EFFICIENCY ENHANCEMENT OF DRILLING MUD BY USING FLY ASH AS AN ADDITIVE

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

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ภรณ์ทิพย์ ก่อสินวัฒนา : การเพิ่มประสิทธิภาพน้ำโคลนขุดเจาะโดยการใช้เถ้าลอยเป็นสารเติมแต่ง (EFFICIENCY ENHANCEMENT OF DRILLING MUD BY USING FLY ASH AS AN ADDITIVE) อาจารย์ที่ปรึกษา : อาจารย์ ดร.บัณฑิตา ธีระกุลสถิตย์, 159 หน้า.

วัตถุประสงค์ของการศึกษาเพื่อวิเคราะห์คุณสมบัติทางกายภาพและทางเคมีของเถ้าลอยและน้ำโคลนขุดเจาะผสมเถ้าลอย ซึ่งทำการเติมเถ้าลอยที่ความเข้มข้นร้อยละ 1, 3 และ 5 โดยมวล ที่อุณหภูมิ 30, 60 และ 90 องศาเซลเซียส จากนั้นนำน้ำโคลนผสมเถ้าลอยที่ความเข้มข้นร้อยละ 3 ผสมกับสารเติมแต่งชนิดอื่น ประกอบด้วย โดโลไมต์ เถ้าแกลบ ปูนขาว และแป้ง ที่ความเข้มข้นร้อยละ 1, 3 และ 5 โดยมวล ที่อุณหภูมิ 30 และ 60 องศาเซลเซียส โดยใช้วิธีการศึกษาผลกระทบของอุณหภูมิและอัตราส่วนผสมต่อคุณสมบัติด้านวิทยากระแสของน้ำโคลนขุดเจาะตามแบบจำลองบิงแฮมและเพาเวอร์ลอว์ การทดสอบคุณสมบัติทางกายภาพประกอบด้วยการซึมผ่าน ความหนาแน่น ความเป็นกรด-ด่าง ความต้านทานไฟฟ้า ปริมาณของแข็ง และปริมาณทรายของน้ำโคลนขุดเจาะที่ผสมสารเติมแต่ง โดยทำการทดสอบตามขั้นตอนมาตรฐาน API RP 13B-1 จากการทดลองพบว่าที่ความเข้มข้นร้อยละ 3 โดยมวลของเถ้าลอย ที่อุณหภูมิ 30 องซาเซลเซียสเหมาะสมใช้เป็นน้ำโคลนพื้นฐานตัวใหม่ ส่วนธาตุและแร่องค์ประกอบของน้ำโคลนขุดเจาะผสมเถ้าลอยและสารเติมแต่งอื่นๆไม่เปลี่ยนแปลงตามอุณหภูมิ โดยค่าร้อยละของธาตุและแร่องค์ประกอบเปลี่ยนแปลงตามสัดส่วนของสารเคมีดังนี้ แร่แบไรต์ 31.65 ถึง 43.37 แร่มอนต์มอริลโลไนต์ 18.66 ถึง 30.60 แร่เคโอลิไนต์ 7.47 ถึง 22.07 แร่ควอตซ์ 5.88 ถึง 15.70 แร่แคลไซต์ 1.87 ถึง 23.29 แร่ฮีมาไทต์ 2.04 ถึง 4.83 แร่ยิปซัม 0.42 ถึง 2.33 แร่โดโลไมต์ 0.03 ถึง 0.53 แร่อะนอร์ไทต์ 0.02 ถึง 6.18 และแร่แอนไฮไดรต์ 0.06 ถึง 1.19 ผลการทดสอบพบว่าน้ำโคลนขุดเจาะผสมเถ้าลอยและแป้งที่ใช้เป็นสารเติมแต่งที่ความเข้มข้นร้อยละ 3 ที่อุณหภูมิ 60 องซาเซลเซียส มีค่าเหมาะสมสำหรับใช้เป็นน้ำโคลนขุดเจาะผลของความหนืดเท่ากับ 58 เซนติพอยส์ ความหนาแน่นเท่ากับ 1.09 กรัมต่อลูกบาก์ศเซนติเมตร ความเป็นกรด-ด่างเท่ากับ 10.69 ค่าการซึมผ่านเท่ากับ 8.50 มิลลิลิตร และค่าความต้านทานไฟฟ้าเท่ากับ 2.73 โอห์ม-เมตร ดังนั้นเถ้าลอยจึงสามารถใช้เพื่อปรับปรุงคุณสมบัติด้านวิทยากระแสและความเป็นกรด-ด่างของน้ำโคลนขุดเจาะได้ และการเปรียบเทียบราคาของเถ้าลอยกับสารเติมแต่งตัวอื่น ๆ พบว่าน้ำโคลนจะต้องใช้รวมกับสารเติมแต่งที่สามารถควบคุมการซึมผ่านได้ ด้วยเหตุนี้ทำให้น้ำโคลนขุดเจาะผสมเถ้าลอยมีต้นทุนการผลิตสูงขึ้น

สาขาวิชา เทคโนโลยีธรณี ลายมือชื่อนักศึกษา ____________________

ปีการศึกษา 2557 ลายมือชื่ออาจารย์ที่ปรึกษา ________________

PORNTHIP KORSINWATTANA : EFFICIENCY ENHANCEMENT OF DRILLING MUD BY USING FLY ASH AS AN ADDITIVE. THESIS ADVISOR : BANTITA TERAKULSATIT, Ph.D., 159 PP.

DRILLING MUD/ FLY ASH/ ADDITIVE/ RHEOLOGY/ FILTRATION

The objective of this study is to investigate the physical and chemical properties of fly ash and drilling mud mixed with fly ash by adding 1, 3 and 5 percentages by weight at 30, 60 and 90^{o}C. The 3 percentages of fly ash containing drilling mud mixed with other additives contain dolomite, rice husk ash, lime and starch at 1, 3 and 5 percentages by weight at 30 and 60^{o}C. The methodology is to use the effect of temperature and mixing ratio on rheological properties of drilling mud on Bingham and Power Law model. The physical properties analysis includes the filtration, density, pH, resistivity, solid content and sand content. The test procedures follow the API RP 13B-1. The result of the 3 percentages by weight of fly ash at 30^{o}C is used as a new-base drilling mud. The elements and minerals composition of drilling mud mixed with fly ash and other additives also do not change along with temperature. However, the percentages of elements and minerals composition have changed by the mixing ratio of the chemicals including the barite 31.65 to 43.34, montmorillonite 18.66 to 30.60, kaolinite 7.47 to 22.07, quartz 5.88 to 15.70, calcite 1.87 to 23.29, hematite 2.04 to 4.83, gypsum 0.42 to 2.33, dolomite 0.03 to 0.53, anorthite 0.02 to 6.18 and anhydrite 0.06 to 1.19. The test results demonstrate that drilling mud mixed with 3 percentages of fly ash and starch as an additive at 60^{o}C that is the appropriate drilling mud. The results of viscosity are 58 cP, density is 1.09 g/cm^3, pH is 10.69, filtration is 8.50 ml and resistivity is 2.73 Ω.m. Therefore, the fly ash can be used to improve the rheological properties and pH of drilling mud. The cost is compared between fly ash and other additives that drilling mud must be combined with other additives that can be controlled filtration. Hence, drilling mud mixed with fly ash has higher production cost.

School of Geotechnology Student's Signature __________________

Academic Year 2014 Advisor's Signature__________________

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SYMBOLS AND ABBREVIATIONS

τ	=	shear stress
τ_0	=	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
ϕ_i	=	viscometer dial reading
ϕ_{300}	=	viscometer dial reading at 300 rpm
ϕ_{600}	=	viscometer dial reading at 00 rpm
N	=	range extension factor of the torque spring of the VG meter
rpm	=	rotational speed
Gel_{in}	=	initial gel strength
Gel_{10}	=	10 minutes gel strength
kg	=	kilogram
gm	=	gram
ml	=	milliliter
%w/w	=	percentage of weight by weight
Temp.	=	temperature

CHAPTER I

INTRODUCTION

1.1 Background of problems and significance of the study

Drilling mud is important to petroleum production due to its use to (1) clean the rock fragment from beneath the bit and carry them to the surface, (2) exert sufficient hydrostatic pressure against subsurface formations to prevent formation fluids from flowing 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 drill string and bit. The drilling mud composition is to a mainly bentonite and barite with the water or oil bases, and other additives such as cement, lime, starch, graphite, lignite, and carboxymethyl cellulose (CMC) etc. These additives are a costly and could be imported from aboard. Fly ash is one of the additives to improve the efficiency of drilling mud, which could replace expensive additives. Because of the fly ash is an industrial by-product from the combustion of coal in the power plants. The growing problem of fly ash waste, there is a large number and the toxic of chemicals such as lead, arsenic, mercury and radioactive uranium, which cause the environmental problems. In a present, the main beneficial use of fly ash includes serving as a raw material in concrete, grout and cement or as a fill material in stabilization projects and roadbeds. Because of the coal fly ash is the light weight particle captured in the exhaust gas by electrostatic precipitators and bag houses of coal power plants. Size of fly ash is very fine with cement like properties and has long been used as an additive.

in cement. These properties of fly ash, it could be used as an additive in the drilling mud mixing for an efficiency improvement, whereas can be used to replace some expensive additives. In addition, the using of fly ash in drilling mud also avert an increasing toxic threat to the environment or the disposal wastes by making them more affordable (Larry, 2006).

1.2 Research objectives

The main aim of this research is to enhance the efficiency of drilling mud. Some more objectives are (1) study the physical and chemical properties of fly ash, (2) study the physical and chemical properties of water-based drilling mud mixed with fly ash, (3) study the effect of temperature and mixing ratio on rheological properties of drilling mud, and (4) comparison the cost of fly ash and other additives.

1.3 Scope and limitation of the study

This research purpose is to study the chemical and physical properties of water-based drilling mud mixed with fly ash while the fly ash concentration and temperature were changed. It was collected from Mae Moh Power Plant, Lampang, Thailand. The physical properties and rheological tests are operated in the laboratory of Suranaree University of Technology. The chemical properties of additives are analyzed both before and after mixed with mud for determine mineral crystals and components in samples by using X-ray diffractrometer (XRD) and X-ray fluorescence spectrometer (XRF). The physical properties test is followed API (1997) including density, viscosity, API filtration, pH, sand content, resistivity and solid content of drilling mud. The drilling mud mixed with additives are determined by mud balance, direct-indicated Viscometers, Baroid standard filter press, analytical pH meter, Baroid sand content set, Baroid resistivity meter, and Baroid oil - water retort kit, respectively which those properties affect to structure and properties of drilling mud should follow (API, 1997). Economists wealthiest of fly ash will compare with other additives after mixed with drilling mud by an appropriate ratio, which follow Department of Primary Industries and Mines (DPIM, 2014).

1.4 Research methodology

The research methodology comprised five steps as shown in Figure 1.1, including literature review, sample collection and preparation, laboratory tests (physical and chemical property's testing), gathering the result of discussions, conclusions, and thesis writing. Each step is described as follows:

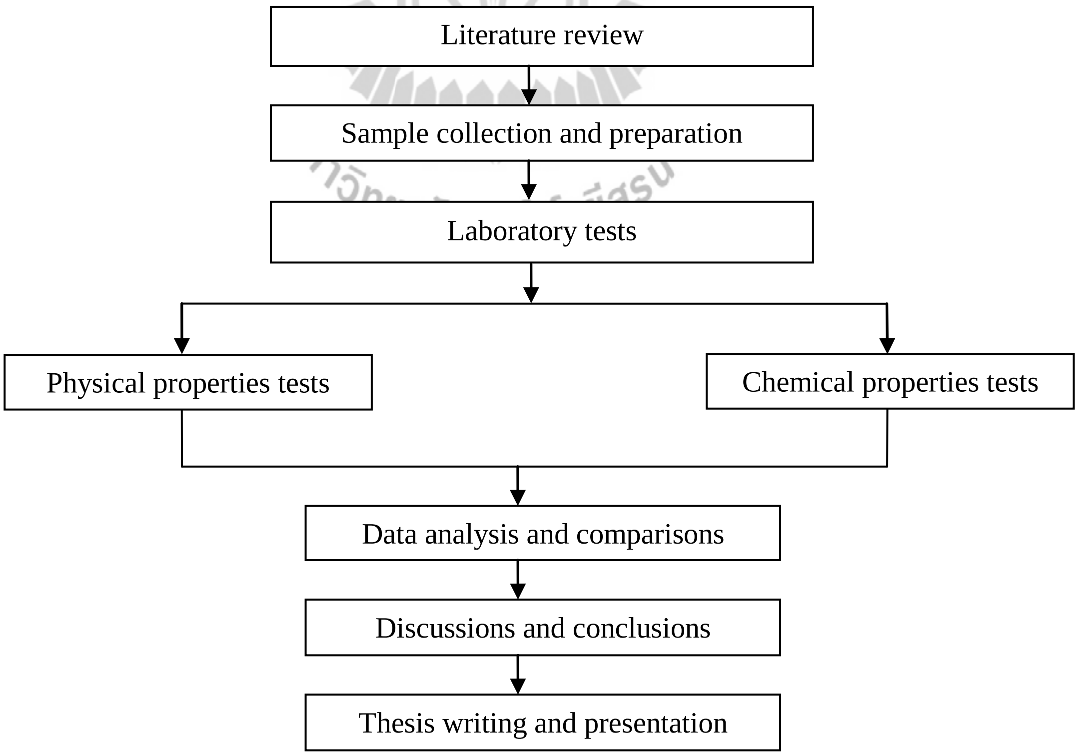

Figure 1.1 Research plan.

1.4.1 Literature review

A literature review was carried out to improve understanding drilling mud properties. It is composed of reviewing and studying water-based drilling mud and applications, using of other additives such as dolomite, lime, starch and rice husk ash in drilling mud, fly ash properties and testing procedure. The sources of information were from journals, researches, dissertation and books concerned.

1.4.2 Sample collection and preparation

The fly ash samples are from Mae Moh Power Plant of Lampang province. The sample was prepared and tested in the laboratory of Suranaree University of Technology. Fly ash was sieved a size less than 75 micrometers (mesh No.200) before stored in zip lock bags. This sample was divided into two parts for chemical property's tests and physical properties tests after mixed with drilling mud. A based bentonite-water suspension was prepared using 60 grams of bentonite per 1,000 grams of water and 100 grams of barite per 1,000 grams of water was added to control density. The drilling mud samples were weighted of 1.00 to 1.4 grams per cubic-centimeter. Various concentrations of fly ash were added to test as viscosities, fluid loss additive, etc.

1.4.3 Laboratory tests

The laboratory tests were divided into two groups; physical and chemical properties tests. The physical properties were determined in condition of temperature at 30, 60 and 90^{o}C, respectively. These samples were tested for each condition. The methods were followed the relevant API standard practice.

1.4.3.1 Physical properties tests

The objective of physical properties was to measure rheological characteristics of drilling mud with various shear rates. The test procedures were followed API standard practice (API RP 13B-1, 1997). The test was performed by rotary Viscometer (Fann VG) which had geometry that gave the following expression for a fit of the data to Bingham Plastic Model (API RP 13D, 2010).

1.4.3.2 Chemical properties tests

The objective of chemical properties was to measure the compositions and elements of the additives by using X-ray Diffractometer (XRD) and X-ray fluorescence spectrometer (XRF), respectively.

1.4.4 Data analysis and comparisons

The research results are analyzed to optimize the drilling mud mix ratio in terms of the physical and chemical properties. The results from the analysis are used in the comparison with other additives.

1.4.5 Discussions and conclusions

The laboratory results of measurements in terms of plastic viscosity, yield point, gel strength, filtrate volume, mud cake thickness and pH, are compared those results from water-based mud and water-based mud mixing additives. Similarity and discrepancy of results have been discussed. An influence of temperature that affected to drilling mud properties parameters were described and the feasibility of using water-base mud mixing additives in onshore and offshore well in Thailand was also considered.

1.4.6 Thesis writing

All research activities, methods, and results are documented and completed in the thesis. The research or findings will be published in the conference proceedings.

1.5 Thesis contents

Chapter I introduces the thesis by briefly describing the background of problem and the 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 water-based drilling mud characteristics and the factor that affects to mud properties. **Chapter III** describes the sample preparation and the experimental procedure for laboratory tests. **Chapter IV** presents the results obtained from the laboratory tests and comparison of the results between each mud formula. **Chapter V** discusses and concludes the research results and provides recommendations for future research studies.

CHAPTER II

LITERATURE REVIEW

2.1 Introduction

Relevant topics and previous research results were reviewed to improve understanding of water-based drilling mud and applications, using of additives in drilling mud, fly ash properties, and API stand practice. This chapter describes the drilling mud rheology that is showed to important roles for mud characteristic. The sources of information were from journals, researches, dissertation and books. The results of the review are summarized as follows.

2.2 Fly ash

Ahmaruzzaman (2010) studied that fly ash, generated during the combustion of coal for energy production, is an industrial by-product which is recognized as an environmental pollutant. The fly ash is generally grey in color, abrasive, mostly alkaline, and refractory in nature. There are very small size from 1-200 micrometers and also contain different essential elements, including both macronutrients P, K, Ca, Mg and micronutrients Zn, Fe, Cu, Mn, B, and Mo for plant growth. The fly ash from pulverized coal combustion is used for mixing in portland-pozzolan cement. This pozzolans are siliceous or siliceous and aluminous materials that together with water and calcium hydroxide form cementitious products at ambient temperatures are also admixtures. The geotechnical properties of fly ash (e.g., specific gravity, permeability, an internal angular friction, and consolidation characteristics) make it suitable for use in construction.

2.2.1 Type of fly ash

Ahmaruzzaman (2010) reported that the principal components of bituminous coal fly ash that is silica, alumina, iron oxide, and calcium, with varying amounts of carbon, as measured by the loss on ignition (LOI). Lignite and sub-bituminous coal fly ash is characterized by higher concentrations of calcium and magnesium oxide and reduced percentages of silica and iron oxide, as well as lower carbon content, compared with bituminous coal fly ash. Very little anthracite coal is burned in utility boilers, so there are only small amounts of anthracite coal fly ash.

2.2.2 Fly ash properties

Ahmaruzzaman (2010) studied the characterization of fly ash in terms of composition, mineralogy, surface chemistry and reactivity which is of fundamental importance in the development of various applications of fly ash.

Physical properties: fly ash consists of fine, powdery particles predominantly spherical in shape, either solid or hollow, and mostly glassy (amorphous) in nature. The carbonaceous material in the fly ash is composed of angular particles. The particle size distribution of most bituminous coal fly ash is generally similar to that of silt (less than a 75 µm. or No. 200 sieve). Although sub-bituminous coal fly ash is also silt-sized, it is generally slightly coarser than bituminous coal fly ash. The specific gravity of fly ash usually ranges from 2.1 to 3.0, while its specific surface area may vary from 170 to 1000 m^2/kg. The color of fly ash can vary from tan to gray to black, depending on the amount of unburned carbon in the ash.

Chemical properties: fly ash is influenced largely by the properties of the coal being burned and the techniques used for handling and storage. There are four types, or ranks, of coal, each type vary in heating value, chemical composition, ash content, and geological origin. Table 2.1 compares the normal range of the chemical constituents of bituminous coal fly ash with those of lignite coal fly ash and sub-bituminous fly ash.

Table 2.1 Normal range of chemical compositions for fly ash produced from different coal types.

Component (%wt.)	**Bituminous**	**Sub-bituminous**	**Lignite**
SiO_2	20-60	40-60	15-45
Al_2O_3	5-35	20-30	10-25
Fe_2O_3	10-40	4-10	4-15
CaO	1-12	5-30	15-40
MgO	0-5	1-6	3-10
SO_3	0-4	0-2	0-10
Na_2O	0-4	0-2	0-6
K_2O	0-3	0-4	0-4
LOI	0-15	0-3	0-5

2.3 Other additives

The purpose of additives is an improvement the drilling mud properties to assist the thickeners, lubricant, bacteria, corrosion inhibitors, viscosity control, clay stabilization, formation damage, shale stabilizer, fluid loss, scavengers and surfactants. Hence, the additives are used to study such as fly ash, dolomite, rice husk ash, lime and starch. Chemical properties of the additives indicate to control pH, increase viscosity and density, reduce fluid loss. The literature review of additives shows below;

Amanullah and Long Yu (2005) studied that the environment friendly fluid loss additives to protect the marine environment from the detrimental effect of mud additives. Experimental results indicate that some of the starches have static and dynamic fluid loss characteristics similar to or better than those of a widely used modified starch used by the mud industry. The static fluid loss properties measured after thermal treatment at different temperatures indicate that the newly developed starch products can be used as fluid loss additives for drilling boreholes having bottom hole temperature up to 150^{o}C.

