500 milliliter of water and 60 grams of barite added to control density. The mud components were mixed for 15 min using high-speed mixture (Hamilton Beach). During mixing, the NRL was added slowly to agitated base fluid to avoid a lump occurring within mud system. The testing mud samples were weighted of 1.12 grams per cubic-centimeter (9.34 pounds per gallon) containing 6 percent bentonite weight by volume as a base composition. The mud weight was measured by mud balance which is an API standard instrument for testing mud weight (Figure 3.2). Various NRL concentrations were added to perform as mud additive. These systems were prepared to compare the properties of the mud. The formulations of the mud are showed in Table 3.2.

Figure 3.2 Mud balance.

Table 3.2 Tested mud's composition.

Mud components	**Bentonite mud**	**Bentonite +1%NRL mud**	**Bentonite +3%NRL mud**	**Bentonite +5%NRL mud**
Water (ml)	500	500	500	500
Bentonite (gram)	30	30	30	30
Barite (gram)	60	60	60	60
NRL (ml)	-	5	15	25

3.3. Rheology tests

The objective of rheology tests is to measure the viscosity and gel strength that relate to the flow properties of mud. The study of deformation and flow of matter is rheology. 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 water-base mud were investigated and calculated.

The rheology test was conducted by use six rotational speeds (600, 300, 200, 100, 6, and 3 rpm) Fann 35SA viscometer (Figure 3.3). It is the rotational coaxial-cylinder type and is used to directly measure the viscosity of the drilling fluid. The shear stress (scale reading) is determined as a function of the shear rate (from the rotational speed). In this study, the test procedures had been followed the recommended practice of standard procedure for field testing drilling fluid (API Recommended Practice, 1985).

Figure 3.3 Fann 35SA model viscometer.

3.3.1 Rheological parameters

In order to fully comprehend the rheology calculation, it is appropriate to discuss some basic drilling fluid flow properties, determination of rheological parameters which describe the flow behavior of a fluid.

Apparent viscosity is a rheological property calculated from rheometer readings. It measures the shear rate of drilling fluid specified by API. Apparent viscosity is expressed in centipoise (cP), it indicates the amount of force required to move one layer of fluid in relation to another. The apparent viscosity can calculated from equation 3.3.

Plastic viscosity 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: (1) between the solids in the mud, (2) between the solids and the liquid that surrounds them, and (3) 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 from equation 3.4 and its ranges value that used in well drilling is showed in Figure 3.4.

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 underflow 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. The yield point value can be calculated from equation 3.5 and its ranges value that used in well drilling is also showed in Figure 3.4.

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.

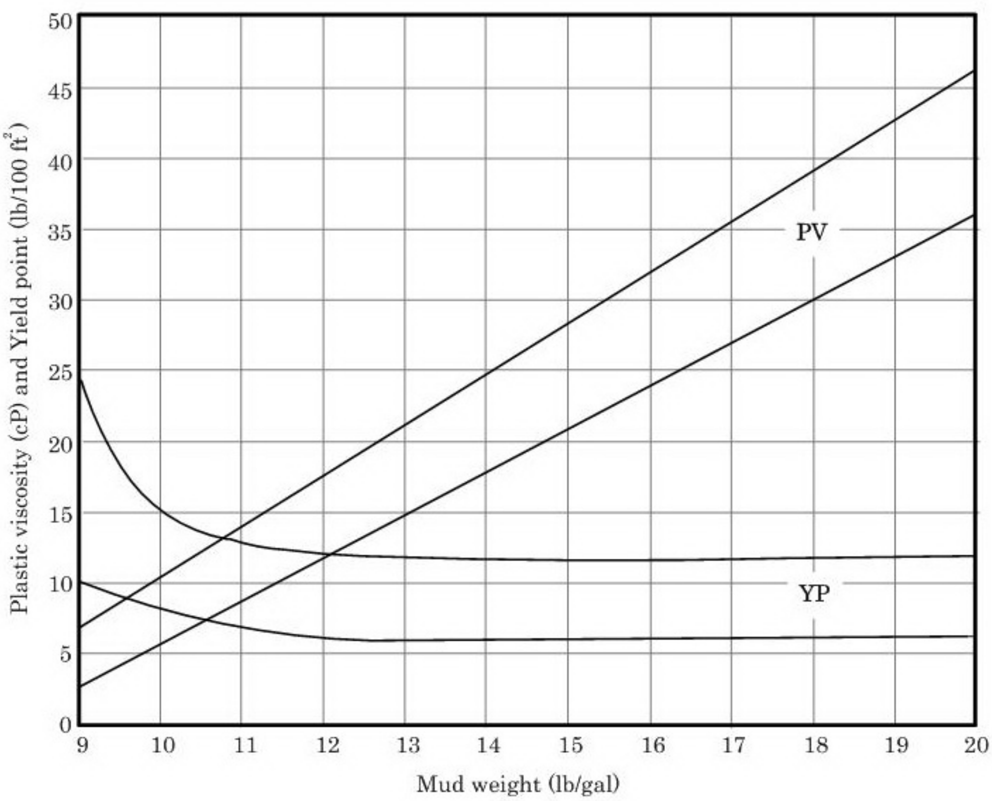

Figure 3.4 Plastic viscosity and yield point ranges for water-base mud (modified from MI Swaco, 1998).

3.3.2 Determination of drilling fluid parameters

The drilling fluids were characterized by their shear rate and shear stress relationships. The shear rate and shear stress were calculated using the viscometer dial readings. The shear stress and shear rate equations are as followed:

$$\tau = 0.01066 \times \phi_i \times \mathrm{N} \tag{3.1}$$

$$\gamma = 1.703 \times \mathrm{RPM} \tag{3.2}$$

Where,

τ = shear stress, lb_f/ft^2

γ = shear rate, sec^{-1}

ϕ_i = viscometer dial reading

N = Range extension factor of the torque spring of the VG meter

rpm = rotational speed

The apparent viscosity, plastic viscosity and yield point were calculated from 300 and 600 rpm readings using following formulas from API recommended practice of standard procedure for field testing drilling fluid (API Recommended Practice, 1985).

$$\mu_a = \phi_{600} / 2 \tag{3.3}$$

$$\mu_p = \phi_{600} - \phi_{300} \tag{3.4}$$

$$\gamma_p = \phi_{300} - \mu_p \tag{3.5}$$

Where, μ_a = Apparent viscosity, cP

μ_p = Plastic viscosity, cP

γ_p = Yield point, lb/100 ft^2

The Power Law model parameters in the term of flow behavior index (n) and consistency (k) were calculated from viscometer readings using following equations.

$$n = 3.322\log(\phi_{600}/\phi_{300}) \tag{3.6}$$

$$k = 510\phi_{300}/511^n \tag{3.7}$$

Where, n = flow behavior index

k = fluid consistency index

ϕ_{600} = viscometer dial reading at 600 rpm

ϕ_{300} = viscometer dial reading at 300 rpm

3.4 Static filtration tests

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 formation are involved in drilling an oil well, there are static filtration and dynamic filtration. Static filtration occurs when the mud is not being circulated and the filter cake grows undisturbed. Dynamic filtration test 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 and the filtration properties of mud samples were evaluated and controlled by API standard filter press.

The experiment was conducted by Baroid standard filter press rig laboratory model 821 (Figure 3.5) which determines (1) the API filtrate loss through standard filter paper and (2) the mudcake thickness under static conditions. It consists of fluid cup supported by a frame, a filtering medium and a pressurized nitrogen gas cylinder and regulator. A graduated cylinder was used to measure the discharged filtrate. 100 psig was applied to a column of fluid for 30 minutes period which filtrate volume and mudcake thickness were measured and recorded. The schematic of API filter press is show in Figure 3.6. The test procedures had been followed the recommended practice of standard procedure for field testing drilling fluid (API Recommended Practice, 1985).

3.5 Hydrogen ion tests

The hydrogen ion (pH) measurements of the fluids were conducted using glass electrode pH meter, Metrohm 713 (Figure 3.7). The instrument determines pH of an aqueous solution by measuring the electro-potential generated between a glass electrode and a reference electrode. 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 were followed the recommended practice of standard procedure for field testing drilling fluid (API Recommended Practice, 1985).

Figure 3.5 Baroid standard filter press.

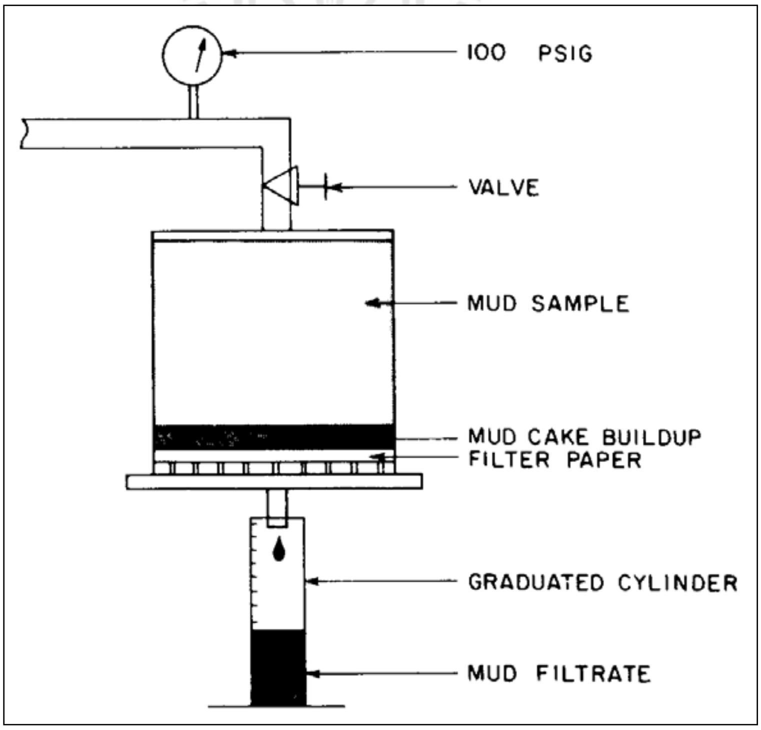

Figure 3.6 Schematic of API filter press.

Figure 3.7 pH meter.

CHAPTER IV

DATA ANALYSIS, RESULTS, AND DISCUSSIONS

4.1 Introduction

This chapter presents and discusses the results of the experiments. Drilling fluid samples were tested and analyzed to determine their rheological, filtration properties, pH values, the cost of new invented mud were discussed and compared to common mud system that used in well drilling. The results of the experiment and analysis are discussed below.

4.2 Determination of rheological properties and parameters

Table 4.1 shows the shear stress and shear rates values for all six viscometer readings of base bentonite mud. The average viscometer readings were used to calculate the shear stress and shear rates by following equation 3.1 and 3.2 in previous chapter. The calculated shear stresses were plotted against shear rates in order to choose the best fit curve for the Power Law or the Bingham Plastic model. As a result, each plot curve was fitted with both linear and power equations. A correlation coefficient was obtained for each fitting curve. However, the Bingham plastic fluids were better fitted with a linear correlation, while the Power Law fluids were fitted with power equations. For example, Figure 4.1 and 4.2 show the consistency plots for based bentonite mud under 30^{o}C. From the two plots, it can be inferred that the fluid is tend to be a Bingham Plastic fluid.

