THIXOTROPIC BEHAVIOR OF PHPA MUD SYSTEM FOR MANAGED PRESSURE DRILLING

Mr. Eakarin Wachirapanyanukul

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for the Degree of Master of Engineering Program in Petroleum Engineering
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พฤติกรรมทิคโซทรอปิคของระบบโคลนพีเอชพีเอสำหรับการเจาะแบบการจัดการความดัน

นายเอกรินทร์ วชิรปัญญานุกูล

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิศวกรรมศาสตรมหาบัณฑิต
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By	Mr. Eakarin Wachirapanyanukul
Field of Study	Petroleum Engineering
Thesis Advisor	Assistant Professor Jirawat Chewaroungroaj, Ph.D.
Thesis Co-advisor	Kreangkrai Maneeintr, Ph.D.

Accepted by the Faculty of Engineering, Chulalongkorn University in Partial Fulfillment of the Requirements for the Master's Degree

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(Assistant Professor Jirawat Chewaroungroaj, Ph.D.)

…………………….............................Thesis Co-advisor
(Kreangkrai Maneeintr, Ph.D.)

…………………………………………External Examiner
(Witsarut Thungsuntonkhun, Ph.D.)

เอกรินทร์วชิรปัญญานุกูล : พฤติกรรมทิคโซทรอปิคของระบบโคลนพีเอชพีเอสำหรับการเจาะแบบการจัดการความดัน. (THIXOTROPIC BEHAVIOR OF PHPA MUD SYSTEM FOR MANAGED PRESSURE DRILLING) อ. ที่ปรึกษาวิทยานิพนธ์หลัก: ผศ.ดร. จิรวัฒน์ ชีวรุ่งโรจน์, อ. ที่ปรึกษาวิทยานิพนธ์ร่วม อ.ดร. เกรียงไกร มณีอินทร์ , 67 หน้า.

การเจาะแบบการจัดการความดันเป็นวิธีการเจาะแบบหนึ่งที่สามารถควบคุมความดันในวงแหวนของหลุมเจาะได้แม่นยำ การเจาะแบบการจัดการความดันมีประโยชน์หลายข้อ ได้แก่ ลดจำนวนท่อกรุ หลีกเลี่ยงการสูญเสียการหมุนเวียนน้ำโคลน บรรเทาการติดของท่อเจาะจากความแตกต่างของความดัน เพิ่มอัตราเร็วของการเจาะ และ ลดความเสียหายที่มีต่อชั้นหิน

คุณสมบัติทางการไหลของของไหลที่ใช้ในการขุดเจาะส่วนใหญ่แสดงพฤติกรรมทิคโซทรอปิค หรือในอีกนัยหนึ่ง ถ้าของไหลอยู่ภายใต้อัตราการเฉือนที่คงที่หลังจากถูกปล่อยให้อยู่นิ่งช่วงเวลาหนึ่ง ความหนืดของของไหลจะมีค่าสูงกว่าในตอนเริ่มและลดลงเมื่อเวลาผ่านไป ซึ่งความหนืดที่สูงกว่านั้นส่งผลให้ความดันก้นหลุมสูงขึ้นและสามารถทำให้เกิดรอยแตกในชั้นหินได้

ในการศึกษานี้ระบบโคลนพีเอชพีเออยู่ภายใต้อัตราการเฉือนที่คงที่หลังจากถูกปล่อยให้อยู่นิ่ง เวลาที่ปล่อยให้น้ำโคลนหยุดนิ่งเพื่อสร้างโครงสร้างเจลถูกแปรค่าเป็น 10 วินาที 3 นาที และ 10 นาที อัตราการเฉือนถูกแปรค่าเป็น 30, 100, 200 และ 300 รอบต่อนาที

ผลการศึกษาพบว่าระบบโคลนพีเอชพีเอแสดงพฤติกรรมทิคโซทรอปิคซึ่งแนวโน้มของผลต่างของเอเอฟพีมีแนวโน้มในการลดลงแบบลอการิธึม เวลาที่ปล่อยให้ของไหลสร้างโครงสร้างเจลไม่ส่งผลกระทบต่อพฤติกรรมทิคโซทรอปิค ยกเว้นกรณีที่มีของแข็งจากการขุดเจาะอยู่ในระบบโคลนที่เวลาที่ปล่อยให้ของไหลสร้างโครงสร้างเจลที่มากขึ้นส่งผลให้ระบบโคลนแสดงพฤติกรรมทิคโซทรอปิคมากขึ้น การเพิ่มอัตราการเฉือนไม่ส่งผลให้น้ำโคลนแสดงพฤติกรรมทิคโซทรอปิคมากขึ้นเสมอไป โดยสรุป ระบบโคลนพีเอชพีเอมีศักยภาพที่จะเหมาะสมสำหรับการเจาะแบบการจัดการความดันอันเนื่องมาจากการสดงพฤติกรรมทิคโซทรอปิคที่น้อย

ภาควิชา..วิศวกรรมเหมืองแร่และปิโตรเลียม.........ลายมือชื่อนิสิต..

สาขาวิชา........วิศวกรรมปิโตรเลียม.......................ลายมือชื่อ อ.ที่ปรึกษาวิทยานิพนธ์หลัก.............

ปีการศึกษา..............2555......................................ลายมือชื่อ อ.ที่ปรึกษาวิทยานิพนธ์ร่วม.............

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EAKARIN WACHIRAPANYANUKUL THIXOTROPIC BEHAVIOR OF PHPA MUD SYSTEM FOR MANAGED PRESSURE DRILLING. THESIS ADVISOR: ASST. PROF. JIRAWAT CHEWAROUNGROAJ, Ph.D., THESIS CO-ADVISOR KREANGKRAI MANEEINTR, Ph.D., 67 pp.

Managed Pressure Drilling (MPD) is an adaptive drilling process to precisely control the annular pressure profile throughout the wellbore. MPD has many advantages such as reduction on the number of casings, avoiding lost circulation, mitigating pipe stuck from differential sticking, increasing in rate of penetration and reducing formation damage compared to conventional drillings.

The rheology of most drilling fluids shows thixotropic behavior. In other word, if they are exposed to a constant shear rate after some time at rest, their viscosities will start at an initial higher value and finally drop over time to lower value. This higher viscosity can cause the high bottomhole pressure during the restarting circulation, which can induce fracture in formation.

In this study, PHPA mud system is subjected to constant shear rate after leaving at rest. Gelling time is varied to be 10 seconds, 3 minutes and 10 minutes. Shear rate is varied to be 30, 100, 200 and 300 rounds per minutes.

The study showed that PHPA mud system exhibits thixotropic behavior which trend in annular frictional pressure loss difference is logarithmic decline. Gelling time does not affect thixotropic behavior except when drilled solid exists in the mud that increasing gelling time results in higher thixotropic behavior. Increasing in shear rate does not always result in higher thixotropic behavior. In conclusion, PHPA mud system has potential to be suitable for MPD based on small thixotropic behavior.

Department...Mining and Petroleum Engineering.....Student’s Signature……......…..
Field of Study......Petroleum Engineering..................Advisor’s Signature…......……....
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Thirdly, I would like to thank M-I Swaco for providing drilling fluid laboratory for this study.

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List of Abbreviations

MPD	Managed Pressure Drilling
CBHP	Constant Bottomhole Pressure
ABP	Application of Back Pressure
AFP	Annular Frictional Pressure Loss
BHP	Bottomhole Pressure
ECD	Equivalent Circulating Density
PHPA	Partially Hydrolyzed Polyacrylamide
PAC	Polyanionic Cellulose
LV PAC	Low viscosity Polyanionic Cellulose
LCM	Lost Circulation Material
FPG	Formation Pressure Gradient
g	Grams
ml	Milliliters
M	Molar concentration
w/w	Mass per mass concentration
g/l	Gram per liter concentration
ppm	Parts per million
lb/bbl	Pounds per barrel
ppg	Pounds per gallon
gpm	Gallons per minute
rpm	Rounds per minute
API	American Petroleum Institute
AAD	Average Absolute Deviation

°F	Degrees fahrenheit
°C	Degree celsius
ft	Feet
ft^2	Square feet
in	Inches
in^2	Square inches
ft/s	Feet per second
s^{-1}	Per second
psi	Pounds per square inch
psi/ft	Pounds per square inch per foot
cp	Centipoises
eq.cp	equivalent centipoises
$lb/100ft^2$	Pounds per a hundred square foot
$dyne\text{-}s/cm^2$	Dyne-seconds per square centimeter
$dyne/cm^2$	Dyne per square centimeter

Nomenclatures

τ	Shear stress
τ_w	Shear stress at wall
$\dot{\gamma}$	Shear rate
$\dot{\gamma}_w$	Shear rate at wall
A_c	Cross-sectional area of the annulus
A_w	Wall area of the annulus
n	Flow index (power law)
k	Consistency index (power law)
ΔP_{Hyd}	Hydrostatic pressure of drilling fluid column
ΔP_{BP}	Applied back pressure at the surface
μ_p	Plastic viscosity
τ_y	Yield point
θ_{600}	Dial reading at 600 rpm
θ_{300}	Dial reading at 300 rpm
θ_{200}	Dial reading at 200 rpm
θ_{100}	Dial reading at 100 rpm
θ_{30}	Dial reading at 30 rpm
θ_6	Dial reading at 6 rpm
θ_3	Dial reading at 3 rpm
v	Average velocity of drilling fluid in annulus
d_1	Inner diameter of the annulus
d_2	Outer diameter of the annulus
R^2	R-squared

CHAPTER I

INTRODUCTION

1.1 Background

Managed Pressure Drilling (MPD) has been more widespread in recent years. The definition of MPD by International Association of Drilling Contractors is "an adaptive drilling process to precisely control the annular pressure profile throughout the wellbore" [1]. MPD has many various advantages on drilling operation and planning. For example, reduction on the number of casings required, avoiding lost circulation, mitigation on pipe stuck from differential sticking, increase in rate of penetration and reduction in formation damage compared to conventional drillings.

There are many ways to classify types of MPD. The one that is referred by many literatures about MPD is by Hannegan [2]. Hannegan classified MPD into four major variations which are Constant Bottomhole Pressure (CBHP), Pressurized Mud Cap, Dual Gradient Drilling and Closed System. Each variation is divided into methods.

CBHP which is further divided into two methods [3]: Continuous Circulation System and Application of Backpressure (ABP). The one that is related to this study is CBHP by ABP method.

ABP method is usually done by drilling with the mud which has the hydrostatic gradient less than pore pressure gradient. This method makes use of Annular Frictional Pressure loss (AFP) to prevent the influx while drilling and makes use of backpressure (by chokes or backpressure pumps) while the well is in static condition during making connections.

The gel breaking phenomenon is resulted from a non-newtonian fluid which is "thixotropy". The rheology of most drilling fluids shows thixotropy [4]. In other word, if they are exposed to a constant shear after some time at rest, they will exhibit higher viscosity at initial time then drop to a lower value as time goes by. It is important to point out that value of measured shear stress which is used for pressure loss calculation is the lower value that is measured when thixotropic behavior has already faded away. Therefore, there is a period of time that the real Bottomhole Pressure (BHP) is higher than the calculated value. However, this higher BHP is typically small and is negligible for normal pressure window. But MPD is often used in the narrow pressure window which higher BHP period from thixotropic behavior could be large enough to result in fracture propagation which is undesired.

Inhibitive muds are designed to minimize the reaction with the formation including shale and other clay minerals. Inhibitive mud can be both water-based and oil based-mud. One of the most popular inhibitive muds is Partially Hydrolyzed Polyacrylamide (PHPA) which is a water-based polymer system. Water-based mud is easier for study because the effect of pressure can be neglected due to incompressibility of water. Therefore, PHPA mud system is selected for this study.

Typically, for normal pressure reservoir, gas or water is used as the drilling fluid for MPD. These fluids are Newtonian fluid which has no thixotropic behavior. But for abnormal pressure reservoir, weighted fluid is required and therefore drilling mud (which is more viscous than gas and water) is needed to provide adequate lifting capacity to suspend weighting material. Therefore, weighted PHPA mud system is the scope of this study.

1.2 Objectives

1. Study the thixotropic behavior of PHPA mud system on changing applied shear rate from rest to a new constant shear rate.
2. Study the effect of changing gelling time and changing applied shear rate on thixotropic behavior in the first objective.
3. Assess the suitability of PHPA mud system for MPD in aspect of tendency to cause high pressure period during circulation resumption.

1.3 Expected benefits

The results can be used as information to be considered that PHPA system is appropriate for MPD or not (in term of higher pressure during circulation resumption).

1.4 Thesis outline

The rest of this thesis is divided into five chapters as outline below

Chapter II introduces the basic knowledge on PHPA mud system, thixotropic behavior, fluid rheological models and related drilling hydraulics.

Chapter III presents previous works that related to PHPA mud system and thixotropic behavior.

Chapter IV explains the scope of research including rationale behind each parameter and related assumption. Then, experimental procedures and related equipment are described.

Chapter V presents and discusses the results on basic properties and thixotropic behavior assessment. Thixotropic behavior of PHPA mud is characterized by mathematical model. Pressure window that PHPA mud system is applicable is also identified.

Chapter VI provides conclusion and recommendation.

CHAPTER II

THEORY AND CONCEPT

First of all, this chapter presents the basic principles and theories related to thixotropic behavior of drilling fluids. Then, PHPA mud system is described for fundamental understanding. Finally, rheological models and drilling hydraulics related to this study are introduced.

2.1 Thixotropic behavior of drilling fluids

Drilling fluids are generally thixotropic, non-Newtonian fluids that are shear-time-dependent are thixotropic if the apparent viscosity decreases with time after the shear rate is increased to a new constant value [5]. **Figure 2.1** shows that thixotropic behavior of drilling fluids by shear stress-time plot. Thixotropic behavior also can be shown by shear stress-shear rate hysteresis loop. However, this has no application in drilling engineering.

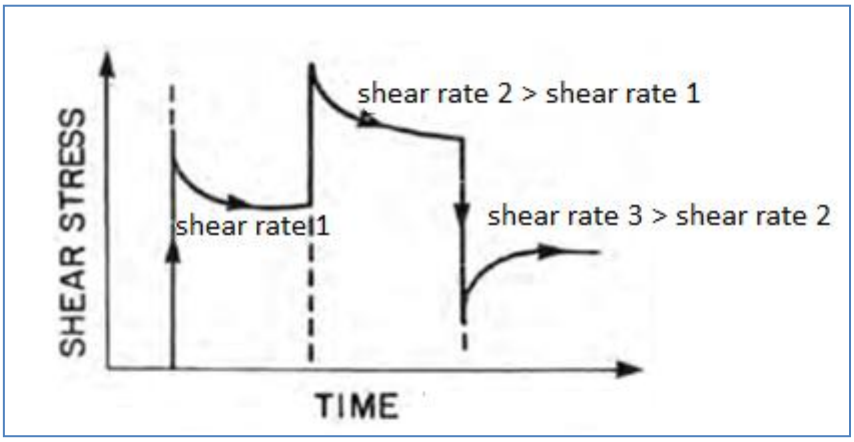

Figure 2.1Thixotropic behavior of drilling fluids by shear stress vs time plot [5].

Thixotropic behavior relates to drilling engineering when drilling fluid circulation rate is changed which is the time that shear rate is changed. This can be explained by **Figure 2.2** which shows the equivalent circulating density (ECD) field data obtained during a systematic step-ramp of flow rate, first up then down. After the flow rate is increased, the ECD starts with higher value then gradually decreases. In contrast, after the flow rate decreases, ECD starts with lower value then gradually increases. The peak BHP after increasing the circulation rate may cause the fractures and lost circulation, while the low BHP after decreasing the circulation rate may cause kicks. However, thixotropic effect on BHP is considered insignificant for conventional drilling which has wide pressure window and large kick margin/trip margin. But in case of MPD which is candidate for narrow pressure window wells, thixotropic effect can be significant.

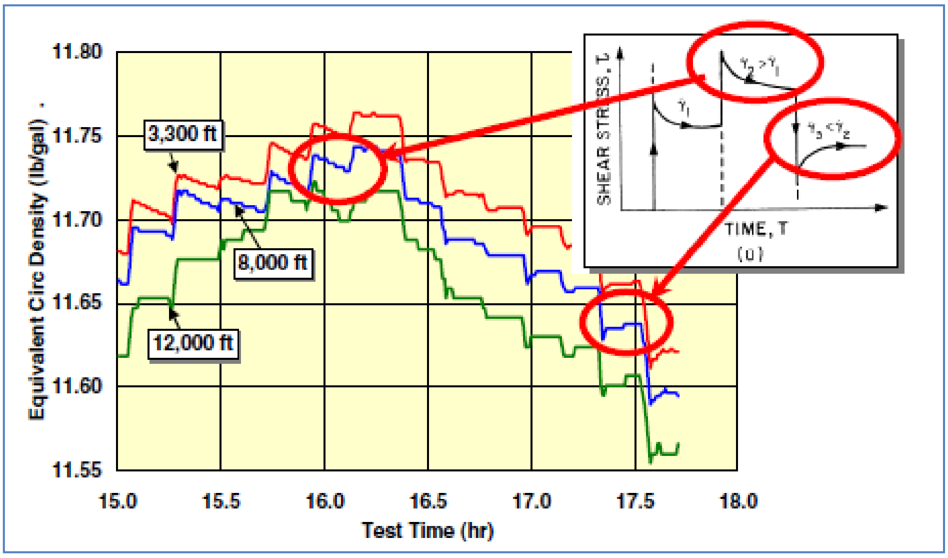

Figure 2.2 Effects of mud thixotropy and acceleration/deceleration on measured ECD with superimposed graph showing expected results [6].

After applied shear is stopped, drilling fluids form gel structure. Most water-base drilling fluids exhibit this property due to the presence of electrically charged particles or special polymers that link together to form a rigid matrix. The strength of the gel formed is a function of the amount and type of solids in suspension, time, temperature and chemical treatment. In other words, anything promoting or preventing the linking of particles will increase or decrease the gelling tendency of a fluid [7].

At present, the only standard measurement on thixotropic behavior of drilling mud by American Petroleum Institute (API) are 10-second and 10-minutes gel strength. However, this measurement is designed to quantify the ability to suspend cuttings.

Progressive gel refers to gel strength that increases with time [5] while fragile gel refers to gel strength that is easy to break which will result in low gel breaking pressure and then gelled back very fast after it is at rest [7]. Fragile gel is common in polymer drilling fluids [7]. Behaviors of fragile and progressive gel are shown in **figure 2.3**.

Ghofrani, Bosch and Strahl's experiment work[8] showed that bentonite suspension in distilled water (17.5 and 24.5 lb/bbl concentration) exhibited progressive gel strength.

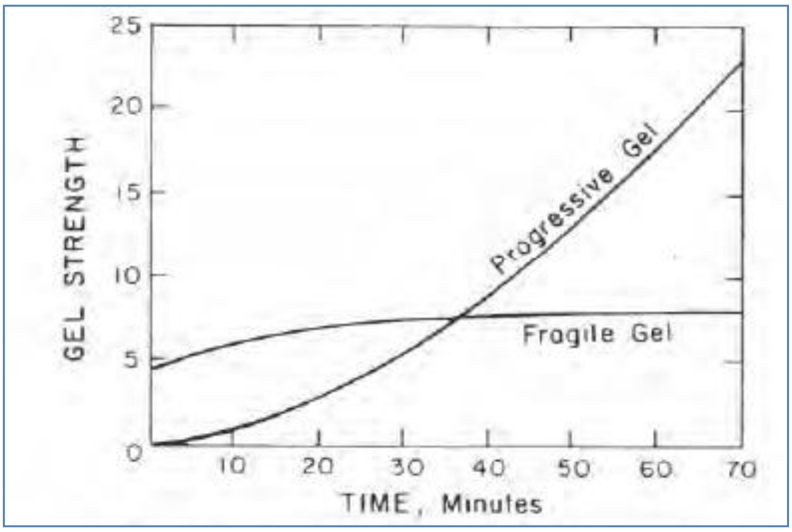

Figure 2.3 Fragile and progressive gel strength [5].

2.2 PHPA mud system

The basic knowledge about PHPA and PHPA mud system are well described in Drilling Fluids Engineering Manual by M-I Swaco[7]. PHPA is often used to identify the copolymer polyacrylamide/polyacrylate. The end product of a PHPA is the same polymer that is formed by a polyacrylamide/polyacrylate copolymerization. Even though the product is frequently referred to as PHPA, it is actually made by the copolymerization of acrylamide and sodium acrylate monomers. For the sake of simplicity, the material will be referred to as PHPA. The most commonly used PHPA in drilling fluids is the high-molecular-weight version which is prepared with 65 to 70% acrylamide and the remaining percentage acrylate. Molecular weights range up to 20 million.

PHPA is used as a shale inhibitor and solids-encapsulating polymer in freshwater, seawater, NaCl and KCl systems. In addition to its shale-inhibiting properties, it also provides drilled cuttings encapsulation and viscosity in freshwater system. The shale-inhibition feature of PHPA occurs when the polymer attaches to clays on the wellbore and blocks the hydration and dispersion that normally occurs. The anionic carboxyl groups attach to the positive charges on the edges of the clay particles. Since the polymer has a high molecular weight and is relatively long, it combines with several sites along the wellbore. This has the effect of coating the wellbore and restricting water from entering the clay. PHPA also aids in shale stabilization by thickening the water phase. PHPA increases the viscosity of the drilling fluid filtrate, which has the effect of limiting the filtrate depth of invasion [7].

In a salt environment, PHPA is still very effective in a shale-stabilizing capacity, although its concentration must be increased to obtain a significant effect on filtrate viscosity. As it does not hydrate free water as readily, this leads to a decrease in the viscosifying characteristic of the polymer [7].

One of the drawbacks to PHPA is its sensitivity to soluble calcium. Like polyacrylate, the anionic carboxyl site reacts with calcium. This is particularly a problem in freshwater system, where calcium can precipitate the PHPA polymer as well as whatever solids the polymer is adsorbed on. In some cases, PHPA functions as a flocculent in the presence of calcium, particularly when the solids content of the drilling fluid is low. Removing calcium from the system requires adding a carbonate source, such as soda ash or bicarbonate of soda, which may flocculate the system [7].

Kadaster et al.[9] recommended maintaining excess active PHPA for at least 1 lb/bbl to ensure inhibition of shales and cuttings. pH should be maintained in the 8.5 to 9.5 range because PHPA is sensitive to higher pH [9].

2.3 Rheological models

2.3.1 Conversion factors

Shear stress (lb/100 ft^2) can be calculated by multiplying the dial reading by 1.066. Shear rate (s^{-1}) can be obtained by multiplying the rotor speed (rpm) by 1.703 [10]. These conversion factors are valid only with a standard viscometer (as specify by API RP 13B-1 [11])

Shear stress (dyne/cm^2) is determined by multiplying the shear stress (lb/100 ft^2) by 4.79. Plastic viscosity (dyne-s/cm^2) is determined by multiplying the plastic viscosity (cp) by 0.1. Consistency index (lb-s^n/ft^2) is determined by dividing consistency index (equivalent cp, eq. cp) by 47,900. Consistency index (dyne-s^n/cm^2) is determined by dividing consistency index (equivalent cp, eq. cp) by 100 [5].