Gregory et al. (2012) illustrated that starch was added to some treatments to determine whether it stabilized the coating and prevented vertical slumping. A commercial fire protection gel coating was included in the study for comparison. Coatings containing starch and the SB gel sample had negligible slumping during burn tests while the commercial gel and the SB foam slumped severely during the test. In rheology studies, samples containing starch had higher G' (elastic modulus), G'' (viscous modulus), and higher yield stress than the commercial gel or SB samples without starch. Surprisingly, the samples containing starch heated more slowly than samples without starch. This could be explained, in part, by the continuous boundary layer (crust) that formed during the burn test that shielded the substrate surface from direct heat exposure, minimized the exposed surface area, and, initially, lowered water vapor flux. Drying tests were performed at 44^{o}C to determine how long the coatings could remain hydrated under severe conditions. The SB gel coatings remained hydrated longer than the SB foam samples. Starch prolonged the drying time (reduced evaporation rate) for both the SB foam and gel samples.

Kudaybergenov et al. (2012) investigated about thermally treated adsorbents based on rice husks are an efficient absorber for heavy crude petroleum and petroleum products, since they possess high porosity and reactive surface functionalities including carboxyl, carbonyl and methylene groups. The results of the SEM studies strongly indicate that thermal treatment is a suitable method to improve structure of husk particles regarding porosity compared to virgin samples. The results of XRD and SEM/EDAX microanalyses show that thermally treated rice husk consist mainly of amorphous silica (SiO_2). The optimal conditions for the treatment are as follows: heating temperature 700 °C and sorption time 25 min in case of heavy crude petroleum; under these conditions, the maximum sorption capacity of TRH700 reached about 15 g petroleum per gram of husks. In conclusion, this study demonstrates the possibility to obtain effective petroleum adsorbents from rice husks, which are currently considered to be an agricultural waste.

2.4 Drilling mud

Guichard et al. (2008) described the drilling mud. It is usually classified as either water base muds (WBMs) or oil base muds (OBMs), depending upon the continuous phase of the mud. However, WBMs may contain oil and OBMs may contain water. They generally use hydrocarbon oil as the main liquid component, with other materials such as clays or colloidal asphalts being added to provide the desired viscosity together with emulsifiers, polymers, and other additives including weighting agents. Water may also be present, but in an amount not usually greater than 50% by volume of the entire composition. If more than about 5% of water is present, the mud is often referred to as an invert emulsion, i.e., a water-in-oil emulsion. They conventionally contain viscosifiers, fluid loss control agents, weighting agents, lubricants, emulsifiers, corrosion inhibitors, salt, and pH control agents. Water makes up the continuous phase of the mud, and is usually present as at least 50 volume percent of the entire composition. Oil is also usually present in small amounts, but will typically not exceed the amount of the water, so that the mud will retain its character as a water- continuous-phase material.

Johannes (2011) detailed about important parameters for characterizing the properties of a drilling mud, which are viscosity, specific weight, gel strength, and filtration. The viscosity is measured by means of a Marsh funnel. The funnel is dimensioned so that the outflow time of 1 qt (926 ml) fresh water at 70^{o}F (21^{o}C) is 26 second. Viscosity is also measured with a rotational viscometer. The mud is placed between two concentric cylinders. One cylinder rotates with constant velocity, while the other is connected by spring. The torque on this cylinder results in a deviation of its position from rest, which may serve as a measure of viscosity. A filter press is used to determine the wall-building characteristics of a mud. This press consists of a cylindrical chamber, which is resistant to alkaline media. A filter paper is placed on the placed on the bottom of the chamber. The mud is placed into the chamber and a pressure of 0.7 MPa is applied. After 30 min the volume of filtrate is reported. The filter cake is inspected visually and the consistency is noted as hard, soft, tough, rubbery, or firm. Alkalinity is measured by acid-base titration, with methylorange or phenolphthalein as an indicator. Phenolphthalein changes color at pH 8.3, whereas methylorange changes color at pH 4.3. At pH 8 the neutralization of the strongly alkaline components such as NaOH is essentially complete. Further reduction of the pH to 4 will also measure the levels of carbonates and bicarbonates that are present. Colorimetric tests and glass electrode systems are used to determine pH.

Schroeder (1987) described the effects of temperature and various chemical additives on the rheological filtration, and chemical properties of fluids and muds under simulated circulating conditions can be elucidated in a roller over.

Johannes (2011) reported the drilling mud properties, which are developed after improvement by added additives. Bentonite is highly colloidal and swells in water to form thixotropic gels. This property results from their micaceous sheet structure. Because of these viscosity-building characteristics, bentonite are used as viscosity enhances or builders in such areas as drilling muds and fluids, concrete and mortar additives, foundry and molding sands, and compacting agents for gravel and sand, as well as cosmetics. Most bentonites that are found in nature are in their sodium or calcium form API and Turkish Institute of Standards (TSE), apparent viscosity of at least 15 cp is assumed to be an acceptable value which corresponds to 90 barrels per ton slurry yield.

Jarrett and Clapper (2010) investigated that filtration control is an important property of a drilling fluid, particularly when drilling through permeable formations, where the hydrostatic pressure exceeds the formation pressure. It is important for a drilling fluid to quickly form a filter cake to effectively minimize fluid loss, but which also is thin and erodible enough to allow product to flow into wellbore during production to API and Turkish Institute of Standards (TSE) limited a fluid loss of 15 ml or less.

2.5 Drilling mud improvement

Petchote and Sikong (2005) studied the properties of drilling mud blended with dolomite powder and fly ash in order to improve the formula of drilling mud with low cost. Furthermore, the properties of dolomite and fly ash affected on properties of drilling were also investigated such as particle size distribution, density, pH, viscosity and dispersion of drilling mud. It was found that drilling mud, which have the properties of barite: dolomite: fly ash. The good suspension property of drilling mud is 70:10:20 and 70:30:0 of barite: dolomite: fly ash; respectively, when the 3 % weight of bentonite was added. The formula of 70:5:25 and 70:0:30 were also good suspension when the 3% by weight of bentonite and 0.6 g/l of CMC were added. 4 formulas of drilling mud follow the drilling mud properties of API standard.

Xianghai Meng et al. (2012) indicated the rheological properties of bentonite dispersion with carbon ash are improved markedly in yield point (YP), and especially for the low solid content of bentonite dispersion. The filtration and density test are also carried out using an API Filter Press and mud balancer respectively. From the results, it could be observed that the filtrate loss and filter cake thickness increase dramatically whereas the density of bentonite dispersion decreases slightly as the addition of carbon ash increases. Furthermore, the stability of bentonite dispersion incorporated with carbon ash is evaluated. The experimental results indicate that carbon ash is better than RM in stability. Through this study, carbon ash is an excellent potential additive for improving the rheological properties of water-based drilling fluids.

Vassilios et al. (2009) concluded the results of an extensive study investigating whether addition of 3% w/w Greek lignite to 6.42% w/w water–bentonite suspensions, after being exposed to high temperatures, can prevent gelation and control filtration characteristics. Two different bentonites and eight lignites from different Greek basins have been used while a commercial lignite product has been used as standard. The lignite-free bentonite suspensions heated to 177 °C for 16 hours (thermal aging) thicken considerably, increasing the yield stress and the yield point. Furthermore, addition of lignite in most cases provided very good filtration control of the water–bentonite suspensions after exposure to 177 °C, with some Greek lignites being superior to the commercial product. The same lignite parameters examined for rheological control, were also examined to determine their effect on fluid loss of these suspensions for both bentonites. The content of humic and fulvic acids of two groups of lignites showed weak inverse correlations with the fluid loss volumes for both bentonites, while all other parameters did not seem to directly correlate with the effectiveness of the lignite.

2.6 Drilling mud rheology

Rheology described the drilling mud 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. The rheological model describes the flow behavior of a fluid by developing a mathematical relationship between shear stress and shear rate. In general, drilling mud rheology is described by two widely used models, namely: the Bingham plastic model and the Power law model. These two models are discussed in this study.

2.6.1 Bingham plastic model

Bingham plastic fluid that have a linear shear stress and strain rate relationship require a finite yield stress before they begin to flow. Several examples are clay suspensions, drilling mud, etc. 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. The graphical representation of this model has shown in Figure 2.1. The plastic viscosity decreased with increased shear rate due to a phenomenon called "shear thinning".

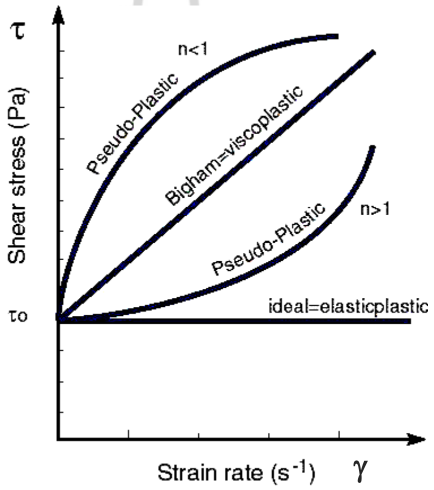

Figure 2.1 Flow curve for Bingham plastic model.

2.6.2 Power law model

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. For n greater than 1, the fluid is classified as dilatants. Dilatants 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 2.2 shows the graphical representation of Power law fluids.

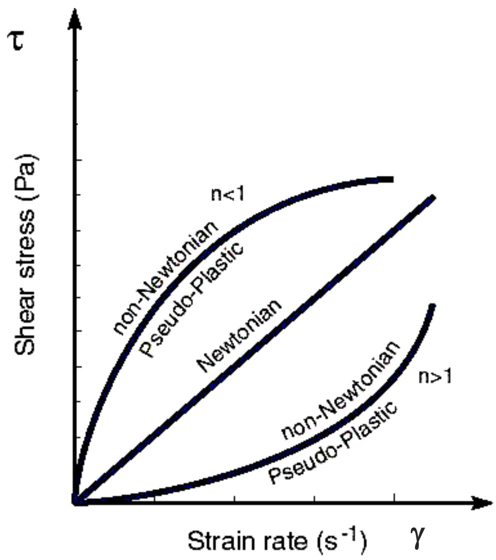

Figure 2.2 Flow curve of Power law model.

This model also called the modified power law model and yield pseudoplastic model. The model is used to describe the flow of pseudoplastic drilling muds that require 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.

2.7 Cost of drilling mud chemicals

Department of Primary Industries and Mines, DPIM (2014) and reported drilling muds, which are generally expensive. They are essential to calculated and compare its cost between fly ash drilling mud system and conventional drilling mud system that used in drilling well. Table 2.2 lists the cost of chemicals used in drilling mud and this was later used to evaluate cost of drilling mud system.

Table 2.2 Cost of drilling chemicals.

Drilling mud chemicals	Formula	Cost/Unit (Baht/Metric ton)
Bentonite	$Al_2O_34SiO_2H_2O$	600
Barite	$BaSO_4$	3,895
Lime	CaO	3,895
Starch	$(C_6H_{10}O_5)_n$	12,900
Dolomite	$(Ca,Mg)CO_3$	350
CMC	Sodium carboxymethyl cellulose	58,000
Fly ash	Silica, alumina, iron oxide, and calcium oxide	200

CHAPTER III

METHODOLOGY

3.1 Introduction

The objective of the experiments is to estimate the effects of temperature and mixing ratio on rheological and physical properties of drilling mud mixed with additives. This chapter includes the sample collection, sample preparation, testing instruments and experimental methods. The tests divide into two groups; physical properties tests and chemical properties tests.

3.2 Sample collection

The fly ash is obtained from Mae Moh Power Plant at Lampang province. Bentonite is supported from Thai Nippon Chemical Industry Co., Ltd. Barite was assisted from Weatherford International Thailand Company. The other additives are purchased from store, Thailand.

3.3 Sample preparation

The fly ash and other additives were prepared and tested at laboratory of Suranaree University of Technology. These additives divide into two parts for chemical property's tests by sieving size less than 75 micrometers (mesh No.200) before stored in zip lock bags for X-ray diffraction (XRD) and X-ray fluorescence (XRF) tests. Physical property tests by mixing with water-based drilling mud. A water-based drilling mud suspension prepares to use 60 grams of bentonite per 1,000 grams of water and 100 grams of barite per 1,000 grams of water was added to control density.

3.4 Typical well drilling

The range of drilling mud's density for typical well drilling is 1.5 to 8.5 percentages bentonite weight by volume. Mud weight varied around 8.85 to 18 pounds per gallon depends 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.

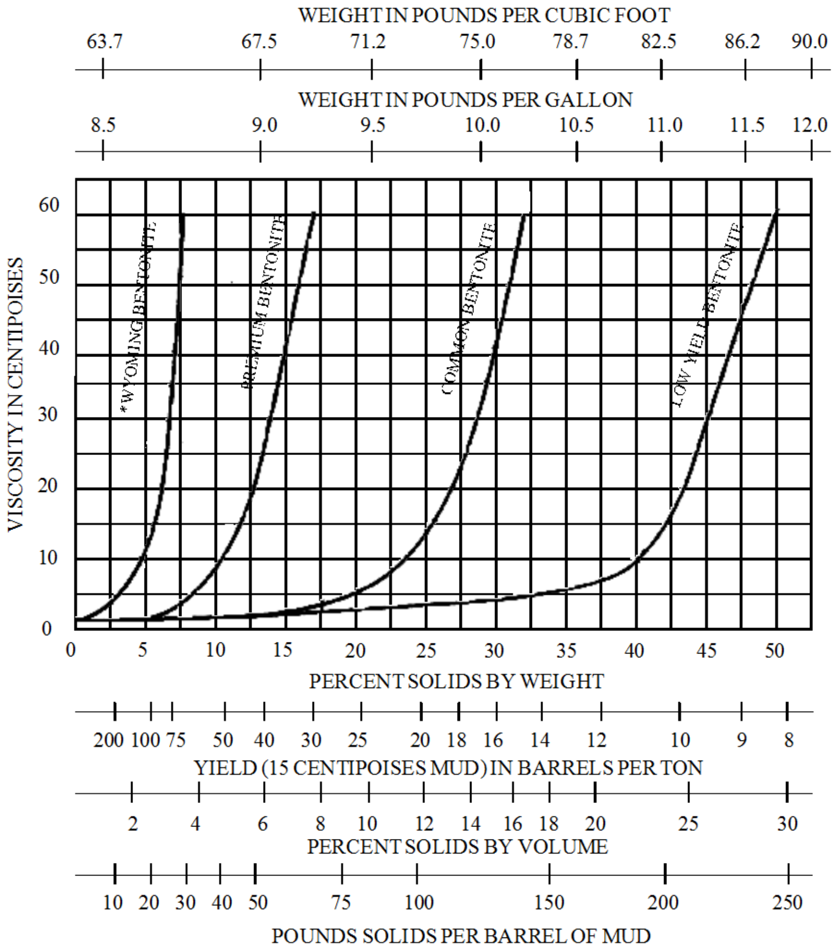

Figure 3.1 Yield curve for typical clays (modified from Gatlin, 1960).

Since the grade of bentonite clay that uses in the experiment is not Wyoming grade. It is necessary to find the appropriate amount of bentonite that meets the viscosity required for typical well drilling. Table 3.1 shows bentonite water-based suspension at 2, 4, 6, and 8 percentages bentonite weight by volume meet a minimum required viscosity for typical well drilling. Therefore, the experiment has been selected 6 percentages of bentonite weight by volume as a base composition.

Table 3.1 Bentonite water-based suspension.

Bentonite (%weight by volume)	**Average apparent viscosity (cP)**
2	6.0
4	12.5
6	21.5
8	39.0

A water-based bentonite suspension was prepared using 60 grams of bentonite per 1,000 grams of water and 100 grams of barite added to control density. The mud components are mixed for 15 minutes using a high-speed mixture. During mixing, the fly ash was slowly to agitated base fluid to avoid a lump occurring within the mud system. The testing mud samples are weighted of 1.10 grams per cubic-centimeter (9.20 pound per gallon) containing 6 percentages bentonite weight by volume as a based composition. The mud weight are measured by mud balance that is an API standard instrument for testing mud weight (Figure 3.2). Various concentrations of fly ash and the other additives are added to perform as a mud additive. These systems were prepared to compare the properties of the mud. The formulations of the mud are shown in Table 3.2.

Figure 3.2 Mud balance.

Table 3.2 Compositions of drilling mud samples.

Composition of mud	Bentonite mud	Bentonite +1%fly ash mud	Bentonite +3%fly ash mud	Bentonite +5%fly ash mud
Water (gram)	1,000	1,000	1,000	1,000
Barite (gram)	100	100	100	100
Bentonite (gram)	60	60	60	60
Fly ash (gram)	-	11.6	34.8	58.0

3.5 Chemical properties tests

The objective of chemical property's testing is to determine the mineral crystals and components of samples by using X-ray fluorescence spectrometer (XRF) and X-ray diffractrometer (XRD).

Sample preparations were sieved by the mesh No. 200 (0.075 mm) and was dried at 60^{o}C in the oven for 24 hours**.**

3.5.1 X-ray fluorescence

Samples are prepared to use 0.5 to 1.0 gram. Samples are compacted and spread out to the holder. Sample holders are analyzed by X-ray fluorescence spectrometer (XRF), Holiba-XGT 5200 (Figure 3.3) and spent time to 200 seconds per sample. A typical X-ray generator passes an electric current through a filament, which cases an electron to be emitted. These electrons are then accelerated by high voltage (usually somewhere between 20 and 100 kV) towards an anode (target).

Results are analyzed in the spectrum, including Rayleigh and Compton scattered characteristic line from the X-ray generator, peak caused by X-ray diffraction, and sum/escape peak. A quantitative technique, the peak height of any element is directly related to the concentration of that element within the sampling volume. The XRF results are presented as the percentage of major elements.

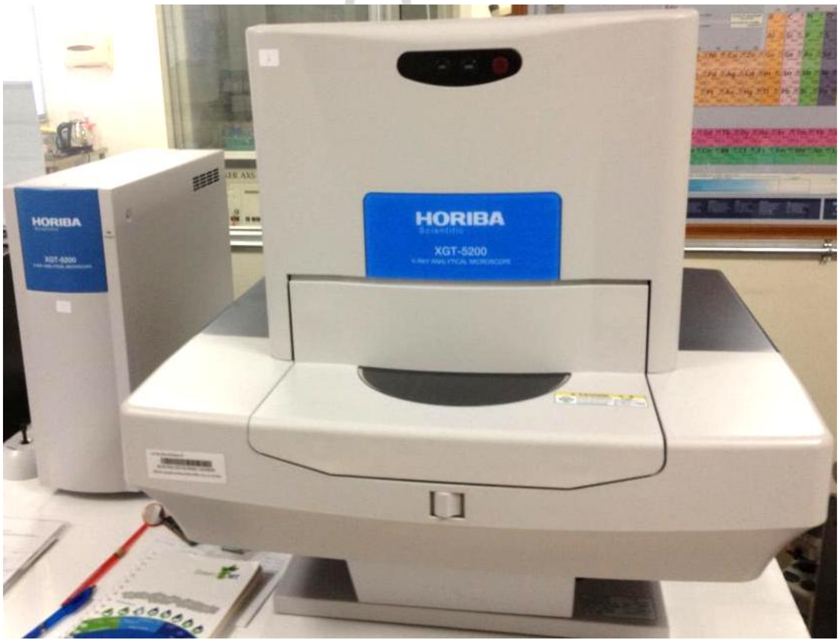

Figure 3.3 Horiba (XGT-5200) X-ray fluorescence.

3.5.2 X-ray diffraction

Amount of 1.0 to 1.5 grams of samples are compacted and spread out to holder. Sample holder is analyzed by X-ray diffractrometer (XRD), Bruker-D2 Phaser (Figure 3.4) and spent time 15 minutes per sample. XRD performed on polycrystalline material the incident X-ray beam is diffracted by innumerous crystallites in specific 2 Theta directions. Data is recorded the exact 2 Theta positions a narrow slit in front of a point detector is required. Conditions of analysis include a Cu standard ceramic sealed tube (0.4x12 mm), X-ray generation (30 kV, 10mA), angular range analysis (2θ, 5^o to 80^o) and accuracy (±0.02^o throughout the entire measuring range)

Results are calculated relative intensity, divide the absolute intensity of every peak by the absolute intensity of the most intense peak, and then convert to a percentage.

Figure 3.4 Bruker (D2 Phaser) X-ray diffractrometer.