Table 4.1 Shear stress and shear rates resulted from the base bentonite mud calculation.

rpm	average reading	γ (sec^{-1})	τ (lb_f/ft^2)
600	21.67	1021.8	0.046
300	17.00	510.9	0.036
200	14.67	340.6	0.031
100	11.67	170.3	0.025
6	9.00	10.2	0.019
3	8.00	5.1	0.017

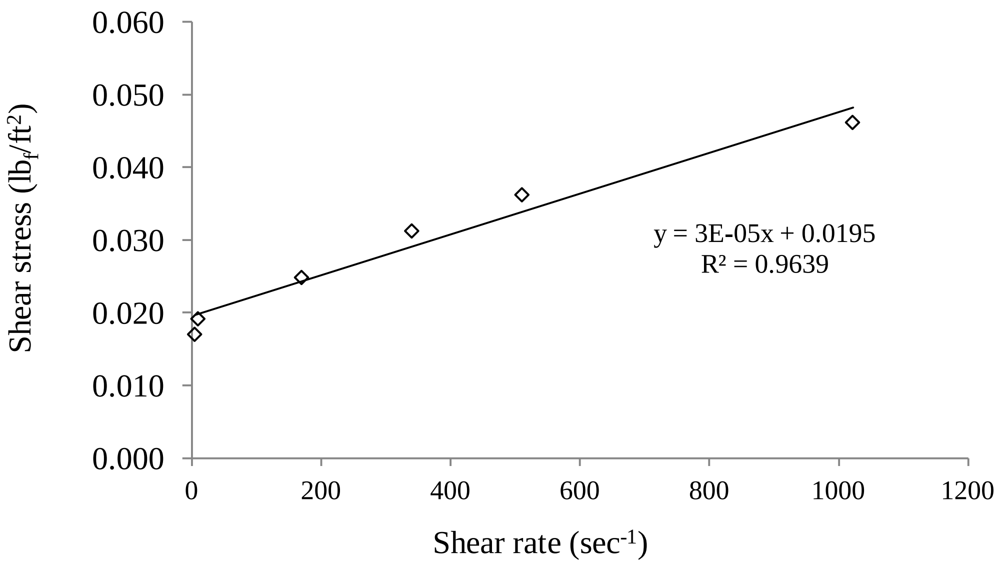

Figure 4.1 Consistency plot of base bentonite mud with a linear correlation.

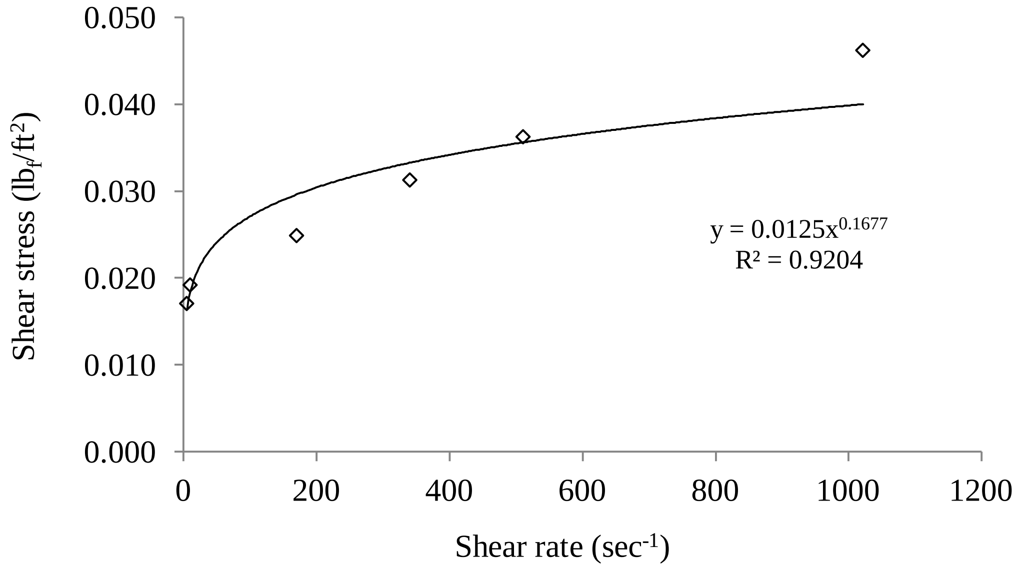

Figure 4.2 Consistency plot of base bentonite mud with a power correlation.

The appropriate rheological model for all other mud samples was determined in similar way. The mud samples were categorized into four groups of tested temperature. Their consistency curves were plotted in Figure 4.3 through 4.6. Based on the plots, all mud samples that tested under 30°C condition exhibited Bingham Plastic behavior but Power Law behavior presented after elevated treatment temperature to 45, 60, and 80°C. It can be seen that the based bentonite mud and NRL containing mud behaved both of behavior depending on temperature. However, it cannot exactly match the flow property of fluid with either the Bingham Plastic or Power Law model. Most of drilling mud demonstrates the flow behavior in between the Bingham Plastic and the Power Law model. The rheological properties of each fluid were calculated for both models. Both models were used for each fluid just for comparison purposes. The results of rheological calculation are shown in Table 4.2.

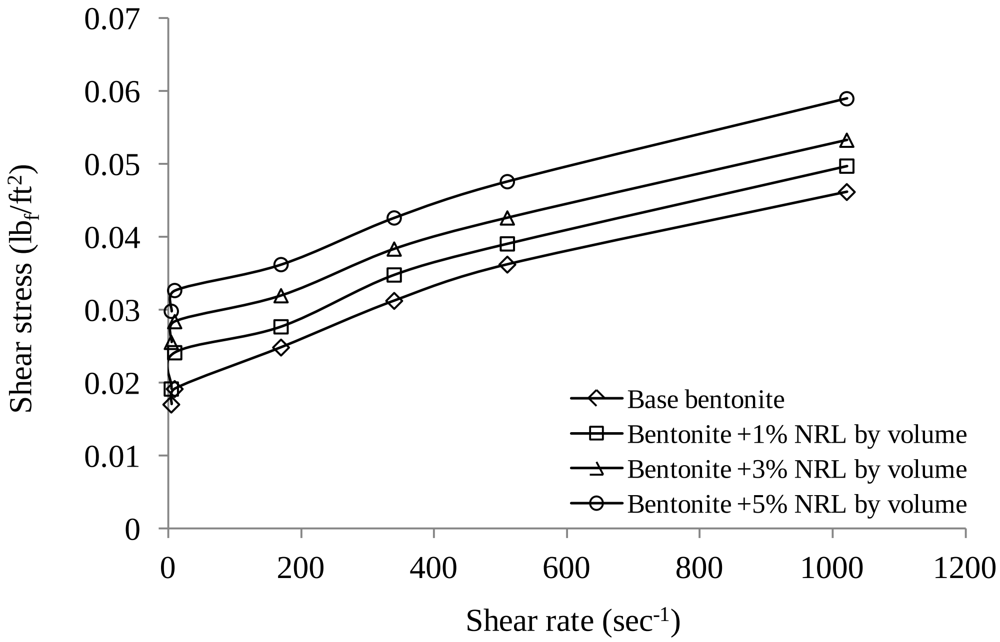

Figure 4.3 Consistency plots of mud samples at 30°C.

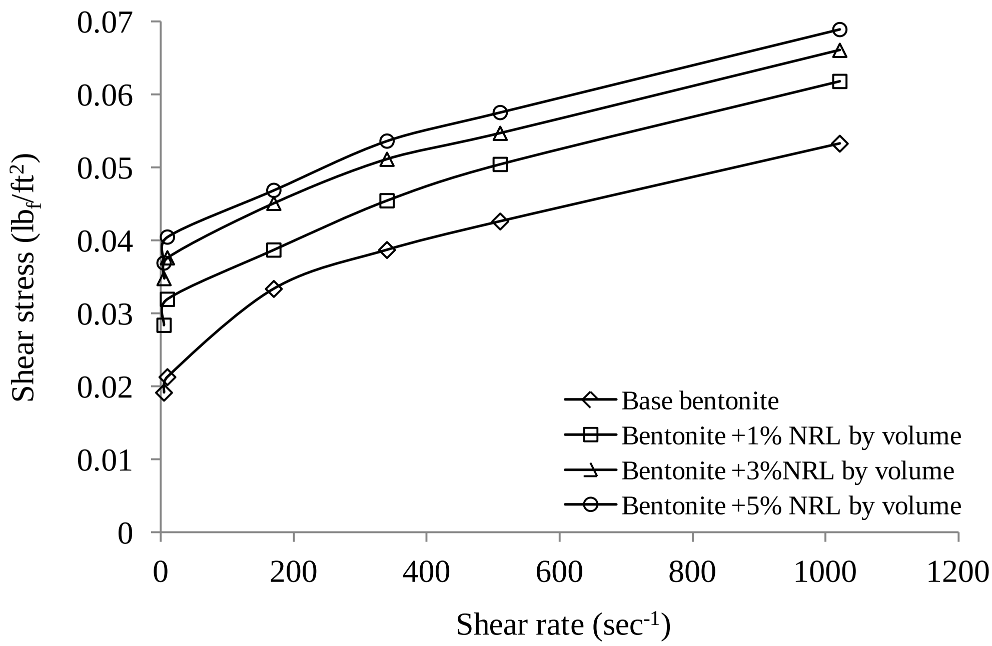

Figure 4.4 Consistency plots of mud sample at 45°C.

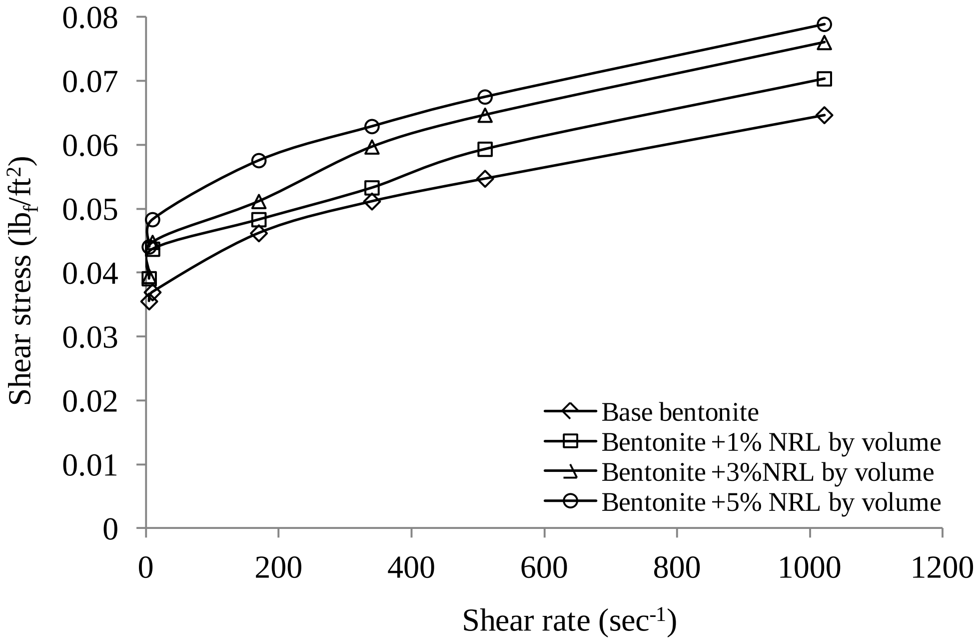

Figure 4.5 Consistency plots of mud samples at 60 ^{o}C.

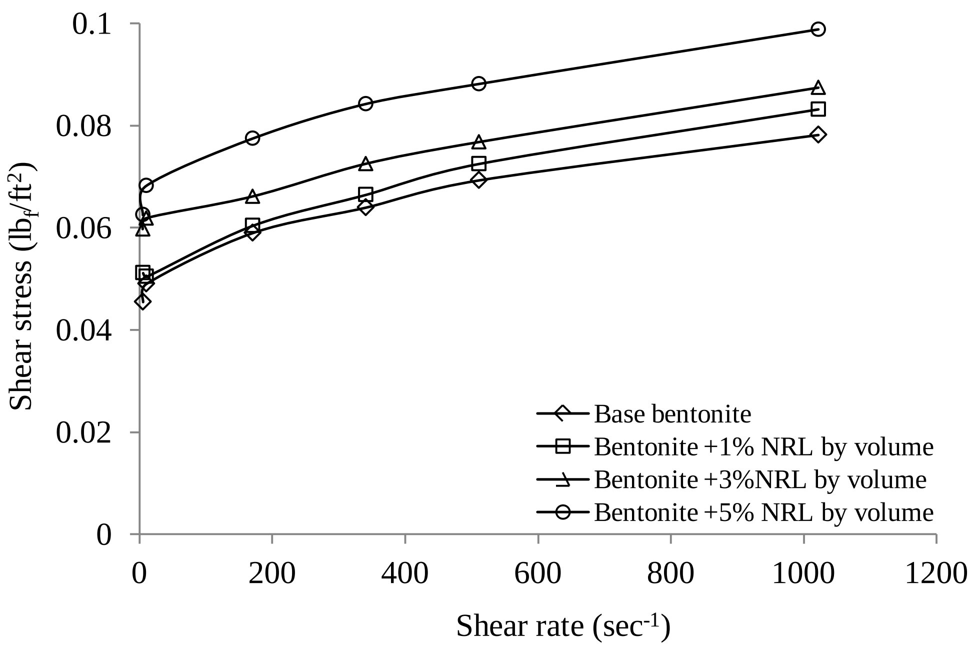

Figure 4.6 Consistency plots of mud samples at 80^{o}C.