2.3.2 Bingham plastic model

This model is characterized by two parameters which are plastic viscosity and yield point. These two parameters are determined from shear rates of 511 s^{-1} and 1022 s^{-1} (300 and 600 rpm of API viscometer respectively). Calculations for these two parameters are following [5]:

$$\tau = \tau_y + \mu_p \dot{\gamma} \qquad (2.1)$$

where

τ is shear stress in dyne/cm^2

$\dot{\gamma}$ is shear rate in s^{-1}

μ_p is plastic viscosity in dyne-s/cm^2

τ_y is yield point in dyne/cm^2

and

$$\mu_p = \theta_{600} - \theta_{300} \qquad (2.2)$$

$$\tau_y = \theta_{300} - \mu_p \qquad (2.3)$$

where

μ_p is plastic viscosity in cp

τ_y is yield point in lb/100 ft^2

θ_{300} is dial reading at 300 rpm

θ_{600} is dial reading at 600 rpm

2.3.3 Power-law model

This model is characterized by two parameters which are flow-behavior index and consistency index. These two parameters are determined from shear rates of 511 s^{-1} and 1022 s^{-1} (300 and 600 rpm of API viscometer respectively). Calculations for these two parameters are following [5]:

$$\tau = k\dot{\gamma}^n \tag{2.4}$$

and

$$n = 3.32\ log_{10}\left(\frac{\theta_{600}}{\theta_{300}}\right) \tag{2.5}$$

$$k = \frac{510\theta_{300}}{511^n} \tag{2.6}$$

where

n is flow-behavior index (dimensionless)

k is consistency index in eq. cp

2.4 Drilling hydraulics

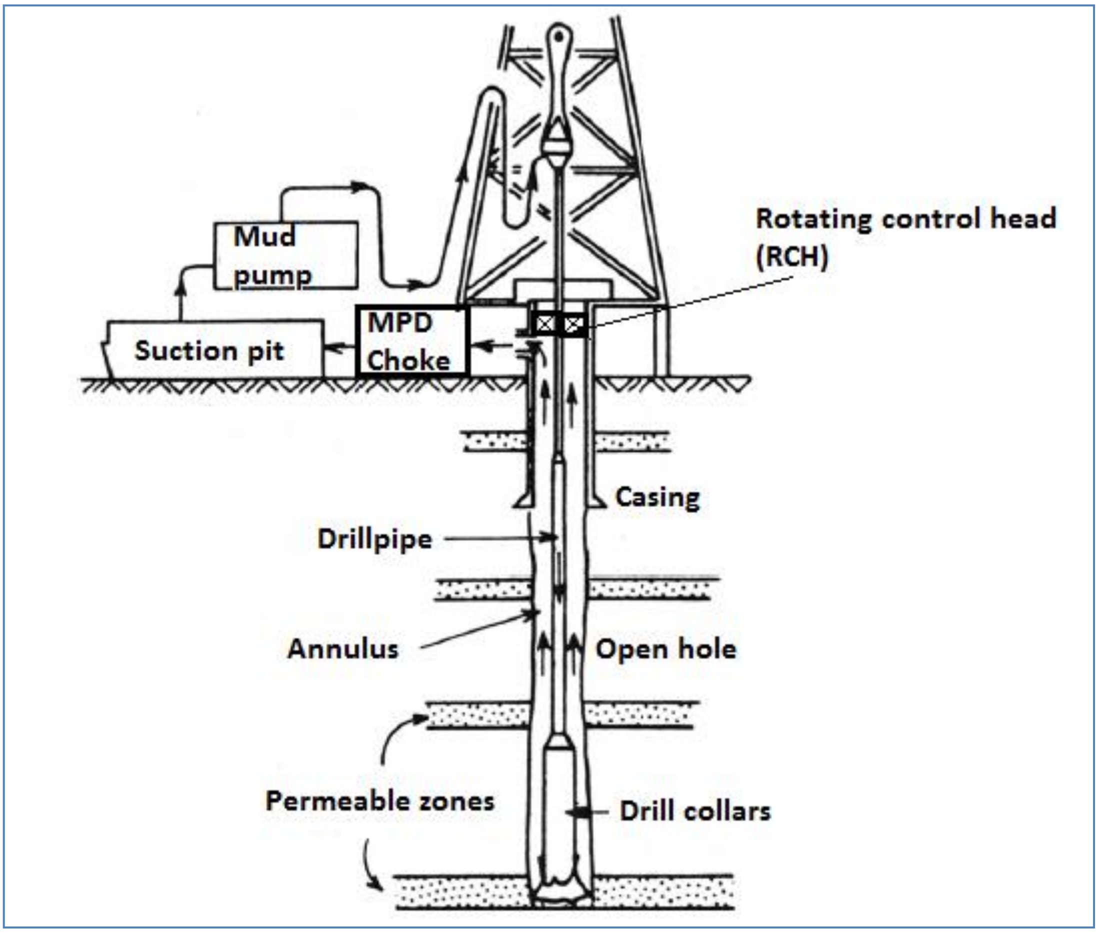

Figure 2.4 The well fluid system in CBHP MPD by ABP method.

Figure 2.4 shows the well fluid system in CBHP MPD by ABP method, additional parts to conventional drilling is rotating control head (RCH) and MPD choke. RCH is the equipment that is used to seal around the drillstring at the surface and isolate the pressure at the top of the annulus from atmospheric pressure. Then, the return fluid from annulus has to pass MPD before suction pit. MPD choke is used to create restriction in the flow by reducing the flow area at the choke which is adjustable. This restriction causes additional pressure loss in the system and this addition pressure loss is utilized to compensate annular frictional pressure loss during static and transitioning condition to sustain constant BHP. RCH rating is the one that limit the allowable back pressure at surface which RCH pressure rating can be as high as 2500 psi dynamic and 5000 psi static condition. BHP can be determined based on annular side by following equation:

$$BHP = \Delta P_{Hyd} + AFP + ABP \qquad (2.7)$$

where

ΔP_{Hyd} is hydrostatic pressure of drilling fluid column

AFP is frictional pressure loss in the annulus

ABP is the applied back pressure at surface

Pressure gradient (psi/ft) often mentioned in form of equivalent mud density (ppg). Pressure gradient in form of equivalent mud density can be determined by multiplying pressure gradient in psi/ft by 0.052.

2.4.1 Frictional pressure loss in annulus (AFP)

In conventional drilling, frictional pressure loss in both pipe and annulus is the value at steady state which thixotropy of drilling fluid has already subsided. Calculation for friction pressure during steady state condition is determined by well developed equations which require rheological parameters, for example, τ_y, μ_p, n and k. However, these parameters are not constant during transitioning which thixotropic behavior exists. AFP during transitioning in annulus can be determined by basic calculation based on the schematic in **figure 2.5**. Shear stress at wall can be measured by viscometer which measured shear stress in dial reading unit. The equation is as following:

$$AFP = \frac{\tau_w A_w}{A_c} \qquad (2.8)$$

where

AFP is frictional pressure loss in the annulus in psi

A_c is cross-sectional area of the annulus in in^2

A_w is wall area of the annulus in 100 ft^2

τ_w is shear stress at wall in lb/100 ft^2

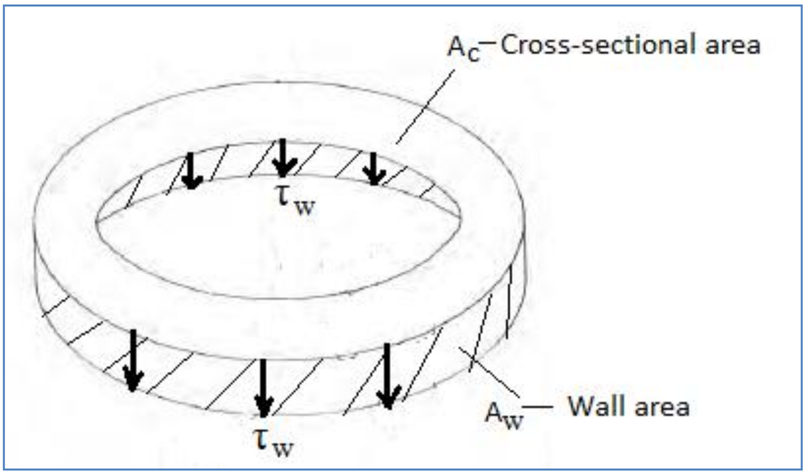

Figure 2.5 Schematic of frictional pressure loss in annulus.

2.4.2 Shear rate at wall in annulus

For laminar flow regime, shear rate at wall in annulus during steady state condition can be calculated by following equations [5]:

$$\dot{\gamma}_w = \frac{144v}{d_2 - d_1} + 239.5\frac{\tau_y}{\mu_p}$$, for Bingham plastic model (2.9)

$$\dot{\gamma}_w = \frac{48v}{d_2 - d_1}(2 + 1/n)$$, for power-law model (2.10)

where

$\dot{\gamma}_w$ is shear rate at wall (s^{-1})

d_1 is inner diameter of the annulus in in.

d_2 is outer diameter of the annulus in in.

v is average velocity of drilling fluid in the annulus in ft/s

CHAPTER III

LITERATURE REVIEW

Many studies related to PHPA mud system have been done, most of these studies focused on application and guidelines for running PHPA mud system.

There are a number of studies on thixotropic behavior of drilling muds. However, these studies focused on hysteresis loop of shear stress – shear rate which has no direct application for drilling engineering purpose.

There is only one study so far that emphasized on thixotropic behavior for drilling purpose.

In this chapter, the literature reviews are categorized in three sections: PHPA mud system, thixotropic behavior of drilling muds and thixotropic behavior for drilling purpose.

3.1 PHPA mud system

Clark et al.[12] discussed the success of a potassium-based polymer mud that has been used to control shales in many wells. Shale inhibition is from potassium chloride combined with a high-molecular-weight PHPA. Laboratory and field studies show that adding a polyacrylamide and potassium chloride to a water-based drilling mud can protect water-sensitive. Maintain an adequate chemical content and an effective solid-control system utilization are key factors to achieve acceptable performance.

Chesser[13] discussed the technique of using PHPA to control active shales. Many case studies show that PHPA alone can control active shales in the absence of potassium chloride. High pH should be avoided because it will cause the clay to excessively disperse and become too viscous.

Kadaster et al.[9] summarized guidelines for running PHPA muds based on field experience. Some recommendations are maintaining the pH in the 8.5 to 9.5

range, using prehydrated Wyoming bentonite of 8 to 12 lb/bbl to achieve base viscosity and using Polyanionic Cellulose (PAC) of 1 to 2 lb/bbl for fluid loss control.

3.2 Thixotropic behavior of drilling fluids

Bekkour et al.[14] investigated the thixotropic behavior of bentonite including hysteresis loop of shear stress-shear rate and constant shear rate condition. The results are bentonite shows time-dependent behavior.

Kelessidis[15] investigated the thixotropic behavior of Wyoming and Zenith bentonites at 5.0% and 6.42% concentrations with 0.0 M, 0.01 M and 0.1 M NaCl. The experiment is hysteresis loop of shear stress-shear rate curve which compose of decreasing shear rate from 600 to 3 rpm then increasing shear rate from 3 to 600 rpm then decreasing shear rate from 600 to 3 rpm again. The result is that bentonite suspension with the presence of NaCl shows both thixotropic behavior and rheopectic behavior.

Dolz et al.[16] investigated hysteresis loop of shear stress-shear rate curve on bentonite suspension at concentrations of 6-12% (w/w) in the presence of sodium carboxymethyl cellulose at two different concentrations. The conclusion is that the formulation that shows the most thixotropic behavior is the one that has lowest concentration of carboxymethyl cellulose and lowest concentration of bentonite.

3.3 Thixotropic behavior for drilling purpose

In drilling operation, flow rate is brought to full flow rate and then kept constant. Therefore, thixotropic behavior assessment that is done under constant shear rate condition can represent the thixotropic behavior of drilling mud in the well during circulation resumption. Bjørkevoll et al.[4] demonstrated laboratory measurements on gel breaking stress by API standard viscometer. The sample fluid is laponite suspension in water at concentration of 7.5 and 10 g/L. The method used in this study is constant applied shear rate. Gelling time is varied to be 0.5, 1, 2, 4, 8, 16 and 32 minutes. Shear rate is varied to be 1.8, 3, 6 and 30 rpm. The result shows that the sample exhibits higher shear stress at initial which sharply drops over the first 2 minutes and then gradually decreases to a final lower value. Gelling time results in higher shear stress. Controlled field measurements are also conducted and result has the same shape to the result from laboratory experiment by viscometer.

CHAPTER IV

SCOPE OF RESEARCH AND EXPERIMENTS

This chapter presents scope of research and experimental procedures including related equipments especially viscometer which is the main equipment.

4.1 Scope of Research

4.1.1 Formulation

Weighted formulation of PHPA mud system is formulated based on M-I Swaco company [7]. Two modifications on this guideline have been made. The first modification is not to put additional fluid loss control because the formulation already has bentonite and PAC (polyanionic cellulose) which provide normal fluid loss control. The other modification is using LV PAC (low viscosity polyanionic cellulose) instead of PAC due to availability at the laboratory. Distilled water is used as the base fluid. Bentonite is prehydrated for 1 hour before adding other composition. The formulation is shown in **table 4.1**. Barite will be adjusted if other mud weight is used or there is any additional composition in this formula.

Table 4.1 Formulation of PHPA mud system used in this study.

Composition	lb/bbl
Caustic soda	0.12
Bentonite	2.5
PHPA	1.5
Xanthan gum	1.0
LV PAC	0.5
Barite	89.3 (for 10.0 ppg mud)
pH range (pH unit)	8.5 to 10.0

All additives are solid except caustic soda solution and distilled water. The amount of distilled water and all solid additives are within ± 0.02 g of the required weight.

Distilled water has chloride content ranging between 6.5 to 8.0 ppm and pH ranging between 5.33 to 6.00 pH unit.

Caustic soda solution (100 g/L) is prepared by adding 5±0.03 g. of caustic soda (solid) into 50 ml cylinder (resolution of 1.0 ml), then adding distilled water into the cylinder until the level reaches 50 ml.

Bentonite has specification as per API specification 13A. PHPA is solid PHPA with percent active more than 90%. Barite is from local supplier (2 batches). The first batch has specific gravity of 4.26 and the second batch has specific gravity of 4.28.

Caustic soda solution is added by 1 ml syringe with the resolution of 0.02 ml. Schematic of mixing procedure is shown in **figure 4.1**. The detailed procedures are as follow:

1. Add 0.5 ml of 100 g/l caustic soda solution.
2. Start adding bentonite by turning the mixer at 13000 rpm and immediately begin to gradually put bentonite into the mixing cup over the period of around 1 minute.
3. Continue mixing until 30 minutes from start adding bentonite.
4. Cover the mixing cup with aluminium foil and let bentonite hydrate for another 30 minutes at ambient condition.
5. Start adding LV PAC by turning the mixer at 13000 rpm and immediately begin to gradually put PAC into the mixing cup over the period of around 1 minute.
6. Add PHPA into the mixing cup over the period of around 1 minute.
7. Add xanthan gum into the mixing cup over the period of around 1 minute.
8. At 10 minutes after start adding LV PAC, add 0.7 ml of 100 g/l caustic soda solution. Then, start adding barite gradually.
9. In cases that has LCM or API standard evaluation base clay, start adding LCM or API standard evaluation base clay at 20 minutes after start adding LV PAC
10. Keep agitating until 1 hour after start adding LV PAC.

11. Finish mixing and cover the mixing cup with aluminium foil and age the sample for 1 hour after finish mixing.

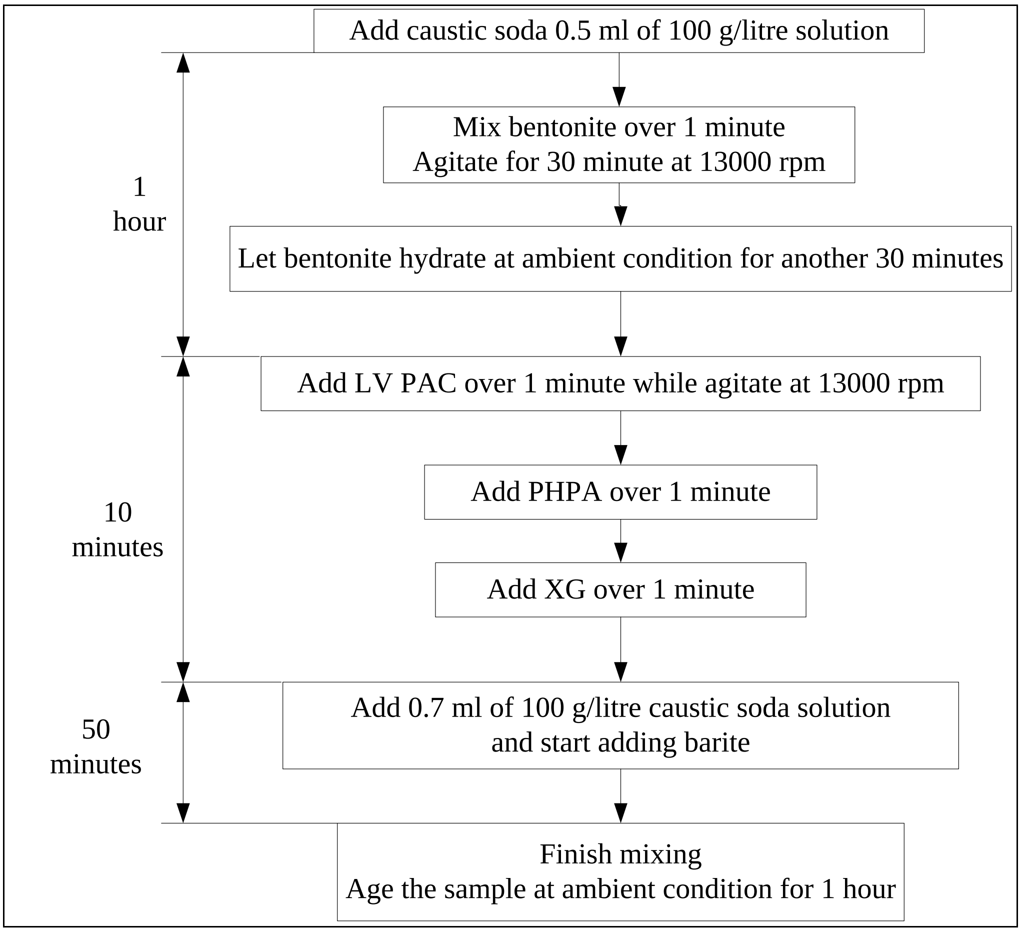

Figure 4.1 Sample mixing procedures.

4.1.2 Base case and variation

All experiments are performed at atmospheric pressure due to the limitation of equipment (pressure calibration is not available at the laboratory). However, PHPA system is water-based and water is incompressible fluid. Therefore, effect of pressure can be assumed to be negligible. Shear rate of 30, 100, 200 and 300 rpm are used in all sets of experiment to observe shear rate effect. Shear rate of 100, 200 and 300 rpm are from 6 standard speeds (3, 6, 100, 200, 300 and 600 rpm) for API viscometers. Note that shear rate of 200 rpm results in flow rate around the typical flow rate (250 gpm) used in 6.125 in. hole section with 3.5 in. drillpipe (based on fluid that has flow-behavior index ranges from 0.35 to 0.50). Higher gel breaking shear stress is expected from higher shear rate due to higher velocity gradient in flow field. 30 rpm is selected to represent low circulation rate (around 40 gpm for flow-behavior index ranges from 0.35 to 0.50) which lower gel breaking shear stress is expected.

Gelling time, which is defined as the time that samples are left at rest before start applying shear rate, are selected to be 10 seconds, 3 minutes and 10 minutes. 10 seconds and 10 minutes are to be in compliance with gel strength measurement while 3 minutes is the maximum expected time required for making a pipe connection. If the fluid is progressive gel, higher gelling time will result in higher thixotropic behavior. Bentonite suspension in distilled water is progressive gel [8] while fragile gel is common in polymer system [7]. The formulation that is selected for this study, both clay and polymer exists which is hard to predict that thixotropic behavior will be more like progressive gel or flagile gel.

The base case (Test set#1) is the sample with mud weight of 10.0 ppg that is performed at 120 °F. Temperature of 120 °F is selected from standard temperature (120 °F and 150 °F) for oil-based mud field testing by API RP 13B-2 [17]. API RP 13B-1 [11] which is for water-based mud field testing does not specify standard temperature, however standard temperature for oil-based of 120 °F is practically used as standard temperature for water-based testing.

Test set#2 is done to assess that how much the rheology change during thixotropic behavior assessment affect thixotropic behavior. Gelling time used for this test set is only 3 minutes because the result on test set#1 (which is the base case) shows that varying gelling time from 10 seconds to 10 minutes has little effect on thixotropic behavior. Thixotropic behavior for each shear rate is repeated for 2 times in this test set.

The variation of mud weight is mud weight of 12.0 ppg (test set#3). Higher thixotropic behavior is expected because higher solid content should create more resistance to flow.

Mud weight is directly related to formation pressure gradient that the mud is applicable. In MPD, BHP is designed to be equal to formation pressure gradient (FPG) which BHP composed of 3 components which are hydrostatic pressure, annular frictional pressure loss and applied back pressure (ABP). Mud weight is designed to be less than FPG, while AFP and ABP are utilized to achieve BHP equal to FPG.

During the dynamic condition, magnitude of ABP is limited by the rating of rotating control head (RCH) which RCH rating can be as high as 2,500 psi dynamic. However, the higher ABP results in less precision on maintaining ABP which can make BHP to exceed pressure window. In this study, precision on controlling ABP is assumed to be 20 percent of ABP value and ABP tolerance during steady condition (thixotropic has already faded away) is assumed to be 25 psi. Therefore, the maximum allowable ABP is 125 psi (25 psi is 20 percent of 125 psi).

If ABP is assumed to be 125 psi (maximum allowable ABP) and AFP is assumed to has gradient of 0.06 psi/ft, mud weight of 10.0 to 12.0 ppg will be applicable for FPG of 10.7 to 12.7 ppg at depth of 5,000 ft. If the depth is 12,500 ft, mud weight of 10.0 to 12.0 ppg will be applicable for FPG of 10.3 to 12.3 ppg. There are some example fields that FPG near these ranges. South Lewisburg field in Louisiana[18] has FPG ranges between 11.3 ppg (at 12,400 ft) and 12.3 ppg (at 9,400 ft). One offshore well of UKCS[19] has operating pressure window ranges between 12 ppg and 12.8 ppg at depth of 12,500 ft.