3.6 Physical properties tests

The physical properties consist of density, rheology, filtration, hydrogen ion, resistivity, solid content and sand content. They are determined following API standard.

3.6.1 Rheological tests

The rheological calculation, it is appropriate to discuss some basic drilling fluid flow properties, determination of rheological parameters that 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 centipoises (cP), it indicates the amount of force required to move one layer of fluid in relation to another. The apparent viscosity can calculate from equation 3.1

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 shear of the liquid itself. Therefore, all practical viscosities can be calculated from equation 3.2 and its range value that used in well drilling is shown in Figure 3.5

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 condition. 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 solids, and (3) the electro-chemical environment of ions. The yield point could 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 3.3 and its range value that used in drilling well is shown in Figure 3.5

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

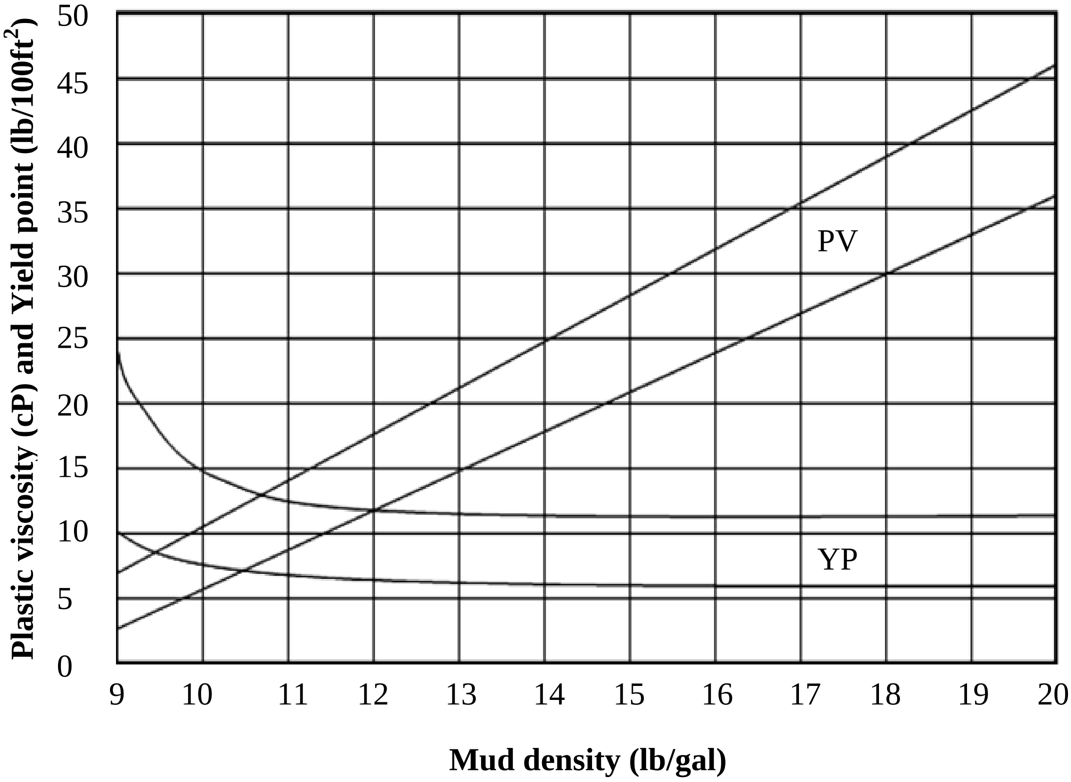

Figure 3.5 Plastic viscosity and yield point ranges for water-based mud (modified from MI-Swaco, 1998).

Drilling mud is tested for the rheological properties at 30, 60 and 90^{o}C. The Rheology testing is carried out by a Fann 35SA model Viscometer (Figure 3.6) and measured by using six rotational speeds (3, 6, 100, 200, 300 and 600 rpm) for the viscosity, yield point and gel strength that relate to flowing properties of drilling mud.

Figure 3.6 Fann (35SA 115 Volt) Viscometer.

The apparent viscosity, plastic viscosity and yield point are calculated from 300 and 600 rpm reading following formulas from API standard.

$$\mu_a = \phi_{600}/2 \quad (3.1)$$

$$\mu_p = \phi_{600}/\phi_{300} \quad (3.2)$$

$$\gamma_p = \phi_{300}/\mu_p \quad (3.3)$$

where μ_a = apparent viscosity (cP)

μ_p = plastic viscosity (cP)

γ_p = Yield point ($lb_f/100\ ft^2$)

It is the rotational coaxial cylinder type used to measure the viscosity of the drilling mud. The shear stress is determined as a function of the shear rate. The drilling mud is calculated by the shear rate and shear stress relationships. The equations are as follows:

$$\tau = 0.01066\phi_i N \tag{3.4}$$

$$\gamma = 1.703rpm \tag{3.5}$$

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 power law model's parameters in the term of behavior index (*n*) and consistency (*k*) are calculated from viscometer reading 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} = viscosity dial reading at 600 rpm

ϕ_{300} = viscosity dial reading at 300 rpm

3.6.2 Static filtration tests

Filtration is tested by using Fann filter press (Figure 3.7) which determines the API filtrate loss through standard filter paper and the filter cake thickness under static conditions. It consists of fluid cup support by a frame, a filtering medium and a pressurized nitrogen gas cylinder and regulator. A graduated cylinder is used to measure the discharged filtrate. The 100 psig is applied to a column of fluid for the 30 minutes period, which filtrate volume and filter cake thickness are measured and recorded.

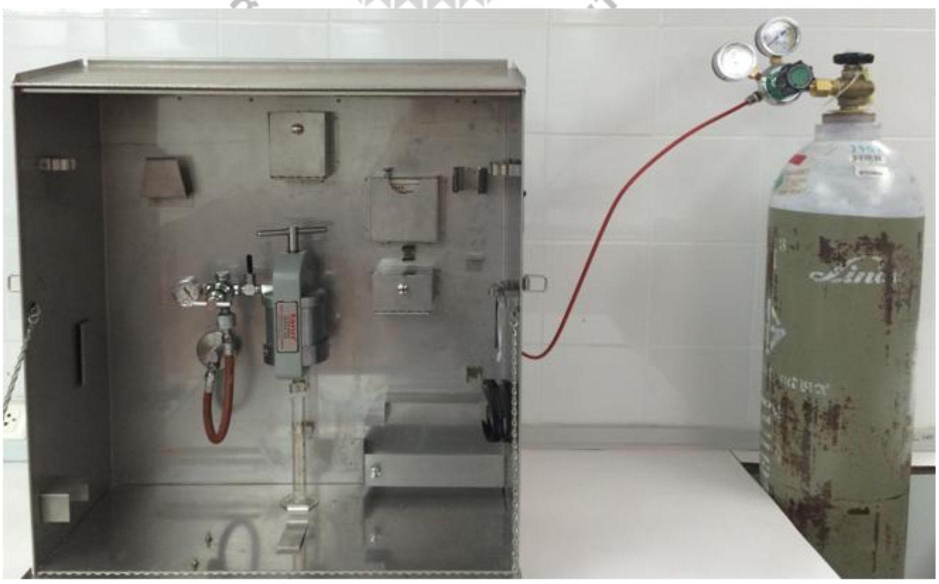

Figure 3.7 Fann (series 300) filter press.

3.6.3 Hydrogen ion tests

The hydrogen ion (pH) measurements of the fluids are conducted by using the glass electrode pH meter (OAKTON pH 700 model) (Figure 3.8). The instrument determines the pH of an aqueous solution by measuring the electro-potential generated between a glass electrode and a reference electrode. Measurement and adjustments of pH are fundament of drilling fluid control. Clay interactions, solubility of various components and effectiveness of additives are all dependent on pH, as in the control of acidic and sulfide corrosion processes.

Figure 3.8 OAKTON (pH 700 model) pH meter.

3.6.4 Resistivity tests

The drilling mud, filtrate and mud cakes are measured by the Fann 88C model resistivity meter (Figure 3.9). The resistivity meter provides a direct digital reading of resistivity in three ranges, including 2, 20, and 200 Ω/m^2. The direct measurement of the sample's resistivity and temperature is in the transparent cell.

Instrument calibration is used salt solution and calculated the correction factor for accurate data.

Figure 3.9 Fann (88C model) resistivity meter.

3.6.5 Sand content tests

Fann sand content set (Figure 3.10) is used for determining the account of sand and defined as the percentage by volume of solids in the drilling mud that retained on 75 micrometers (No.200 mesh) sieve. The excessive sand makes a filter cake thickness with increasing; because abrasive wear of a pump parts, a bit and pipe and may settle when circulation is stopped and interferes with the pipe move-mentor the setting of the casing.

Figure 3.10 Fann sand content set.

3.6.6 Solid content tests

Fann oil and water retort kit (Figure 3.11) is used for determining the account of water and solid defined as the percentage by volume in the drilling mud. The excessive sand makes a filter cake thickness with increasing due to abrasive wear of the pump parts, the bit and pipe and may settle when circulation stopped and interfered with the pipe move-mentor the setting of the casing.

Figure 3.11 Fann retort kit.

CHAPTER IV

RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter describes the data analysis and results of laboratory experiments used to determinate their chemical, physical, rheological properties and the cost of new invented mud are compared with a common mud system that used in well drilling. The results of the experiment and analysis are displayed below.

4.2 Determination of chemical properties

The objectives of these tests are to determine the elements and minerals of drilling mud both before and after mixed with additives. The step of methods is the rheological and physical properties. These results lead to the determination that the most suitable mixing ratios and temperature of drilling mud mixed with additives.

4.2.1 Chemical properties before mixing of drilling mud

The elements are determined by an X-ray fluorescence spectrometer. The minerals are measured by an X-ray diffractrometer. Tables 4.1 and 4.2 show the major elements and minerals of materials before mixing.

Table 4.1 Major elements of varying materials using X-ray fluorescence.

Major elements (weight %)	Materials					
	Barite	Bentonite	Fly ash	Dolomite	Rice husk ash	Lime
SiO_2	17.86	59.32	34.90	5.48	96.73	-
Fe_2O_3	1.24	10.34	15.51	2.16	-	0.13
CaO	-	4.24	16.57	89.37	1.34	99.58
Al_2O_3	-	10.65	18.98	2.99	-	-
SO_3	27.08		8.40	-	-	0.29
K_2O	-	1.38	1.85	-	1.93	-
MgO	-	10.51	2.92	-	-	-
TiO_2	-	3.56	0.87	-	-	-
BaO	53.82	-	-	-	-	-
Total	100	100	100	100	100	100

Table 4.2 Mineral contents of varying materials using X-ray diffraction.

Materials	Minerals (weight %)				
	Barite	Bentonite	Fly ash	Dolomite	Lime
Quartz	21.33	5	24.26	3.49	-
Anhydrite	1.35	-	14.28	-	-
Hematite	-	6.38	20.46	-	-
Calcite	-	6.79	15.33	73.20	100
Montmorillonite	-	56.69	-	-	-
Barite	77.32	-	-	-	-
Dolomite	-	-	-	23.31	-
Gypsum	-	4.62	-	-	-
Anorthite	-	8.52	-	-	-
Lime	-	-	8.44	-	-
Kaolinite	-	17.00	-	-	-

Table 4.2 Mineral contents of varying materials using X-ray diffraction (continued).

Materials	Minerals (weight %)				
	Barite	Bentonite	Fly ash	Dolomite	Lime
Mullite	-	-	17.23	-	-

4.2.2 Chemical properties after mixing of drilling mud

Drilling mud mixed with additives by varies mixing ratio and temperature are measured by the X-ray fluorescence and X-ray diffraction to determine the compositions of the element and mineral. Tables 4.3 and 4.4 are display X-ray fluorescence and X-ray diffraction of drilling mud mixed with additives.

Table 4.3 Elements of drilling mud mixed with additives using X-ray fluorescence.

Sample No.	Major elements (weight %)						
	Al_2O_3	SiO_2	SO_3	CaO	Fe_2O_3	BaO	Total
1	10.9	32.8	13.8	1.8	8.8	31.9	100
2	12.1	45.2	16.3	1.7	8.5	16.2	100
3	11.5	42.8	18.7	3.8	9.6	13.6	100
4	10.9	42.0	15.7	2.9	14.7	13.8	100
5	10.9	31.4	10.5	12.9	14.2	20.1	100
6	12.2	32.4	11.3	15.8	11.2	17.1	100
7	12.2	40.6	14.3	11.7	10.4	10.8	100
10	9.3	38.8	17.5	5.1	10.1	19.2	100
14	9.6	30.0	12.8	11.1	8.0	28.5	100
16	7.5	48.5	16.9	3.6	8.4	15.1	100
20	9.5	20.3	9.3	23.7	12	25.2	100
24	11.1	31.3	17.1	1.9	19.5	19.1	100
28	8.8	35.7	12.2	11.4	12.9	19.0	100
33	13.0	55.1	13.8	4.1	6.8	7.2	100
37	13.5	35.5	14.2	9.2	14.3	13.3	100
45	10.0	41.6	12.3	9.4	13.3	13.4	100
48	10.0	45.9	18.9	10.0	10.4	4.8	100

Table 4.4 Mineral contents of variation materials using X-ray diffraction.

No.	Minerals (weight %)									
	Bar.	**Qtz.**	**Cal.**	**Hem.**	**Mont.**	**Gyp.**	**Dol.**	**Kao.**	**Anor.**	**Anh.**
1	43.74	11.81	3.37	3.68	23.15	1.61	0.37	11.33	0.72	0.49
2	42.20	11.98	6.96	3.66	24.87	0.55	0.27	8.35	0.87	0.29
3	42.52	13.35	2.50	3.33	25.79	0.59	0.27	10.50	0.75	0.40
4	42.49	10.22	4.43	4.18	25.40	1.13	0.31	9.80	1.17	0.87
5	10.16	36.77	4.62	3.14	28.02	2.75	0.09	7.47	6.18	0.80
6	37.56	10.44	5.04	4.83	30.60	1.07	0.41	7.70	1.16	1.19
7	42.07	10.79	4.21	3.31	25.44	2.21	0.13	10.98	0.33	0.54
10	42.87	12.33	3.48	3.23	25.05	1.59	0.12	10.29	0.91	0.14
14	34.92	9.23	21.36	2.25	18.66	3.96	0.34	8.06	0.52	0.70
16	41.25	9.40	1.87	2.96	26.29	1.58	0.40	13.10	2.84	0.31
20	35.42	6.91	23.29	3.41	19.34	1.18	0.23	8.84	0.93	0.45
24	41.12	10.70	2.68	2.82	22.55	5.13	0.21	12.05	2.53	0.21
28	34.65	5.88	11.25	2.79	23.27	5.25	0.37	11.02	5.46	0.06
33	31.65	8.30	4.33	2.25	26.23	1.20	0.03	22.07	3.79	0.15
37	34.39	15.70	5.48	2.04	26.08	1.41	0.24	12.12	1.68	0.86
45	42.43	13.22	6.01	4.52	23.51	1.30	0.19	7.56	0.47	0.79
48	43.11	12.75	6.30	3.97	20.98	1.80	0.53	9.96	0.02	0.58

*Bar. = barite, Qtz. = quartz, Cal = calcite, Hem. = hematite, Mont. = montmorillonite, Gyp. = gypsum, Dol. = dolomite, Kao. = kaolinite, Anor. = anorthite and Anh. = anhydrite

4.3 Determination of physical properties

The varied composition of drilling mud mixed with additives describes by Table 4.5. Base-composition consists of 1,000 grams of water, 100 grams of barite, and 60 grams of bentonite. Additives include a fly ash, dolomite, rice husk ash, lime, and starch. The water-based drilling mud is mixed with 3 percentages of fly ash. It is the appropriate value. Therefore, the 3 percentages of fly ash are the new-base drilling mud that mixed with other additives.

Table 4.5 The compositions of drilling mud mixed with additives.

No.	**Temperature (^oC)**	**Base**	**Fly ash (%w/w)**	**Additives (%w/w)**
1	30	100 g of barite and 60 g of bentonite	-	-
2	60	100 g of barite and 60 g of bentonite	-	-
3	90	100 g of barite and 60 g of bentonite	-	-
4	30	100 g of barite and 60 g of bentonite	1	-
5	30	100 g of barite and 60 g of bentonite	3	-
6	30	100 g of barite and 60 g of bentonite	5	-
7	60	100 g of barite and 60 g of bentonite	1	-
8	60	100 g of barite and 60 g of bentonite	3	-
9	60	100 g of barite and 60 g of bentonite	5	-
10	90	100 g of barite and 60 g of bentonite	1	-
11	90	100 g of barite and 60 g of bentonite	3	-
12	90	100 g of barite and 60 g of bentonite	5	-
13	30	100 g of barite and 60 g of bentonite	-	1% dolomite
14	30	100 g of barite and 60 g of bentonite	-	3% dolomite
15	30	100 g of barite and 60 g of bentonite	-	5% dolomite
16	30	100 g of barite and 60 g of bentonite	-	1% rice husk ash
17	30	100 g of barite and 60 g of bentonite	-	3% rice husk ash
18	30	100 g of barite and 60 g of bentonite	-	5% rice husk ash
19	30	100 g of barite and 60 g of bentonite	-	1% lime
20	30	100 g of barite and 60 g of bentonite	-	3% lime
21	30	100 g of barite and 60 g of bentonite	-	5% lime
22	30	100 g of barite and 60 g of bentonite	-	1% starch

Table 4.5 The compositions of drilling mud mixed with additives (continued).

No.	Temperature (^oC)	Base	Fly ash (%w/w)	Additives (%w/w)
23	30	100 g of barite and 60 g of bentonite	-	3% starch
24	30	100 g of barite and 60 g of bentonite	-	5% starch
25	30	100 g of barite and 60 g of bentonite	3	1% dolomite
26	30	100 g of barite and 60 g of bentonite	3	3% dolomite
27	30	100 g of barite and 60 g of bentonite	3	5% dolomite
28	60	100 g of barite and 60 g of bentonite	3	1% dolomite
29	60	100 g of barite and 60 g of bentonite	3	3% dolomite
30	60	100 g of barite and 60 g of bentonite	3	5% dolomite
31	30	100 g of barite and 60 g of bentonite	3	1% rice husk ash
32	30	100 g of barite and 60 g of bentonite	3	3% rice husk ash
33	30	100 g of barite and 60 g of bentonite	3	5% rice husk ash
34	60	100 g of barite and 60 g of bentonite	3	1% rice husk ash
35	60	100 g of barite and 60 g of bentonite	3	3% rice husk ash
36	60	100 g of barite and 60 g of bentonite	3	5% rice husk ash

Table 4.5 The compositions of drilling mud mixed with additives (continued).

No.	Temperature (^oC)	Base	Fly ash (%w/w)	Additives (%w/w)
37	30	100 g of barite and 60 g of bentonite	3	1% lime
38	30	100 g of barite and 60 g of bentonite	3	3% lime
39	30	100 g of barite and 60 g of bentonite	3	5% lime
40	60	100 g of barite and 60 g of bentonite	3	1% lime
41	60	100 g of barite and 60 g of bentonite	3	3% lime
42	60	100 g of barite and 60 g of bentonite	3	5% lime
43	30	100 g of barite and 60 g of bentonite	3	1% starch
44	30	100 g of barite and 60 g of bentonite	3	3% starch
45	30	100 g of barite and 60 g of bentonite	3	5% starch
46	60	100 g of barite and 60 g of bentonite	3	1% starch
47	60	100 g of barite and 60 g of bentonite	3	3% starch
48	60	100 g of barite and 60 g of bentonite	3	5% starch

4.3.1 Rheological properties and parameters

The shear stress and shear rate values for all six viscometer readings of water-based drilling mud describe by Table 4.6. The average viscometer reading is used to calculate the shear stress and shear rates by following equations 3.4 and 3.5 in previous chapter. The calculated shear stresses are plotted against shear rates in order to choose the best-fit curve for Bingham Plastic model, which they are fitted with a linear correction representing in Figure 4.1. The result of a graph can be inferred that the fluid is tended to be a Bingham Plastic fluid, showing the consistency plot of water-based drilling mud under temperature at 30^{o}C.

Table 4.6 Results of shear stress and shear rates from water-based drilling mud.

rpm	average reading	γ (sec^{-1})	τ (lb_f/ft^2)
600	46	1021.8	0.099
300	38	510.9	0.082
200	34	340.6	0.074
100	31	170.3	0.067
6	29	10.2	0.063
3	28	5.1	0.060

The Bingham Plastic model demonstrates the appropriate rheological model for other drilling mud samples. The water-based drilling mud samples are categorized into ten different groups of testing temperature (30, 60 and 90^{o}C) and mixing ratios. Their consistency curves are plotted in Figures 4.2 through 4.16.