Table 4.2 Rheological parameters of mud samples.

Tested Temperature	Mud composition	apparent viscosity (cp)	Bingham Plastic model		Power Law model		Gel_{in} (lb_f/100 ft^2)	Gel_{10} (lb_f/100 ft^2)
			Plastic viscosity (cp)	Yield point (lb_f/100 ft^2)	n	K (eq.cP)		
30°C	Bentonite	10.8	4.7	12.3	0.35	978	11.3	13.7
	Bentonite+ 1%NRL	11.7	5	13.3	0.35	1068	11.3	13.7
	Bentonite+ 3%NRL	12.5	5	15.0	0.32	1370	13.2	15.7
	Bentonite+ 5%NRL	13.8	5.3	17.0	0.31	1659	14.7	15.7
45°C	Bentonite	12.5	5	15.0	0.32	1370	14.8	18.7
	Bentonite+ 1%NRL	14.5	5.3	17.3	0.29	1939	16.3	19.3
	Bentonite+ 3%NRL	15.5	5.3	20.3	0.27	2395	18	21.2
	Bentonite+ 5%NRL	16.2	5.3	21.7	0.26	2720	19.0	19.3
60°C	Bentonite	15.2	4.7	21.0	0.24	2912	20.7	20.2
	Bentonite+ 1%NRL	16.6	5.2	22.2	0.25	3068	21	21.3
	Bentonite+ 3%NRL	18	5.3	23.3	0.23	3602	22.7	22.2
	Bentonite+ 5%NRL	18.5	5.3	25.7	0.22	3981	23.3	22.3
80°C	Bentonite	18.3	4.2	28.3	0.17	5599	24.7	24.2
	Bentonite+ 1%NRL	19.5	5	29	0.20	5046	26	24.5
	Bentonite+ 3%NRL	20.5	5	31	0.19	5698	31.5	27.7
	Bentonite+ 5%NRL	23.2	5	36.3	0.16	7545	31.7	31.3

4.3 Rheological behavior of NRL containing mud.

The rheological properties of base bentonite mud and NRL containing mud samples are summarized in Table 4.2 and rheological data of triplicate test is shown in Appendix A. The Power Law model parameters in the term of flow behavior index (n) and consistency (K) were calculated by equation 3.6 and 3.7 as showed in previous chapter. The index n indicated that all mud samples exhibited pseudoplastic flow with n less than 1. As mentioned above, the flow behavior of typical drilling mud usually acted between the Bingham Plastic and the Power Law model which was called pseudoplastic fluid. The consistency factors of mud sample clearly increase as the NRL containing mud increased. The constant was analogous to the apparent viscosity of the fluid that described the thickness of the fluid. The power Law model did not describe the behavior or drilling fluids exactly but the constant n and K normally desirable in the interest of hydraulic horsepower utilization which was used in hydraulic calculations.

Figure 4.7 through 4.16 are the plots of the rheological parameters obtained from the calculation with various NRL concentrations. The apparent viscosity was plotted as a function of NRL concentration as showed in Figure 4.7. For all tested temperature, the results indicate a significant increase in the apparent viscosity as the NRL concentration increase. This is due to greater colloidal fraction of bentonite and NRL in mud sample that result of increasing flow resistance. The influence of temperature on the apparent viscosity is shown in Figure 4.8. It clearly sees that for all of NRL compositions, the apparent viscosity increase with increasing temperature. The consequence of temperature increase interaction energy of mud system (Luckham and Rossi, 1999). It induces more inter-particle attractive force between solid particles and so the clay particles come into contact with another and agglomerate which is known as flocculation.

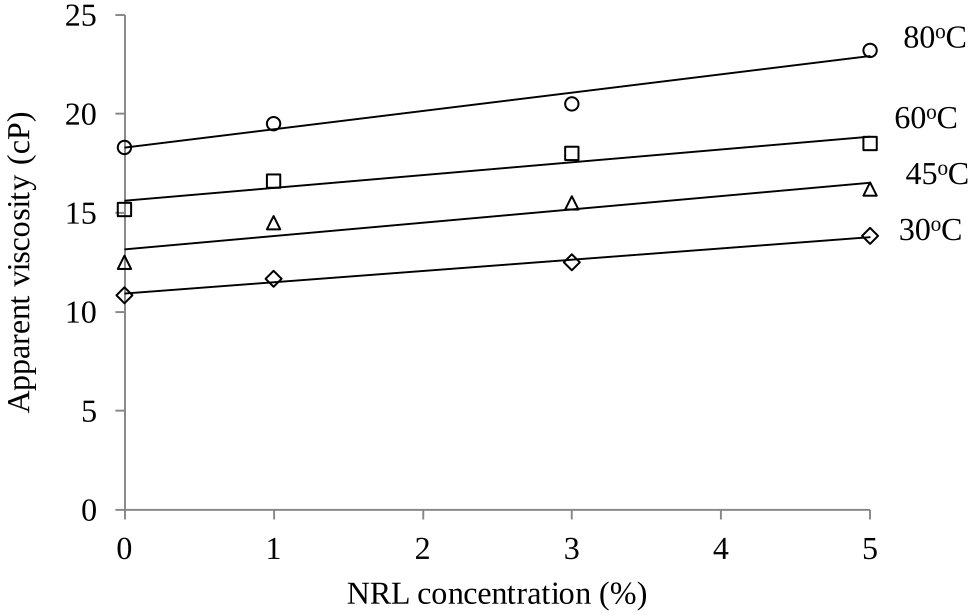

Figure 4.7 Apparent viscosity of mud samples versus NRL concentration.

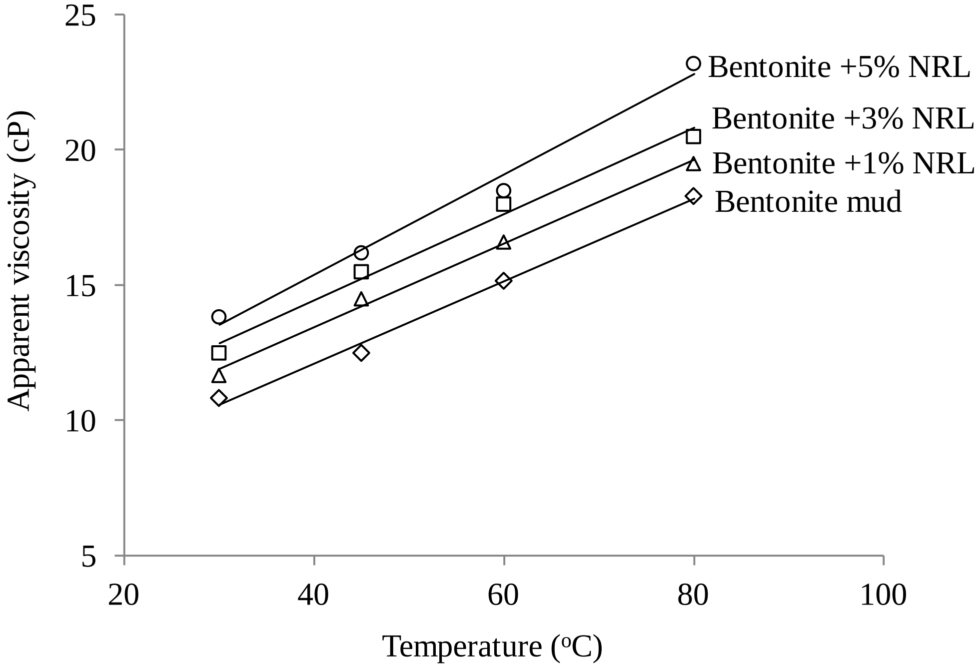

Figure 4.8 Apparent viscosity of mud samples versus temperature.

The Bingham plastic model in the term of plastic viscosity was plotted versus NRL concentrations and temperature and showed in Figure 4.9 and 4.10. The results indicated that the plastic viscosity of NRL containing mud slightly increased with increasing NRL concentration from 1 to 5 percent for all tested temperature. Considering effect of elevated temperature, the influence of elevated temperature treatment was shown slightly decreased of plastic viscosity after elevating temperature from 45°C to 80°C. The trend of line indicated that the mud behaved non-Newtonian and shear-thinning as temperature increased (up to 80°C), and displayed lower plastic viscosities and higher yield stress. The effect of temperature on bentonite suspension could be described as follows: heating up the bentonite suspension increased the conductivity of the system. This was indicated that more cations (Na^+) were dissolved from the surface of the particles. It was also suggested that this effect was responsible for the reduction of the normalised plastic viscosity and the observed of the yield stress increasing, the latter also due to thermal induced swelling (Luckham and Rossi 1999).

The yield point of NRL containing mud was plotted as function of NRL concentrations and temperature as showed in Figure 4.11 and 4.12. For all tested temperature, the result indicated that the yield stress clearly increased with NRL containing mud increasing. This is because large amount of solid in mud sample tend to agglomerate and result in increasing yield stress. For all NRL containing mud, the yield stress increased with elevated temperature. Rising of temperature increases interaction energy of clay system that leads bentonite suspension become thickened. From the experiment, it can be concluded that the presence of NRL increase yield strength of mud which enhance carrying capacity of drilling fluid while drilling circulation periods.

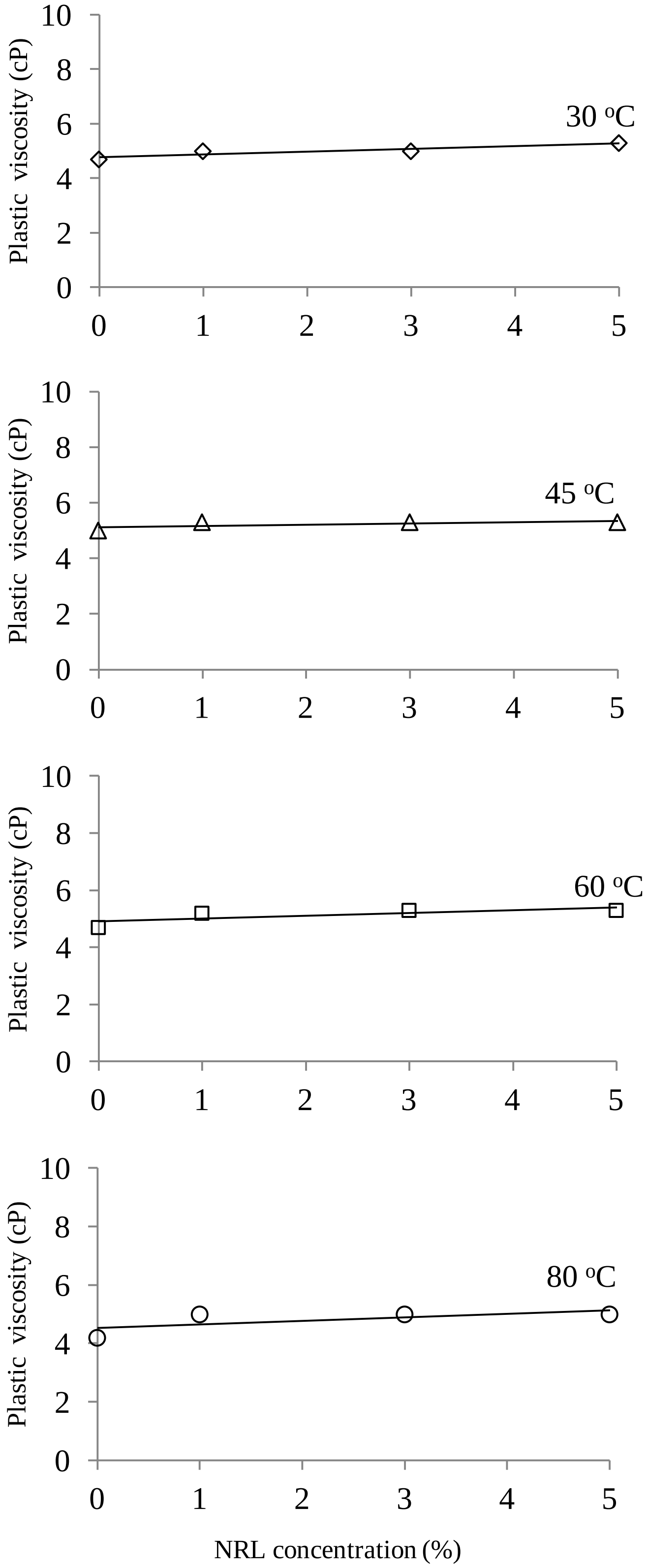

Figure 4.9 Plastic viscosity of mud samples versus NRL concentration.