In real wells, drilling fluid is contaminated with drilled solids which the concentration of drilled solids depends on various factors. Therefore, test set#4 is performed to assess effect of drilled solids by adding 35 lb/bbl (10 percents weight by weight) of API standard evaluation base clay to the 10.0 ppg mud formulation in **table 4.1**. Higher thixotropic behavior is expected because more clay exists in the mud and clay platelet can create gel structure. Progressive gel is also expected because bentonite exhibit progressive gel. Additional caustic soda solution is added at 30 minutes from start adding LV PAC (the total concentration of caustic soda is 2.1 lb/bbl) to archive the pH near other tests. This case is conducted at 120 °F.

MPD is typically employed in narrow pressure window which loss circulation can occur. Therefore, test set#5 is performed to assess effect of LCM (lost-circulation material) by adding 35 lb/bbl of coarse graphite (which is granular type LCM) to the 10.0 ppg mud formula in **table 4.1**. 35 lb/bbl course graphite is the middle of the recommended range for partial losses[13] (mud flow out less than mud flow in but still has mud return) treatment. This case is conducted at 120 °F. Adding LCM should increase thixotropic behavior regardless of the type of LCM because both fibrous and granular can create gel structure. Granular type is selected because it is likely to have higher thixotropic behavior than the fibrous type due to its larger particle size.

In real well, temperature in annulus depends on many factors. The variation of temperature is 150 °F (test set#6). 150 °F is one of the two standard temperatures (120 °F and 150 °F) for oil-based mud field testing by API RP 13B-2 [17]. Lower thixotropic behavior is expected when the temperature is increased because expansion of fluid increases the distance between molecule-molecule and particle-particle.

Table 4.2 Summary on cases in experiment.

Case	Mud weight (ppg)	Temperature (°F)	Additional composition
Test set#1	10.0	120	-
Test set#2	10.0	120	-
Test set#3	12.0	120	-
Test set#4	10.0	120	35 lb/bbl of API standard evaluation base clay (drilled solids)
Test set#5	10.0	120	35 lb/bbl of coarse graphite (LCM)
Test set#6	10.0	150	-

4.2 Experiments

The workflow of experiments on all test sets, except test set#2, is shown in **figure 4.2**. The detailed procedures are as follow:

1. After finish mixing for 30 minutes, measure the temperature of the sample in the mixing cup and perform mud weight measurement.
2. After finish mixing for 1 hour, stir the sample at 13,000 rpm by mixer for 5 minutes.
3. Measure the pH of the sample.

4. Load the sample into the test cell and load the test cell into Fann 75.
5. Start heating up the sample to 120° F (150° F for test set#6) at 15 minutes after finish stirring the sample in step 2. Keep stirring the sample at 200 rpm while heating up.
6. Measure dial reading at shear rate of 600, 300, 200, 100, 30, 6 and 3 rpm respectively. At each rpm, the sample is sheared at that rpm for 1 minute and dial reading are collected at 57±1 seconds after staring applying that shear rate.
7. Stir the sample at 600 rpm for 1 minute to destroy gel structure.
8. Leave the sample at rest for 10 seconds of gelling time. At this step, pressure and temperature data are collected every 30 seconds.
9. Start applying shear rate of 30 rpm and collect dial reading, rpm and temperature data every second. Keep shearing and collecting data for 5 minutes.
10. Repeat step 7 to 9 with gelling time of 3 and 10 minutes.
11. Repeat step 7 to 10 with shear rate of 100, 200 and 300 rpm respectively for thixotropic behavior assessment in step 9.
12. Repeat step 6.
13. Unload the sample and measure the pH of the sample with minimum delay.

The workflow of experiment on test set#2 is shown in **figure 4.3**. The detailed procedures are as follow:

1. After finish mixing for 30 minutes, measure the temperature of the sample in the mixing cup and perform mud weight measurement.
2. After finish mixing for 1 hour, stir the sample at 13,000 rpm by mixer for 5 minutes.
3. Measure the pH of the sample.
4. Load the sample into the test cell and load the test cell into Fann 75.
5. Start heating up the sample to 120° F at 15 minutes after finish stirring the sample in step 2. Keep stirring the sample at 200 rpm while heating up.
6. Measure dial reading at shear rate of 600, 300, 200, 100, 30, 6 and 3 rpm respectively. At each rpm, the sample is sheared at that rpm for 1 minute and

dial reading are collected at 57±1 seconds after staring applying that shear rate.

7. Stir the sample at 600 rpm for 1 minute to destroy gel structure.
8. Leave the sample at rest for 10 seconds of gelling time. At this step, pressure and temperature data are collected every 30 seconds.
9. Start applying shear rate of 30 rpm and collect dial reading, rpm and temperature data every second. Keep shearing and collecting data for 5 minutes.
10. Repeat step 7 to 9 with shear rate of 100, 200 and 300 rpm respectively.
11. Repeat step 7 to 10 with shear rate of 100, 200 and 300 rpm respectively for 2 times.
12. Repeat step 6.
13. Unload the sample and measure the pH of the sample with minimum delay.

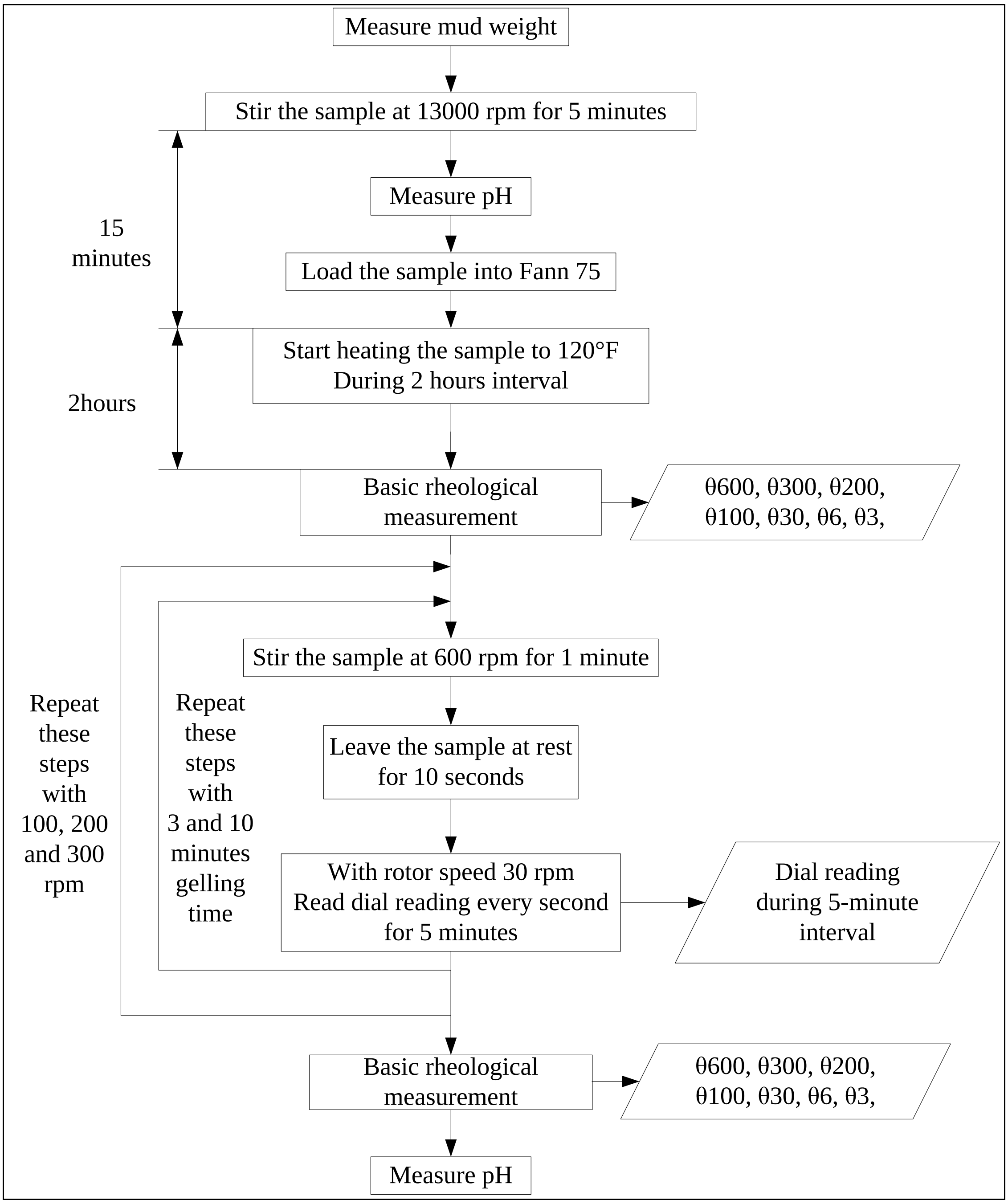

Figure 4.2 Experimental procedures on all test set (except test set#2).

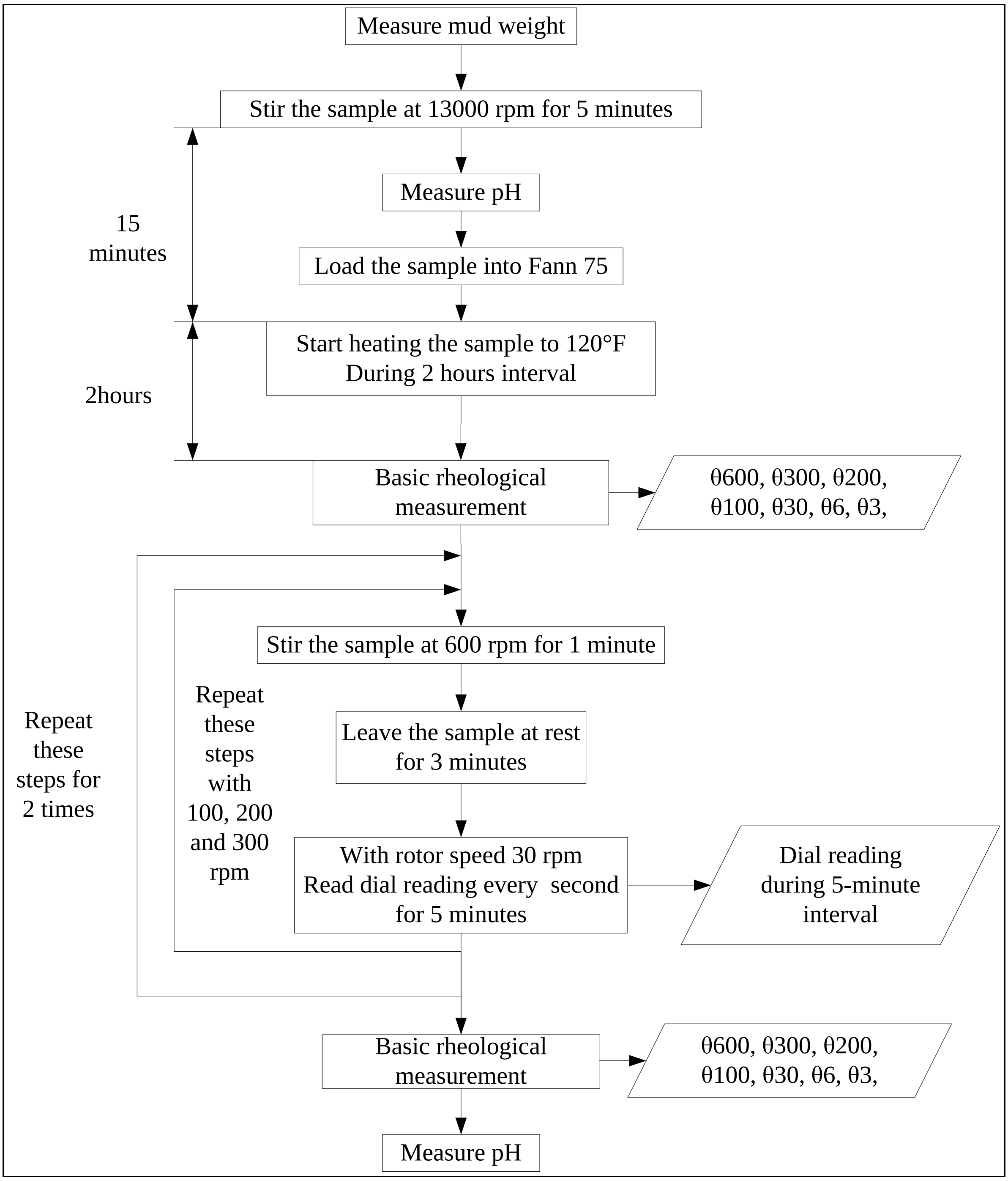

Figure 4.3 Experimental procedures on test set#2.

4.3 Equipment

4.3.1 Viscometer

In this study Fann 75 viscometer is used to assess sample's rheological properties. Fann 75 viscometer is a rotational viscometer, which is a Couette type viscometer. This model has operating pressure from 0 to 20,000 psi and operating temperature from 20 °F to 500 °F. Rotor speed can be varied from 3 to 600 rpm, which shear rate in s^{-1} can be determined by multiplying rpm by 1.703. This conversion factor is valid for only standard direct-reading viscometer (Fann 75 is a standard one) which the specification is shown in **table 4.3**. Shear stress measurement has the resolution of 0.1 dial reading with accuracy of ±0.5% full scale. Temperature measurement has the resolution of 0.1 °F. Pressure measurement has the resolution of 1 psi. Rotor speed measurement has the resolution of 1 rpm.

Table 4.3 Specification on standard direct-reading viscometers [15].

Rotor	Bob	Torsion spring
Inside diameter : 36.83 mm.	Diameter : 34.49 mm.	Spring constant : 386 dyne-centimeters/degree
	Height : 38.05 mm.	

The test cell consists of three components which are torsion spring assembly, bob and bob shaft assembly and rotor assembly as shown in **figure 4.4**.

Test sample heating is produced by an electric resistance heater attached to the wall of the heater well. Heat transfers through a narrow gap from the wall of the heater well directly to the wall of the test cell. The temperature is sensed by means of a single RTD (Resistance Temperature Device) that is permanently mounted in the center of the heater well. It projects up from the center bottom of the well. It fits into the test cell as the cell is lowered into the heater well. This places it near the center of the fluid sample.

The rotor is magnetically driven through the wall of the test cell. A powerful samarium-cobalt permanent magnet is attached to the bottom of the rotor. It magnetically locks to a cylindrical permanent magnet, which rotates with an insulating can, around the heaters of the heater well. The insulating can is driven through a 10:1 worm gear reducer by a small permanent magnet motor. The motor's speed is sensed by means of an optical encoder which generates a frequency proportional to the speed. This frequency is used by a phase-locked loop to control a power field effect transistor, which regulates the power to the motor. The high mass of the rotating parts, and the relatively small size of the motor, limits the system to steady speed measurements. The speed response of the system is relatively rapid.

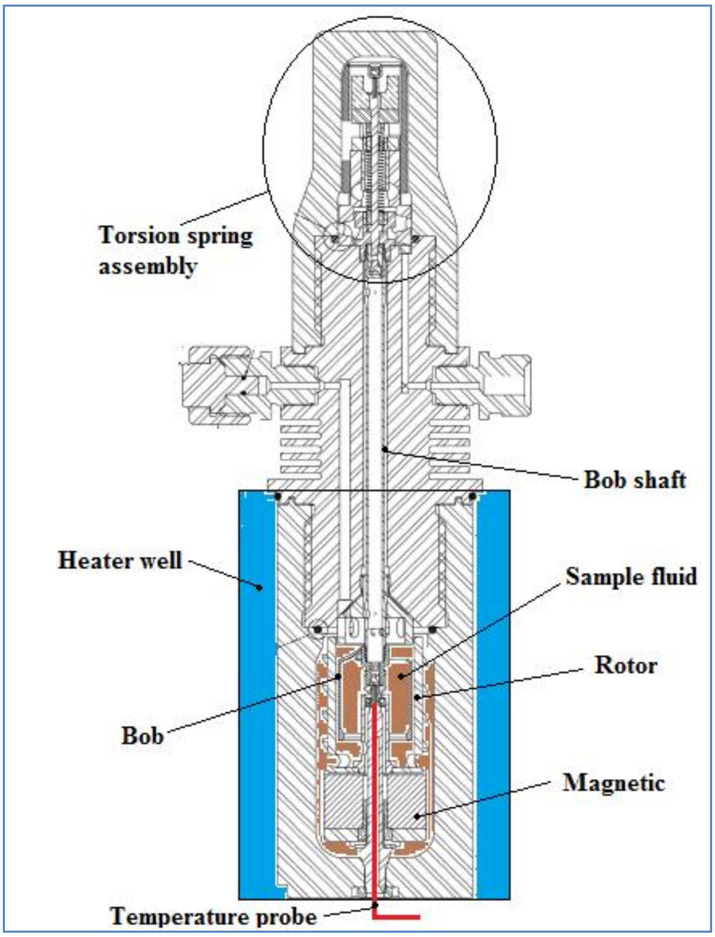

Figure 4.4 Schematic of the test cell (cross section).

Calibration on Fann 75 is done in three steps which are setting the mechanical zero, calibrating the torsion spring and system calibration

Setting mechanical zero of the test cell torsion assembly is the angle to which the torsion assembly rotates with no fluid in the cell.

Calibrating the torsion spring is done by operate the viscometer at a speed of 300 rpm with 200 centipoises fluid batch#M200-0310 from Fann instrument company. Compare the raw angle to the calculated angle from the calibration fluid table, for the indicated temperature. An error of 0 to 5 dial reading is acceptable because the system will be calibrated again in system calibration.

System calibration is accomplished by comparing the calculated shear stress angle to the actual shear stress angle reading (without correction) at various speeds. The microprocessor derives breakpoints that represent the ends of straight lines that approximate the error curve. The breakpoints obtained are used by the microprocessor to generate a correction table. This is done by the same batch of 200 centipoises calibration fluids. During calibration, the viscometer is stepped through a series of rotational speeds from 9 to 488 rpm which results in actual dial reading of 5.5 to 291.5. The calibration is conducted at temperature (measured by Fann 75's RTD) between 76.8 to 80.2 °F.

Temperature probe (RTD) that is checked with Fann 75 is compared with thermocouple. During the assessment, torsion spring assembly, bob shaft and bob are removed so that the thermocouple probe can be placed in the test cell. The probe's tip of the thermocouple is placed 17.8 cm apart from the location that bottom of torsion spring assembly is placed, which the probe's tip is near the center of the sample fluid. The sample fluid used in the assessment is 10.0 ppg PHPA mud as shown in **table 4.1**. Preparation of the sample is similar to the sample in experiment except all additive are added at 30 minutes after start adding bentonite, the sample is stirred for 1 hour after start adding bentonite. Then proceed the same procedure in **figure 4.2** but do not read shear stress. Temperature from Fann 75 (RTD) and temperature from thermocouple are read every 10 minutes (begin at 2 hours after start heating up the sample) instead. This process is conducted for temperature of 120 °F and 150 °F. Results of temperature variation assessment are shown in **figure 4.5, 4.6, 4.7** and **4.8**. Then, the result is presented in form of average absolute deviation (AAD) which the equation is as follow:

$$AAD = \frac{100}{N} \sum_{i=1}^{N} \left| \frac{TC_i - RTD_i}{TC_i} \right| \qquad (4.1)$$

where

AAD is average absolute temperature deviation on measured temperature from thermocouple and Fann 75's RTD (%)

TC_i is measured temperature from thermocouple (°F)

RTD_i is measured temperature from Fann 75's RTD (°F)

N is number of data point on temperature

At 120 °F, measured temperature data from Fann 75 temperature probe (RTD) and temperature from calibrated thermocouple have similar trend but do not match very well as shown in **figure 4.5**. **Figure 4.6** shows the difference in temperature between Fann 75's RTD and calibrated thermometer (temperature from RTD subtracted by temperature from calibrated thermocouple). The difference ranges between -1.0 to 1.7 °F. AAD is 0.61%. At 150 °F, measured temperature data from Fann 75 temperature probe (RTD) and temperature from calibrated thermocouple also have similar trend but do not match very well as shown in **figure 4.7**. **Figure 4.8** shows the difference in temperature between Fann 75's RTD and calibrated thermometer (temperature from RTD subtracted by temperature from calibrated thermocouple). The difference ranges between -1.5 to 2.4 °F. AAD is 0.65%. It can be seen that almost all measured temperature from calibrated thermocouple is difference from RTD's measured temperature in the range of thermocouple accuracy. Therefore, measurement by Fann 75's RTD is acceptable.

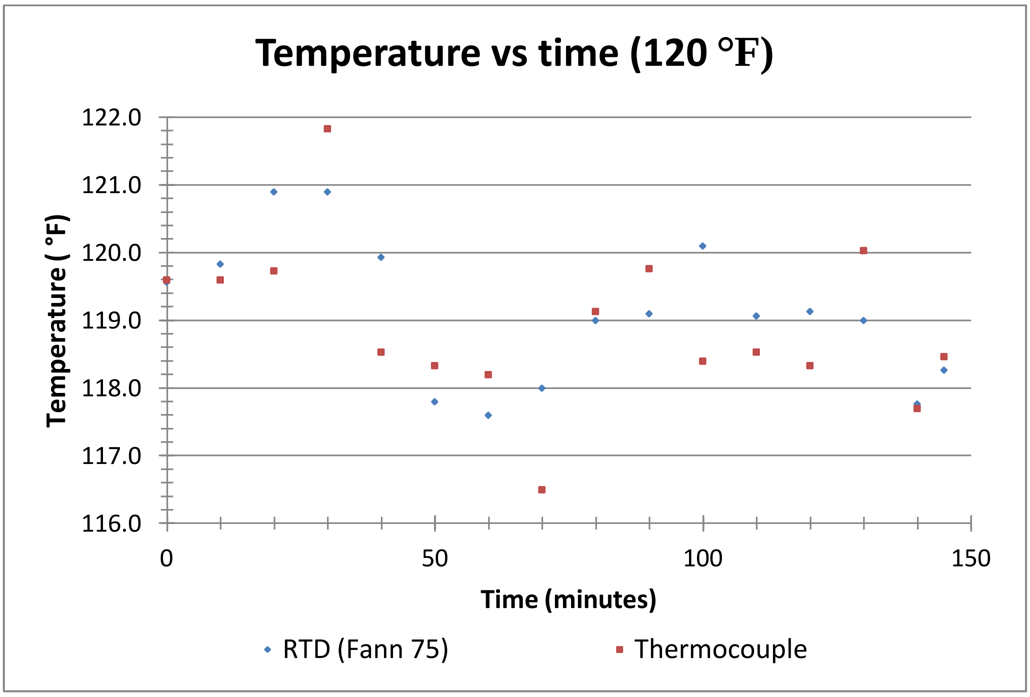

Figure 4.5 Result on temperature variation assessment (120 °F).