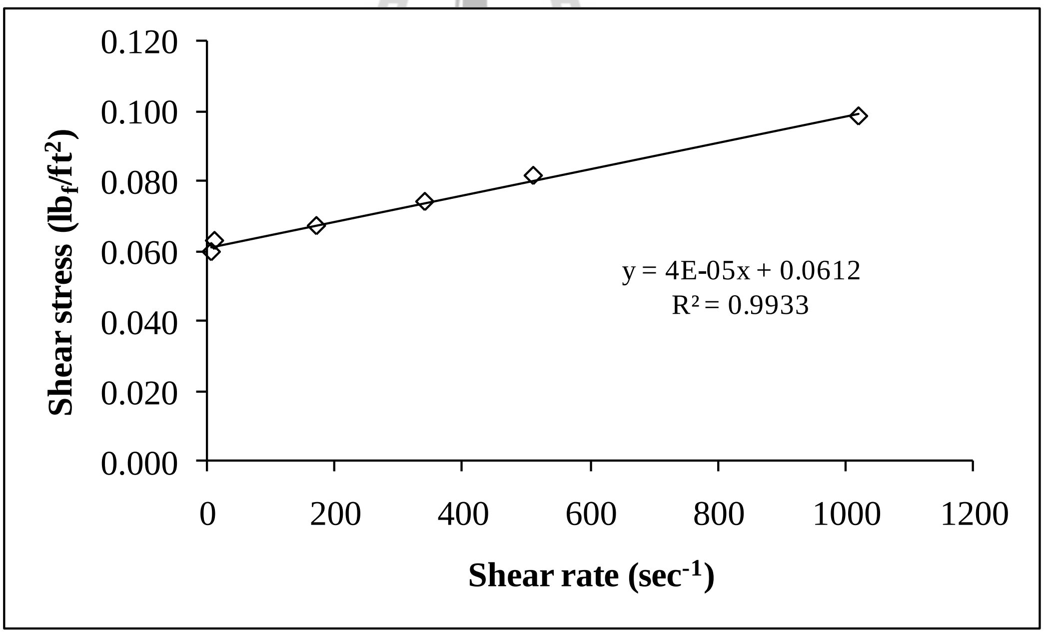

Figure 4.1 Consistency plot of water-based drilling mud with a linear correction.

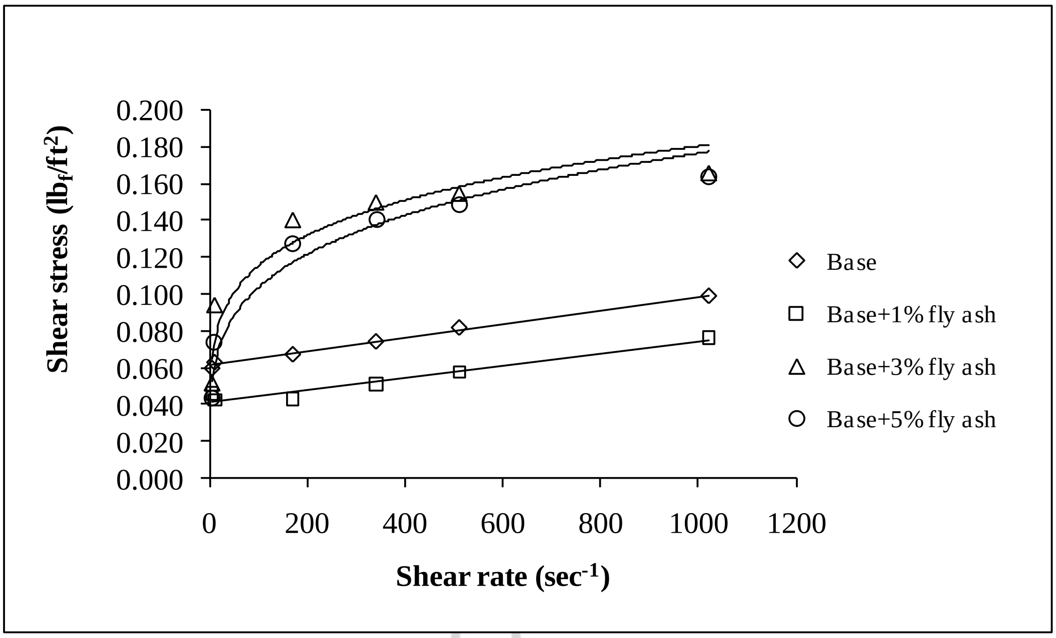

Figure 4.2 Consistency plot of drilling mixed with fly ash at 30^{o}C.

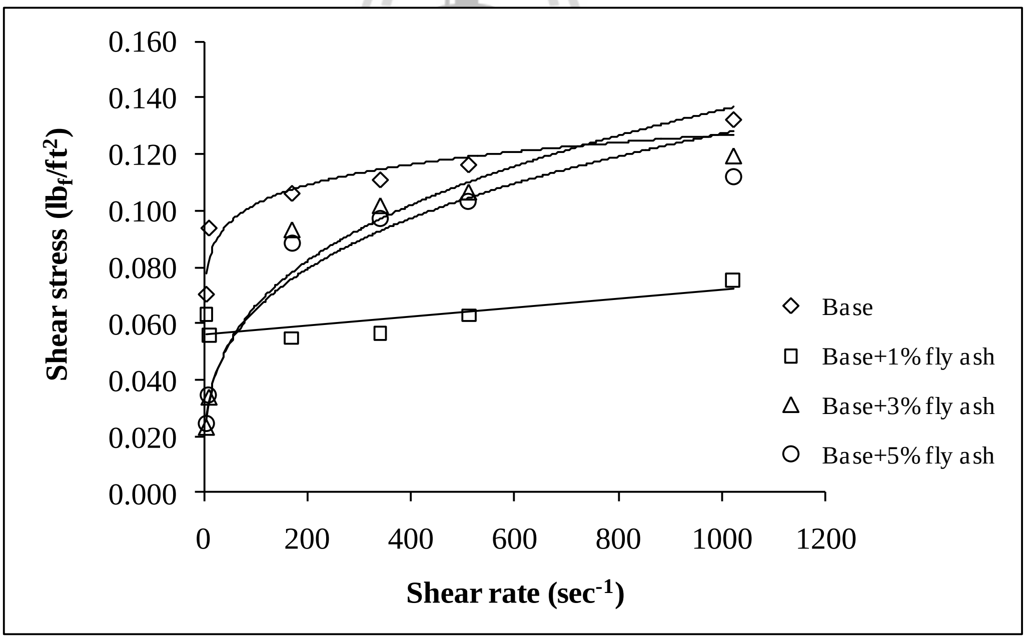

Figure 4.3 Consistency plot of drilling mixed with fly ash at 60^{o}C.

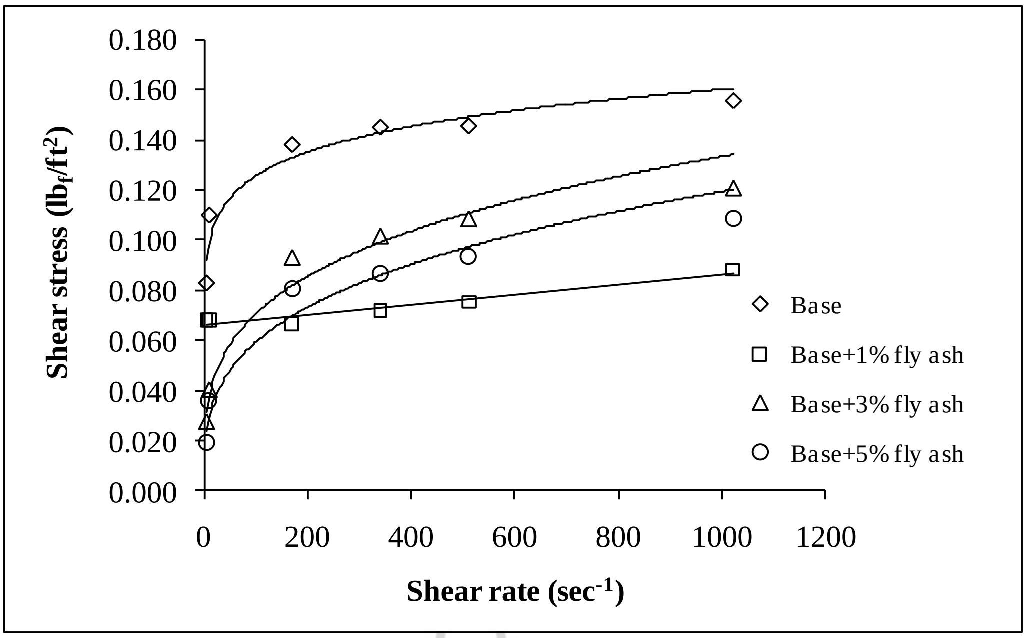

Figure 4.4 Consistency plot of drilling mixed with fly ash at 90^{o}C.

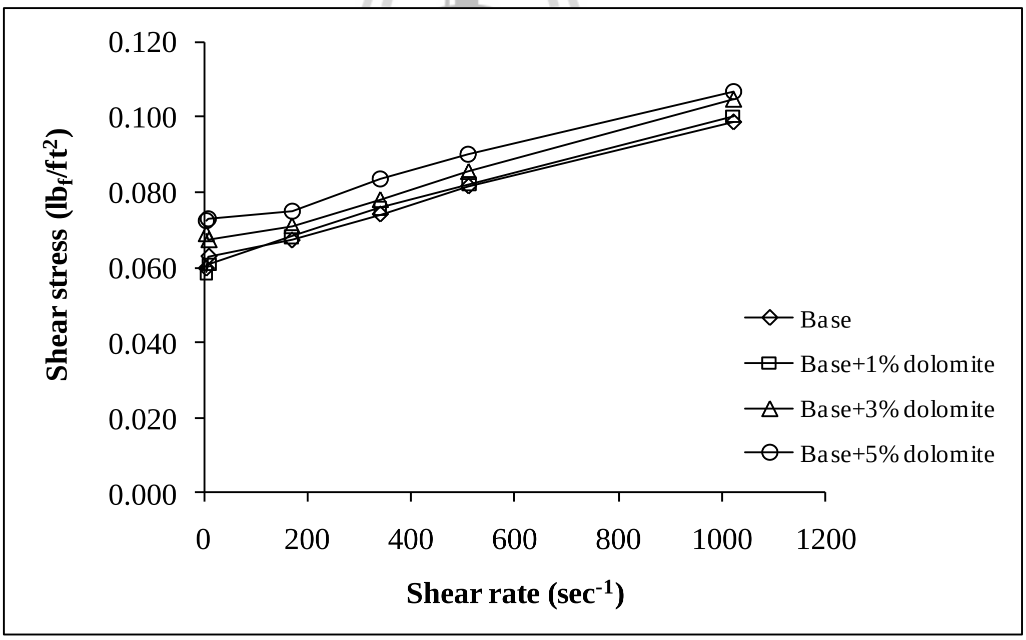

Figure 4.5 Consistency plot of drilling mixed with dolomite at 30^{o}C.

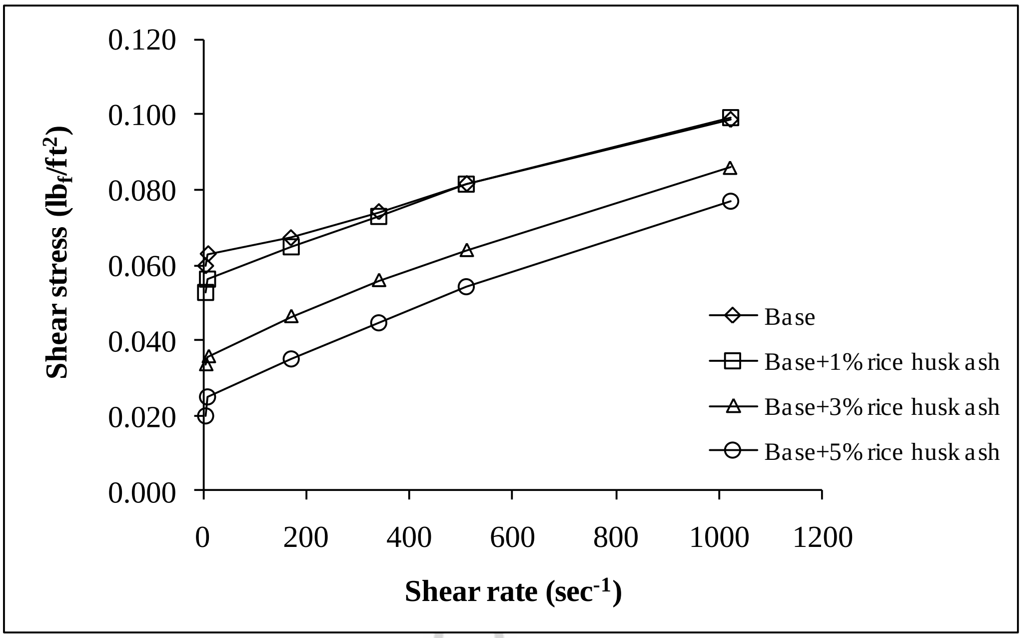

Figure 4.6 Consistency plot of drilling mixed with rice husk ash at 30^{o}C.

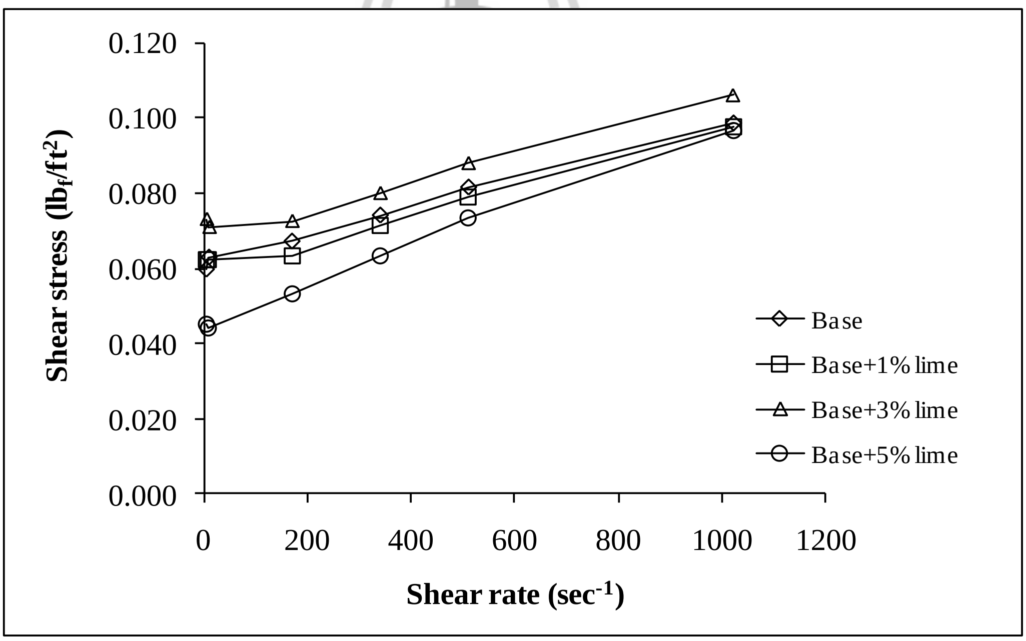

Figure 4.7 Consistency plot of drilling mixed with lime at 30^{o}C.

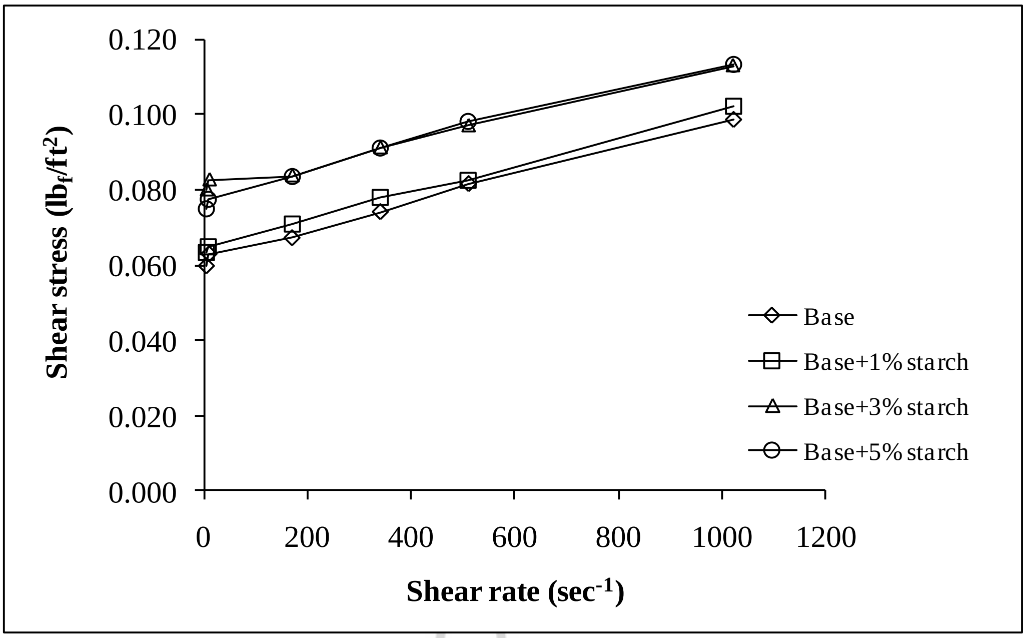

Figure 4.8 Consistency plot of drilling mixed with starch at 30°C.

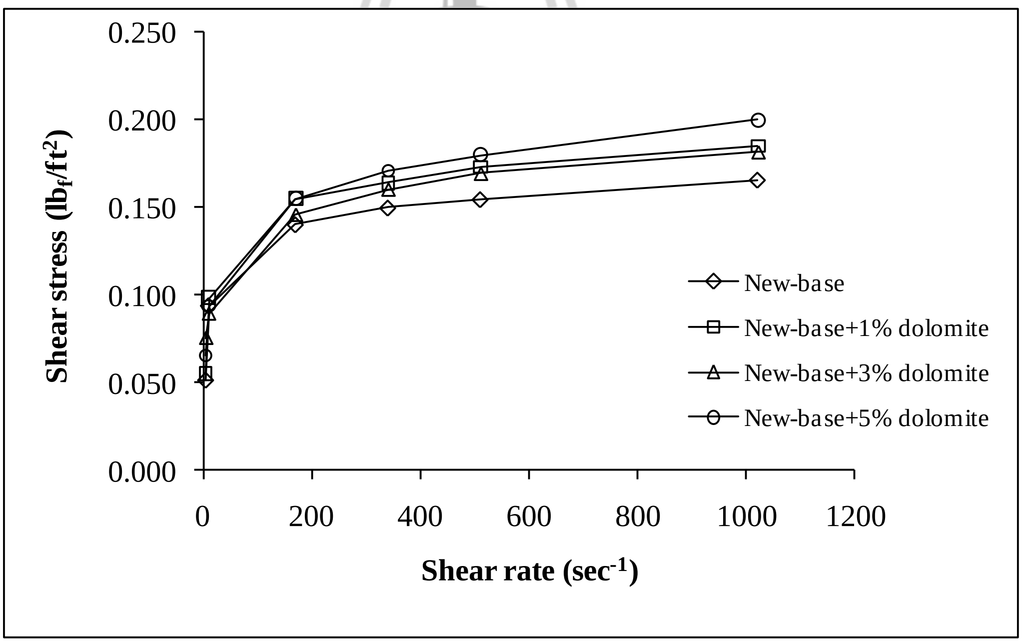

Figure 4.9 Consistency plot of new-base drilling mixed with dolomite at 30°C.