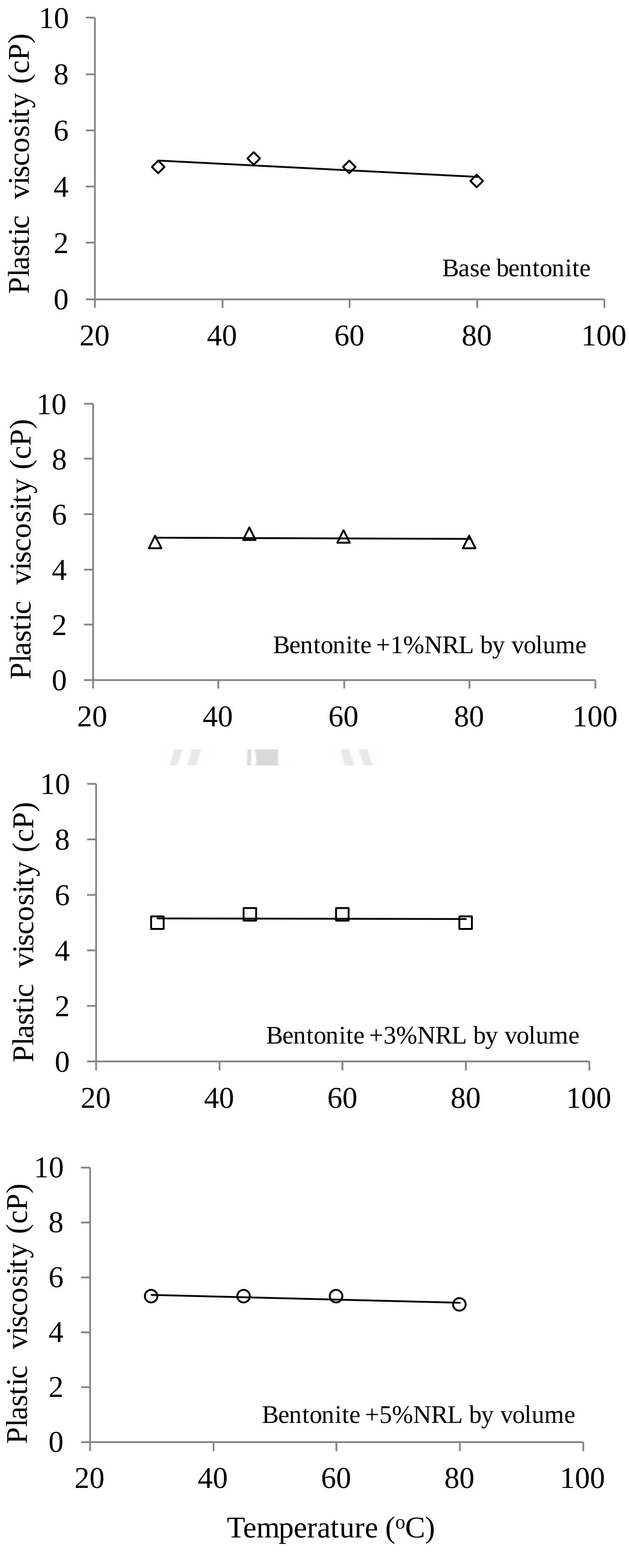

Figure 4.10 Plastic viscosity of mud samples versus temperature.

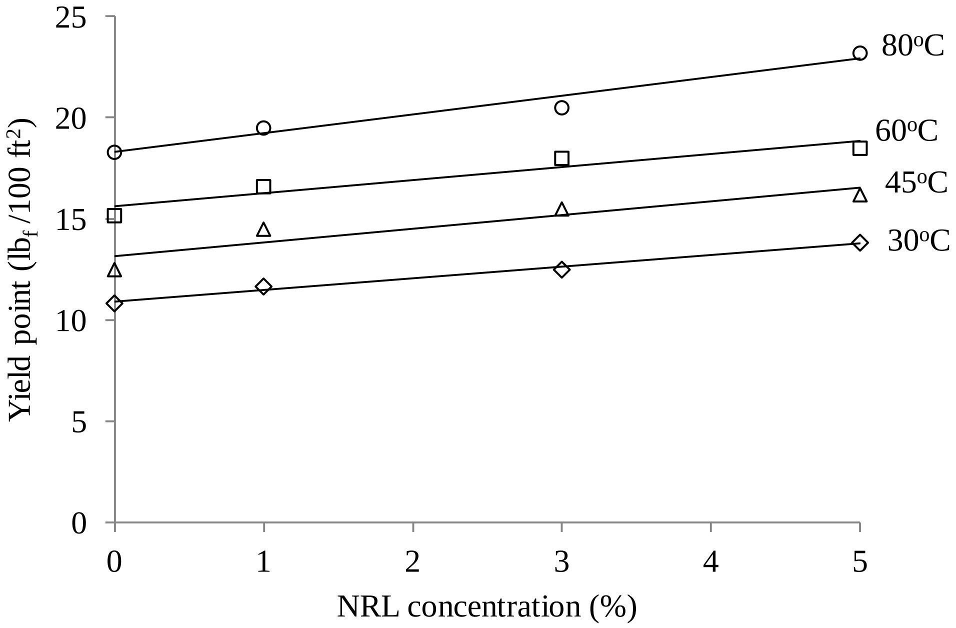

Figure 4.11 Yield point of mud samples versus NRL concentration.

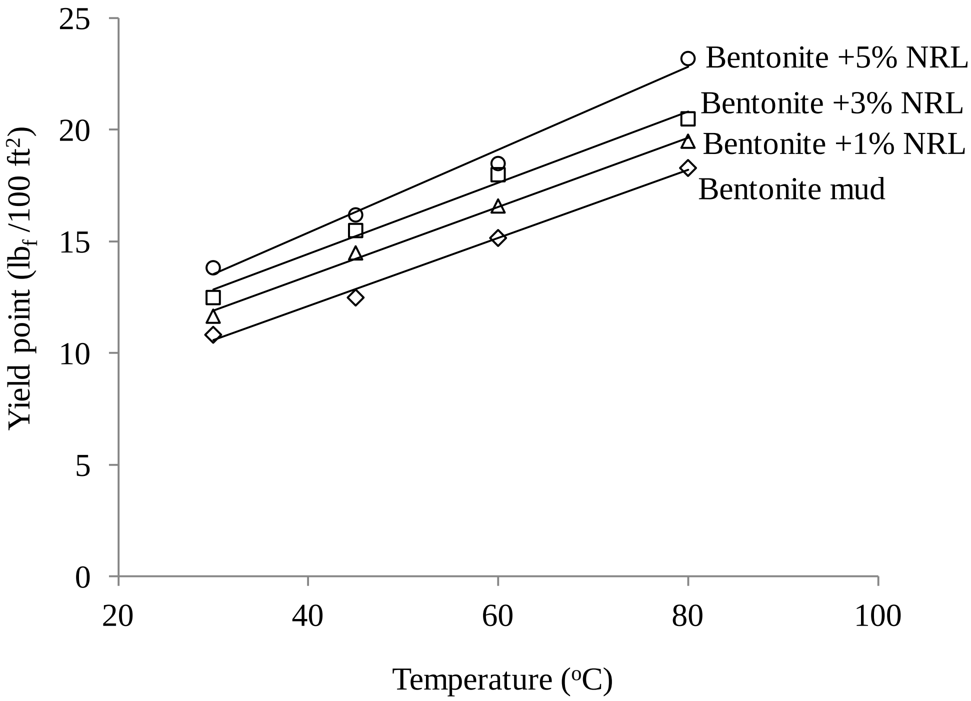

Figure 4.12 Yield point of mud samples versus temperature.

The initial and 10 minutes gel strength of NRL containing mud were investigated and their result was plotted as function of NRL concentration and temperature as showed in Figure 4.13 through 4.16. The result showed insignificant improvement of gel strength with an increasing NRL concentration and temperature. Considering NRL containing mud at 30 and 45^{o}C tested temperatures (Table 4.2), the 10 minutes gel strength was greater than initial gel strength. This is because of more undisturbed mud standing time would lead mud to form stronger gel structure compared to less undisturbed time. Considering NRL containing mud at 60 and 80^{o}C tested temperatures, the 10 minutes gel strength tended to became less than initial gel strength. The result indicated that the great temperature drop occurred while 10 minutes standing time period, which in turn, led to the lower of 10 minutes gel strength. This can be noted that gel strength is strongly influenced by time and temperature. From the experiment, it can be concluded that the presence of NRL increase gel strength of mud which enhance hole cleaning efficiency of drilling fluid by suspend cutting and weighting material when circulation is ceased.

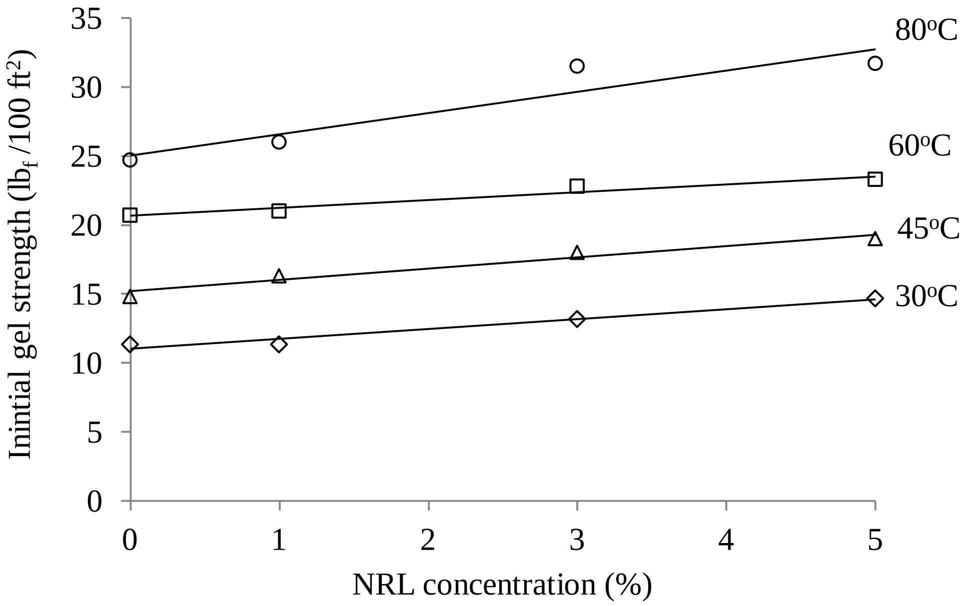

Figure 4.13 Initial gel strength of mud samples versus NRL concentration.