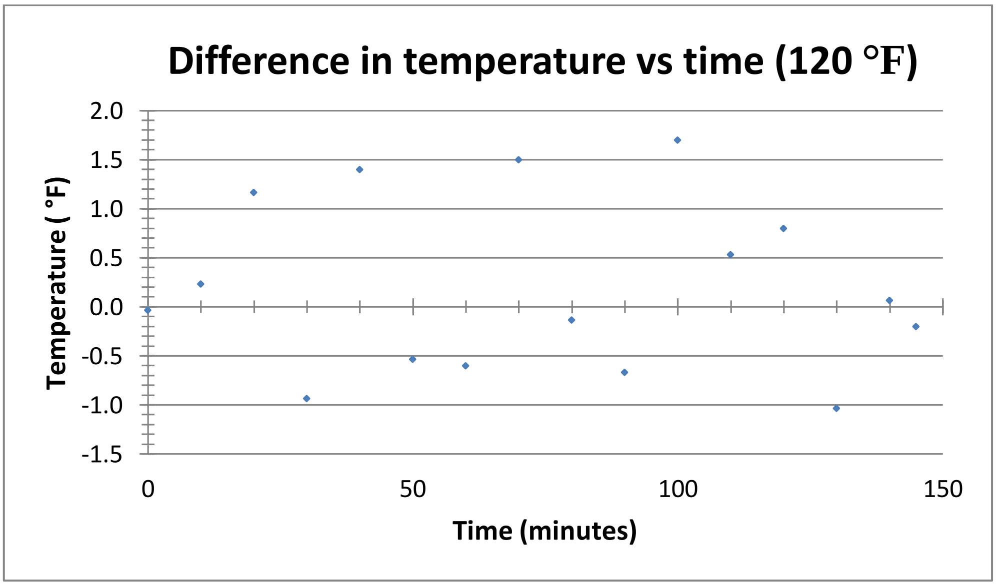

Figure 4.6 Result on temperature variation assessment (120 °F).

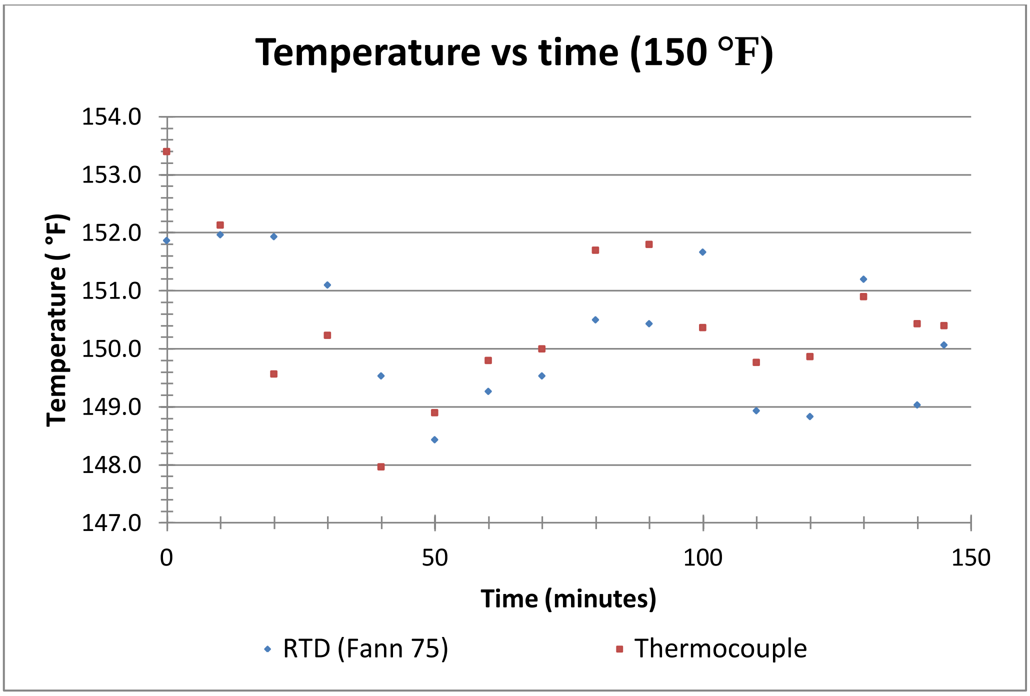

Figure 4.7 Result on temperature variation assessment (150 °F).

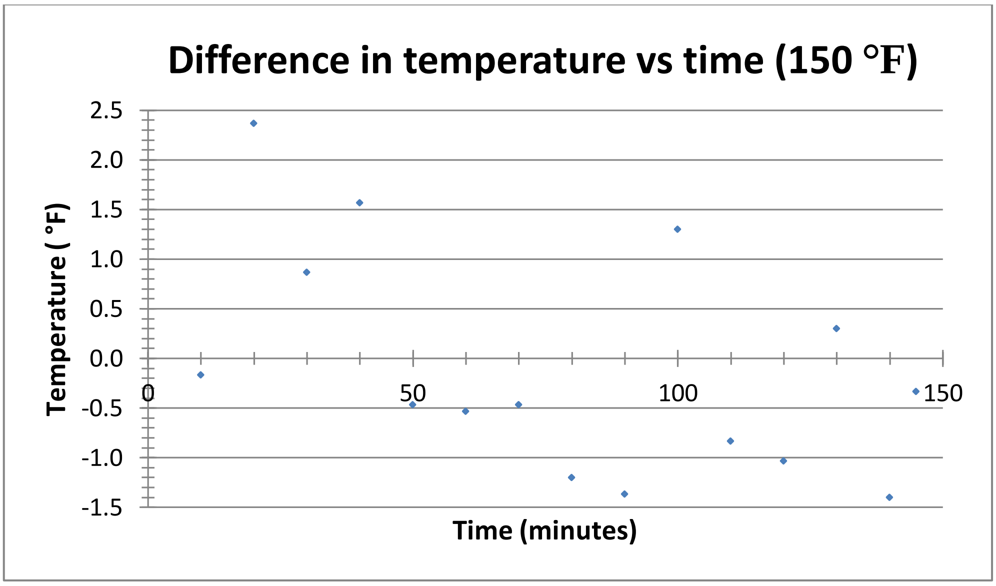

Figure 4.8 Result on temperature variation assessment (150 °F).

4.3.2 Other equipments

Type, specification, calibration and procedure on using other equipments are summarized in **table 4.4**.

Table 4.4 Summary on other equipments.

Instruments	Type	Specification	Calibration	Procedure
Scale	Digital	Range: 0 – 1500 g Resolution: 0.01 g Accuracy: ±0.015 g	3rd party (once a month)	-
Thermometer	Thermocouple	Range: -50 °C to 1230 °C (-58 °F to 1999 °F) Resolution: 1/0.1 °C or 1/0.1 °F Accuracy: ±1% + 1 °C (±1% + 2 °F).	3rd party (once a year)	-
Mud balance	Pressurized (API RP 13B-1*)	API RP 13B-1*	API RP 13B-1*	API RP 13B-1*
Mixer	API RP 13I**	API RP 13I**	-	-
pH meter	API RP 13B-1*	API RP 13B-1*	Similar to API RP 13B-1*. The difference is temperature at calibration and measurement is higher than 24° C but using auto temperature compensation function.	

*API recommended practice 13B-1: standard practice for field testing water-based drilling fluids[15]

** API recommended practice 13I: recommended practice for laboratory testing of drilling fluids[20]

CHAPTER V

RESULTS AND DISCUSSION

Firstly rheological properties, mud weight and pH of each test set are shown. Next, results on thixotropic behavior assessment are exhibited and mathematical model for thixotropic behavior prediction is presented. Then, effects of gelling time and shear rate on thixotropic behavior are discussed. Lastly, comments on suitability of PHPA mud system for MPD are made.

5.1 Measurement of basic properties

Rheological properties of the samples in all cases before thixotropic behavior assessment, are shown in **table 5.1**. The average rheological properties (before and after) are used to calculate best fit rheological model between Bingham plastic model and power law model.

Test set#1 is the base case (mud weight of 10.0 ppg, test is performed at 120 °F). Test set#2 is the case that is carried out to assess the effect of shear time during experiment (also has mud weight of 10.0 ppg and is performed at 120 °F). Test set#2 has slightly lower rheology than test set#1 at all shear rates which could result from low repeatability of mixing procedure.

Test set#3 which is the case of 12.0 ppg mud weight exhibits higher rheology comparing to the base case due to more solid content. Test set#4 which is the case that drilled solid is added also exhibits higher rheology than the base case. Test set#5 which is the case that Lost Circulation Material (LCM) is added exhibits slightly higher rheology compared to the base case. These higher rheology are expected due to addition of solid particles. Test set#6 which is the case that the experiment is conducted at 150°F exhibits lower rheology compared to the base case which is the typical effect of increased temperature because fluid expansion result in longer distance between particles which leads to lower resistance to flow.

Data on rheology of each test set are used to find rheological parameters which are τ_y, μ_p, n and k. These parameters then are used to plot shear stress- shear rate curve based on Bingham plastic model and power law model. After that, the curves from these two models are compared with the measured data. The result shows that all test sets can fit well with power-law model. Some examples are shown in **figure 5.1** and **5.2**.

pH is controlled in the range of 8.5 to 10.0 which is the recommended range for PHPA mud system. Test set#6 exhibits higher decrease in pH compared to other test sets which may be resulted from higher temperature in the experiment. Temperature during mud weight measurement ranges from 41 to 42 °C.

Table 5.1 Basic properties of all test set.

		Test set#1	**Test set#2**	**Test set#3**	**Test set#4**	**Test set#5**	**Test set#6**
Rheology before thixotropic assessment (dial reading)	600 rpm	70.8	69.3	100.2	119.4	75.3	55.2
	300 rpm	52.1	50.6	72.4	88.3	56.1	42.4
	200 rpm	42.7	41.5	59.8	75.6	46.6	35.3
	100 rpm	31.0	30.1	43.5	58.3	34.1	25.7
	30 rpm	17.8	16.2	24.0	37.4	19.3	13.8
	6 rpm	7.8	6.1	10.0	19.0	8.1	5.5
	3 rpm	4.5	3.3	6.2	15.0	5.2	3.6
Best fit model		Power law					
n		0.44	0.45	0.47	0.44	0.42	0.38
K (eq.cp)		1685	1526	1987	2987	2028	2017
Minimum temperature (°F)		117.0	117.0	117.2	117.1	117.4	146.9
Maximum temperature (°F)		121.9	123.4	122.1	121.1	121.1	153.0
Mud weight (ppg)		10.0	10.0	12.0	10.0	10.0	10.0
pH before test		9.4	9.4	9.4	9.5	9.5	9.5
pH after test		9.2	9.2	9.1	9.1	9.2	8.7

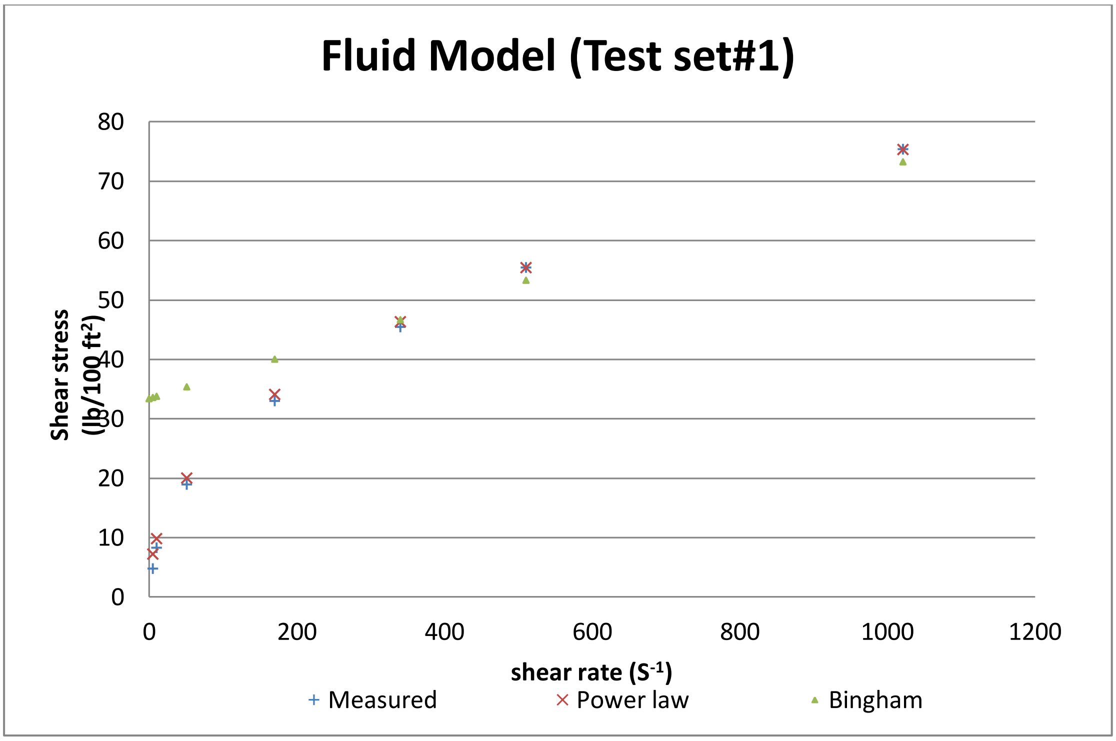

Figure 5.1 Rheology of test set#1.

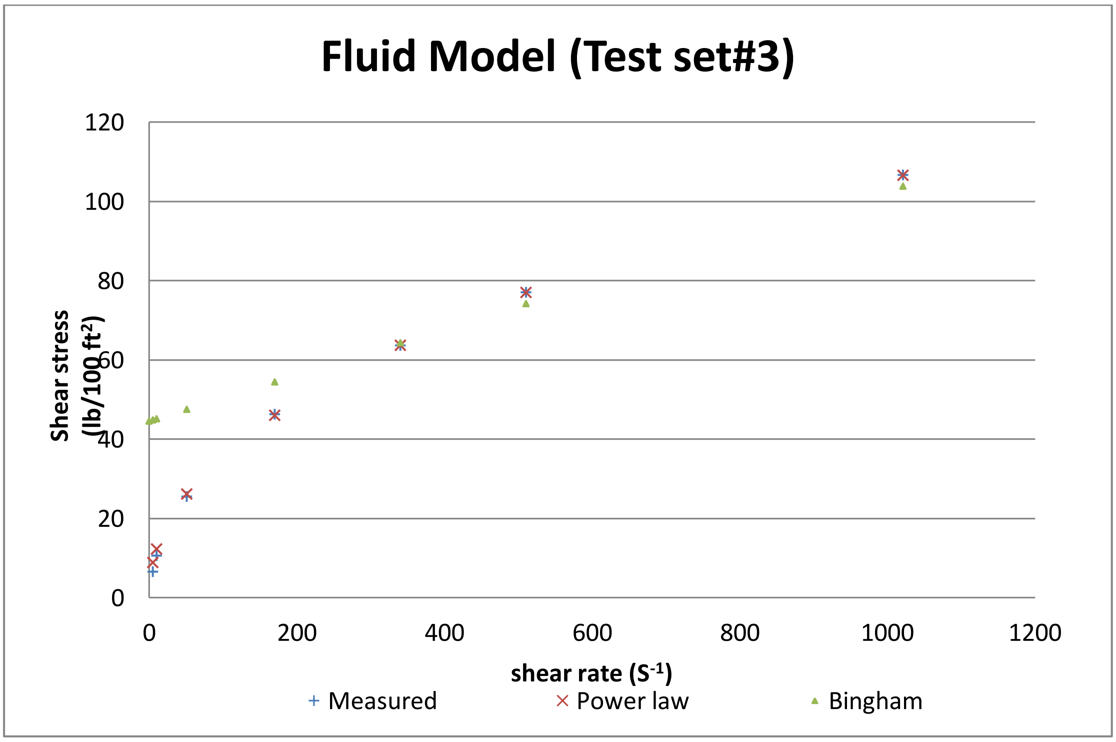

Figure 5.2 Rheology of test set#3.

5.2 Results on thixotropic behavior assessment

In this study, dial reading in the first 4 seconds of thixotropic behavior assessment are excluded because shear rate has not reached the required value yet. AFP (Annular Frictional Pressure loss) is directly depends on dial reading which is shear stress. AFP can be determined by multiplying dial reading (shear stress) to the wall area of the annulus and divide by cross-sectional area of the annulus as in **equation 2.8**. For application purpose, dial reading will be converted to AFP. The well configuration is assumed to be 6.125 in. hole, 3.5 in. drillpipe at well depth of 10,000 ft.

$$AFP = \frac{\tau_w A_w}{A_c} \quad (2.8)$$

Fluid velocites are determined from shear rate at wall of 30, 100, 200 and 300 rpm by using **equation 2.10**. Flow rates (gallons per minute, gpm) are determined by multiplying cross-sectional area to fluid velocities. Because decreasing in AFP is low compared to the value of AFP itself, the new parameter is defined to scope only the changing in AFP. This new parameter is AFP difference which is AFP at each second subtracted by the lowest AFP in that data set.

$$\dot{\gamma}_w = \frac{48v}{d_2 - d_1}(2 + 1/n), \text{ for power law model} \quad (2.10)$$

In the experiments, data on dial reading is observed every 1 second. However, when all data points are plotted on the graph, the fluctuation results in band-like shape on the graph. Therefore, only data from every 5-second interval will be shown in the graph. Note that there are some data points that are missing and the adjacent data points will be used instead. For example, if data at 10th second is missing, the data at 9th or 11th second will be used instead.

Test set#1 results which is the base case are shown in **figure 5.3, 5.4, 5.5** and **5.6**. Gelling time has little effect on thixotropic behavior for all four shear rates in the experiment. The reason could be that concentration of clay (2.5 lb/bbl API treated bentonite) is too small to cause the mud to be progressive gel. At shear rate of 30 rpm, AFP difference has low repeatability. Results on other test sets at shear rate of 30 rpm also have low repeatability and some exhibit trend that does not conform to result on other shear rate. Therefore, results at shear rate of 30 rpm will be shown but will be excluded from some discussion and conclusion. Trend in AFP difference at shear rate of 100 rpm, 200 rpm and 300 rpm are similar. AFP difference sharply decreases at first then gradually decreases. Shear rate of 100 rpm exhibits highest thixotropic behavior followed by 200 rpm and 300 rpm respectively. Increasing shear rate results in lower thixotropic behavior which is different from expectation in that increasing shear rate should result in higher thixotropic behavior.

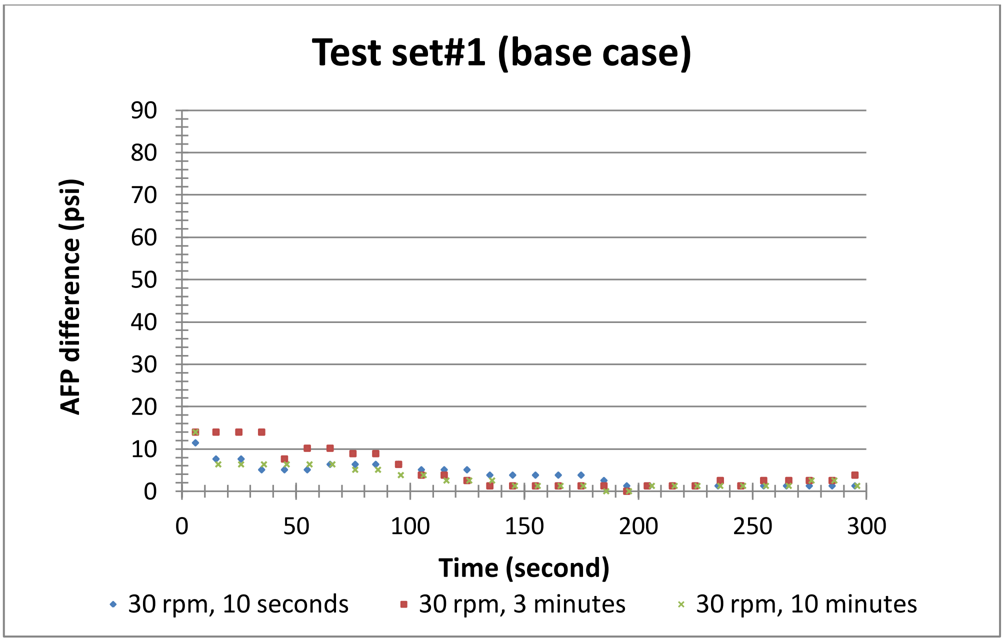

Figure 5.3 Thixotropic behavior assessment on test set#1 (shear rate of 30 rpm).

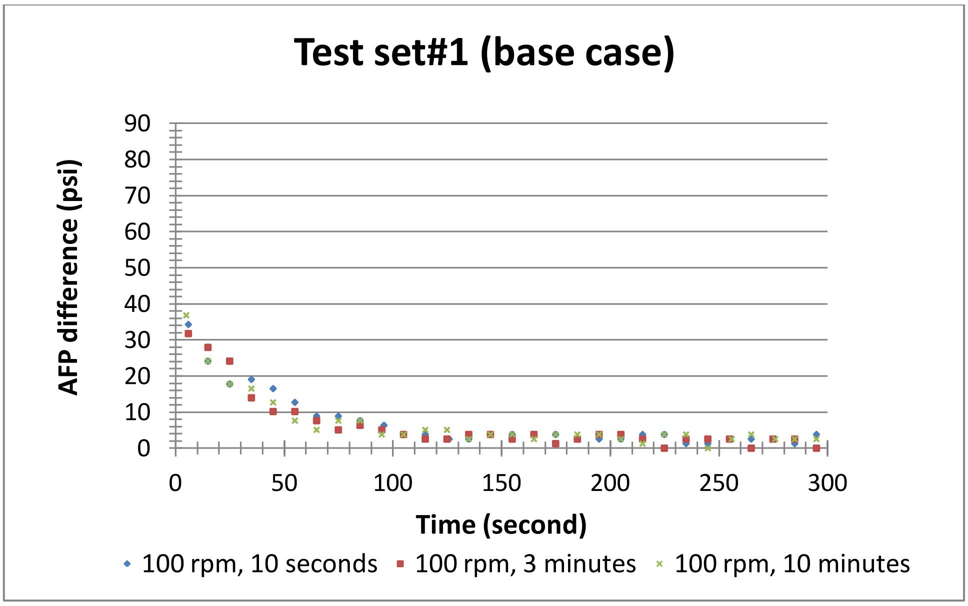

Figure 5.4 Thixotropic behavior assessment on test set#1 (shear rate of 100 rpm).