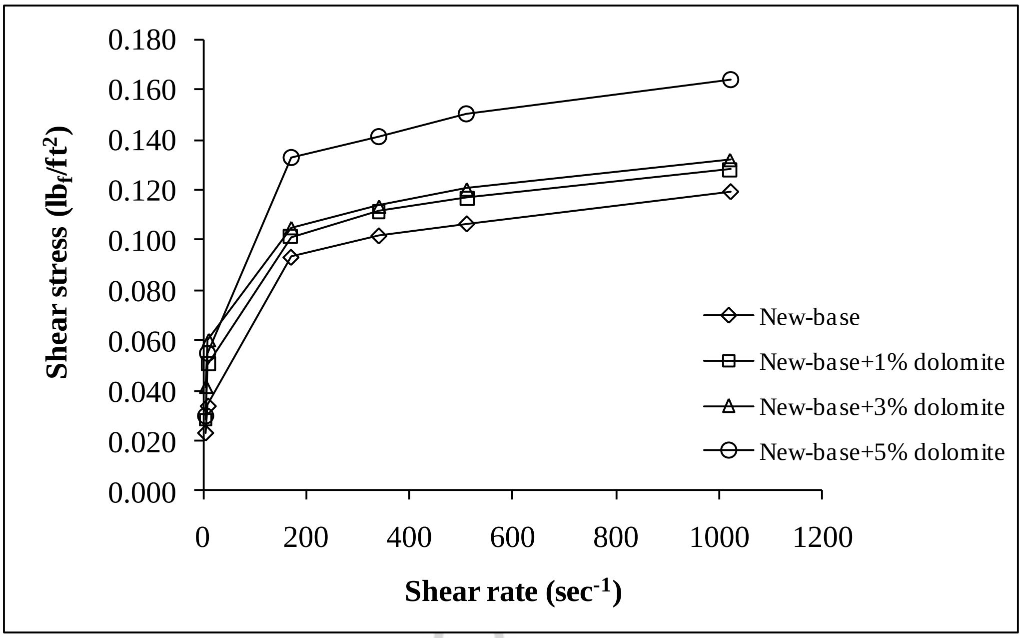

Figure 4.10 Consistency plot of new-base drilling mixed with dolomite at 60°C.

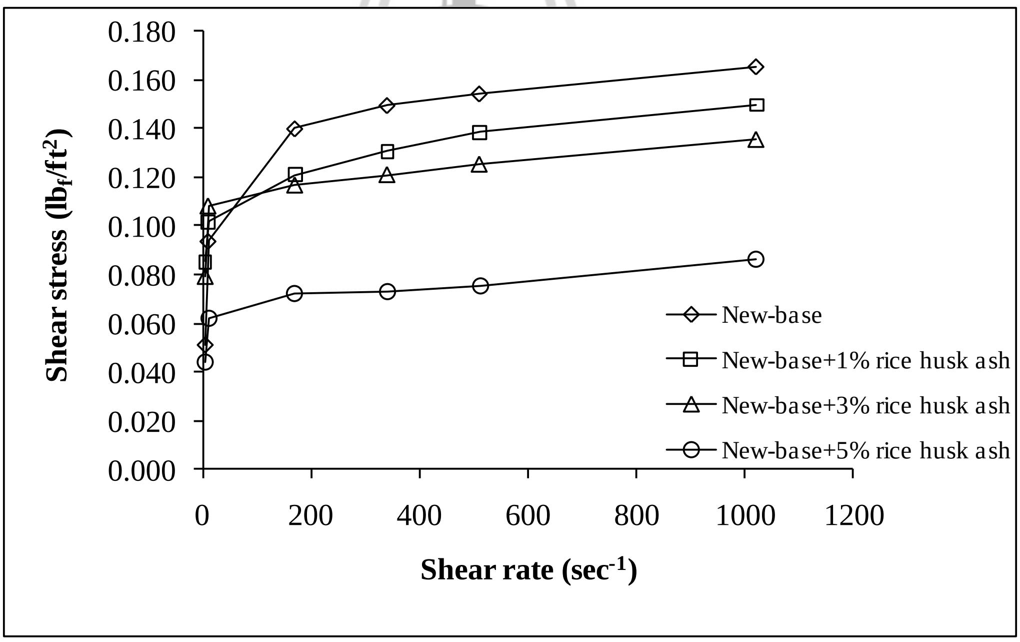

Figure 4.11 Consistency plot of new-base drilling mixed with rice husk ash at 30°C.

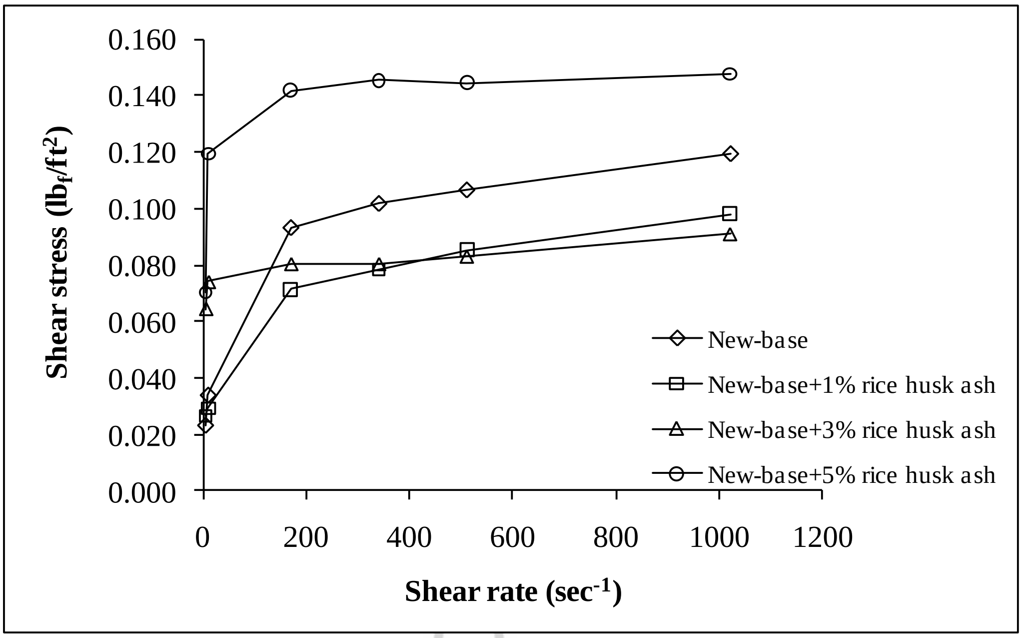

Figure 4.12 Consistency plot of new-base drilling mixed with rice husk ash at 60^{o}C.

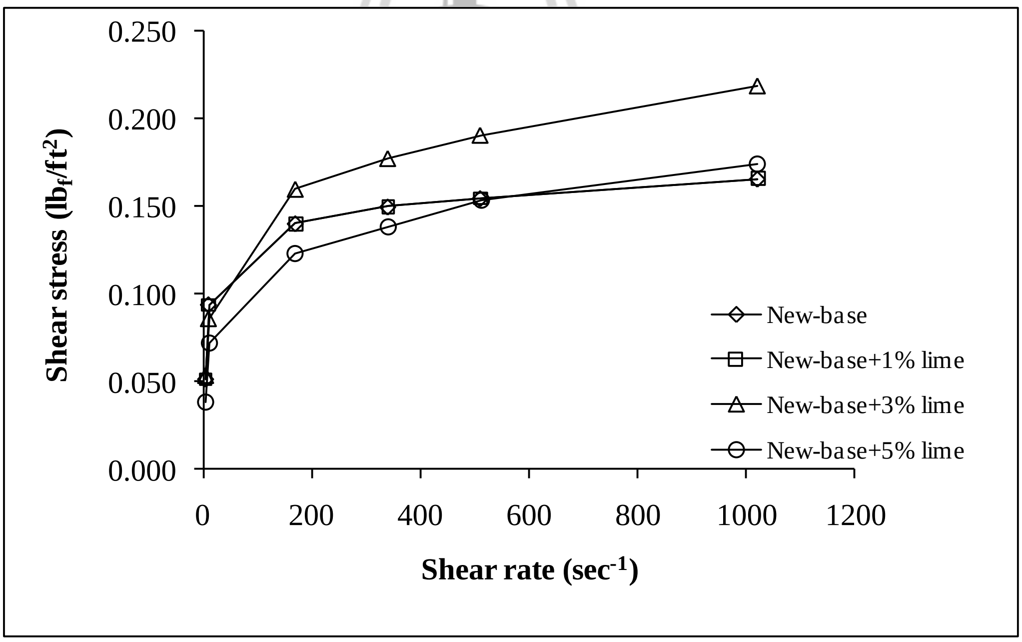

Figure 4.13 Consistency plot of new-base drilling mixed with lime at 30^{o}C.

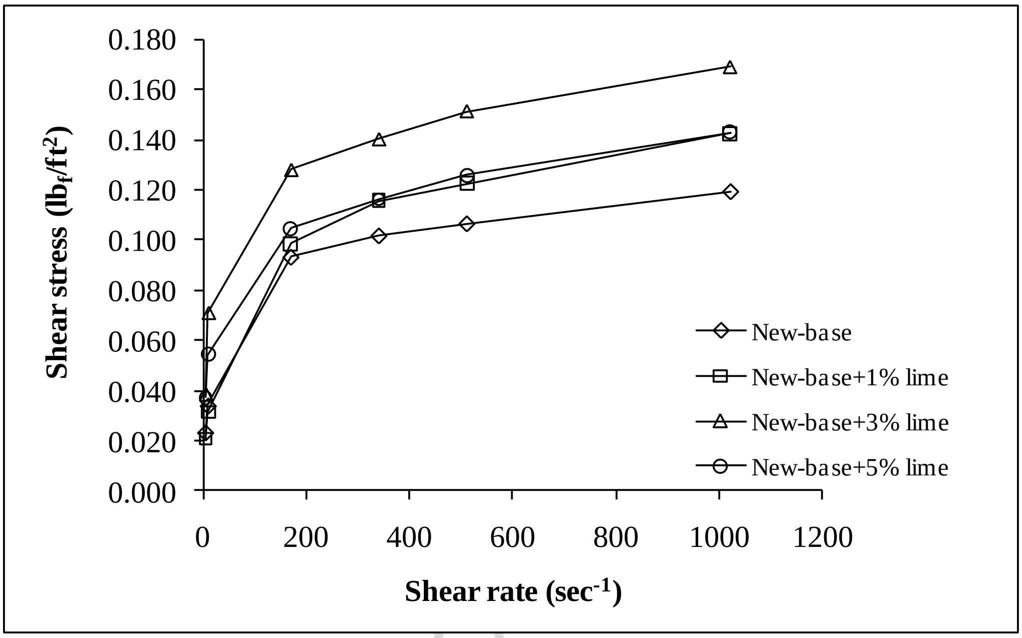

Figure 4.14 Consistency plot of new-base drilling mixed with lime at 60°C.

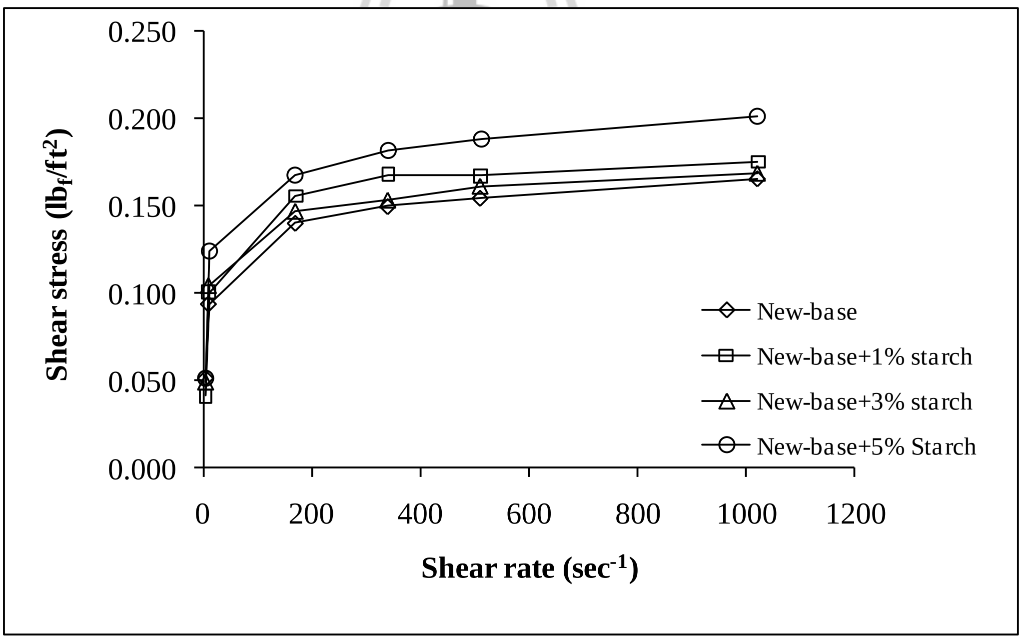

Figure 4.15 Consistency plot of new-base drilling mixed with starch at 30°C.

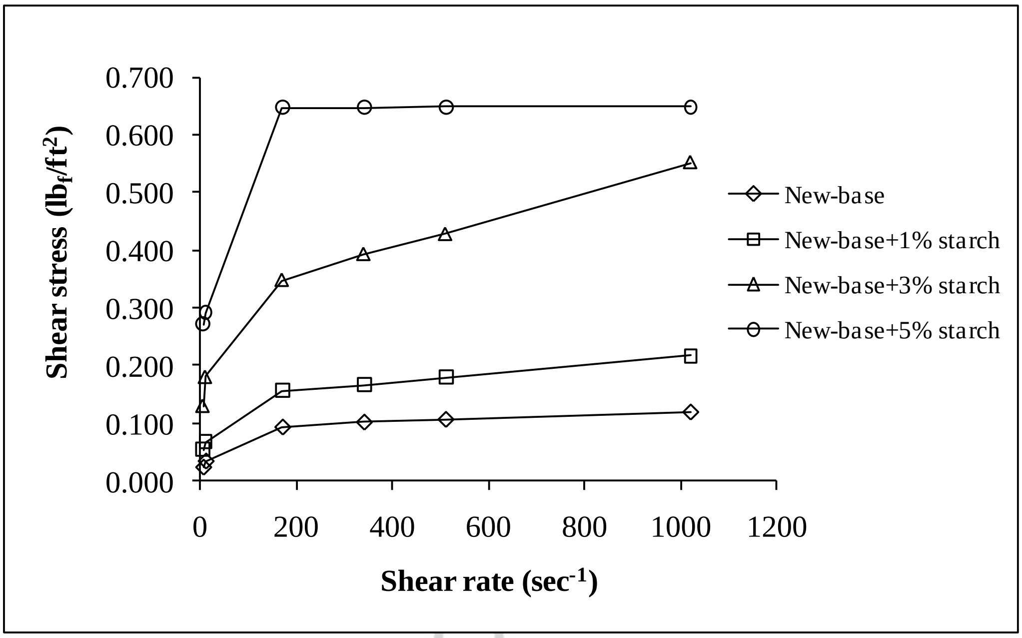

Figure 4.16 Consistency plot of new-base drilling mixed with starch at 60^{o}C.

Table 4.7 Rheological parameters of drilling mud mixed with additives.

Test Temp. (^oC)	No.	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	1	Base	23	8	30	0.27	3554	27	31
	4	Base+1%fly ash	18	9	18	0.41	1088	19	26
	5	Base+3%fly ash	39	5	67	0.10	19598	21	22
	6	Base+5%fly ash	39	8	62	0.15	14097	22	19
	13	Base+1%dolomite	24	9	30	0.29	3262	22	33
	14	Base+3%dolomite	25	9	31	0.29	3286	28	38
	15	Base+5%dolomite	25	8	35	0.24	4735	33	37
	16	Base+1%rice husk ash	23	8	30	0.28	3365	22	28
	17	Base+3%rice husk ash	20	10	20	0.42	1087	15	19
	18	Base+5%rice husk ash	18	11	15	0.50	584	9	9
	19	Base+1%lime	23	9	28	0.31	2795	24	33
	20	Base+3%lime	25	9	33	0.27	3898	31	40
	21	Base+5%lime	23	11	24	0.39	1533	21	26

Table 4.7 Rheological parameters of drilling mud mixed with additives (continued).

Testing Temp. (^oC)	No.	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	22	Base+1%starch	24	9	30	0.31	2880	26	35
	23	Base+3%starch	27	8	38	0.22	5880	34	41
	24	Base+5%starch	27	7	39	0.21	6287	32	40
60	2	Base	31	8	47	0.19	8713	30	32
	7	Base+1%fly ash	18	6	24	0.26	2992	28	35
	8	Base+3%fly ash	28	5	46	0.16	9198	10	13
	9	Base+5%fly ash	26	4	45	0.11	12124	12	10
90	3	Base	37	5	64	0.10	19001	37	42
	10	Base+1%fly ash	16	5	22	0.23	3296	27	35
	11	Base+3%fly ash	28	6	45	0.15	9947	11	13
	12	Base+5%fly ash	26	7	37	0.21	5945	5	10
30	5	New-base	39	5	67	0.10	19598	21	22
	25	New-base+ 1%dolomite	43	6	76	0.09	22985	32	18

Table 4.7 Rheological parameters of drilling mud mixed with additives (continued).

Testing Temp. (°C)	No.	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	26	New-base + 3%dolomite	43	6	74	0.10	21763	31	34
	27	New-base + 5%dolomite	47	9	75	0.15	16763	24	25
	31	New-base +1%rice husk ash	35	5	60	0.11	16481	21	36
	32	New-base +3%rice husk ash	32	5	54	0.11	14886	31	34
	33	New-base +5%rice husk ash	20	5	30	0.20	5155	21	19
	37	New-base+1%lime	46	8	77	0.12	20154	32	12
	38	New-base+3%lime	51	13	76	0.10	24291	26	19
	39	New-base +5%lime	41	10	62	0.18	11713	11	18
	43	New-base+1%starch	46	6	81	0.09	25222	31	15
	44	New-base+3%starch	40	4	72	0.07	25731	24	18
	45	New-base +5%starch	47	6	83	0.09	25014	26	19
60	8	New-base	28	5	46	0.16	9198	10	13
	28	New-base+ 1%dolomite	30	5	50	0.13	12251	20	8

Table 4.7 Rheological parameters of drilling mud mixed with additives (continued).

Testing Temp. (°C)	No.	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)		
60	29	New-base + 3%dolomite	31	6	51	0.13	12492	20	17
	30	New-base + 5%dolomite	38	6	64	0.12	16744	26	9
	34	New-base +1%rice husk ash	23	6	34	0.20	5801	24	10
	35	New-base +3%rice husk ash	21	4	35	0.13	8708	32	32
	36	New-base +5%rice husk ash	34	4	61	0.08	19784	22	35
	40	New-base+1%lime	33	9	48	0.22	7662	14	6
	41	New-base+3%lime	40	8	63	0.16	13467	15	18
	42	New-base +5%lime	34	8	51	0.18	9584	21	13
	46	New-base+1%starch	51	18	66	0.28	7634	23	25
	47	New-base+3%starch	129	58	142	0.37	10306	68	44
	48	New-base+5%starch	-	-	-	-	-	131	130

4.3.2 Rheological behavior of drilling mud

The rheological parameters of water-based drilling mud and drilling mud mixed with additive samples are summarized in Table 4.6. The additives are divided into five parts, consisting of fly ash, dolomite, rice husk ash, lime, and starch. The theological data of total test are shown in Appendix A. The Power Law model parameter in the term of flow behavior index (n) and consistency (k) is calculated by equation 3.6 and 3.7 as shown in the previous chapter. The index n indicated that all drilling 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 Power Law model. It is called pseudoplastic fluid. The trendy consistency factor of drilling mud sample increases as the increasing of fly ash. The constant is similar to the apparent viscosity of the fluid that described the thickness of the fluid. The Power Law model did not describe the behavior of drilling fluids exactly, but the constant n and k normally describe in the interest of hydraulic utilization that is used in hydraulic calculations.

4.3.3 Filtration properties of drilling mud

The aim of filtration is to create a low-permeability mud cake to seal between the wellbore and the formation. Control of fluid loss restricts the invasion of the formation by filtrate and minimizes the thickness of mud cake. Table 4.8 shows the average API static filtration loss within 30 minutes of drilling mud mixed with additives. Total data testing of filtration properties and mud cake thickness are displayed in Appendix A.

The plot of filtration properties of water-based drilling mud is measured at 30°C and elevated temperature (Figure 4.17). The filtration properties of drilling mud mixed with additives are shown in Figures 4.18 through 4.25. These graphs show time-dependent filtration behavior of water-based drilling mud and indicate that the fluid loss exponentially increases as the time increase. The decreasing of filtrate volume is resulted from continuous mudcake deposition and compactions until the formation of a constant thickness and stable mud cakes have been formed completely.

Table 4.8 API static filtrate loss of drilling mud mixed with additives.