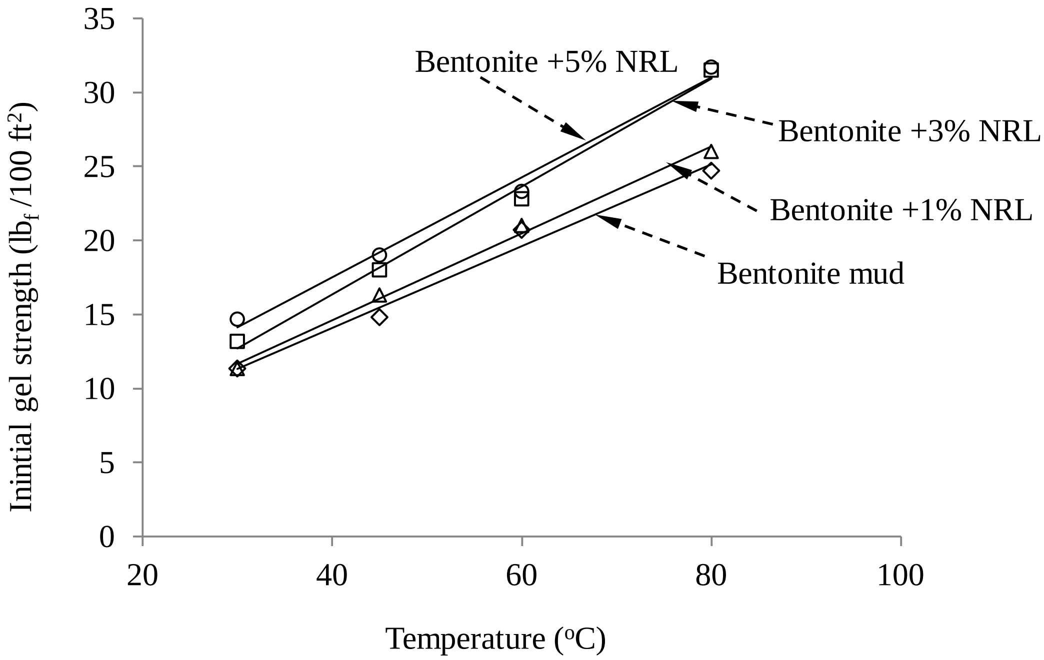

Figure 4.14 Initial gel strength of mud samples versus temperature.

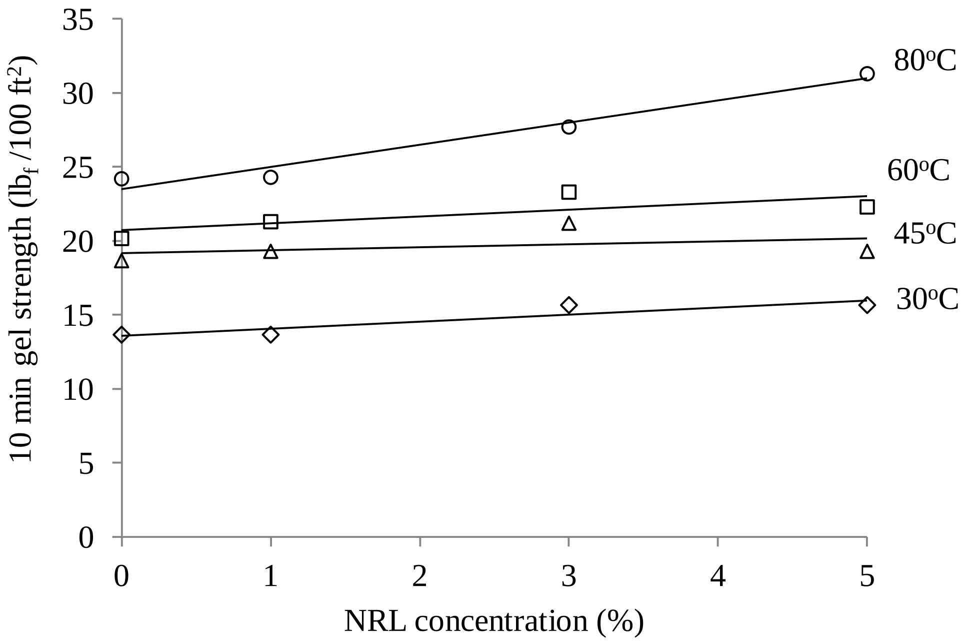

Figure 4.15 10 minutes gel strength of mud samples versus NRL concentration.

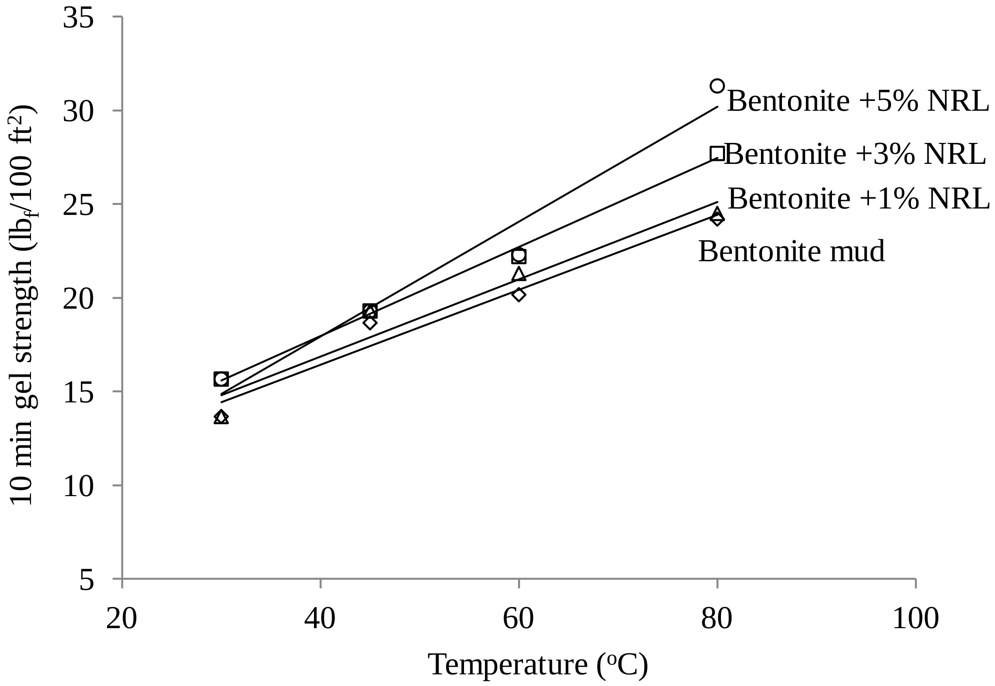

Figure 4.16 10 minutes gel strength of mud samples versus temperature.

4.4 Filtration properties of NRL containing mud

Table 4.3 summarizes the test results on average API static filtrate loss within 30 minutes of NRL containing mud. A data of triplicate test of filtration properties and mud cake thickness are shown in Appendix A.

Figure 4.17 is the plot of the filtration properties of base bentonite mud that measured at 30^{o}C and elevated temperature. The filtration properties of NRL containing mud measured at 30^{o}C are displayed in Figure 4.12. Both of graphs show time-dependant filtration behavior of base bentonite mud and indicate that the fluid loss exponentially increases as the time increase. The data also show a progressive decrease in filtration rate of mud with increasing time of filtration. The decreasing in filtration was resulted from continuous mudcake deposition and compaction until formation of a constant thickness and stable mudcake had been formed completely. From Figure 4.17, comparison of curves indicates a significant increase in the static filtration of bentonite mud as the temperature increasing. This is due to adverse temperature effects on filtration that result in fluid phase viscosity decreasing and a colloidal fraction tend to flocculate which consequences of mudcake permeability increasing.

Table 4.3 API static filtrate loss of NRL containing mud.

Tested Temperature	Mud composition	Average filtration loss (ml)					
		1 min	4min	9 min	16 min	25 min	30 min
30°C	Bentonite	2.0	5.6	9.2	12.7	16.3	18.0
	Bentonite+ 1%NRL	2.0	5.7	9.2	12.9	16.4	18.1
	Bentonite+ 3%NRL	2.0	5.4	8.8	12.0	15.6	17.1
	Bentonite+ 5%NRL	1.7	5.0	8.3	11.6	14.8	16.3
45°C	Bentonite	2.5	6.7	10.8	15.0	19.1	21.1
	Bentonite+ 5%NRL	2.2	6.1	9.9	13.6	17.3	19.1
60°C	Bentonite	2.9	7.4	11.9	16.2	20.9	23.0
	Bentonite+ 5%NRL	2.6	6.8	10.9	14.9	18.8	20.7
80°C	Bentonite	3.3	8.1	12.8	17.7	22.5	24.8
	Bentonite+ 5%NRL	2.7	7.0	11.1	15.2	19.2	21.2

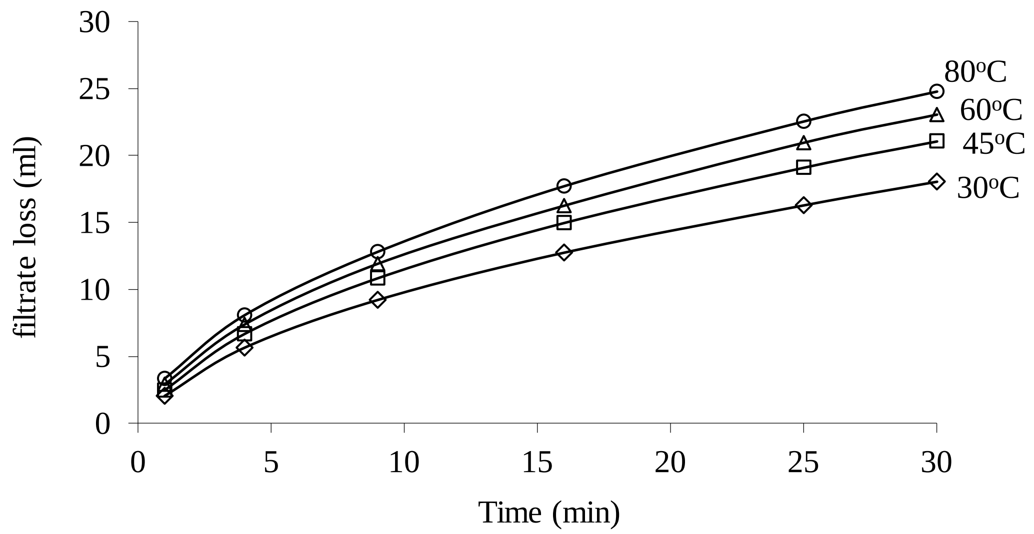

Figure 4.17 Static filtration versus time of bentonite mud.

Figure 4.18 shows the effect of NRL concentration on filtration properties at 30°C. The static filtration curves indicate that at 1 percent NRL concentration shows no any improvement in filtration behavior of bentonite mud. Comparison of 3 and 5 percent NRL concentration with base bentonite mud; it clearly shows reduction of fluid loss rate. The 3 and 5 percent NRL bentonite mud indicate about 5 and 10 percent improvement of 30 minutes filtration properties respectively. This is due to the effective swelling and distributing of NRL additive in bentonite mud which facilitated quick and tight mudcake layer on the filter paper.

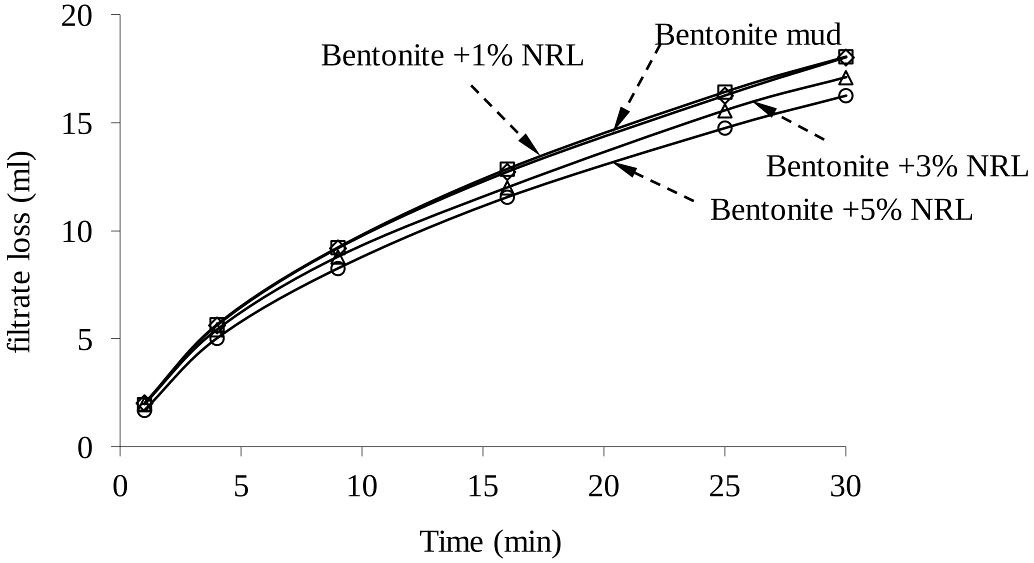

Figure 4.18 Static filtration of NRL containing mud versus time at 30°C.