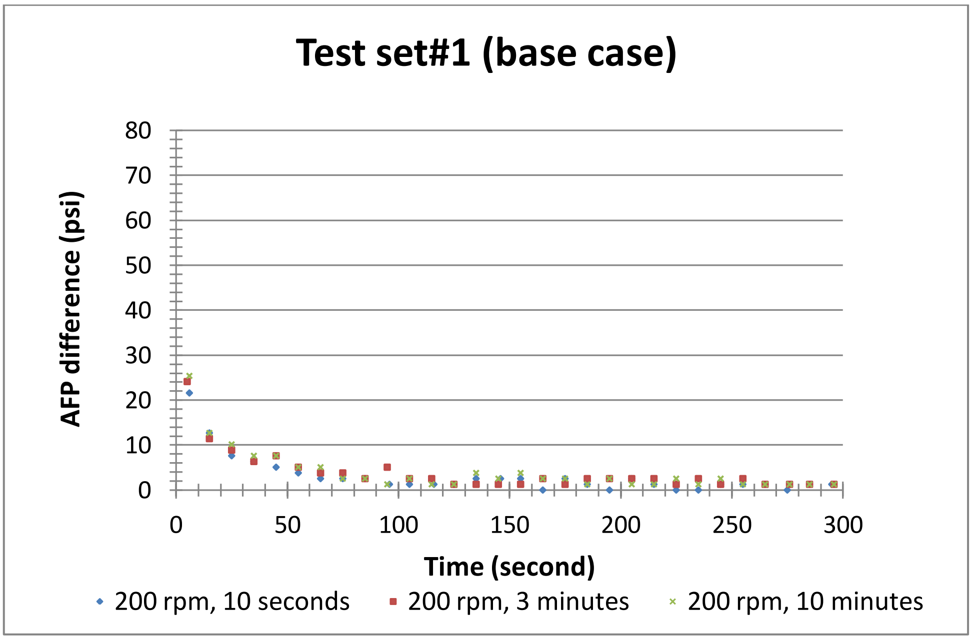

Figure 5.5 Thixotropic behavior assessment on test set#1 (shear rate of 200 rpm).

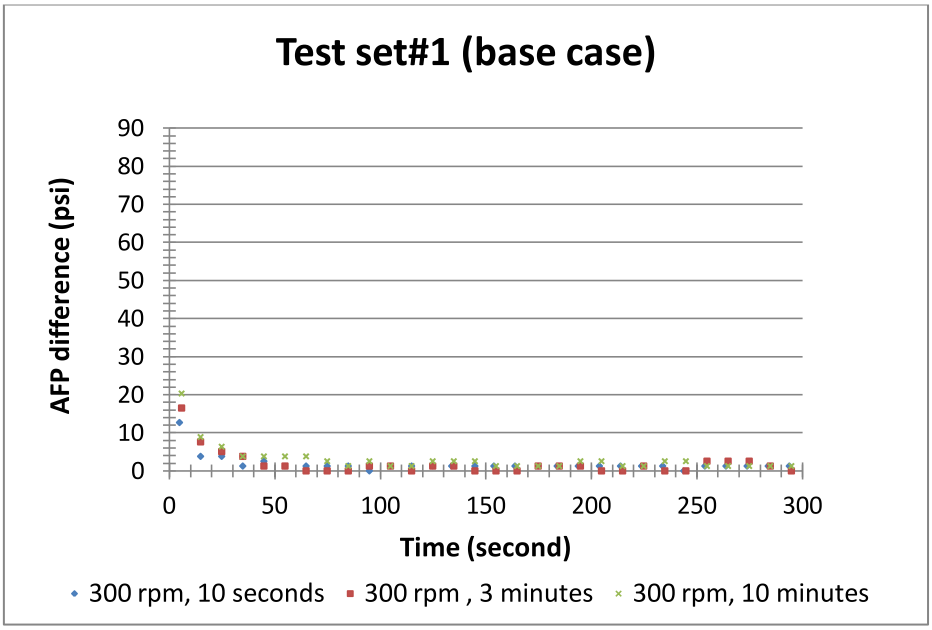

Figure 5.6 Thixotropic behavior assessment on test set#1 (shear rate of 300 rpm).

Test set#2 is conducted to find effect of rheology change as time changes in experiment. Note that all test sets take around 2.5 hours in experiments. Test set#2 results are shown in **figure 5.7, 5.8, 5.9** and **5.10**. Most of the results overlay each other except the result on shear rate of 30 rpm. At shear rate of 100, 200 and 300 rpm, the trend in AFP difference is similar to test set#1 but lower in magnitude. This may result from lower rheology of the sample in test set#2 compared to the test set#1. Therefore, it is reasonable to assume that rheology change during thixotropic behavior assessment has small effect on thixotropic behavior.

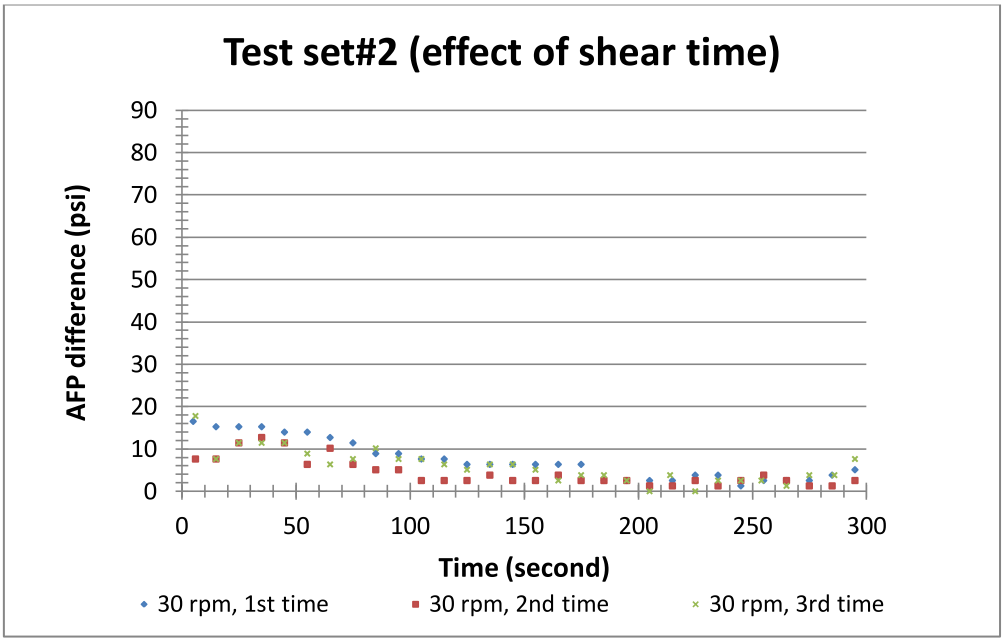

Figure 5.7 Thixotropic behavior assessment on test set#2 (shear rate of 30 rpm).

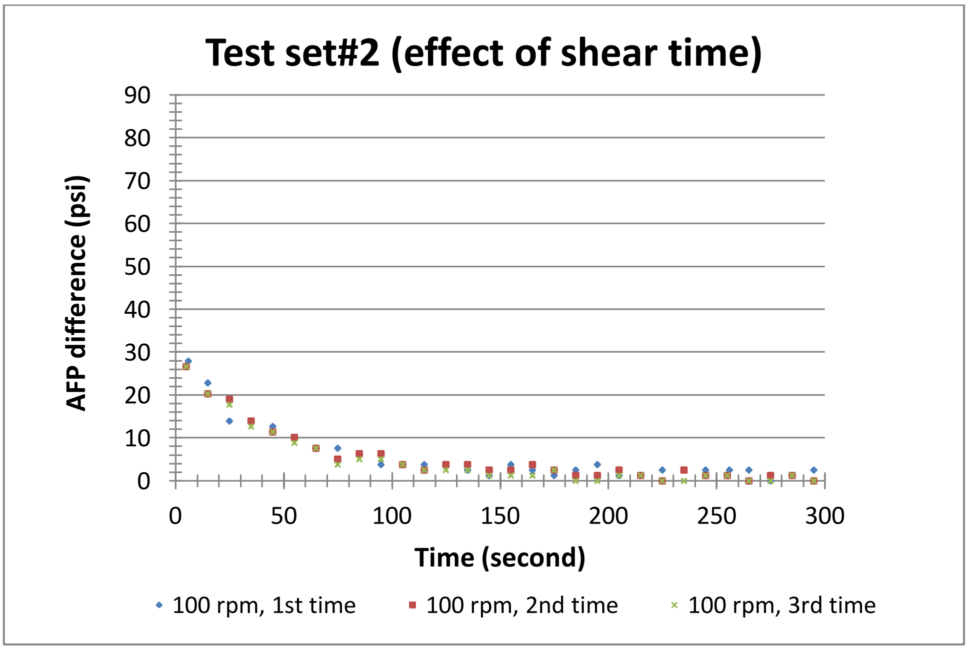

Figure 5.8 Thixotropic behavior assessment on test set#2 (shear rate of 100 rpm).

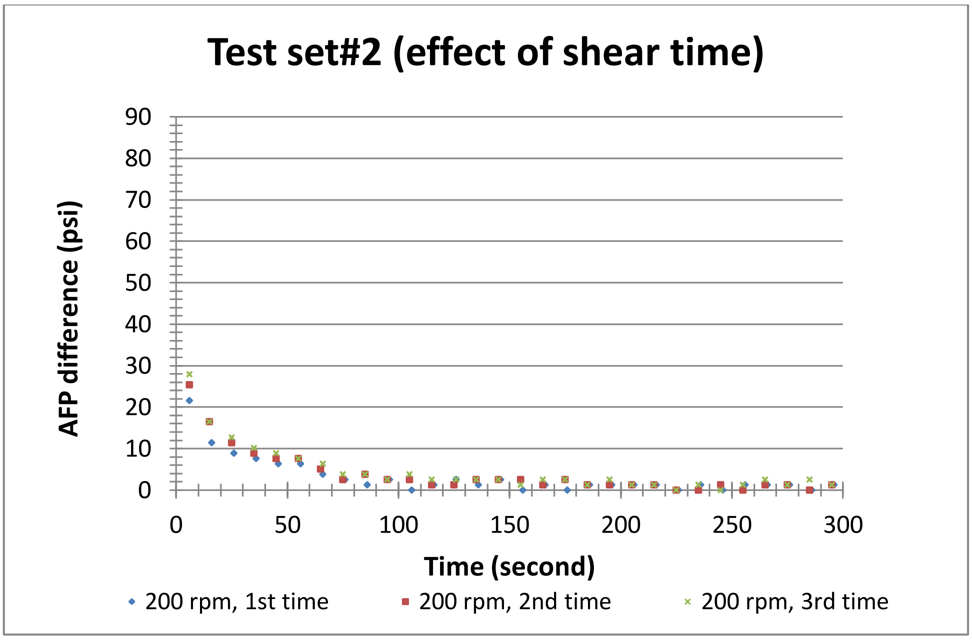

Figure 5.9 Thixotropic behavior assessment on test set#2 (shear rate of 200 rpm).

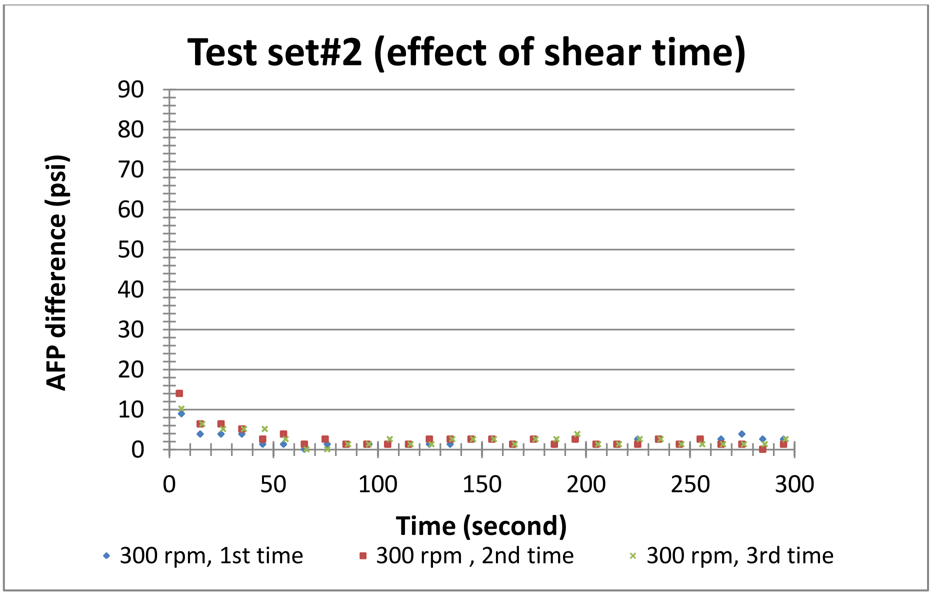

Figure 5.10 Thixotropic behavior assessment on test set#2 (shear rate of 300 rpm).

Test set#3 (mud weight of 12.0 ppg) is conducted to observe effect of mud weight which barite is used as weighting material in this study. Test set#3 results are shown in **figure 5.11, 5.12, 5.13** and **5.14**. Gelling time has little effect on thixotropic behavior for all four shear rates in the experiment. At shear rate of 100, 200 and 300 rpm, trend of AFP difference is similar to the base case but different in magnitude. At shear rate of 200 and 300 rpm test set#3 results have higher thixotropic behavior compared to that of the base case which is as anticipated. But at 100 rpm, test set#3 has lower thixotropic behavior than the base case.

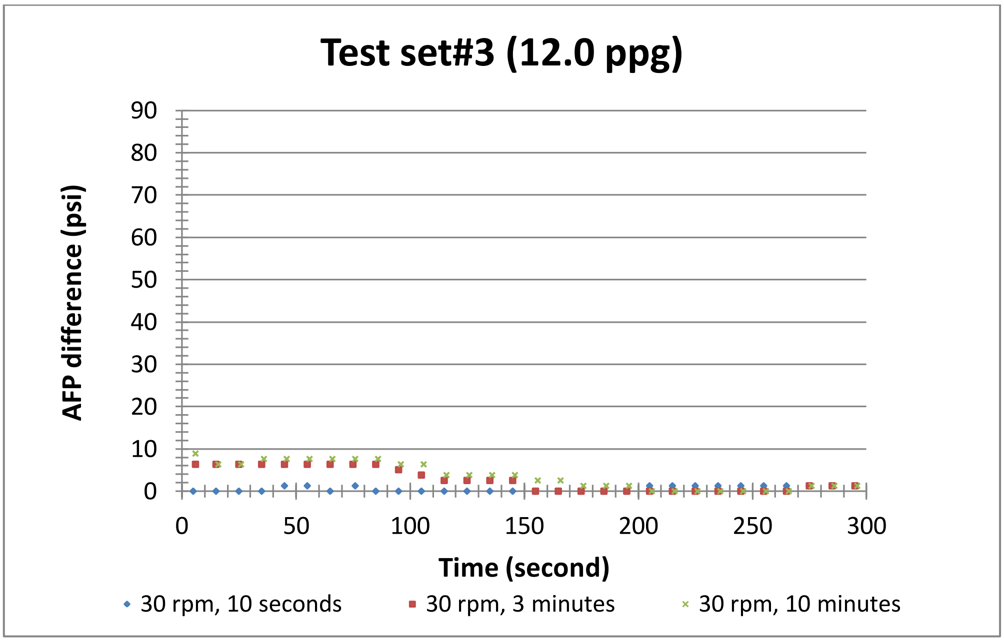

Figure 5.11 Thixotropic behavior assessment on test set#3 (shear rate of 30 rpm).

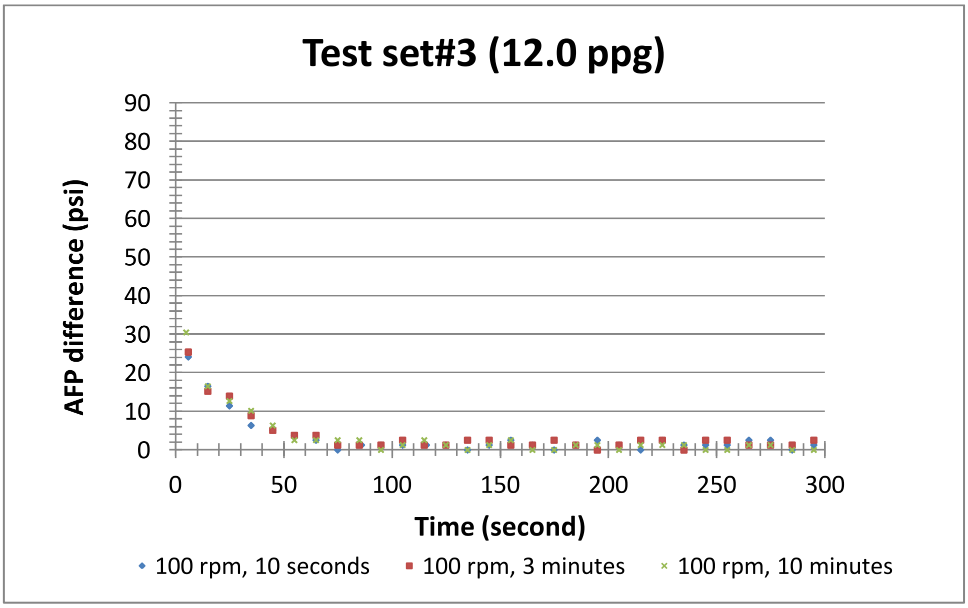

Figure 5.12 Thixotropic behavior assessment on test set#3 (shear rate of 100 rpm).

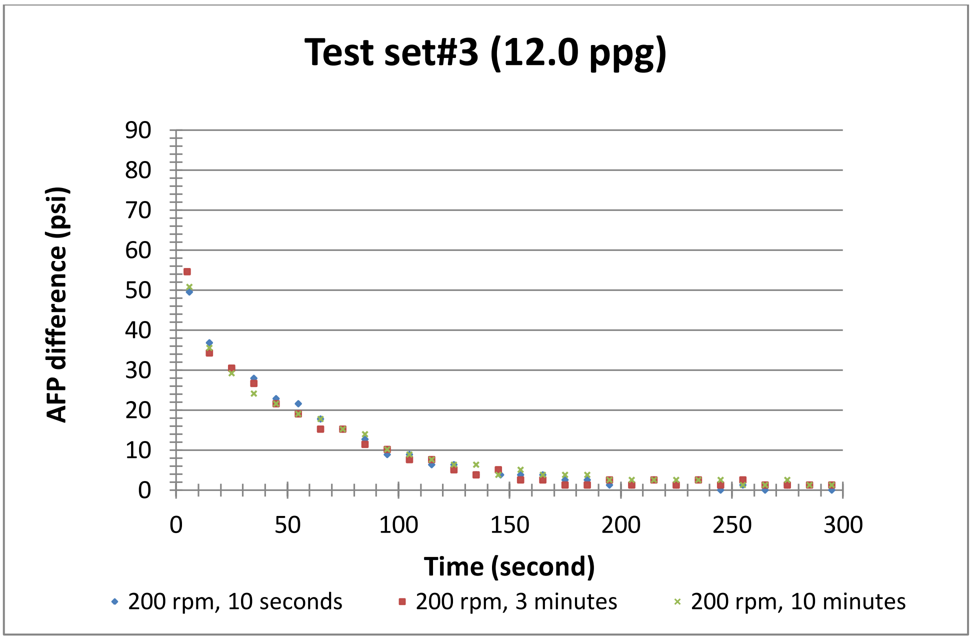

Figure 5.13 Thixotropic behavior assessment on test set#3 (shear rate of 200 rpm).

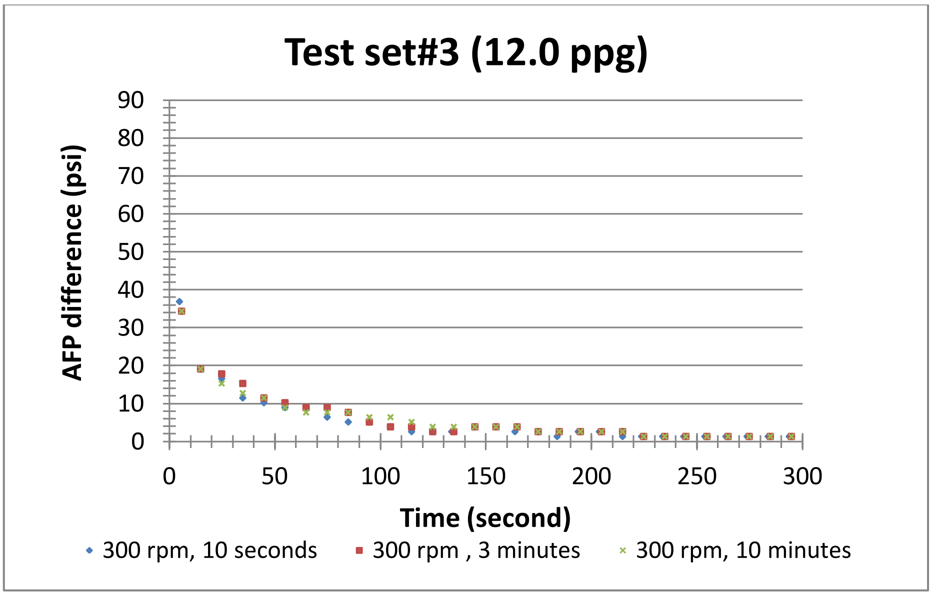

Figure 5.14 Thixotropic behavior assessment on test set#3 (shear rate of 300 rpm).

Test set#4 is conducted to observe the effect of drilled solid which API standard evaluation base clay is used to represent drilled solid. Test set#4 results are shown in **figure 5.15, 5.16, 5.17** and **5.18**. Gelling time results in higher thixotropic behavior at shear rate of 100, 200 and 300 rpm. At Shear rate of 200 and 300 rpm, test set#4 exhibits higher magnitude in AFP difference (compared to the base case) for all gelling times. At shear rate of 100 rpm, test set#4 exhibits higher magnitude in AFP difference (compared to the base case) for gelling time of 3 and 10 minutes but lower magnitude in AFP difference for gelling time of 10 seconds. Maximum AFP difference among all test set is observed in test set#4 at shear rate of 300 rpm (gelling time of 10 minutes) which is around 86 psi.

In test set#4, drilled solid is API standard evaluation based clay which is a type of clay. Ghofrani, Bosch and Strahl[8] did an experiment on finding gel strength at room condition using Fann VG 35 model viscometer with the gelling time of 1, 10, 20 and 30 minutes which the result showed that bentonite suspension in distilled water (17.5 and 24.5 lb/bbl concentration) exhibited progressive gel strength. Therefore, it is reasonable to say that adding 35 lb/bbl drilled solid results in higher thixotropic behavior when gelling time is increased.

In addition, all data set on test set#4 have higher thixotropic behavior than the base case except the case of 100 rpm, 10 seconds gelling time. Gelling is resulted from both molecule-molecule linkage and particle-particle linkage. The presence of drilled solid may increase the distance between molecules of polymer which decreases gelling from polymer structure. At the same time, drilled solid that is a type of clay increases gelling from attraction between clay platelets which effect of gelling time can be the sign of linkage from this type. Most of the cases in test set#4 show higher thixotropic behavior than the base case. Maybe these are cases that gelling from clay platelet linkage is dominant. While the case of 10 seconds gelling time at 100 rpm shows lower thixotropic behavior than the based case. It could be that this case is the case that clay increases the distance between polymer molecules and then decreases gelling from polymer while the gelling time is not long enough to promote gelling from clay to be strong enough to result in higher thixotropic behavior than the base case. Therefore, it can be concluded that the presence of drilled solid results in higher thixotropic behavior except the case of 10 seconds gelling time at 100 rpm.