Temp. (°C)	**No.**	**Filtrate loss (ml)**					
		1 min	**4 min**	**9 min**	**16 min**	**25 min**	**30 min**
30	1	2.5	5.5	8.5	11.5	14.5	16.0
60	2	2.5	6.5	9.5	13.0	16.5	18.0
90	3	3.0	6.5	11.0	14.5	18.5	20.0
30	4	2.5	6.0	10.0	13.5	17.5	19.5
	5	5.0	10.5	17.0	24.0	32.0	37.0
	6	9.0	17.0	26.0	36.0	47.0	53.0
60	7	2.5	7.5	12.5	17.0	21.5	24.0
	8	12.0	26.0	40.5	56.5	73.0	80.0
	9	13.0	25.5	41.0	58.0	74.5	83.5
90	10	4.5	9.5	15.5	20.0	25.0	27.0
	11	17.0	36.0	57.5	79.5	102.5	113.0
	12	19.0	37.0	59.5	82.0	105.5	116.5
30	13	2.5	6.0	9.0	12.0	15.5	17.0
	14	2.0	5.5	8.5	11.0	14.0	16.0
	15	2.0	4.5	8.0	11.5	14.5	16.0
	16	2.0	5.0	8.0	11.0	13.5	15.0
	17	3.0	5.5	9.0	12.5	16.0	17.5
	18	3.5	6.5	9.5	13.0	16.5	18.5
	19	2.5	6.0	10.0	13.0	16.0	17.0

Table 4.8 API static filtrate loss of drilling mud mixed with additives (continued).

Temp. (^oC)	No.	Filtrate loss (ml)					
		1 min	**4 min**	**9 min**	**16 min**	**25 min**	**30 min**
30	20	2.5	5.5	8.5	11.5	14.5	16.0
	21	2.5	5.5	8.5	12.0	15.0	16.5
	22	2.5	5.5	9.5	12.5	15.5	17.0
	23	2.0	5.0	8.0	10.5	13.5	15.0
	24	2.0	4.5	7.5	10.0	12.5	14.0
	25	5.0	11.5	18.0	26.0	33.0	36.5
	26	5.5	13.0	21.0	28.5	37.0	41.5
	27	6.5	13.0	21.0	28.5	37.0	41.0
60	28	9.0	18.5	27.0	37.5	49.5	55.0
	29	8.0	18.0	28.5	40.5	53.0	59.0
	30	9.5	20.5	32.5	45.5	59.0	65.0
30	31	4.5	10.5	18.0	22.0	29.0	32.0
	32	2.5	10.0	15.0	21.0	27.5	30.5
	33	2.0	9.0	13.5	19.0	26.0	28.5
60	34	7.5	17.0	27.0	37.5	50.0	56.0
	35	7.5	16.5	26.0	36.0	48.0	55.0
	36	5.5	15.0	21.0	29.0	38.0	42.0
30	37	6.0	13.0	20.5	28.5	36.5	40.5
	38	7.0	16.5	25.0	35.0	44.0	49.5
	39	8.0	17.5	26.0	36.0	47.5	51.5
60	40	8.0	17.5	28.0	40.0	52.5	58.5
	41	9.0	19.5	32.0	45.0	59.0	66.0
	42	13.0	24.5	40.0	57.0	73.0	83.0
30	43	5.0	10.5	17.0	22.5	30.0	33.0
	44	5.0	10.0	16.0	22.5	29.0	32.5
	45	4.5	10.0	15.5	21.5	27.5	30.5
60	46	4.5	7.5	10.5	13.5	17.0	18.0
	47	2.0	4.0	5.5	6.5	8.0	8.5
	48	2.0	3.0	4.5	5.5	6.0	7.0

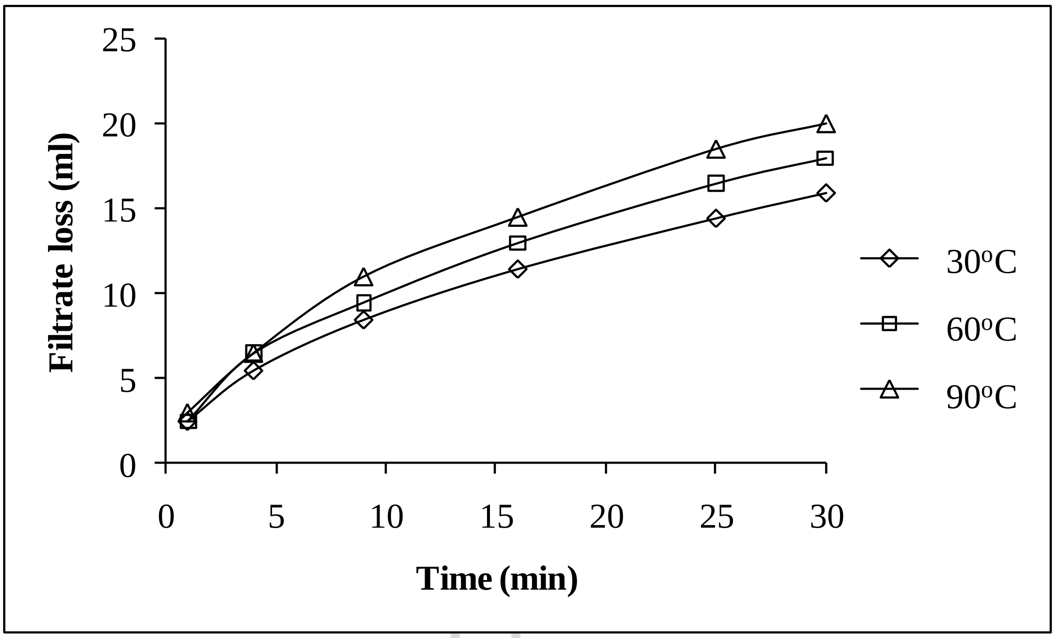

Figure 4.17 Static filtration and time of water-based drilling mud.

The drilling mud mixed with additives on filtration properties at 30°C has shown in Figures 4.18 through 4.22. The static filtration curves indicate that at water-based drilling mud compares the drilling mud mixed with 1, 3 and 5 percentages of additives at 30°C. They are tested for determine the appropriate amount of additives for control filtration loss of drilling mud after mixing with fly ash.

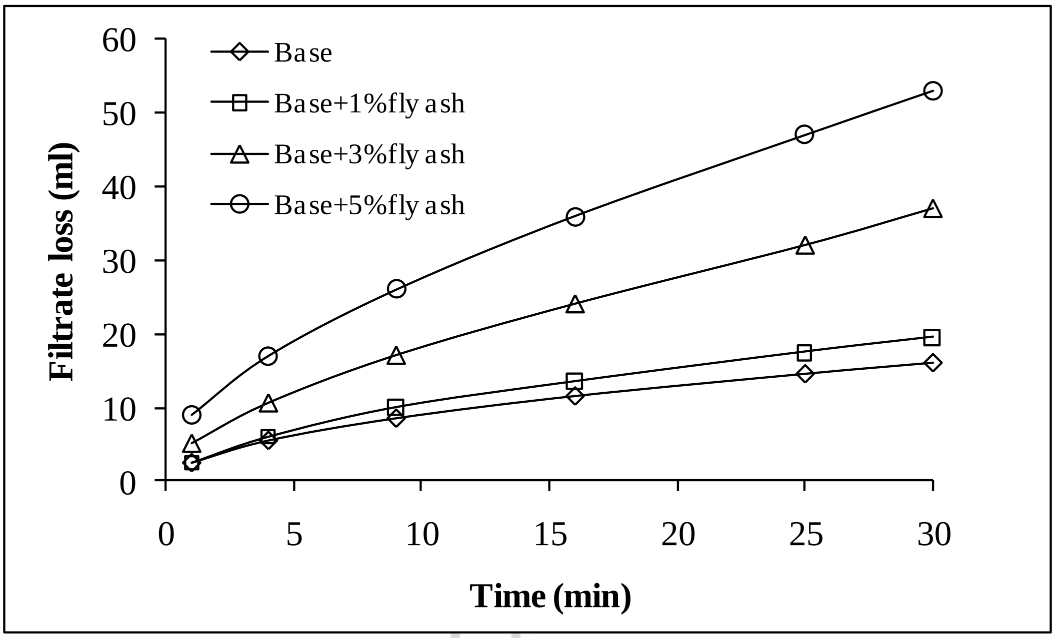

Figure 4.18 Static filtration of fly ash versus time at 30°C.

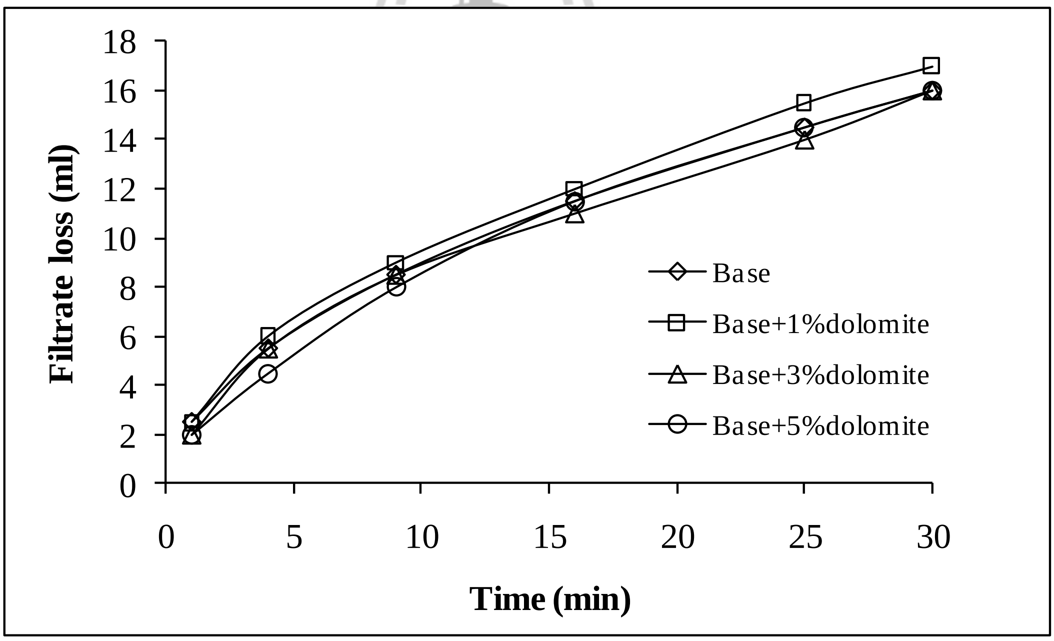

Figure 4.19 Static filtration of dolomite versus time at 30°C.

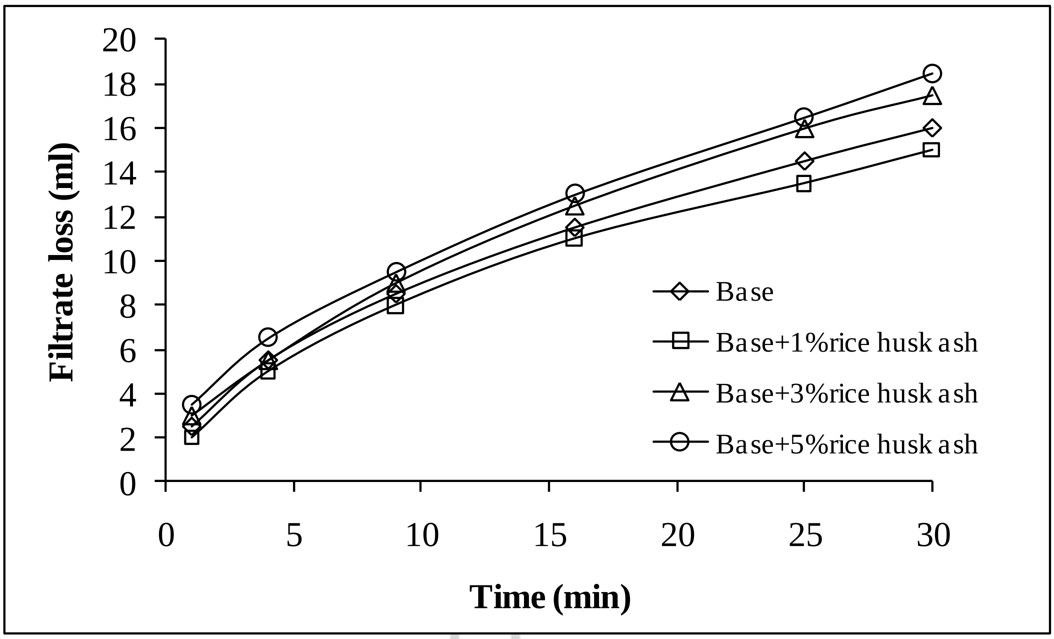

Figure 4.20 Static filtration of rice husk ash versus time at 30^{o}C.

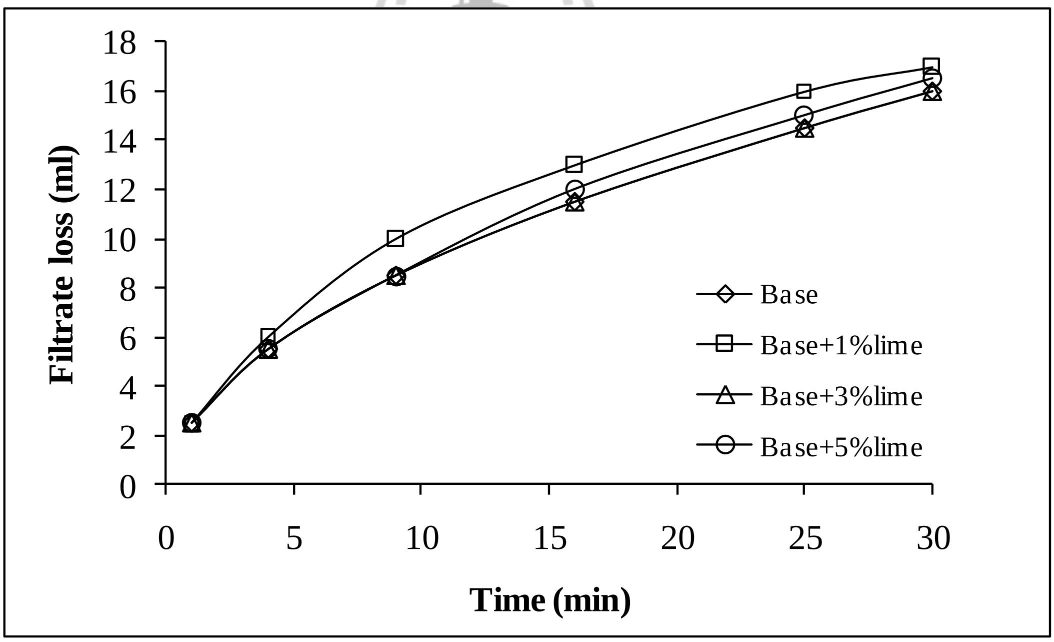

Figure 4.21 Static filtration of lime versus time at 30^{o}C.

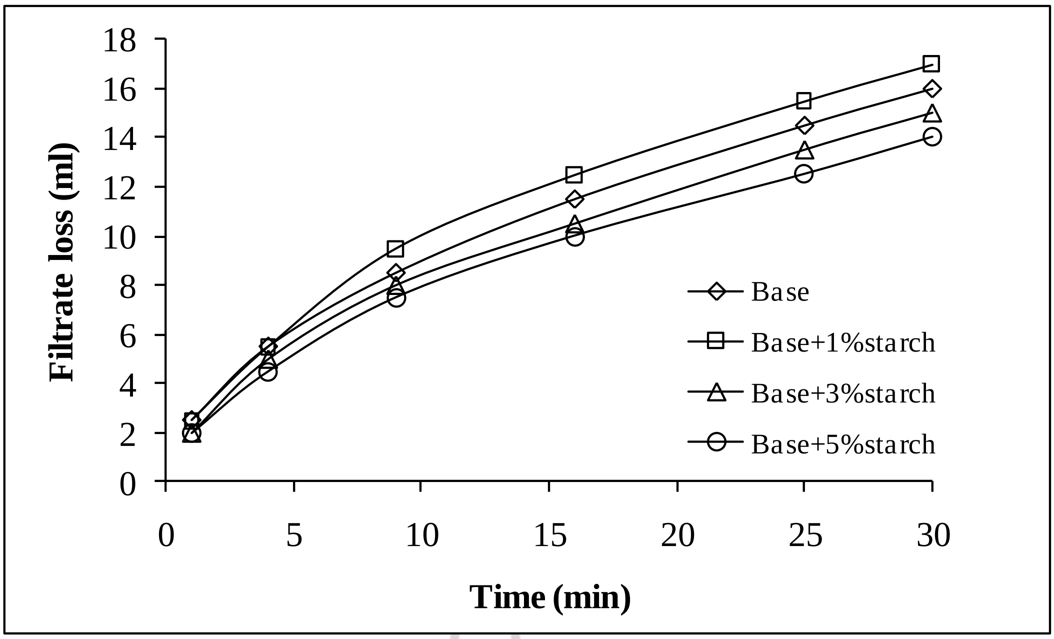

Figure 4.22 Static filtration of starch versus time at 30°C.

The appropriate additive is 3 and 5 percentages of starch. They can control fluid loss both low and high temperatures. The other additives include 3, 5 percentages of dolomite, respectively 1 percentage of rice husk ash and 3 percentages of lime, decreasing the fluid loss but it is not significant for drilling mud. Filtration behavior analyses of the drilling mud at 60 and 90°C are demonstrated in Figure 4.23. The static fluid loss values of drilling mud mixed with 3 percentages of fly ash indicate to the increasing of filtration. However, other properties of 3 percentages of fly ash are improved the drilling mud characterizations. Therefore, the drilling mud mixed with 3 percentages of fly ash is used to new-base composition of drilling mud.

The new-base drilling mud mixed with additives is displayed in Figures 4.24 through 4.31 that tested to solve the problem of filtration and improve rheological properties.

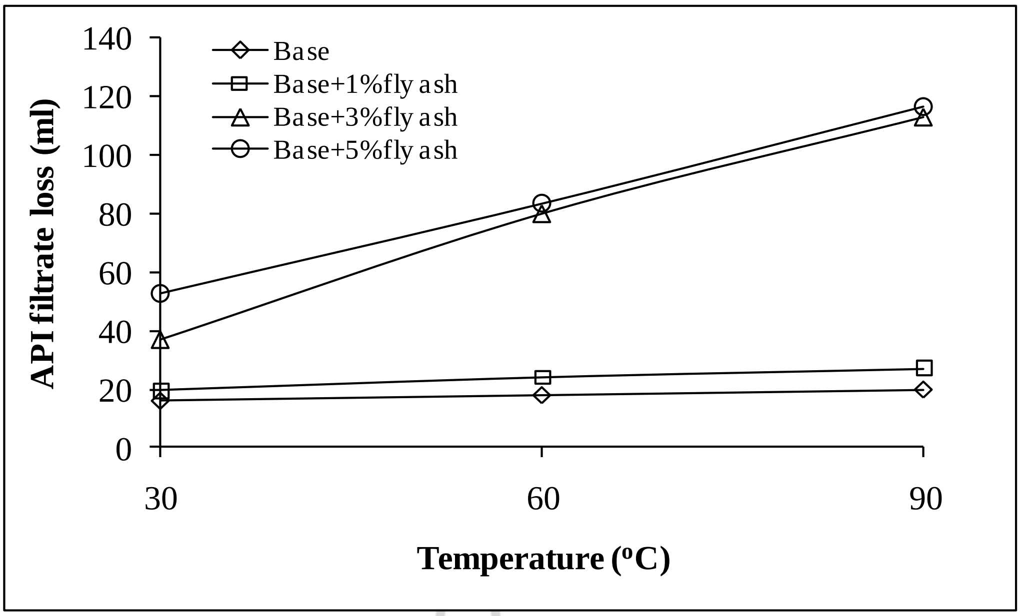

Figure 4.23 API filtrate loss at 30 minutes of drilling mud.