Analyses of filtration behavior of the mud after thermal treatment at 45, 60, and 80°C are demonstrated in Figure 4.19. The Figure represents 30 minutes static fluid loss values of 5 percent NRL containing mud and indicates that the presence of 5 percent NRL in bentonite can reduce fluid loss about 10 to 15 percent. In this case there is no sign of thermal degradation of NRL in bentonite mud. Therefore, it can be concluded that the NRL additive could be performed under this temperature range. Thus the fluid loss behavior of the mud after thermal treatment also indicated that most of mud possesses a good thermal stability under tested temperatures. The thermal stability of the NRL mud indicated that the NRL additive could be used in subterranean well formation having downhole temperature up to 80°C. For example, in Gulf of Thailand, geothermal gradients generally vary from 2.95 to 7.00°C per 100 meter in area of hydrocarbon exploration (Lekuthai, *et al*. 1995). Hence the NRL containing mud could be used in the drilled well depth in range between 700 and 1600 meter depended on ambient temperature of well formation.

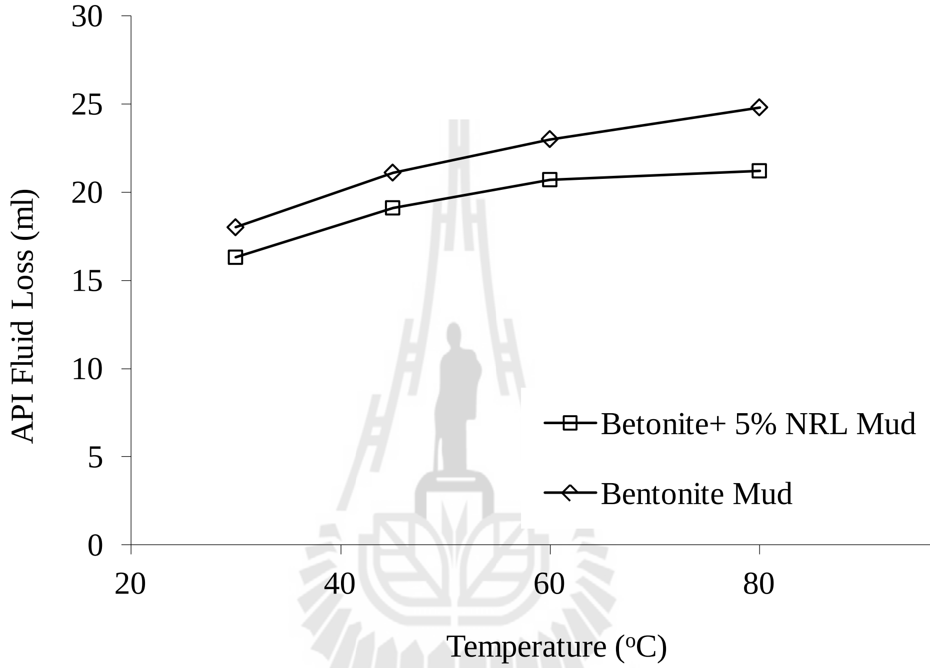

Figure 4.19 30 minutes API fluid loss of mud system.

Figure 4.20 and 4.21 show the thickness of mudcake deposited by NRL containing mud. The histograms show the thicker mudcake as the NRL concentration and temperature increasing. The qualities of mudcakes deposited by the NRL containing mud were investigated. The toughness and slickness of NRL containing mud is more than base bentonite mud and this indicates the presence of mudcake stability and lubricity. Moreover, filtration test results indicated that the presence of NRL containing mud had a favorable mudcake quality under the tested temperature range. A good quality mudcake is an effective means of preventing inflow, minimized formation damage by screening out fines migration to invaded formation and easily removed when reservoir fluid is produced (Amanullar, *et al*. 1995).

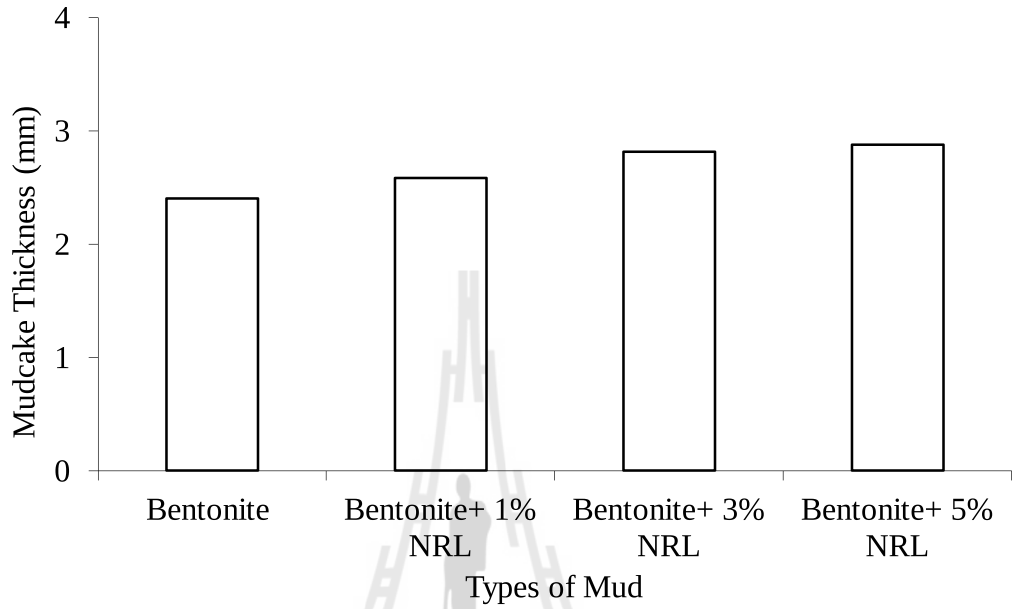

Figure 4.20 Mudcake thickness deposited by mud system at 30^{o}C.

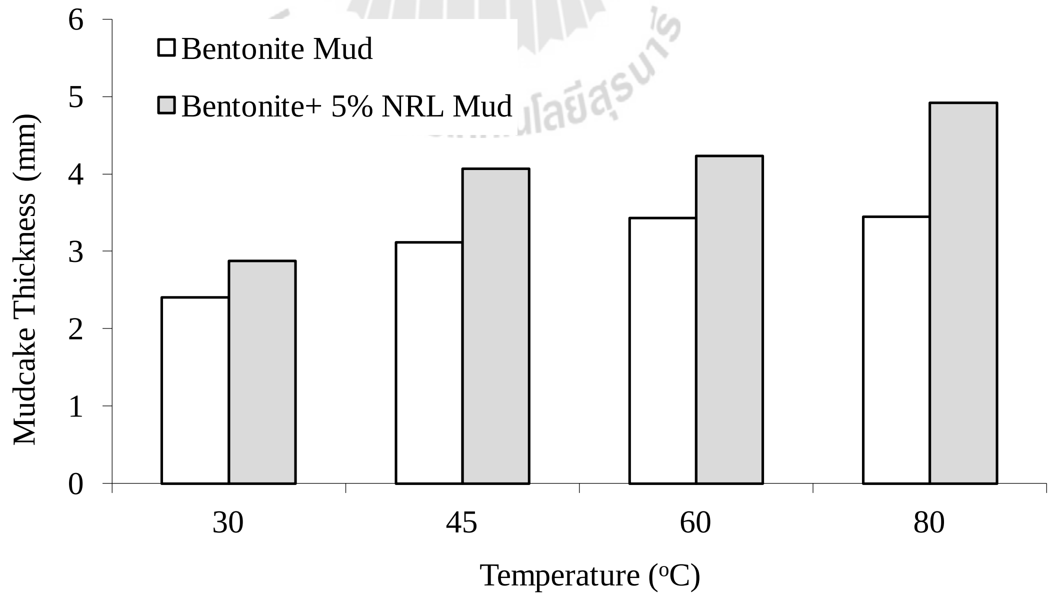

Figure 4.21 Mudcake thickness deposited by 5 percent NRL containing mud.

Determining of spurt loss of mud by filtrate volume versus square root of time plotting and extrapolate to zero time is shown in Figure 4.22 and 4.23. The graph shows the fluid loss linearly increases as the square root of time increasing. This indicates that the filtrate volume is proportional to the square root of the time period used. The result also indicated no sign of spurt loss observed at zero time, this might be the cause of low permeability of filter paper was used. Because of this study use very fine mesh paper as the filter medium, all of the bridging particles were stopped at the surface of the paper and the spurt loss phase was not simulated properly. This usually leads to underestimates of the spurt loss. A better static filtration test is the PPT (permeability plugging test) which uses ceramic disks as a medium of known permeability.

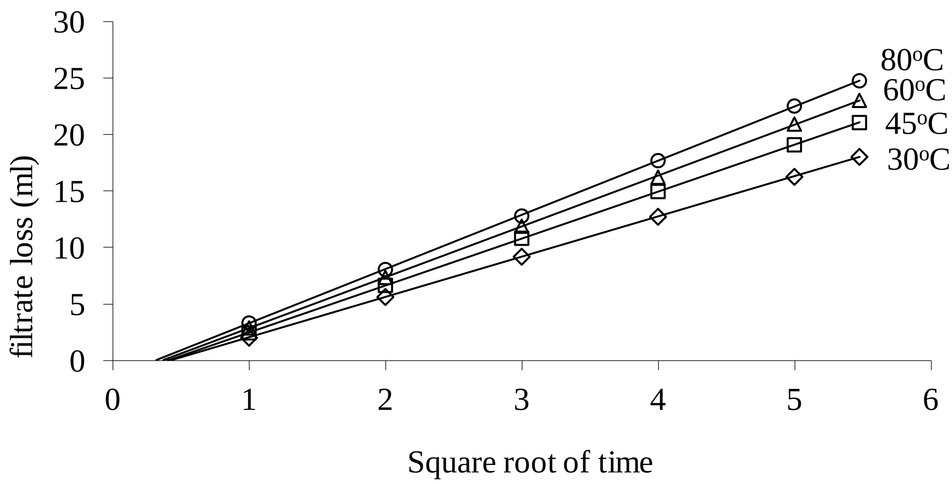

Figure 4.22 Static filtration versus square root of time of bentonite mud.

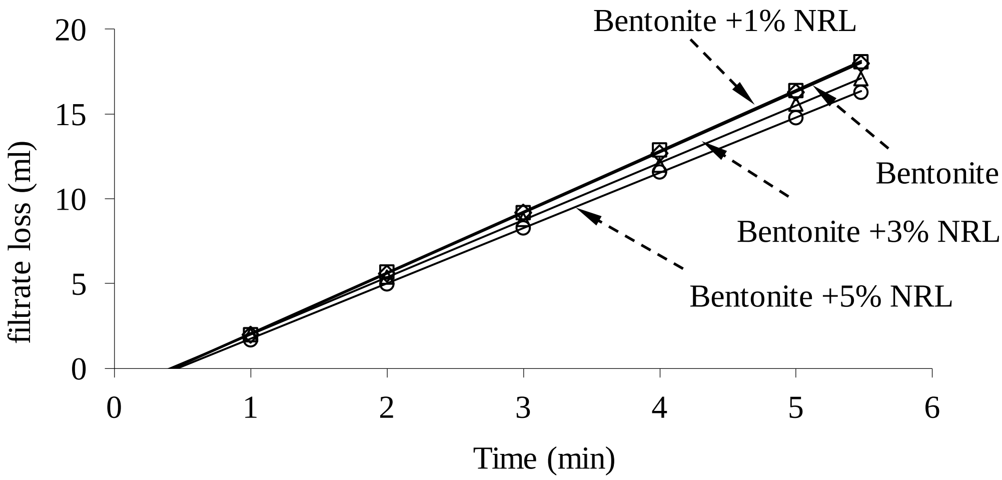

Figure 4.23 Static filtration versus square root of time of NRL containing mud at 30^oC.