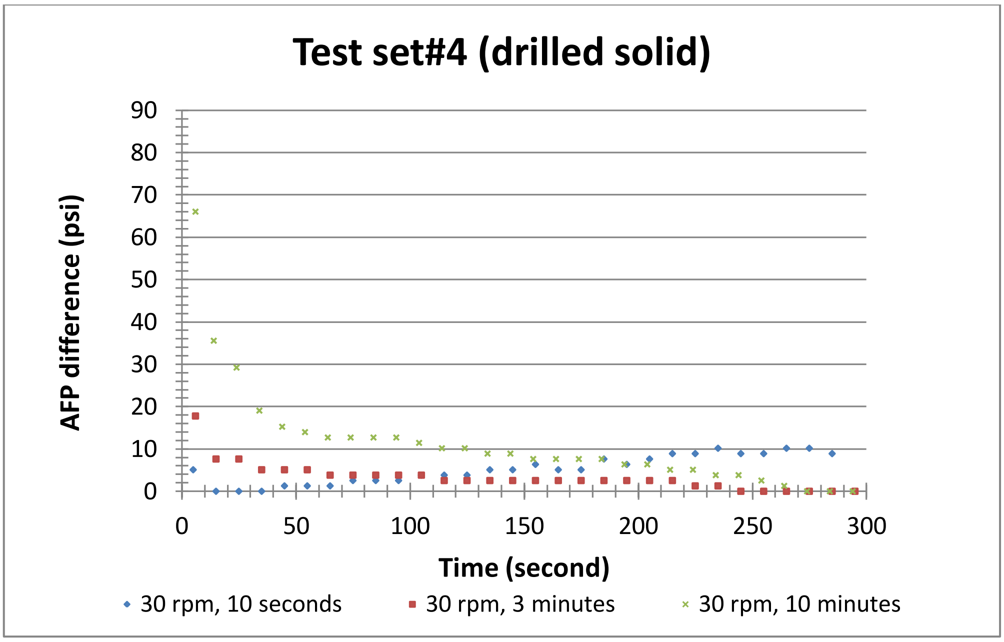

Figure 5.15 Thixotropic behavior assessment on test set#4 (shear rate of 30 rpm).

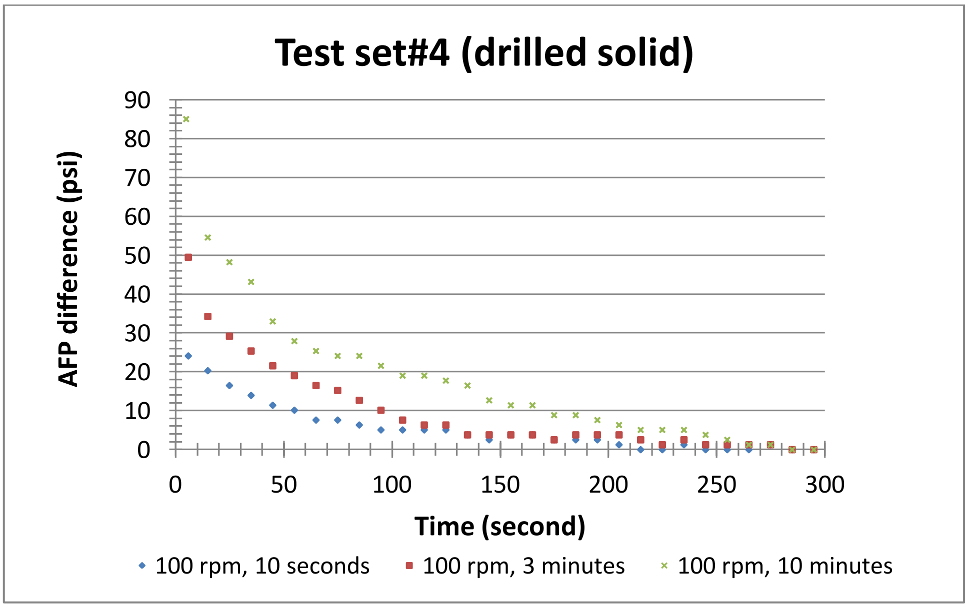

Figure 5.16 Thixotropic behavior assessment on test set#4 (shear rate of 100 rpm).

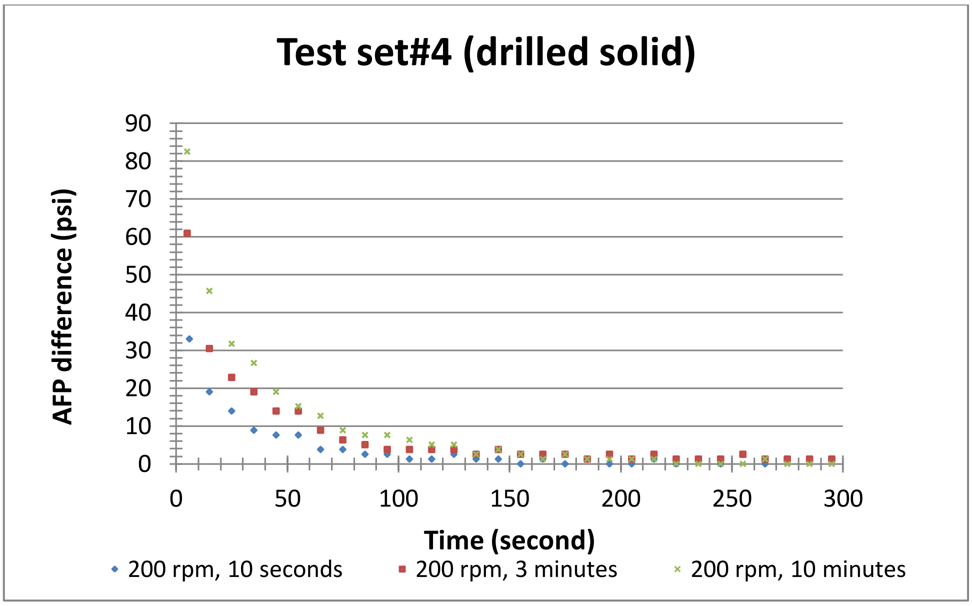

Figure 5.17 Thixotropic behavior assessment on test set#4 (shear rate of 200 rpm).

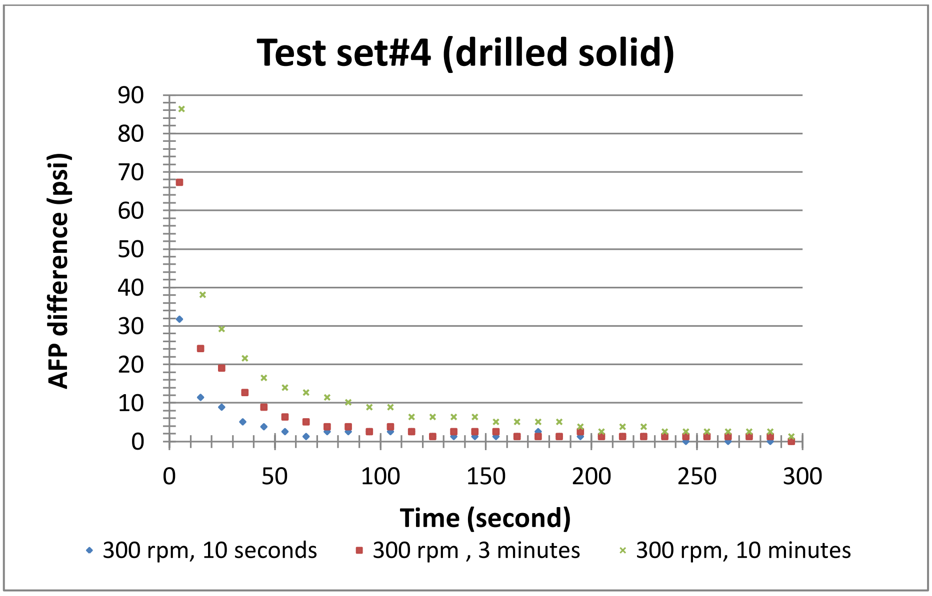

Figure 5.18 Thixotropic behavior assessment on test set#4 (shear rate of 300 rpm).

Test set#5 is conducted to observe the effect of LCM which coarse graphite is used to represent LCM. Test set#5 results are shown in **figure 5.19, 5.20, 5.21** and **5.22**. Gelling time has little effect on thixotropic behavior. At 100 rpm, trend in AFP difference is similar to the base case but lower in magnitude. At shear rate of 300 rpm, trend in AFP difference is similar to the base case but a bit higher in magnitude. At shear rate of 200 rpm, unique trend is observed. AFP difference at 200 rpm sharply decreases at early then becomes constant for a few ten seconds then sharply decreases again to zero.

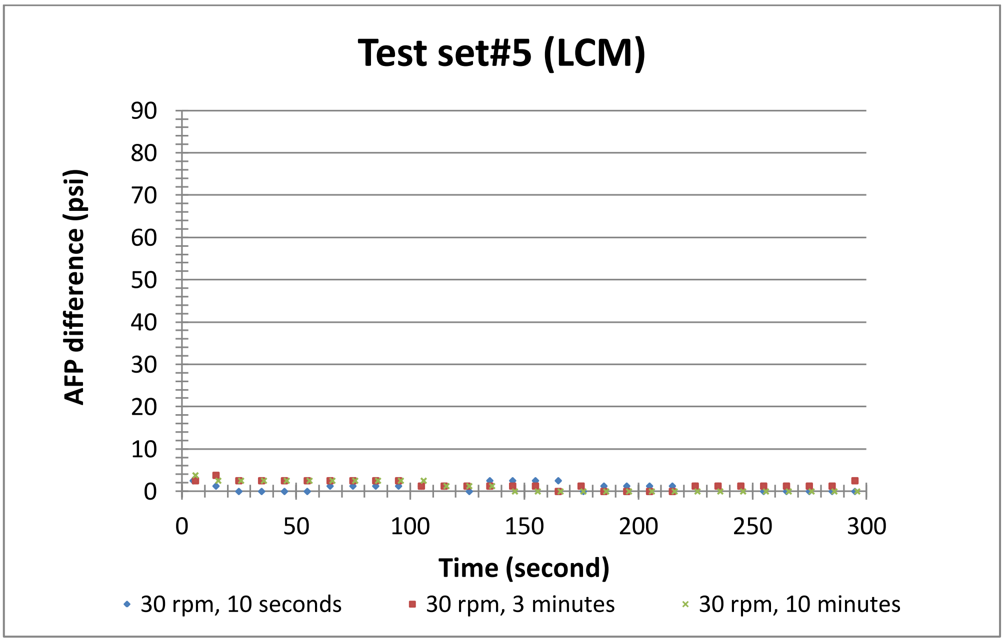

Figure 5.19 Thixotropic behavior assessment on test set#5 (shear rate of 30 rpm).

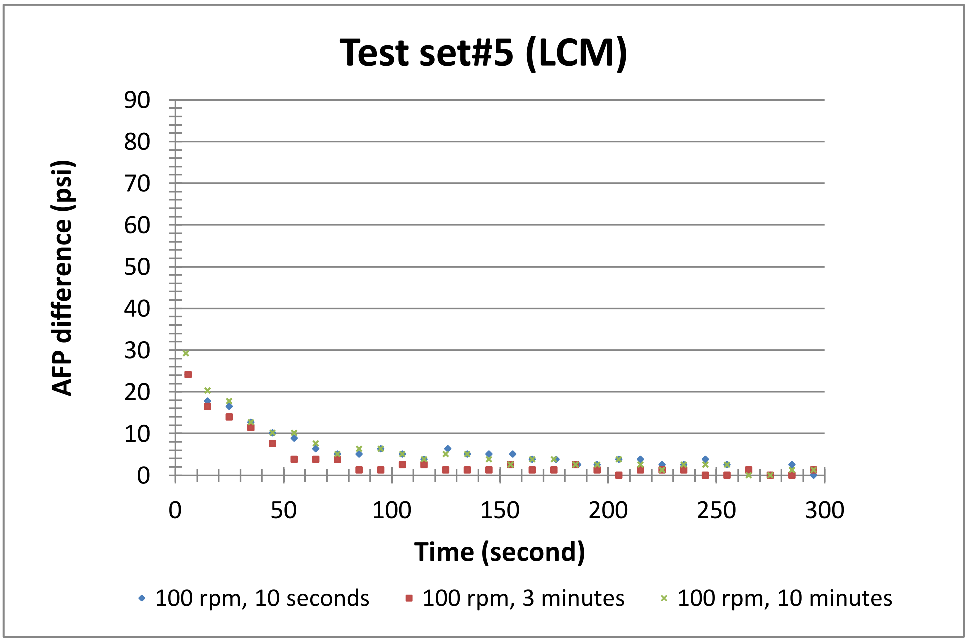

Figure 5.20 Thixotropic behavior assessment on test set#5 (shear rate of 100 rpm).

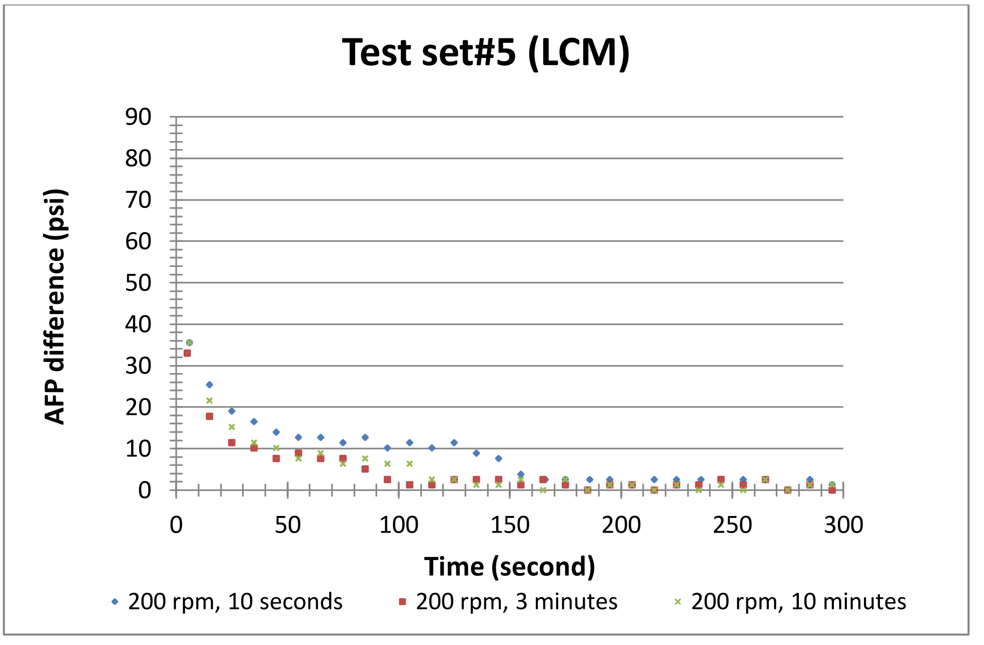

Figure 5.21 Thixotropic behavior assessment on test set#5 (shear rate of 200 rpm).

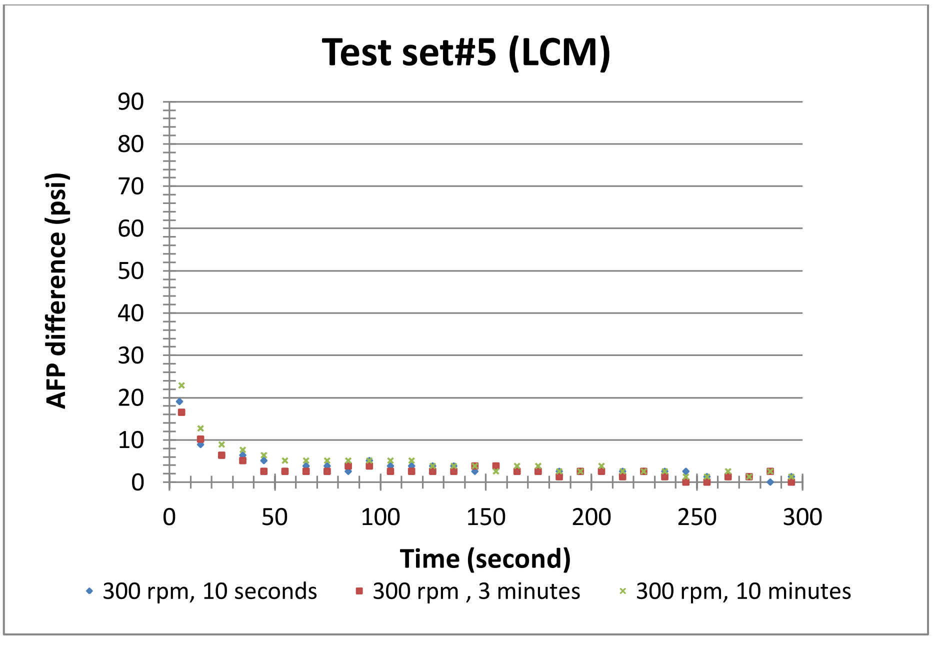

Figure 5.22 Thixotropic behavior assessment on test set#5 (shear rate of 300 rpm).

Test set#6 is conducted to observe the effect of temperature which temperature of 150°F is used in test set#6. Test set#6 results are shown in **figure 5.23, 5.24, 5.25** and **5.26**. Gelling time has little effect on thixotropic behavior. At shear rate of 100, 200 and 300 rpm, test set#6 exhibits clearly lower thixotropic behavior except gelling time of 10 minutes at shear rate of 200 rpm which unique trend is observed.

At shear rate of 200 rpm, AFP difference decreases to zero within 50 seconds for gelling time of 10 seconds and 3 minutes. But for gelling time of 10 minutes, AFP difference decreases to around 8 psi then becomes constant and decrease again to zero at around 210th second. However, if we consider the initial value of AFP difference, test set#6 has lower initial AFP difference than the base case for case of 200 rpm, 10 minutes gelling time.

It is as anticipated that test set#6 (which has higher temperature) has lower thixotropic behavior. This is because thixotropic behavior depends on the degree of linkage of polymer or particle. Higher temperature increases the distance between molecules and hence reduces thixotropic behavior. Amani and Al-Jubouri's experimental work[21] measuring of rheology and 10-second gel strength on water-based mud (field sample) reported decreasing gel strength from increasing temperature (100 °F to 350 °F) on water-based mud at ultra-high pressure range between 15000 and 35000 psi.

Therefore, it can be concluded that increasing the temperature results in lower initial AFP difference.

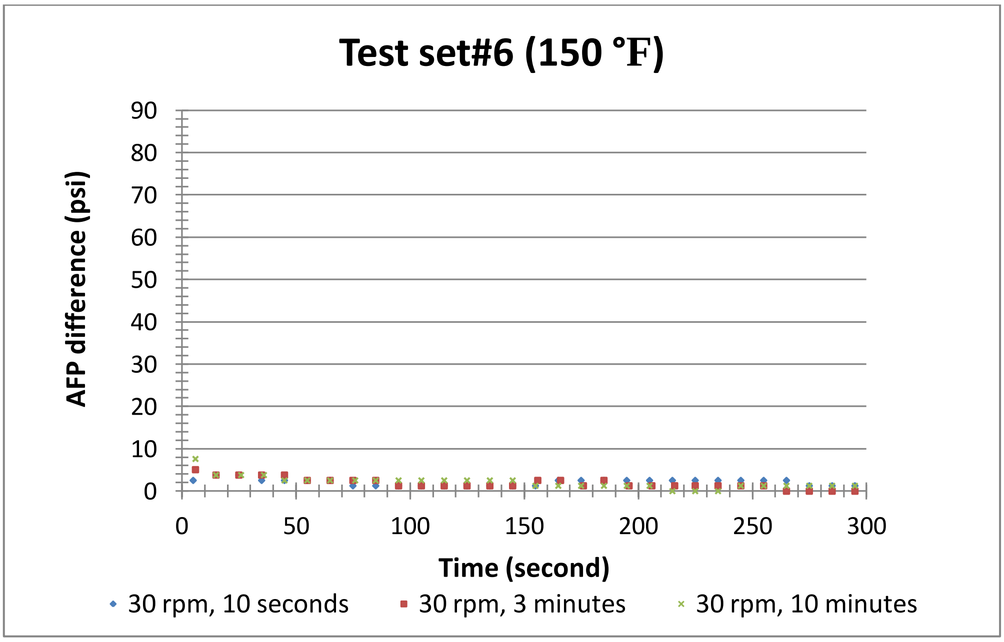

Figure 5.23 Thixotropic behavior assessment on test set#6 (shear rate of 30 rpm).

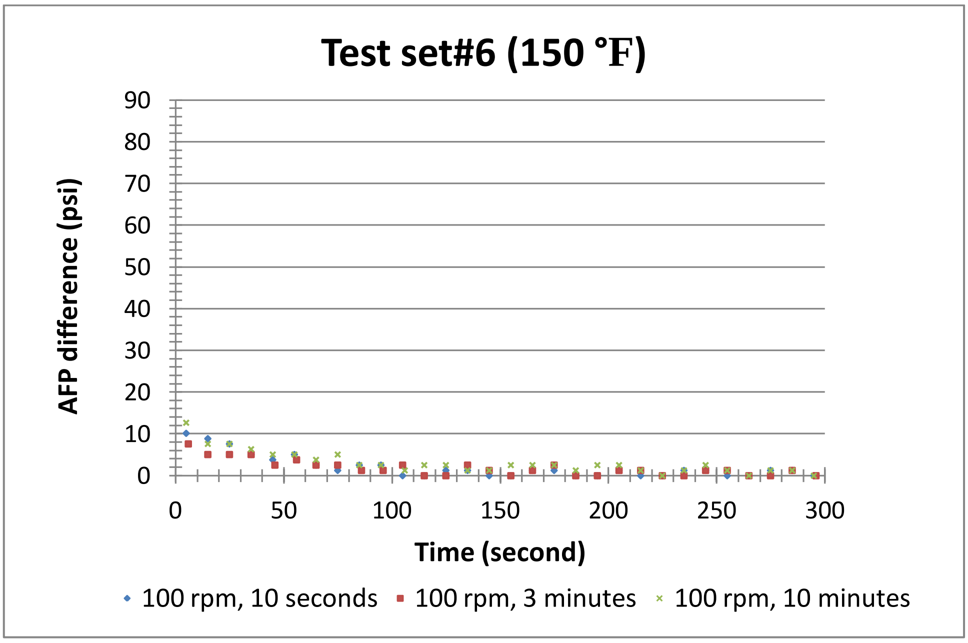

Figure 5.24 Thixotropic behavior assessment on test set#6 (shear rate of 100 rpm).