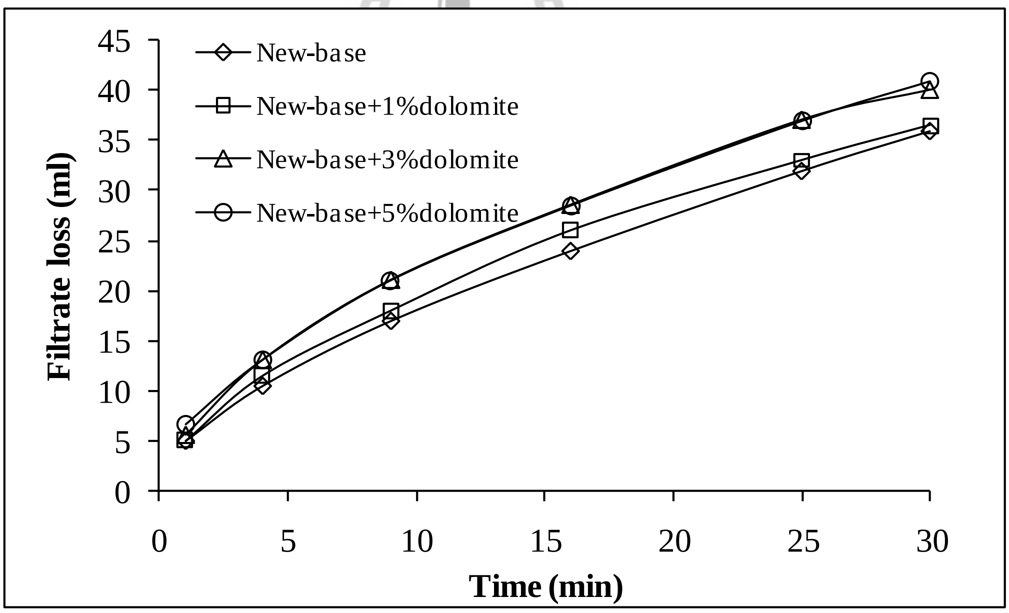

Figure 4.24 Static filtration of dolomite in new-base mud versus time at 30^{o}C.

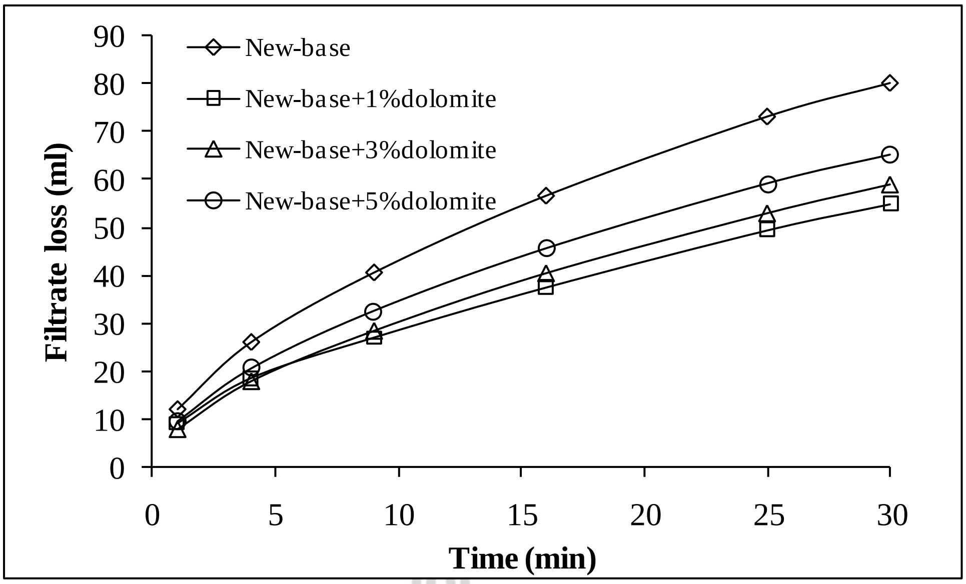

Figure 4.25 Static filtration of dolomite in new-base mud versus time at 60^{o}C.

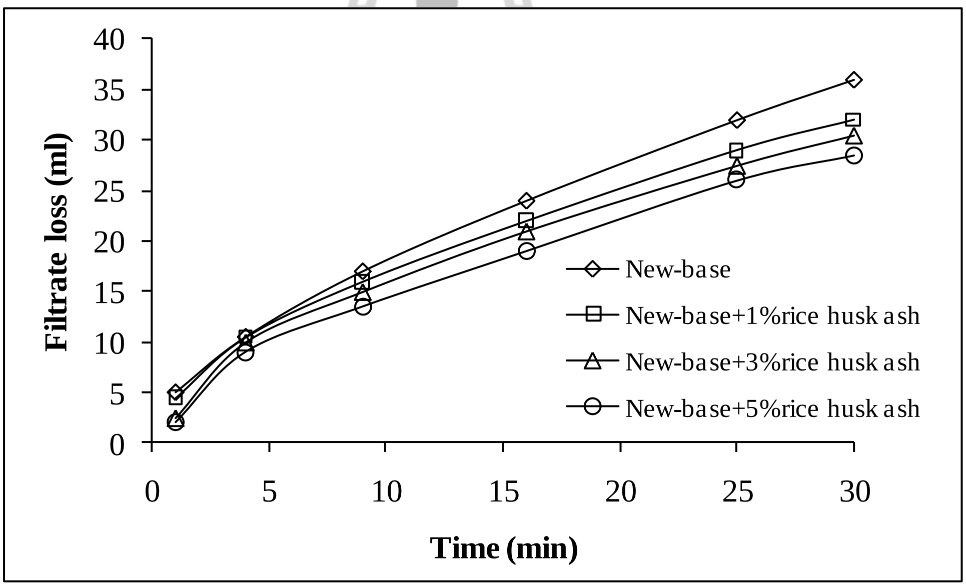

Figure 4.26 Static filtration of rice husk ash in new-base mud versus time at 30^{o}C.

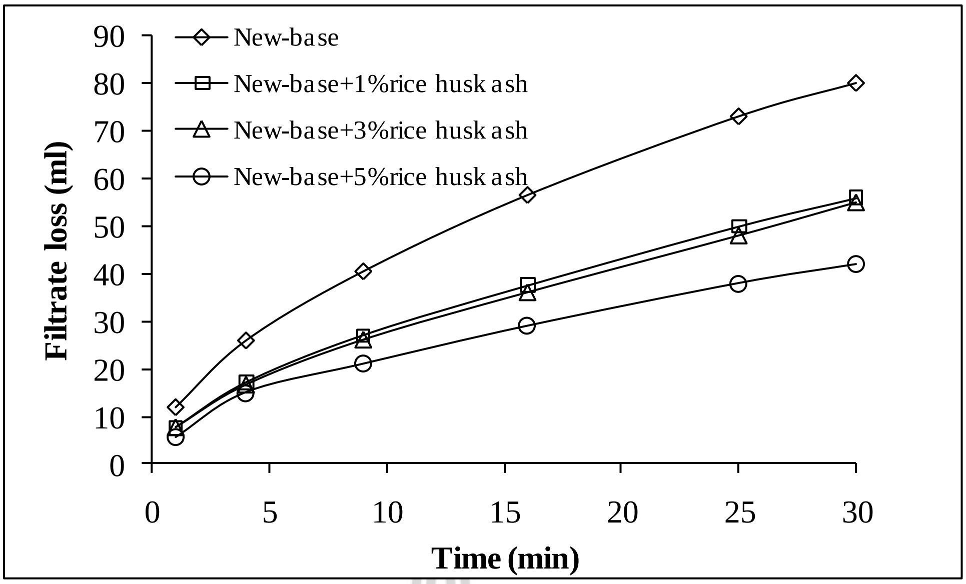

Figure 4.27 Static filtration of rice husk ash in new-base mud versus time at 60^{o}C.

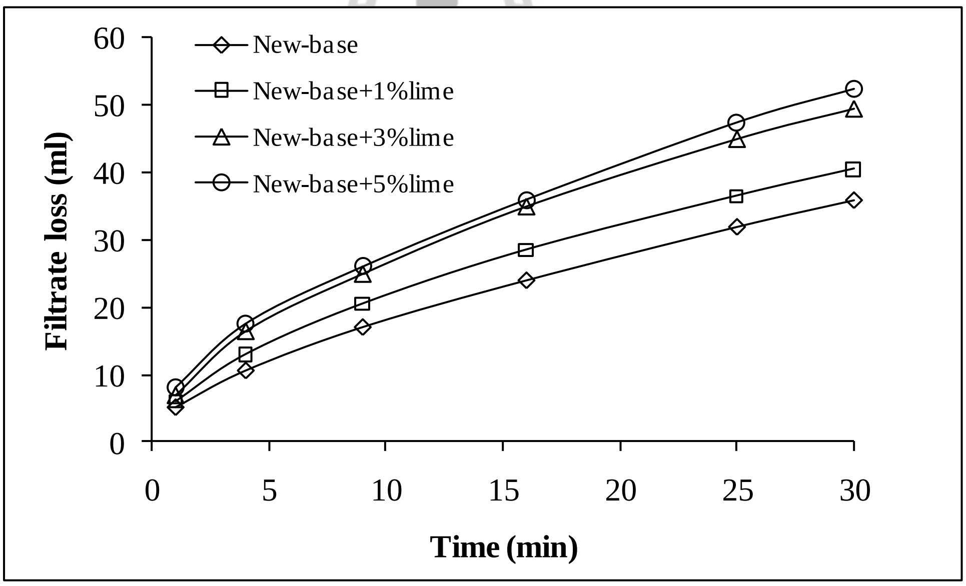

Figure 4.28 Static filtration of lime in new-base mud versus time at 30^{o}C.

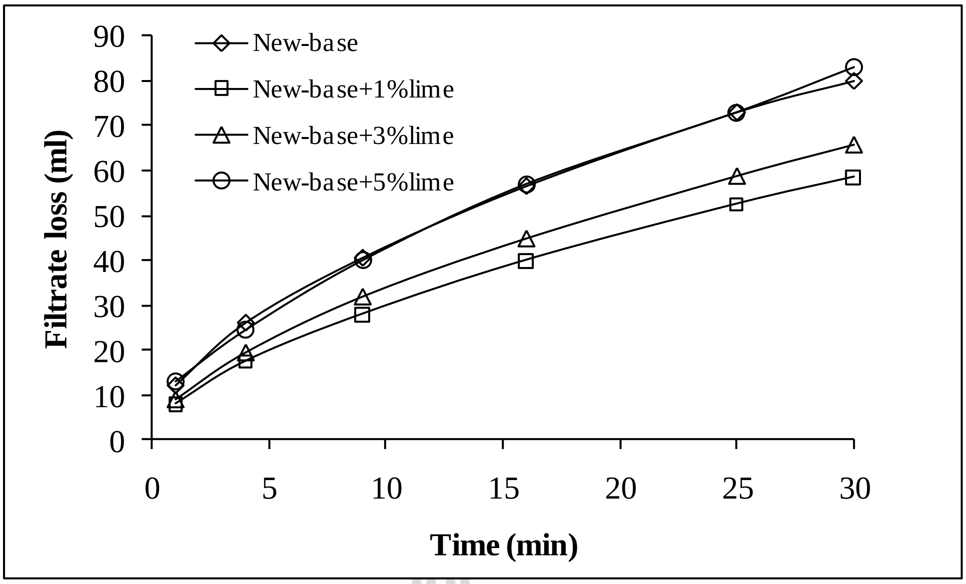

Figure 4.29 Static filtration of lime in new-base mud versus time at 60^{o}C.

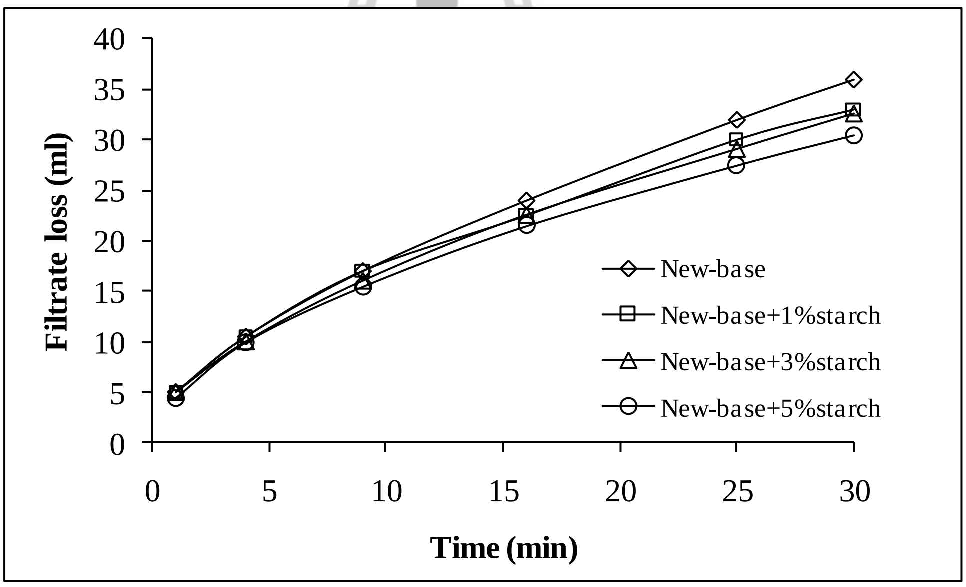

Figure 4.30 Static filtration of starch in new-base mud versus time at 30^{o}C.

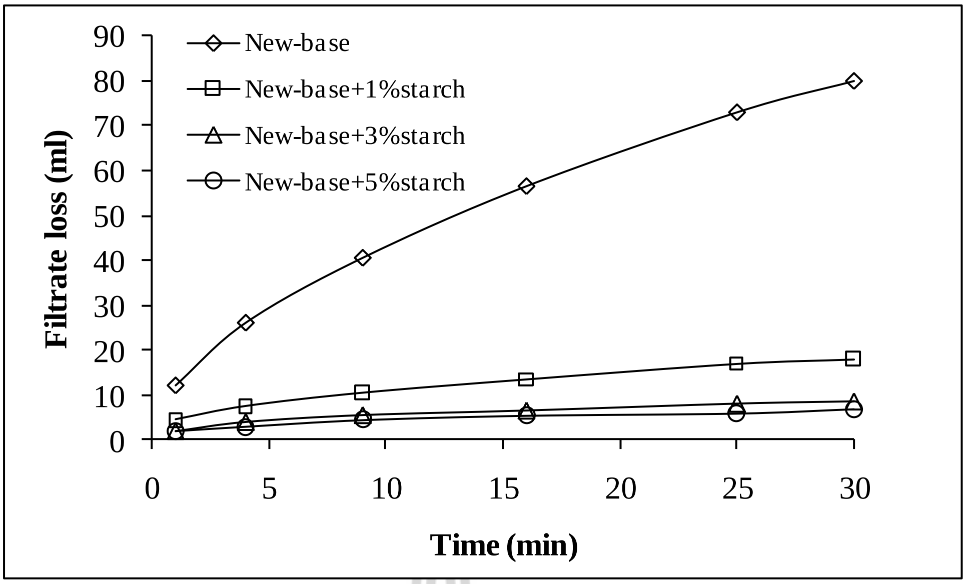

Figure 4.31 Static filtration of starch in new-base mud versus time at 60^{o}C.

The mudcake thickness of the drilling mud mixed with additives is shown in Figure 4.32. The new-base drilling mud mixed with additives displayed in Figures 4.33 through 4.36. The histograms show that the mudcake thickness is depending on the additives concentration and temperature increasing. The mudcake qualities deposited by the additive containing drilling mud are measured. The slickness and toughness of starch in drilling mud are more than water-based drilling mud, but the dolomite, rice husk ash, and lime are less than water-based drilling mud. Because of the starch property could be improved the stability and lubricity of mudcake. The quality of mudcake that referred to build up on the borehole wall, helping for reduces the formation damage and the chance of differential sticking of drill pipe.

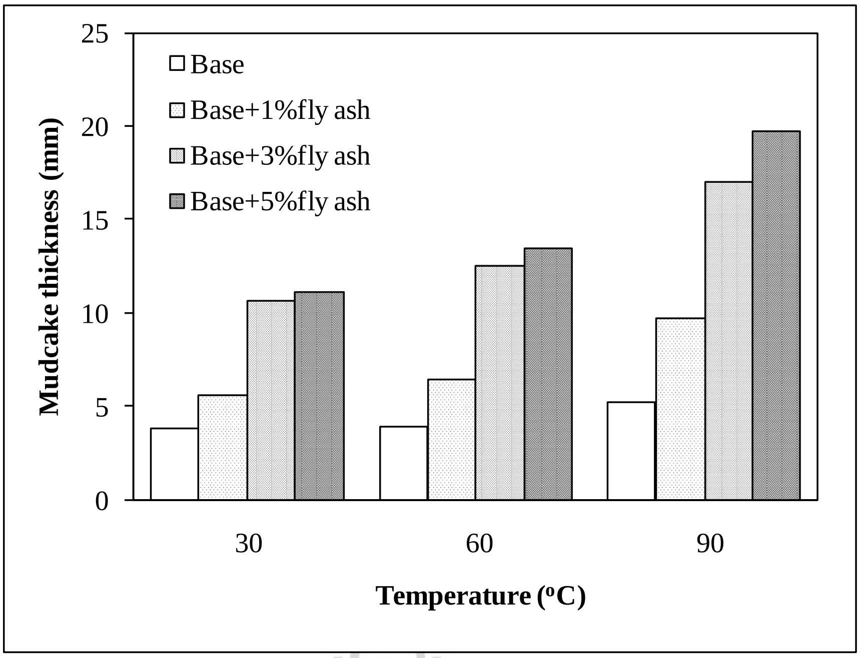

Figure 4.32 Mudcake thickness of fly ash containing drilling mud at 30, 60 and 90°C.

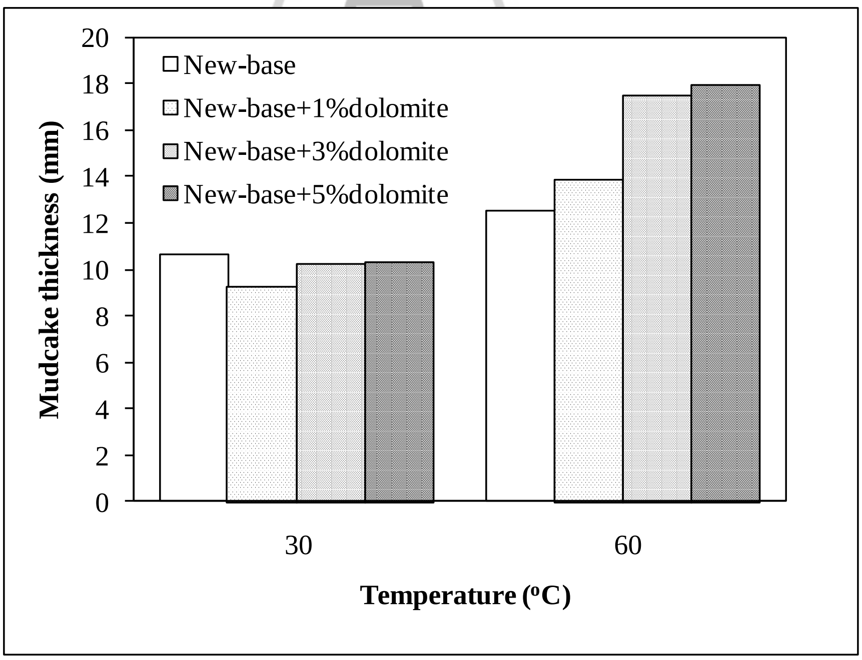

Figure 4.33 Mudcake thickness of dolomite in new-base at 30 and 60°C.

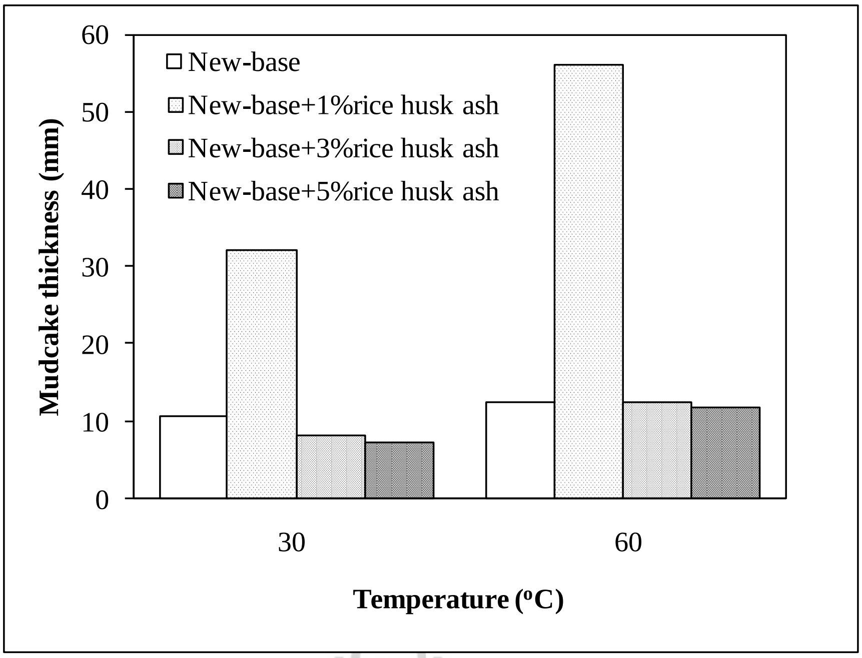

Figure 4.34 Mudcake thickness of rice husk ash in new-base at 30 and 60^{o}C.