4.5 The pH of NRL containing mud.

Table 4.4 summarizes the test results on hydrogen determination of NRL containing mud at 30^oC. The triplicate test were averaged and plotted in Figure 4.24. The result indicated that the pH increased as NRL concentration increased. It can be implied that the greater of NRL presence, the more mud alkalinity. The pH of many water-based drilling fluid systems is usually maintained in the range of 9.5 to 10.5 (Baker Hughes, 2006). This context is corresponding with the results that the NRL containing mud systems have pH of 9.9 to 10.2. It can be concluded that the alkalinity of NRL containing mud can minimize corrosion problem of steel tubular and solids-control devices. This is an advantage of using NRL containing mud because an organic additive generally achieves maximum effectiveness in an alkaline environment.

Table 4.4 The pH of NRL containing mud.

Mud composition	pH of mud			
	#1	#2	#3	average
Bentonite	9.332	9.235	9.295	9.287
Bentonite+ 1%NRL	10.032	9.912	9.910	9.952
Bentonite+ 3%NRL	10.251	10.226	10.089	10.189
Bentonite+ 5%NRL	10.154	10.300	10.257	10.237

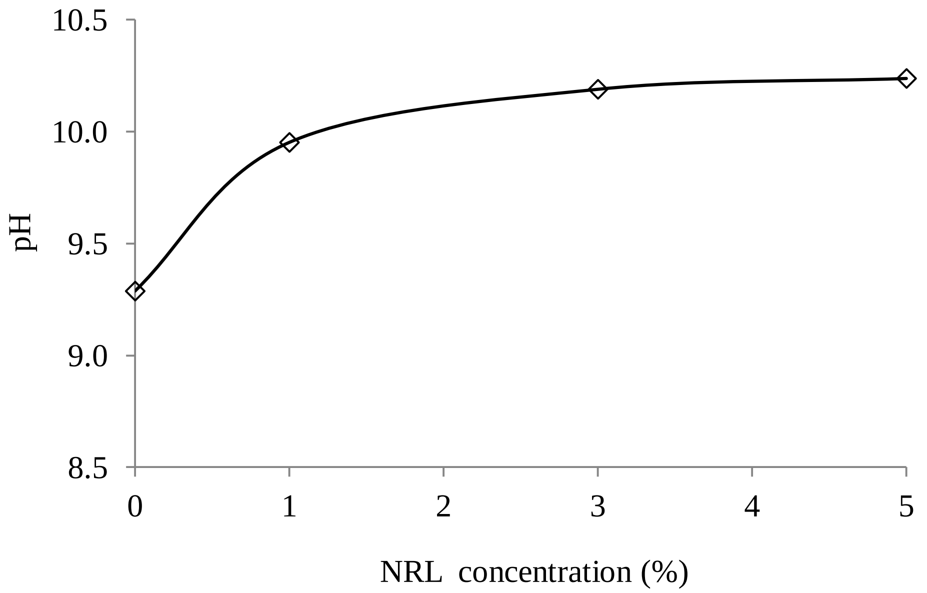

Figure 4.24 pH of NRL containing mud at 30^oC.

4.6 Cost analysis

Drilling fluids are generally expensive. In order to conclusively analyze this system in the term of economic consideration, it is essential to calculate and compare its cost between NRL drilling fluid system and conventional drilling fluid system that used in drilling well. Table 4.5 lists the cost of chemicals used in drilling fluids and this was later used to evaluate cost of drilling fluid system.

Table 4.5 Cost of drilling fluid chemicals.

Chemicals	Cost (Baht)	Unit (Kg)	Cost/Kg (Baht/Kg)
API Bentonite	16,100	1,000	16.10
Barite	4,500	1,000	4.5
PAC Polymer	72,000	25	2,880
Guar Gum	120,00	1,000	120
Xanthan Gum	105,000	1,000	105
Natural Rubber Latex	75	1	75

The table shows the conventional composition of water-base fluid that used in drilling operation. It clearly sees that the price of chemical additives is more expensive than natural rubber latex. Compared with the viscosifier, the price of NRL is 38 and 29 percent cheaper than guar gum and Xhanthan gum respectively. The price is also much cheaper than fluid lost control agent (PAC polymer). Therefore, it can be conclude that the prices for the NRL water-based fluids are cheaper than of common mud system. The inexpensive NRL is ecological friendly biopolymer which is easily affordable in Thailand Hence it is quite suitable for using in drilling fluid system. Moreover, it can minimize drilling fluid cost in drilling operation.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

Based on the results of NRL containing mud properties testing obtained from the study, some conclusions were reached as below.

- The NRL containing mud exhibited pseudo-plastic flow and shear thinning fluid by given flow behavior index less than 1.
- The presence of NRL slightly increased plastic viscosity of drilling fluid. The lower of plastic viscosity can prevents hole problems such as surge and swab pressure, differential stick and slow rate of penetration.
- The presence of NRL increased yield strength of mud which enhance carrying capacity of drilling fluid while drilling circulation periods.
- The presence of NRL increased gel strength of mud which enhance hole cleaning efficiency of drilling fluid by suspend cutting and weighting materials when circulation is ceased.
- The apparent viscosity, plastic viscosity, yield point and gel strength of NRL containing mud increased with increasing temperature while the plastic viscosity slightly decreased with increasing temperature.

- Drilling mud contained 5 percent NRL concentration give appropriate rheological properties for water base mud according to Figure 3.4.
- The API fluid loss values of NRL containing mud indicated a better fluid loss control properties at 3 and 5 percent NRL concentration compared to the base bentonite mud about 5 and 10 percent improvement.
- The NRL containing mud showed insignificant increasing in the filtration properties after elevated tested temperature to 80^{o}C about 10 to 15 percent improvement. It indicates that temperature has negative effects on filtration properties of drilling mud by decreasing effectiveness of polymer and bentonite suspension.
- The presence of slickness and lubricity of mud cake that deposited by NRL containing mud can lubricate drilling string while drilling operation
- The NRL containing mud could be performed at 80^{o}C borehole condition that corresponding well depth about 700 to 1600 meter in the gulf of Thailand without thermal degradation of NRL additive.
- The NRL containing mud systems at 1, 3, and 5 percent NRL concentration had pH in range of 9.9 to 10.2. It can minimize corrosion problem of steel in drilling fluid circulation process.

5.2 Recommendation

The uncertainties and adequacies of the research investigation and results lead to recommendation area for further studies as follows.

- It should be directed to study the thermal behavior of NRL containing bentonite mud at elevated temperature more than 80^{o}C to limited range of usable temperature without serious thermal degradation of NRL and NRL concentration more than 5 percent might be tested.
- The dynamic filtration test should be performed to test NRL containing bentonite mud under high temperature and pressure that represents the real circulated borehole condition. The formation damage are concerned and should be measured due to erodibility of mudcake NRL deposited are presence.
- Effect of salinity or electrolyte on NRL water-base mud properties should be conducted to the experiment because it has influence on bentonite clay suspension. The examples of electrolyte should be sodium chloride, potassium chloride or lime which is commonly used in drilling mud.

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APPENDIX A

EXPERIMENT DATA

Fann viscometer data and parameters for all fluid tested.

Table A1 6 percent Bentonite (weight by volume) at 30°C.

RPM	Reading #1	Reading #2	Reading #3	Average reading	γ (sec^{-1})	τ (lb_f/ft^2)
600	22	20	23	21.67	1021.8	0.046
300	17	16	18	17.00	510.9	0.036
200	15	14	15	14.67	340.6	0.031
100	12	11	12	11.67	170.3	0.025
6	9	9	9	9.00	10.2	0.019
3	8	8	8	8.00	5.1	0.017
Gel_{in}	13	12	9			
Gel_{10}	16	14	11			
Plastic viscosity	5	4	5			
Apparent viscosity	11	10	11.5			
Yield point	12	12	13			

Table A2 6 percent Bentonite (weight by volume) at 45°C.

RPM	Reading #1	Reading #2	Reading #3	Average reading	γ (sec^{-1})	τ (lb_f/ft^2)
600	26	23	26	25.00	1021.8	0.053
300	20	19	21	20.00	510.9	0.043
200	18	17	19.5	18.17	340.6	0.039
100	16	14	17	15.67	170.3	0.033
6	10	9	11	10.00	10.2	0.021
3	9	8	10	9.00	5.109	0.019
Gel_{in}	15	14	15.5			
Gel_{10}	19	18	19			
Plastic viscosity	6	4	5			
Apparent viscosity	13	11.5	13			
Yield point	14	15	16			

Table A3 6 percent Bentonite (weight by volume) at 60^{o}C.

RPM	**Reading #1**	**Reading #2**	**Reading #3**	**Average reading**	**γ (sec^{-1})**	**τ (lb$_f$/ft^2)**
600	32	28	31	30.33	1021.8	0.065
300	27	24	26	25.67	510.9	0.055
200	26	23	23	24.00	340.6	0.051
100	25	20	20	21.67	170.3	0.046
6	19	14	19	17.33	10.2	0.037
3	18	13	19	16.67	5.1	0.036
Gel$_{in}$	24	18	20			
Gel$_{10}$	23	18	19.5			
Plastic viscosity	5	4	5			
Apparent viscosity	16	14	15.5			
Yield point	22	20	21			

Table A4 6 percent Bentonite (weight by volume) at 80^{o}C.

RPM	**Reading #1**	**Reading #2**	**Reading #3**	**Average reading**	**γ (sec^{-1})**	**τ (lb$_f$/ft^2)**
600	35	39	36	36.67	1021.8	0.078
300	30	36	31.5	32.50	510.9	0.069
200	28	34	28	30.00	340.6	0.064
100	25	32	26	27.67	170.3	0.059
6	23	22	24	23.00	10.2	0.049
3	21	20	23	21.33	5.1	0.045
Gel$_{in}$	22	26	26			
Gel$_{10}$	25	23.5	24			
Plastic viscosity	5	3	4.5			
Apparent viscosity	17.5	19.5	18			
Yield point	25	33	27			

Table A5 6 percent Bentonite (weight by volume) +1 percent NRL (volume by volume) at 30^oC.

RPM	Reading #1	Reading #2	Reading #3	Average reading	γ (sec^{-1})	τ (lb_f/ft^2)
600	22	24	24	23.33	1021.8	0.050
300	17	19	19	18.33	510.9	0.039
200	15	17	17	16.33	340.6	0.035
100	12	14	13	13.00	170.3	0.028
6	9	13	12	11.33	10.2	0.024
3	7	10	10	9.00	5.1	0.019
Gel_{in}	10	12	12			
Gel_{10}	12	14	15			
Plastic viscosity	5	5	5			
Apparent viscosity	11	12	12			
Yield point	12	14	14			

Table A6 6 percent Bentonite (weight by volume) +1 percent NRL (volume by volume) at 45^oC.

RPM	Reading #1	Reading #2	Reading #3	Average reading	γ (sec^{-1})	τ (lb_f/ft^2)
600	28	30	29	29.00	1021.8	0.062
300	23	24	24	23.67	510.9	0.050
200	20	23	21	21.33	340.6	0.045
100	17	19.5	18	18.17	170.3	0.039
6	13	15	17	15.00	10.2	0.032
3	11	14	15	13.33	5.1	0.028
Gel_{in}	15	16	18			
Gel_{10}	20	19	19			
Plastic viscosity	5	6	5			
Apparent viscosity	14	15	14.5			
Yield point	18	18	19			

Table A7 6 percent Bentonite (weight by volume) +1 percent NRL (volume by volume) at 60°C.

RPM	Reading #1	Reading #2	Reading #3	Average reading	γ (sec^{-1})	τ (lb$_f$/ft^2)
600	32	33	34	33.00	1021.8	0.070
300	27	27.5	29	27.83	510.9	0.059
200	24	25	26	25.00	340.6	0.053
100	22	22	24	22.67	170.3	0.048
6	19	20	22.5	20.50	10.2	0.044
3	17	17	21	18.33	5.1	0.039
Gel$_{in}$	20	19	24			
Gel$_{10}$	19	22	23			
Plastic viscosity	5	5.5	5			
Apparent viscosity	16	16.5	17			
Yield point	22	22	24			

Table A8 6 percent Bentonite (weight by volume) +1 percent NRL (volume by volume) at 80°C.