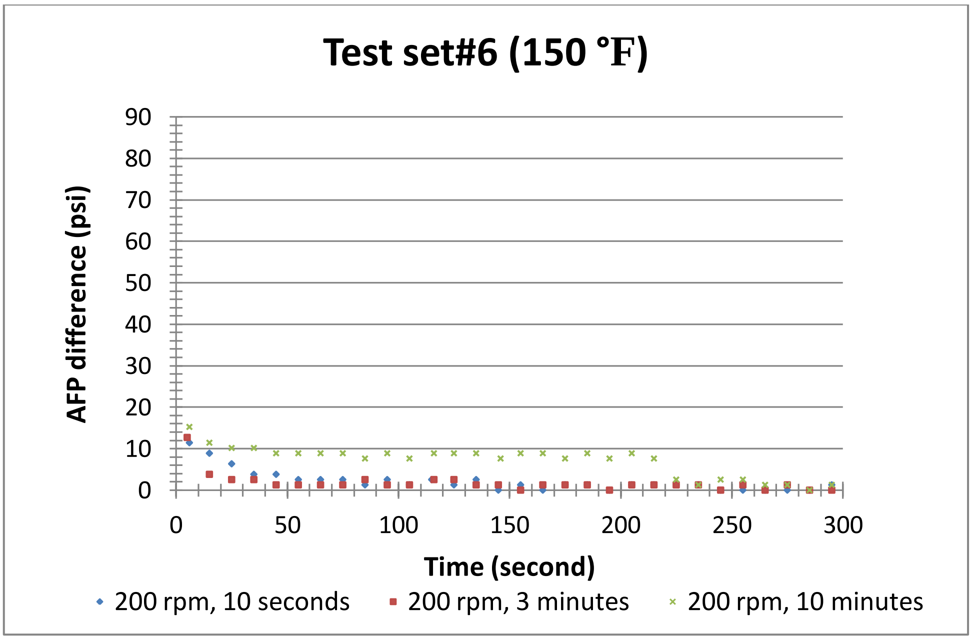

Figure 5.25 Thixotropic behavior assessment on test set#6 (shear rate of 200 rpm).

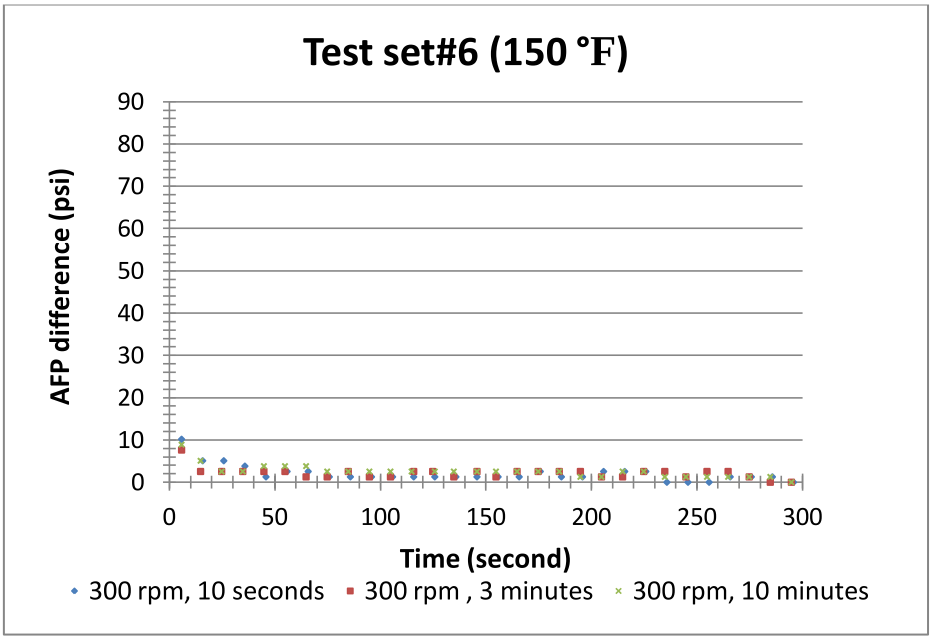

Figure 5.26 Thixotropic behavior assessment on test set#6 (shear rate of 300 rpm).

5.3 Mathematical model for thixotropic behavior prediction

Results on thixotropic behavior show trend of AFP difference that sharply decreases at the beginning and then gradually decreases. This kind of behavior that the rate of decrease is not constant that could be exponential, logarithm or power decline. **Figure 5.27** and **5.28** are examples of using 3 types of curve to fit the data. It can be seen that logarithmic model shows the best fit among three mathematical models as exhibited in highest R^2 value. Note that result at shear rate of 30 rpm is excluded from this section because trend does not conform to the others.

From observation, cases that AFP difference reach zero very fast (within 50 seconds) typically have lower R^2. Shear rate of 300 rpm in test set#1 is an example for this. Fitting with logarithmic model on thixotropic behavior assessment over 5 minutes duration is shown in **figure 5.29**. Logarithmic model can fit well with the result of higher R^2 if only the period that decreases in AFP difference is still significant as shown in **figure 5.30**, i.e. logarithmic model is fitted with data from 3 minutes period. Moreover, 3 minutes duration is long enough to cover period that the decrease in AFP is still significant. Therefore, results from all test sets are fitted well with logarithmic model over 3 minutes intervals and the values of R^2 are summarized in **table 5.2**. Most of all cases have R^2 higher than 0.8. However, some cases at shear rate of 300 rpm have lower R^2 which ranges from 0.5 to 0.7 but the average R^2 at shear rate of 300 rpm is still near 0.8.

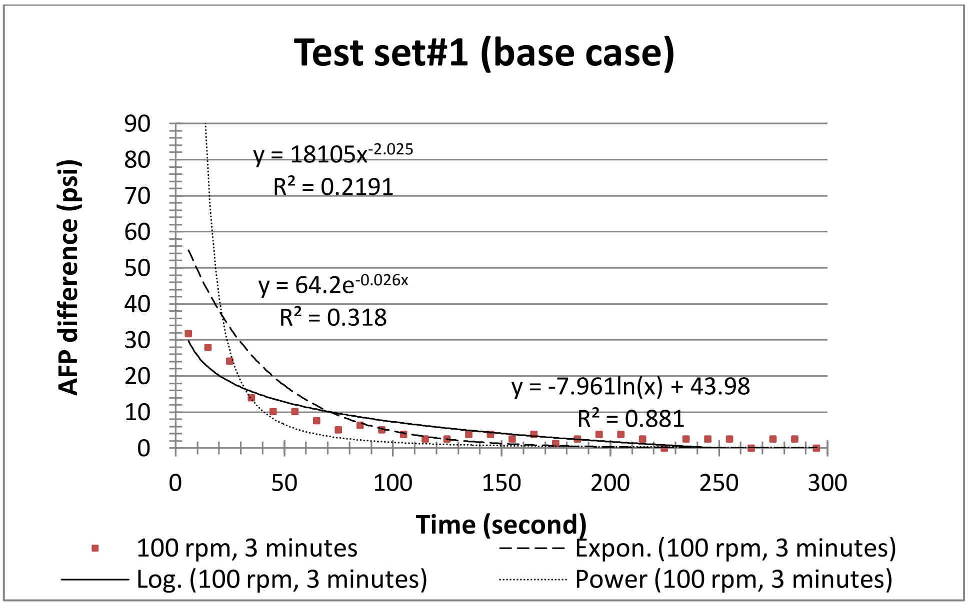

Figure 5.27 Fitting of three models on thixotropic behavior (test set#1, 100 rpm).

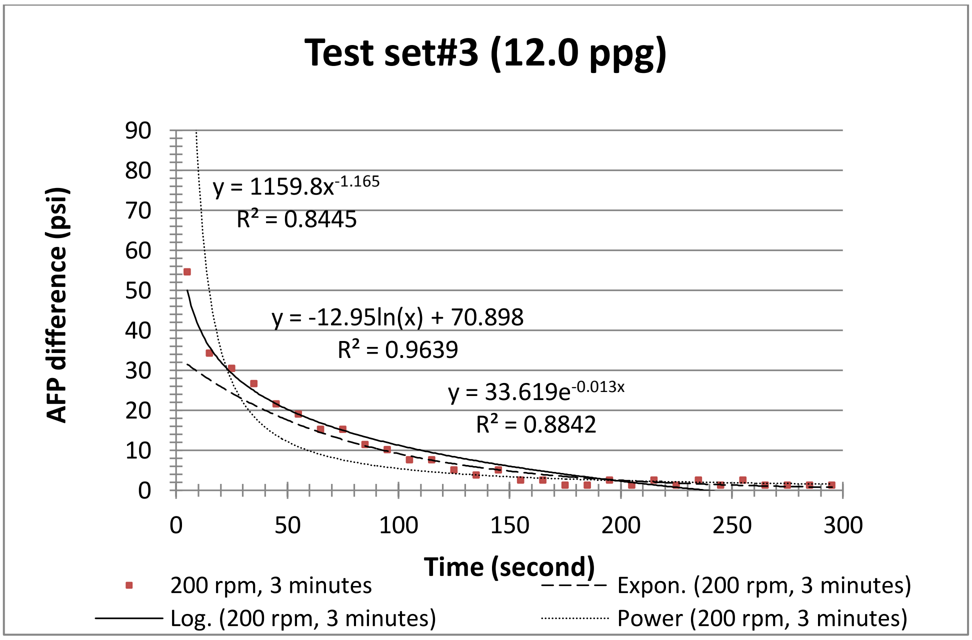

Figure 5.28 Fitting of three models on thixotropic behavior (test set#3, 200 rpm).

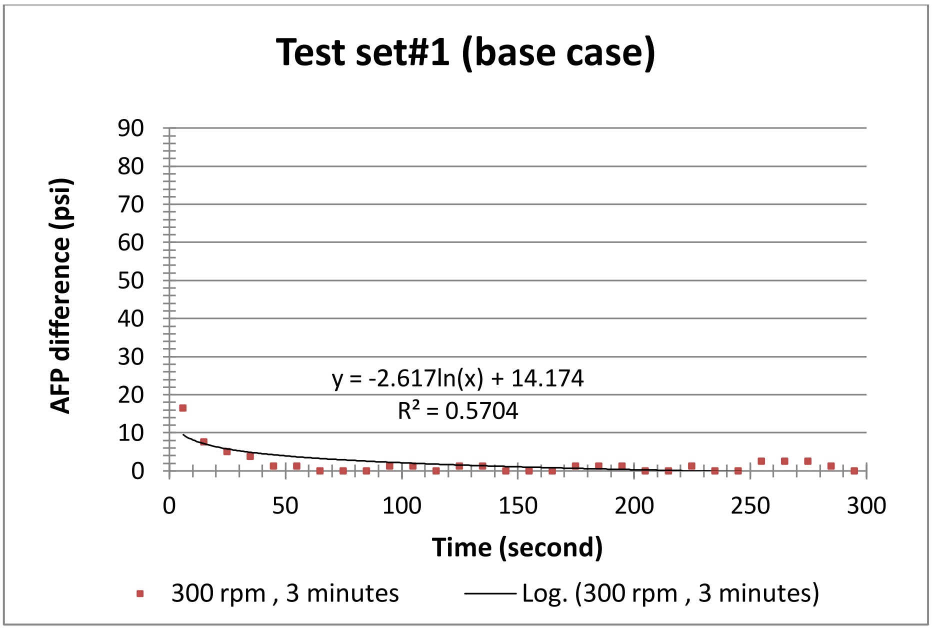

Figure 5.29 Fitting of logarithmic model on thixotropic behavior assessment over 5 minutes period (test set#1, shear rate of 300 rpm).

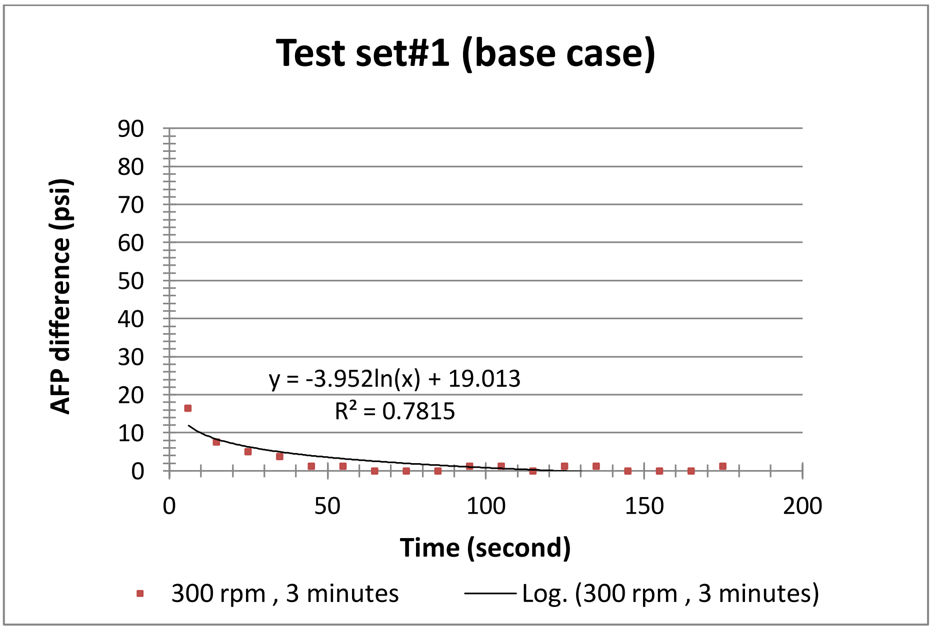

Figure 5.30 Fitting of logarithmic model on thixotropic behavior assessment over 3 minutes period (test set#1, shear rate of 300 rpm).

Table 5.2 R^2 of logarithmic model on thixotropic behavior assessment (over 3 minutes interval)

	gelling time	Shear rate		
Test set #1		100 rpm	200 rpm	300 rpm
	10 seconds	0.9657	0.8613	0.6881
	3 minutes	0.9339	0.9013	0.7815
	10 minutes	0.9441	0.8524	0.7985
	gelling time	Shear rate		
Test set #3		100 rpm	200 rpm	300 rpm
	10 seconds	0.8863	0.9887	0.9386
	3 minutes	0.8808	0.9930	0.9564
	10 minutes	0.9079	0.9943	0.9409
	gelling time	Shear rate		
Test set #4		100 rpm	200 rpm	300 rpm
	10 seconds	0.9813	0.9322	0.7735
	3 minutes	0.9933	0.9268	0.8239
	10 minutes	0.9843	0.9458	0.8574
	gelling time	Shear rate		
Test set #5		100 rpm	200 rpm	300 rpm
	10 seconds	0.9367	0.9348	0.7760
	3 minutes	0.9297	0.9245	0.7442
	10 minutes	0.9645	0.9451	0.8512
	gelling time	Shear rate		
Test set #6		100 rpm	200 rpm	300 rpm
	10 seconds	0.8960	0.9091	0.8029
	3 minutes	0.7846	0.6364	0.4662
	10 minutes	0.9194	0.7697	0.6673
	gelling time	Shear rate		
Average		100 rpm	200 rpm	300 rpm
	10 seconds	0.9332	0.9252	0.7958
	3 minutes	0.9045	0.8764	0.7544
	10 minutes	0.9440	0.9015	0.8231

5.4 Effect of gelling time and shear rate on thixotropic behavior

As the results shown in **figure 5.3** to **figure 5.26** (excluding result from shear rate of 30 rpm), AFP difference on each gelling time almost overlays each other except test set#4 which drilled solid is added. In test set#4, it is clear that increasing in gelling time results in higher AFP difference for shear rate of 100, 200 and 300 rpm.

As discussed before on the result of test set#4 that higher thixotropic behavior from increased gelling time could result from concentration of clays that is high enough to exhibits progressive gel. Therefore, it can be concluded that increasing gelling time does not affect thixotropic behavior except the case that drilled solid exists in the mud.

To see the effects of shear rate on thixotropic behavior, result from each shear rate is plotted in the same graph. Only results from gelling time of 3 minutes are plotted in each test set except test set#4 that gelling time has significant effect on thixotropic behavior. Effects of shear rate on thixotropic behavior are shown in **figure 5.31** to **figure 5.38**. In test set#1, increasing shear rate results in lower thixotropic behavior which this trend is repeated in test set#2. This trend is also observed in test set#4 for gelling time of 10 seconds and 3 minutes while AFP difference trend at shear rate of 100 rpm is almost the same to 200 rpm for gelling time of 10 minutes. In test set#3 and test set#5, increasing shear rate from 100 rpm to 200 rpm results in higher thixotropic behavior but increasing shear rate from 200 to 300 rpm results in lower thixotropic behavior. In test set#6, thixotropic behavior at shear rate of 100, 200 and 300 rpm are comparable. One observation that is common in all test set is the shear rate that result in highest thixotropic behavior is either 100 or 200 rpm.

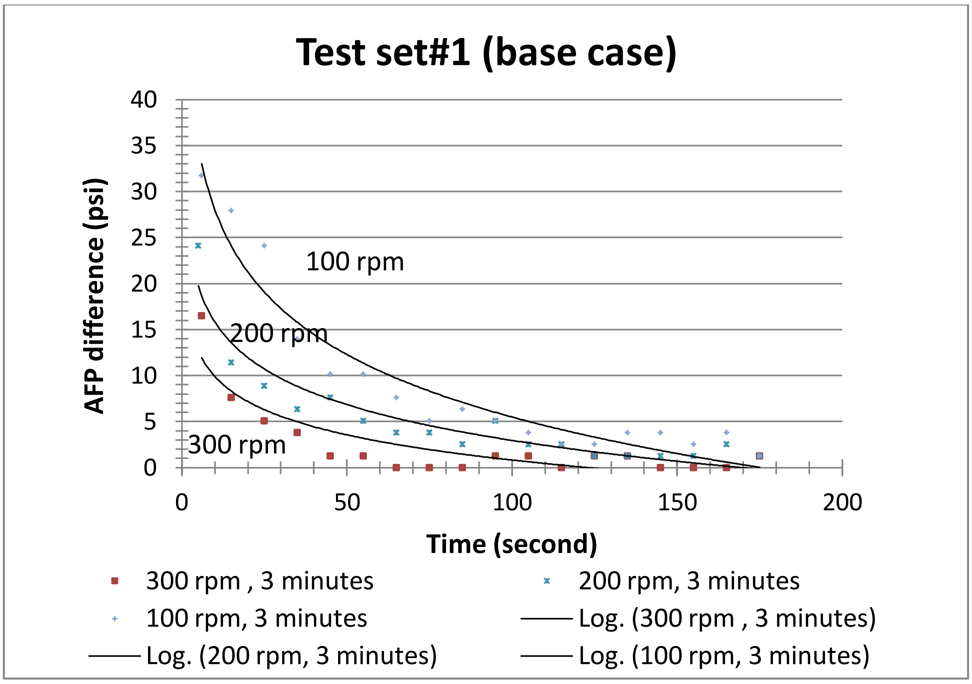

Figure 5.31 Effect of shear rate on thixotropic behavior (test set#1).

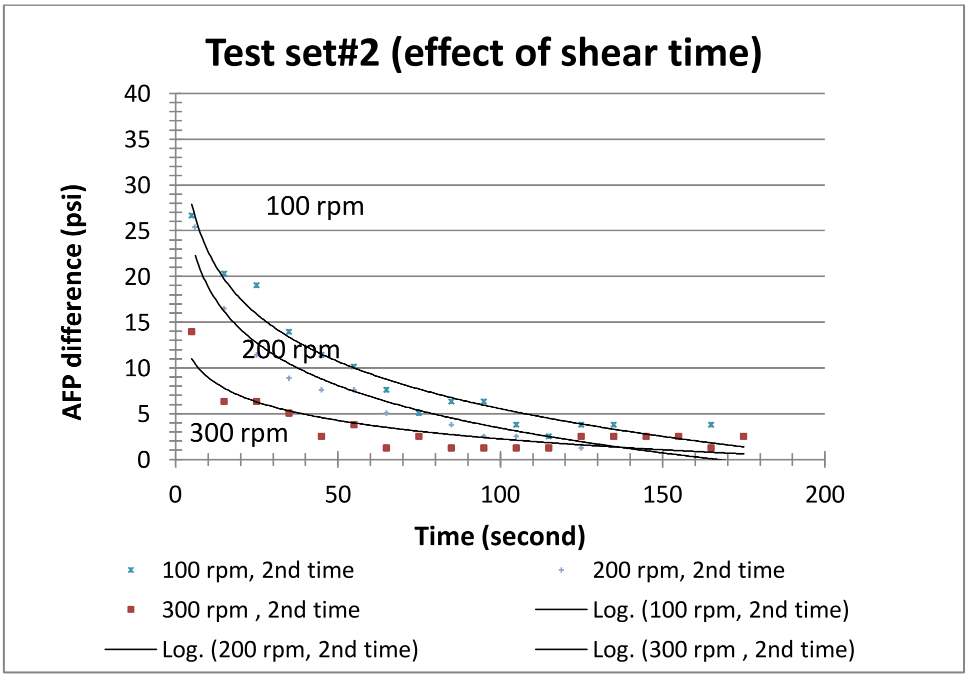

Figure 5.32 Effect of shear rate on thixotropic behavior (test set#2).

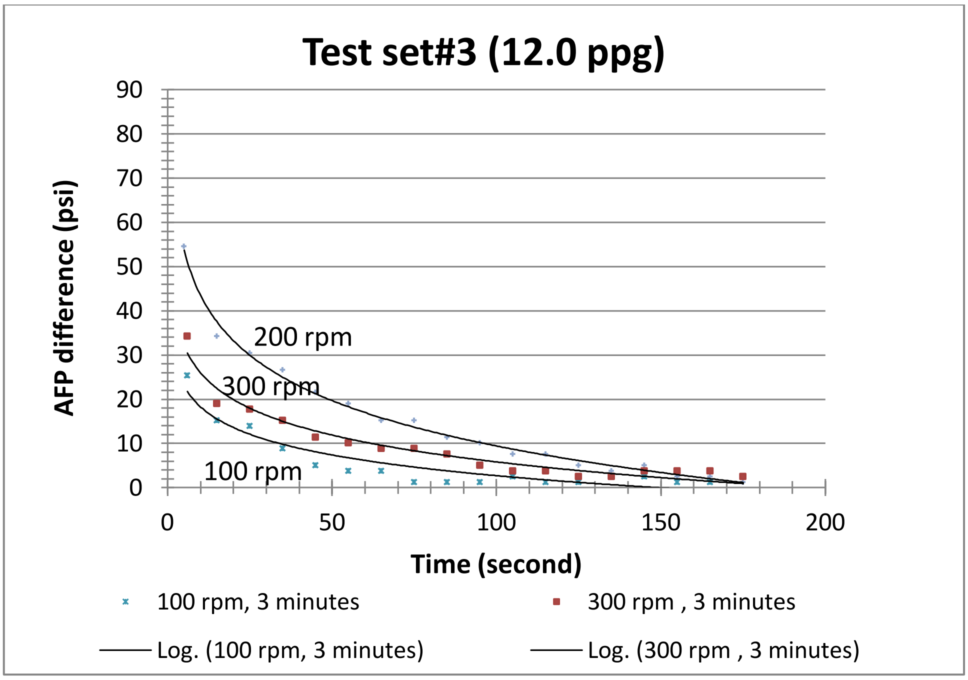

Figure 5.33 Effect of shear rate on thixotropic behavior (test set#3).

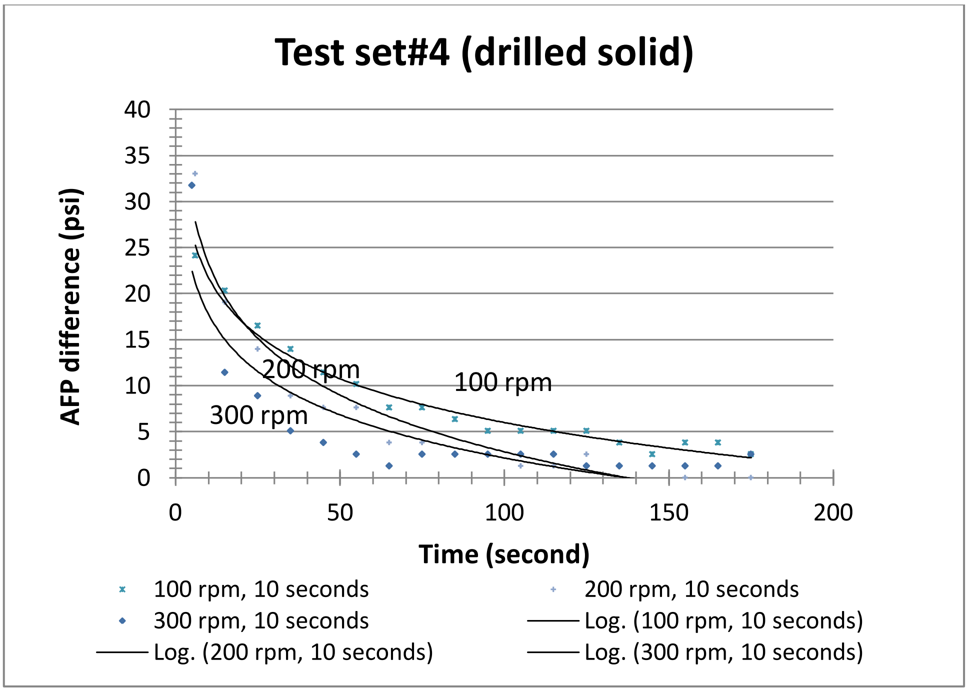

Figure 5.34 Effect of shear rate on thixotropic behavior (test set#4, 10 seconds gelling time).

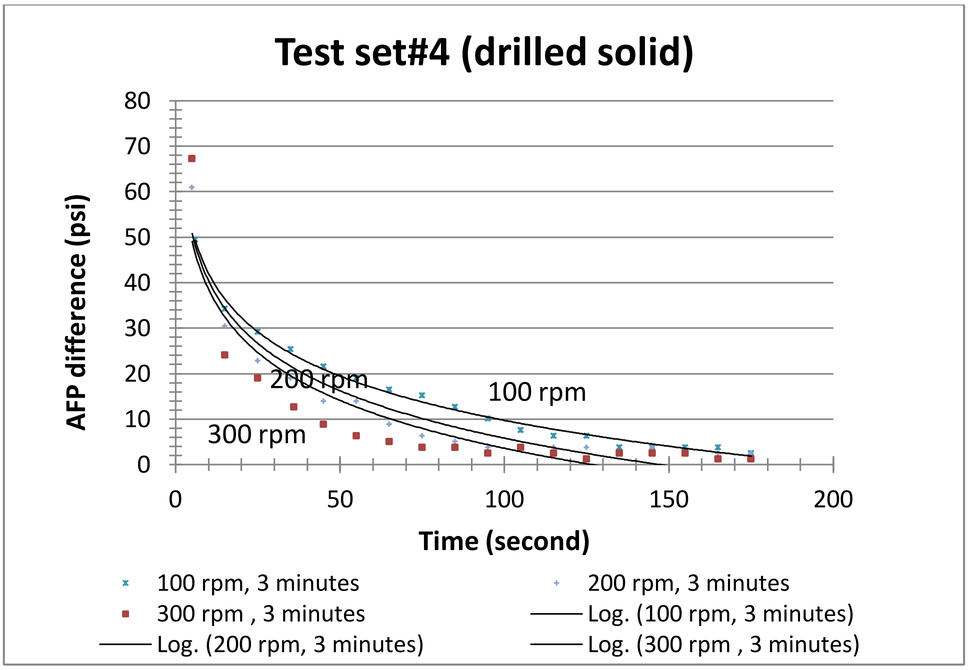

Figure 5.35 Effect of shear rate on thixotropic behavior (test set#4, 3 minutes gelling time).

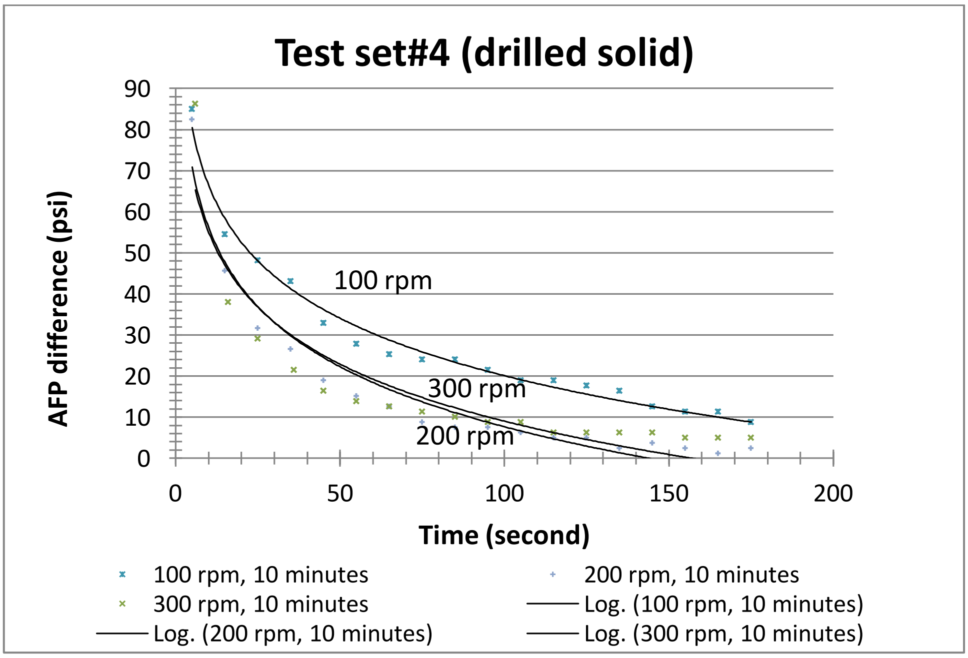

Figure 5.36 Effect of shear rate on thixotropic behavior (test set#4, 10 minutes gelling time).

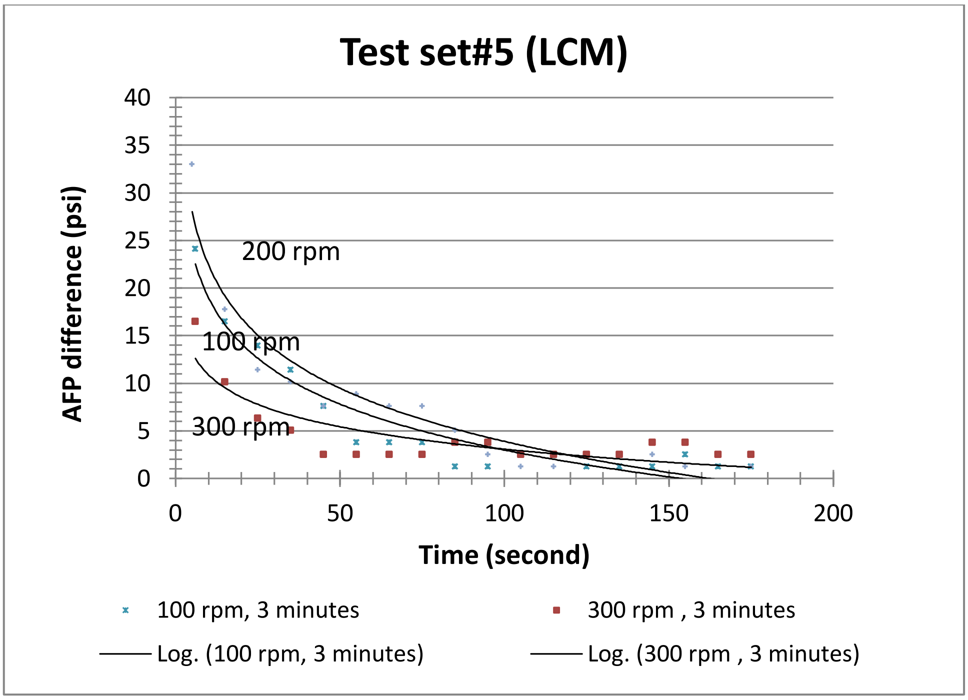

Figure 5.37 Effect of shear rate on thixotropic behavior (test set#5).

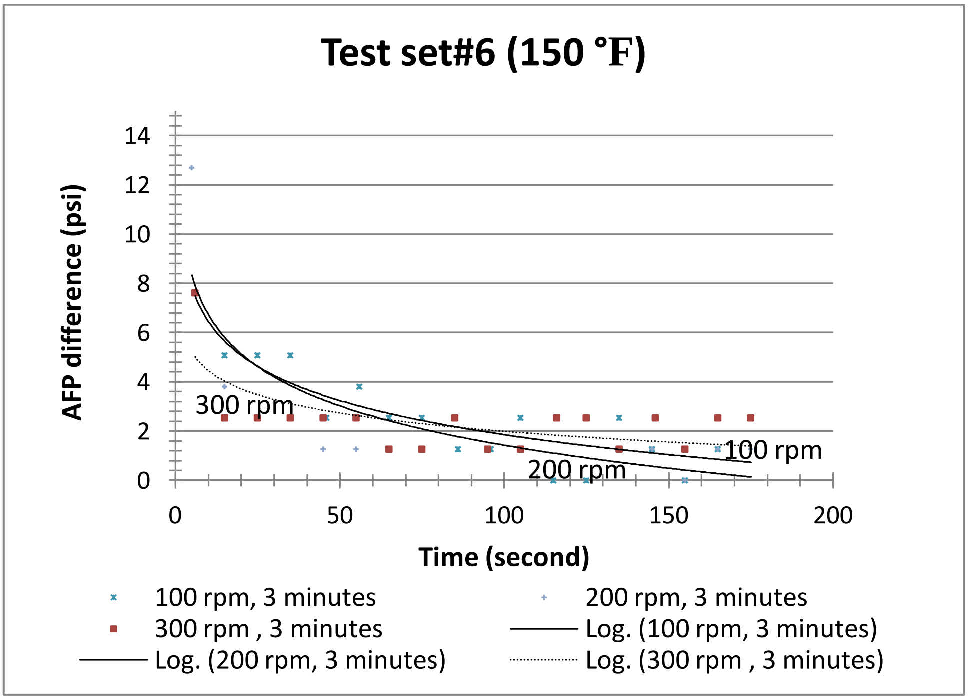

Figure 5.38 Effect of shear rate on thixotropic behavior (test set#6).

5.5 Suitability of PHPA mud system for MPD purpose

In MPD, BHP composes of 3 components which are hydrostatic pressure from drilling fluid column, AFP and ABP (applied back pressure at the surface) as shown in **equation 2.7**. During static condition, there are only applied back pressure and hydrostatic pressure, which drilling fluid density is designed to be less than formation pressure. During dynamic condition, AFP exists. So, ABP will be reduced in the same magnitude to AFP and results in constant BHP during dynamic and static condition, i.e. BHP equals to formation pressure. Note that duration for bringing flow rate from zero to full flow rate is very short (i.e. in a few seconds) and can be assumed to be instantaneous. However, this AFP is calculated based on shear stress in condition that thixotropic behavior is already fades away. Therefore, during early time after resume circulation, thixotropic behavior will results in higher BHP which can cause fracture in the formation if BHP exceeds fracture pressure.

$$BHP = \Delta P_{Hyd} + AFP + ABP \qquad (2.7)$$

Arnone and Viera[22] discussed about the cases that have narrow operating pressure window which in specific and non rare cases are un-drillable but can be drilled only if MPD is employed. Arnone and Viera[22] also mentioned that some real well cases that operating pressure window is not greater than 50 to 100 psi need MPD to be employed. In this study, 75 psi which is the middle between 50 and 100 psi is selected as the criteria pressure window.

Typical flow rate used in the section of 6.125 in. hole with 3.5 in. drillpipe is around 250 gpm, which is near the shear rate of 200 rpm (for flow index of 0.35 to 0.5 which is the range of flow index from test set#1 to test set#6). Time for making a connection is assumed to be 3 minutes. Therefore, if flow rate that results in shear rate of 200 rpm is used, data on AFP difference at shear rate of 200 rpm with gelling time of 3 minutes can be used to represent the magnitude of BHP that exceeding formation pressure. However, these AFP differences must be added by tolerance on maintain ABP which is 25 psi (20 percents of assumed ABP which is 125 psi) to be more representative for possible magnitude BHP that exceeding formation pressure.

Test set#3 (12.0 ppg) and test set#4 (drilled solid) are two test sets that has high thixotropic behavior at 200 rpm, 3 minutes gelling time. Figure 5.39 is AFP difference plus ABP tolerance vs time plot of test set#3 and test set#4. It shows that AFP difference plus ABP tolerance falls below 75 psi (criteria pressure window in this study) within 10 seconds which is not long enough to cause fracture propagation. Therefore, it can be concluded that PHPA mud is suitable for MPD.

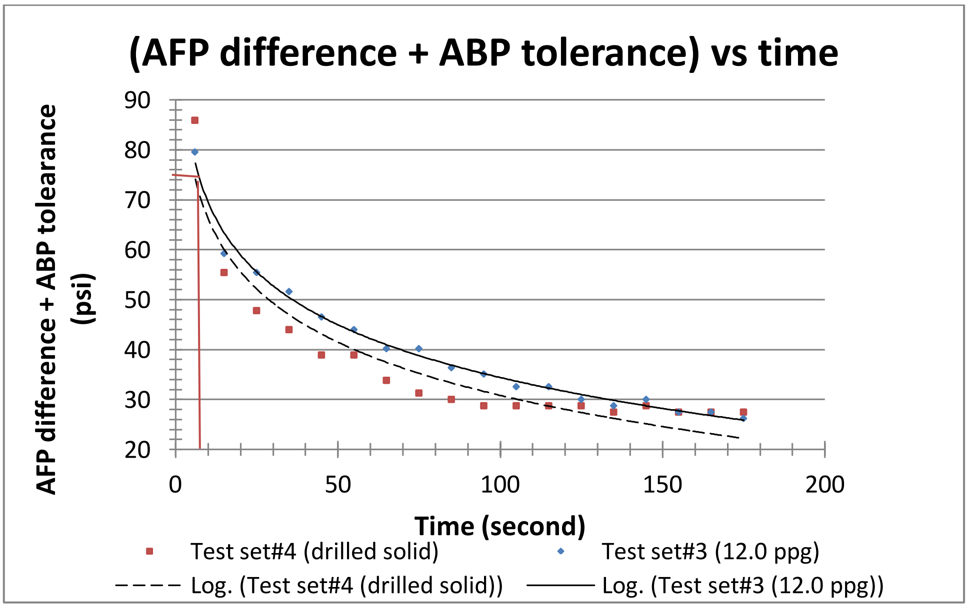

Figure 5.39 AFP difference plus ABP tolerance vs time (200 rpm, 3 minutes gelling time)

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

This chapter concludes thixotropic behavior of PHPA mud system and the mathematical model to predict the behavior. Effect of gelling time and shear rate on thixotropic behavior are also concluded. Suitability of PHPA mud system is also concluded. After that, some recommendations of possible future study are stated.

6.1 Conclusions

Based on results from this study, it can be concluded as follows:

1. PHPA mud system exhibits thixotropic behavior which trend in AFP difference is logarithmic decline for shear rate of 100, 200 and 300 rpm.
2. Gelling time dose not affect thixotropic behavior except the case that drilled solid exists in the mud that increasing in gelling time results in higher thixotropic behavior.
3. Increasing shear rate does not always result in higher thixotropic behavior and shear rate that results in highest thixotropic behavior is either 100 or 200 rpm.
4. Adding drilled solids results in higher thixotropic behavior for shear rate of 100, 200 and 300 rpm except the case of gelling time of 10 seconds at 100 rpm.
5. Increasing temperature from 120 °F to 150 °F results in lower initial AFP difference for shear rate of 100, 200 and 300 rpm.
6. PHPA mud system has potential to be suitability for MPD based on low AFP difference from thixotropic behavior.

6.2 Recommendations

The following points are recommended for future study:

1. Variation on each composition in the formulation should be made because this can lead to the most appropriate formulation that has satisfied rheology and low thixotropic behavior.
2. Thixotropic behavior when the mud is subjected to step-wise increasing shear rate should be assessed since this study can tell that how much thixotropic effect can be reduced if step-wise increasing flow rate is applied.
3. Thixotropic behavior on oil based mud and synthetic based mud should be investigated since oil based mud and synthetic based are widespread used nowadays.

References

[1] International Association of Drilling. UBO and MPD Glossary [Online] 2008. Available from : http://www.iadc.org/committees/ubo_mpd/Documents/UBO%20&%20MPD%20Glossary%20Jan08.pdf [4 September 2012]

[2] Hannegan, D.M., Managed Pressure Drilling in Marine Environments – Case Studies. Paper SPE 92600 presented at the SPE/IADC Drilling Conference held in Amsterdam, Netherlands, 23–25 February 2005.

[3] Nauduri, S., Managed Pressure Drilling Candidate Selection. Ph.D.'s Dissertation, Texas A&M University, TX, 2009.

[4] Bjørkevoll, K.S., Rommetveit, R., Aas, B., Gjeraldstveit, H., and Merio, A., Transient Gel Breaking Model for Critical Wells Applications with Field Data Verification. Paper SPE/IADC 79843 presented at the SPE/IADC Drilling Conference held in Amsterdam, Netherlands, 19–21 February 2003.

[5] Bourgoyne Jr., A.T., Milheim, K.K., Chenevert, M.E., and Young Jr., F.S., Applied Drilling Engineering. Society of Petroleum Engineering, Richardson, TX, 1984.

[6] Zamora, M., and Roy, S., The Top 10 Reasons to Rethink Hydraulics and Rheology. Paper IADC/SPE 62731 presented at the 2000 IADC/SPE Asia Pacific Drilling Technology held in Kuala Lumpur, Malaysia, 11–13 September 2000.

[7] M-I L.L.C., Drilling Fluids Engineering Manual, revision No: A-0. M-I L.L.C., Houston, TX, 2001.

[8] Ghofrani, R., Bosch, V., and Strahl, F.G., New Method of Measuring Gel Strength of Clay-Based Drilling Fluids and the Determination of Their Long-Term Gellation Behavior. Journal of Canadian Petroleum Technology, May 2000: 41 – 48.

[9] Kadaster, A.G., Gulld, G.J., Hanni, G.L., and Schmidt, D.D., Field Applications of PHPA Muds. Paper SPE 19531 presented at the 1989 Annual Technical Conference and Exhibition held in San Antonio, USA, 8-11 October 1989.

[10] American Petroleum Institute, API Recommended practice 13D. American Petroleum Institute, Washington, D.C., 2009.

[11] American Petroleum Institute, API Recommended practice 13B-1, second edition. American Petroleum Institute, Washington, D.C., 2000.

[12] Clark, R.K., Scheuerman, R.F., Rath, H., and Van Laar, H.G., Polyacrylamide-Potassium Chloride Mud for Drilling Water Sensitive Shales. Journal of Petroleum Technology, June 1976: 719 - 727.

[13] Chesser, B.G., Design Considerations for an Inhibitive, Stable Water-Based Mud System. Paper SPE 14757 presented at the 1988 SPE IADC/SPE Drilling Conference held in Dallas, USA, 10-12 February 1988.

[14] Bekkour, K., Leyama, M., Benchabane, A., and Scrivener, O., Time-dependent rheological behavior of bentonite suspensions: An experimental study. Journal of Rheology 49(6), November/December 2005: 1329-1345.

[15] Kelessidis, V.C., Investigations on the Thixotropy of Bentonite Suspensions. Energy Sources 30, 2008: Part A, 1729-1746.

[16] Dolz, M., Jiminez, J., Hernandez, M.J., Delegido, J., and Casanovas, A., Flow and thixotropy of non-contaminating oil drilling fluids formulated with bentonite and sodium carboxymethyl cellulose. Journal of Petroleum Science and Engineering 57, 2007: 294-302.

[17] American Petroleum Institute, API Recommended practice 13B-2, third edition. American Petroleum Institute, Washington, D.C., 1998.

[18] Dickey, P.A., and Shriram, C.R., Abnormal Pressures in Deep Wells of Southwestern Louisiana. Society of Petroleum Engineering, Richardson, TX, 1968.

[19] Oakley, D. and Conn, M., Drilling Fluid Design Enlarge Hydraulic Operating Windows of Managed Pressure Drilling Operation. Paper SPE/IADC 139623 presented at the SPE/IADC Drilling Conference and Exhibition held in Amsterdam, Netherland, 1-3 March 2011.

[20] American Petroleum Institute, API Recommended practice 13I, eighth edition. American Petroleum Institute, Washington, D.C., 2009.

[21] Amani, M., and Al-Jubouri, M., An Experimental Investigation of the Effects of Ultra-High Pressure and Temperature on the Rheological properties of Water-Based Drilling Fluids. Paper SPE 157219 presented at the

APE/APPEA International Conference on Health, Safety and Environment in Oil and Gas Exploration and Production held in Perth, Australia, 11-13 September 2012.

[22] Arnone, M., and Vieira, P., Field Drilling Wells With Narrow Operating Windows Applying the MPD Constant Bottomhole Pressure Technology- How Much the Temperature and Pressure Affects the Operation's Design. Paper SPE/IADC 119882 presented at the SPE/IADC Drilling Conference and Exhibition held in Amsterdam, The Netherland, 17-19 March 2009.

Vitae

Eakarin Wachirapanyanukul was born on March 28th, 1987 in Bangkok, Thailand. He received his Bachelor Degree in Mechanical Engineering from the Faculty of Engineering, Chulalongkorn University in 2009. Then, he continued his study in Master Degree of Petroleum Engineering at graduate school of the Department of Mining and Petroleum Engineering, Chulalongkorn University since 2010.