RPM	Reading #1	Reading #2	Reading #3	Average reading	γ (sec^{-1})	τ (lb$_f$/ft^2)
600	41	37	39	39.00	1021.8	0.083
300	36	31	35	34.00	510.9	0.072
200	32	28	33.5	31.17	340.6	0.066
100	30	24	31	28.33	170.3	0.060
6	26	23	22	23.67	10.2	0.050
3	20	22	30	24.00	5.1	0.051
Gel$_{in}$	24	27	27			
Gel$_{10}$	24	24	25			
Plastic viscosity	5	6	4			
Apparent viscosity	20.5	18.5	19.5			
Yield point	31	25	31			

Table A9 6 percent Bentonite (weight by volume) +3 percent NRL (volume by volume) at 30^{o}C.

RPM	Reading #1	Reading #2	Reading #3	Average reading	γ (sec^{-1})	τ (lb$_f$/ft^2)
600	24	27	24	25.00	1021.8	0.053
300	19	22	19	20.00	510.9	0.043
200	16	20	18	18.00	340.6	0.038
100	14	16	15	15.00	170.3	0.032
6	13	15	12	13.33	10.2	0.028
3	12	14	10	12.00	5.1	0.026
Gel$_{in}$	13	14.5	12			
Gel$_{10}$	14	18	15			
Plastic viscosity	5	5	5			
Apparent viscosity	12	13.5	12			
Yield point	14	17	14			

Table A10 6 percent Bentonite (weight by volume) +3 percent NRL (volume by volume) at 45^{o}C.

RPM	Reading #1	Reading #2	Reading #3	Average reading	γ (sec^{-1})	τ (lb$_f$/ft^2)
600	33	30	30	31.00	1021.8	0.066
300	27	26	24	25.67	510.9	0.055
200	25	24	23	24.00	340.6	0.051
100	21	23	19.5	21.17	170.3	0.045
6	20	18	15	17.67	10.2	0.038
3	19	16	14	16.33	5.1	0.035
Gel$_{in}$	20	18	16			
Gel$_{10}$	24.5	20	19			
Plastic viscosity	6	4	6			
Apparent viscosity	16.5	15	15			
Yield point	21	22	18			

Table A11 6 percent Bentonite (weight by volume) +3 percent NRL (volume by volume) at 60°C.

RPM	Reading #1	Reading #2	Reading #3	Average reading	γ (sec^{-1})	τ (lb_f/ft^2)
600	34	36	37	35.67	1021.8	0.076
300	29	30	32	30.33	510.9	0.065
200	27	28	29	28.00	340.6	0.060
100	23	25	24	24.00	170.3	0.051
6	21	21	21	21.00	10.2	0.045
3	18	19	18.5	18.50	5.1	0.039
Gel_{in}	21	23.5	24			
Gel_{10}	21	25	24			
Plastic viscosity	5	6	5			
Apparent viscosity	17	18	18.5			
Yield point	24	24	27			

Table A12 6 percent Bentonite (weight by volume) +3 percent NRL (volume by volume) at 80°C.

RPM	Reading #1	Reading #2	Reading #3	Average reading	γ (sec^{-1})	τ (lb_f/ft^2)
600	41	42	40	41.00	1021.8	0.087
300	35	38	35	36.00	510.9	0.077
200	33	35	34	34.00	340.6	0.072
100	30	32	31	31.00	170.3	0.066
6	27	31	29	29.00	10.2	0.062
3	26	30	28	28.00	5.1	0.060
Gel_{in}	29	33	32.5			
Gel_{10}	25	30	28			
Plastic viscosity	6	4	5			
Apparent viscosity	20.5	21	20			
Yield point	29	34	30			

Table A13 6 percent Bentonite (weight by volume) +5 percent NRL (volume by volume) at 30°C.

RPM	Reading #1	Reading #2	Reading #3	Average reading	γ (sec^{-1})	τ (lb_f/ft^2)
600	29	25	29	27.67	1021.8	0.059
300	24	20	23	22.33	510.9	0.048
200	22	18	20	20.00	340.6	0.043
100	19	15	17	17.00	170.3	0.036
6	18	13	15	15.33	10.2	0.033
3	16	12	14	14.00	5.1	0.030
Gel_{in}	16	13	15			
Gel_{10}	17	14	16			
Plastic viscosity	5	5	6			
Apparent viscosity	14.5	12.5	14.5			
Yield point	19	15	17			

Table A14 6 percent Bentonite (weight by volume) +5 percent NRL (volume by volume) at 45°C.

RPM	Reading #1	Reading #2	Reading #3	Average reading	γ (sec^{-1})	τ (lb_f/ft^2)
600	30	33	34	32.33	1021.8	0.069
300	26	27	28	27.00	510.9	0.058
200	24	24.5	27	25.17	340.6	0.054
100	22	21	23	22.00	170.3	0.047
6	21	15	21	19.00	10.2	0.041
3	20	14	18	17.33	5.1	0.037
Gel_{in}	21	15	21			
Gel_{10}	19	18	21			
Plastic viscosity	4	6	6			
Apparent viscosity	15	16.5	17			
Yield point	22	21	22			

Table A15 6 percent Bentonite (weight by volume) +5 percent NRL (volume by volume) at 60^{o}C.

RPM	Reading #1	Reading #2	Reading #3	Average reading	γ (sec^{-1})	τ (lb$_f$/ft^2)
600	40	35	36	37.00	1021.8	0.079
300	35	29	31	31.67	510.9	0.068
200	34	25.5	29	29.50	340.6	0.063
100	30	23	28	27.00	170.3	0.058
6	22	21	25	22.67	10.2	0.048
3	21	19	22	20.67	5.1	0.044
Gel$_{in}$	24	22	24			
Gel$_{10}$	23	21	23			
Plastic viscosity	5	6	5			
Apparent viscosity	20	17.5	18			
Yield point	30	23	26			

Table A16 6 percent Bentonite (weight by volume) +5 percent NRL (volume by volume) at 80^{o}C.

RPM	Reading #1	Reading #2	Reading #3	Average reading	γ (sec^{-1})	τ (lb$_f$/ft^2)
600	43	47	49	46.33	1021.8	0.099
300	38	41	45	41.33	510.9	0.088
200	36	40	42.5	39.50	340.6	0.084
100	34	36	39	36.33	170.3	0.077
6	27	35	34	32.00	10.2	0.068
3	25	31	32	29.33	5.1	0.063
Gel$_{in}$	29	32	34			
Gel$_{10}$	28	34	32			
Plastic viscosity	5	6	4			
Apparent viscosity	21.5	23.5	24.5			
Yield point	33	35	41			

Filtration data for all fluids tested

Table A17 6 percent Bentonite (weight by volume) at 30°C.

Sample	Filtrate loss (ml)						Mud cake thickness (mm)		
	1 min	4min	9 min	16 min	25 min	30 min	#1	#2	#3
1	2.1	5.7	9.3	12.8	16.4	18.1	2.52	2.8	2.06
2	2	5.6	9.1	12.6	16	17.8	2.86	2.42	2.5
3	2	5.6	9.2	12.8	16.4	18.2	2.2	2.16	2.12

Table A18 6 percent Bentonite (weight by volume) at 45°C.

Sample	Filtrate loss (ml)						Mud cake thickness (mm)		
	1 min	4min	9 min	16 min	25 min	30 min	#1	#2	#3
1	2.4	6.2	10.3	14.2	18.1	20.1	3.84	3.2	3.19
2	2.4	6.6	10.8	15	19.2	21.2	2.48	2.38	3.1
3	2.6	7.2	11.4	15.7	20	21.9	3.16	3.62	3.1

Table A19 6 percent Bentonite (weight by volume) at 60°C.

Sample	Filtrate loss (ml)						Mud cake thickness (mm)		
	1 min	4min	9 min	16 min	25 min	30 min	#1	#2	#3
1	2.6	7.1	11.5	15.4	20.4	22.5	4.8	3.8	2.7
2	3	7.5	12	16.5	21	23.1	3.12	3	2.76
3	3.1	7.5	12.2	16.8	21.4	23.5	3.72	3.02	3.96

Table A20 6 percent Bentonite (weight by volume) at 80°C.

Sample	Filtrate loss (ml)						Mud cake thickness (mm)		
	1 min	4min	9 min	16 min	25 min	30 min	#1	#2	#3
1	3.4	8.2	13.0	18.0	22.8	25.1	3.54	3.86	3.18
2	3.2	7.8	12.4	17.2	22.0	24.1	3.76	3.60	3.18
3	3.4	8.2	13.0	17.9	22.8	25.1	3.10	3.16	3.64

Table A21 6 percent Bentonite (weight by volume) +1 percent NRL (volume by volume) at 30^{o}C.

Sample	**Filtrate loss (ml)**						**Mud cake thickness (mm)**		
	1 min	**4min**	**9 min**	**16 min**	**25 min**	**30 min**	**#1**	**#2**	**#3**
1	2.0	5.6	9.4	12.9	16.4	18.0	2.78	2.08	3.40
2	1.8	5.4	8.6	12.2	15.5	17.2	2.74	2.32	2.46
3	2.1	6.0	9.7	13.5	17.4	19.0	2.32	2.46	2.66

Table A22 6 percent Bentonite (weight by volume) +3 percent NRL (volume by volume) at 30^{o}C.

Sample	**Filtrate loss (ml)**						**Mud cake thickness (mm)**		
	1 min	**4min**	**9 min**	**16 min**	**25 min**	**30 min**	**#1**	**#2**	**#3**
1	2.0	5.6	9.0	12.4	15.9	17.4	3.52	2.62	2.48
2	1.9	5.2	8.6	11.8	15.3	16.9	2.56	2.56	2.6
3	2.1	5.5	8.8	11.8	15.5	17.0	3.00	3.00	3.00

Table A23 6 percent Bentonite (weight by volume) +5 percent NRL (volume by volume) at 30^{o}C.

Sample	**Filtrate loss (ml)**						**Mud cake thickness (mm)**		
	1 min	**4min**	**9 min**	**16 min**	**25 min**	**30 min**	**#1**	**#2**	**#3**
1	1.6	4.8	8.0	11.2	14.2	15.6	3.24	2.40	3.00
2	1.8	5.0	8.2	11.5	14.8	16.4	3.14	2.88	3.22
3	1.7	5.3	8.6	12.0	15.3	16.8	2.48	2.62	2.92

Table A24 6 percent Bentonite (weight by volume) +5 percent NRL (volume by volume) at 45^{o}C.

Sample	Filtrate loss (ml)						Mud cake thickness (mm)		
	1 min	4min	9 min	16 min	25 min	30 min	#1	#2	#3
1	2.1	5.8	9.5	13.0	16.9	18.4	4.98	2.84	5.26
2	2.2	6.0	9.8	13.4	17.0	18.8	5.00	3.38	3.96
3	2.3	6.4	10.4	14.3	18.1	20.0	3.38	3.6	4.2

Table A25 6 percent Bentonite (weight by volume) +5 percent NRL (volume by volume) at 60^{o}C.

Sample	Filtrate loss (ml)						Mud cake thickness (mm)		
	1 min	4min	9 min	16 min	25 min	30 min	#1	#2	#3
1	2.5	7.0	11.1	15.2	19.2	21.1	5.98	4.70	5.56
2	2.6	6.7	10.6	14.5	18.4	20.2	3.34	3.62	3.16
3	2.6	6.8	10.9	14.9	18.9	20.8	3.78	4.64	3.28

Table A26 6 percent Bentonite (weight by volume) +5 percent NRL (volume by volume) at 80^{o}C.

Sample	Filtrate loss (ml)						Mud cake thickness (mm)		
	1 min	4min	9 min	16 min	25 min	30 min	#1	#2	#3
1	2.6	7.0	11.2	15.4	19.4	21.4	4.34	4.76	3.80
2	2.8	7.0	11	15	18.8	20.8	6.28	4.63	3.68
3	2.7	7.0	11.2	15.3	19.3	21.3	4.60	6.70	5.46

BIOGRAPHY

Mr. Thanarit Riyapan was born on the April 19, 1985 in Kamphaeng Phet province, Thailand. He earned his high school diploma in science-math from Kamphaeng phet Pittayakom School in 2003 and his bachelor's degree in Engineering (Petrochemicals and Polymeric Materials) from Silpakorn University in 2007. He continued to study with a master's degree in Petroleum Engineering Program at School of Geotechnology, Institute of Engineering, Suranaree University of Technology. He has a good knowledge in areas of oil field chemicals and drilling fluids processing.