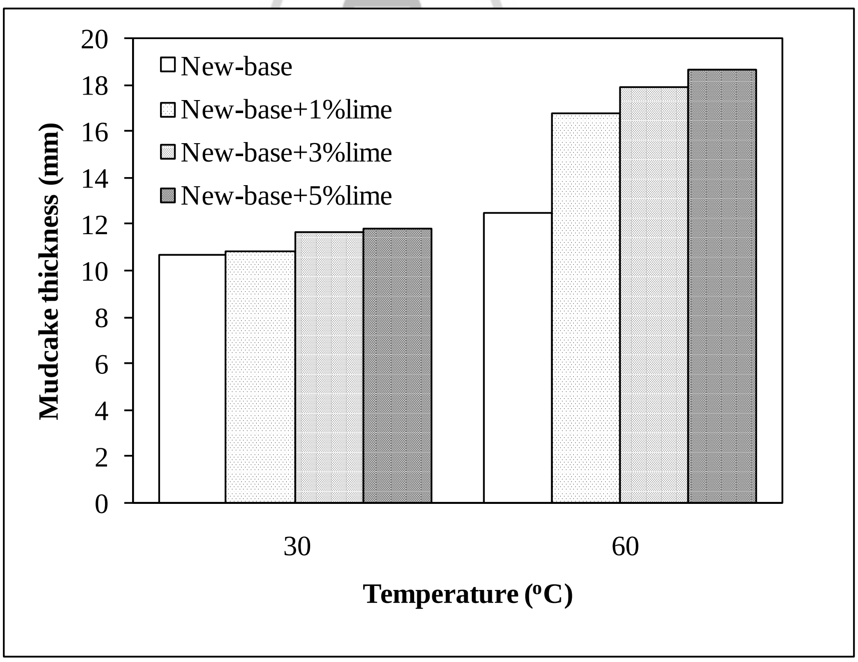

Figure 4.35 Mudcake thickness of lime in new-base at 30 and 60^{o}C.

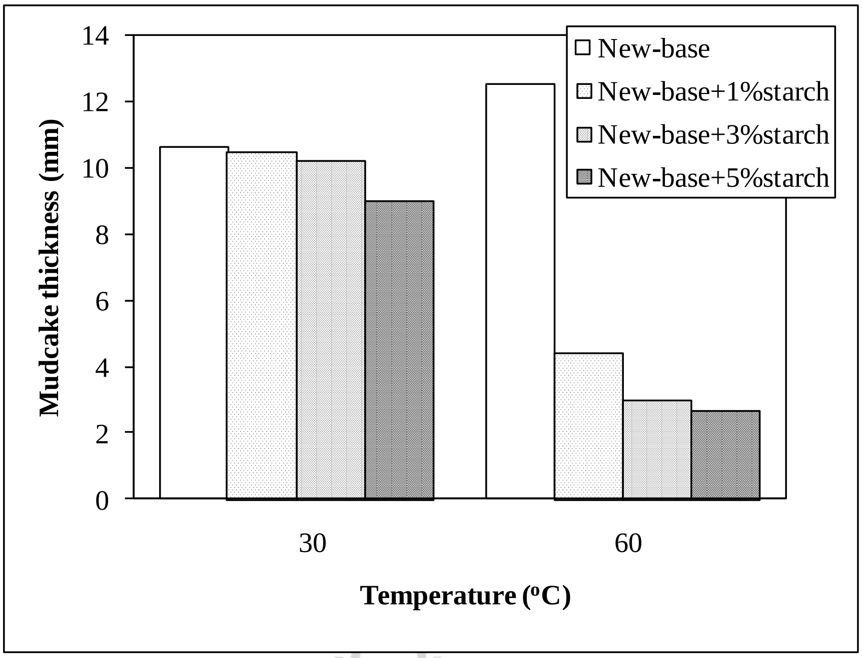

Figure 4.36 Mudcake thickness of starch in new-base at 30 and 60^{o}C.

4.3.4 Density of drilling mud

Hydrostatic pressure is required to prevent the borehole wall from caving in and to keep formation fluid from entering the wellbore. The results of density of drilling mud after mixing additives describe by Figures 4.37 through 4.40. The result demonstrates the ability of additives to provide weight to drilling mud. The range of drilling mud mixed with additives is 1.10 to 1.14 g/cm^3 or 9.16 to 9.50 lb/gal. The density slightly decreases as the temperature increase; however, the concentration of additives increased as the density increased.

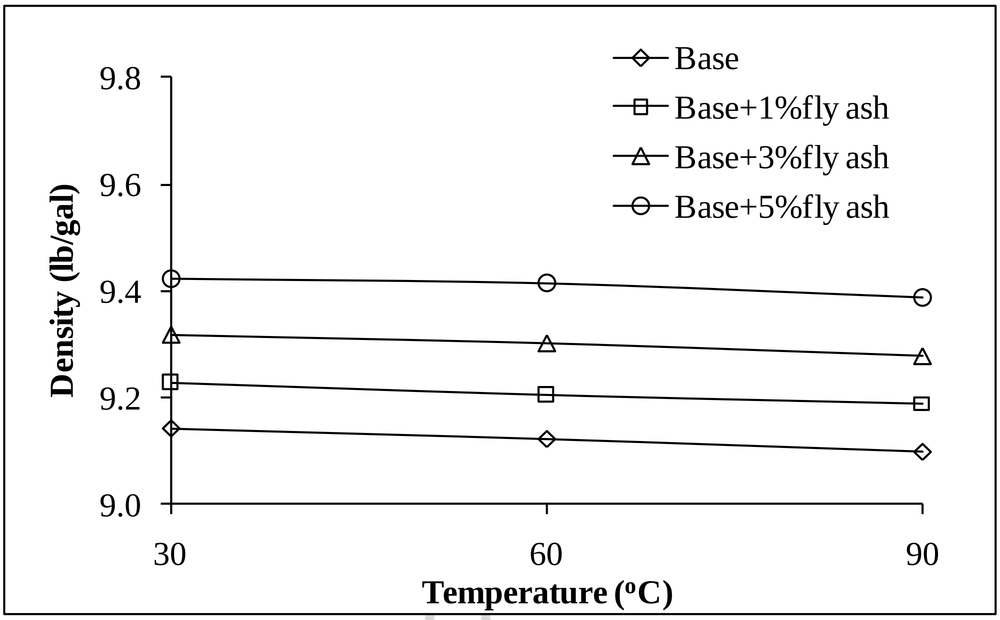

Figure 4.37 Density of fly ash containing mud at 30, 60 and 90°C.

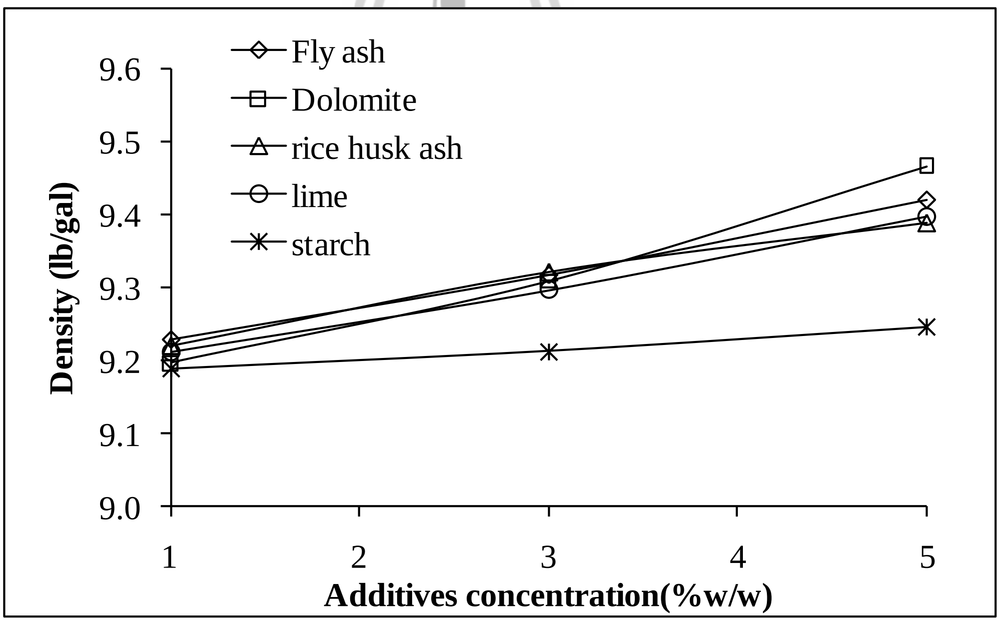

Figure 4.38 Density of additives containing mud at 30°C.

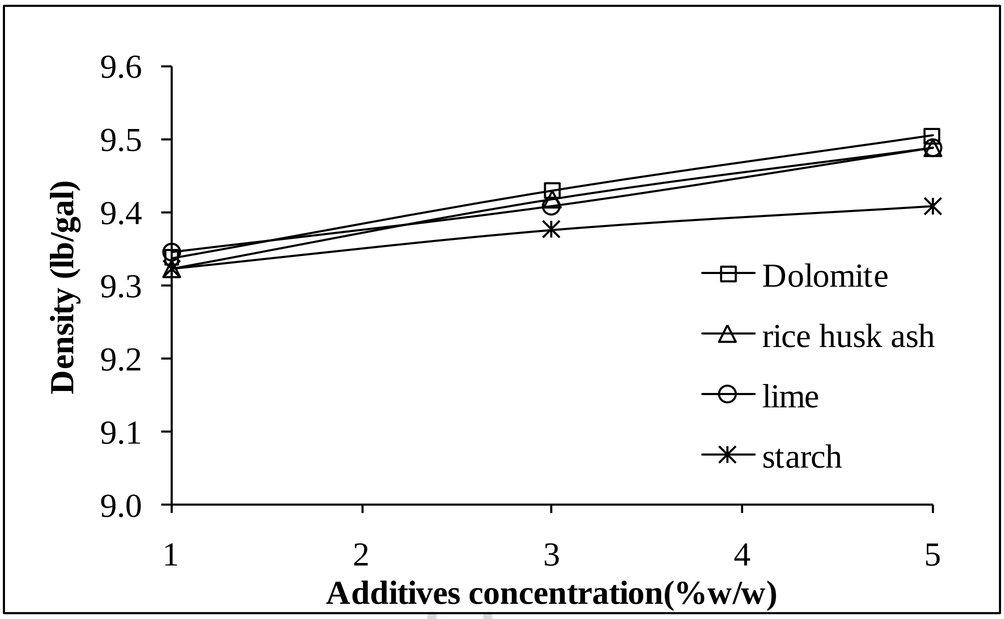

Figure 4.39 Density of additives containing new-base mud at 30^{o}C.

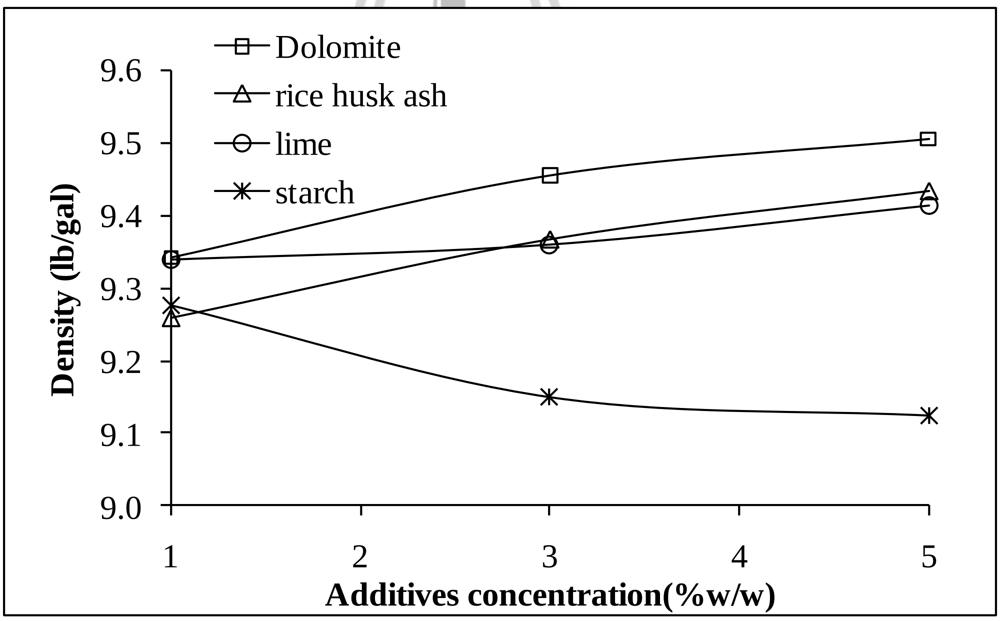

Figure 4.40 Density of additives containing new-base mud at 60^{o}C.

4.3.5 The pH of drilling mud

Table 4.9 and Figures 4.41 through 4.47 summarize the test results on the pH of drilling mud before and after mixing additives at 30, 60 and 90^{o}C. They describe the pH of mud and mud filtrates for filtration test.

Table 4.9 The pH of drilling mud mixed with additives.

No.	Sample	pH reading			Average
		#1	#2	#3	
1	Mud	9.98	9.94	9.95	9.95
	Mud filtrate	9.77	9.70	9.705	9.72
2	Mud	9.78	9.75	9.75	9.76
	Mud filtrate	9.62	9.61	9.61	9.61
3	Mud	9.50	9.52	9.52	9.51
	Mud filtrate	9.38	9.37	9.36	9.37
4	Mud	10.91	10.86	10.87	10.88
	Mud filtrate	10.60	10.63	10.61	10.61
5	Mud	11.45	11.48	11.46	11.46
	Mud filtrate	11.60	11.60	11.59	11.60
6	Mud	11.35	11.40	11.66	11.47
	Mud filtrate	11.69	11.69	11.66	11.68
7	Mud	10.59	10.61	10.73	10.64
	Mud filtrate	10.85	10.72	10.72	10.76
8	Mud	11.13	11.21	11.29	11.21
	Mud filtrate	11.68	11.66	11.67	11.67
9	Mud	11.30	11.37	11.41	11.36
	Mud filtrate	11.60	11.61	11.61	11.61
10	Mud	10.30	10.42	10.48	10.40
	Mud filtrate	10.90	10.90	10.91	10.90
11	Mud	10.97	11.10	11.18	11.08
	Mud filtrate	11.43	11.43	11.45	11.44
12	Mud	11.15	11.16	11.32	11.21
	Mud filtrate	11.44	11.43	11.46	11.44
13	Mud	9.90	9.93	9.92	9.92
	Mud filtrate	9.64	9.67	9.62	9.64

Table 4.9 The pH of drilling mud mixed with additives (continued).

No.	Sample	pH reading			Average
		#1	#2	#3	
14	Mud	9.93	9.92	9.95	9.93
	Mud filtrate	9.69	9.67	9.65	9.67
15	Mud	9.99	9.95	9.94	9.96
	Mud filtrate	9.79	9.70	9.66	9.72
16	Mud	9.89	9.86	9.84	9.86
	Mud filtrate	9.69	9.70	9.71	9.70
17	Mud	9.88	9.80	9.81	9.83
	Mud filtrate	9.66	9.65	9.64	9.65
18	Mud	9.74	9.75	9.71	9.73
	Mud filtrate	9.63	9.60	9.57	9.60
19	Mud	10.31	10.15	10.12	10.19
	Mud filtrate	9.89	9.86	9.82	9.86
20	Mud	10.47	10.48	10.46	10.47
	Mud filtrate	10.08	10.06	10.09	10.08
21	Mud	10.87	10.84	10.88	10.86
	Mud filtrate	10.70	10.71	10.7	10.70
22	Mud	9.89	9.83	9.85	9.86
	Mud filtrate	9.74	9.67	9.71	9.71
23	Mud	9.82	9.79	9.78	9.80
	Mud filtrate	9.72	9.66	9.62	9.67
24	Mud	9.72	9.72	9.7	9.71
	Mud filtrate	9.50	9.54	9.53	9.52
25	Mud	11.52	11.53	11.56	11.54
	Mud filtrate	11.64	11.64	11.65	11.64
26	Mud	11.46	11.48	11.47	11.47
	Mud filtrate	11.62	11.64	11.63	11.63
27	Mud	11.47	11.44	11.46	11.46
	Mud filtrate	11.58	11.61	11.63	11.61
28	Mud	11.22	11.33	11.39	11.31
	Mud filtrate	11.62	11.66	11.68	11.65
29	Mud	11.12	11.17	11.25	11.18
	Mud filtrate	11.45	11.50	11.55	11.50
30	Mud	10.87	10.95	11.00	10.94
	Mud filtrate	11.40	11.43	11.45	11.43

Table 4.9 The pH of drilling mud mixed with additives (continued).

No.	Sample	pH reading			Average
		#1	#2	#3	
31	Mud	11.20	11.31	11.31	11.27
	Mud filtrate	11.30	11.37	11.36	11.34
32	Mud	11.06	11.07	11.12	11.08
	Mud filtrate	11.19	11.23	11.23	11.22
33	Mud	10.70	10.73	10.81	10.75
	Mud filtrate	11.16	11.18	11.19	11.18
34	Mud	10.82	10.88	10.94	10.88
	Mud filtrate	11.32	11.35	11.34	11.34
35	Mud	10.78	10.87	10.94	10.86
	Mud filtrate	11.25	11.28	11.27	11.27
36	Mud	10.59	10.65	10.71	10.65
	Mud filtrate	11.14	11.18	11.16	11.16
37	Mud	11.53	11.51	11.53	11.52
	Mud filtrate	11.67	11.68	11.68	11.68
38	Mud	11.52	11.52	11.50	11.51
	Mud filtrate	11.64	11.71	11.69	11.68
39	Mud	11.49	11.52	11.5	11.50
	Mud filtrate	11.60	11.67	11.72	11.66
40	Mud	11.19	11.19	11.20	11.19
	Mud filtrate	11.43	11.46	11.50	11.46
41	Mud	11.08	11.12	11.14	11.11
	Mud filtrate	11.38	11.44	11.44	11.42
42	Mud	11.00	11.08	11.12	11.07
	Mud filtrate	11.43	11.48	11.53	11.48
43	Mud	11.26	11.25	11.28	11.26
	Mud filtrate	11.40	11.47	11.48	11.45
44	Mud	11.17	11.26	11.24	11.22
	Mud filtrate	11.32	11.35	11.32	11.33
45	Mud	11.19	11.20	11.22	11.20
	Mud filtrate	11.30	11.32	11.32	11.31
46	Mud	10.86	10.86	10.95	10.89
	Mud filtrate	11.36	11.42	11.43	11.40
47	Mud	10.68	10.65	10.74	10.69
	Mud filtrate	11.23	11.17	11.24	11.21

Table 4.9 The pH of drilling mud mixed with additives (continued).

No.	Sample	pH reading			Average
		#1	#2	#3	
48	Mud	10.67	10.66	10.65	10.66
	Mud filtrate	11.35	11.03	10.86	11.08

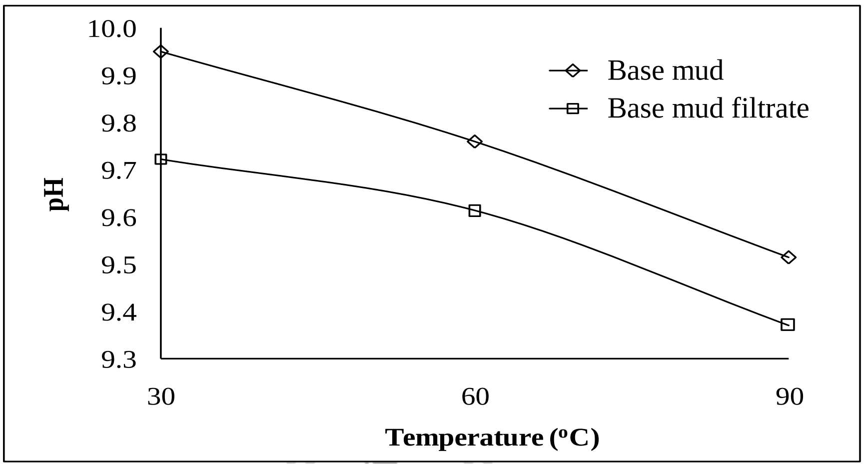

Figure 4.41 pH of water-based drilling mud.

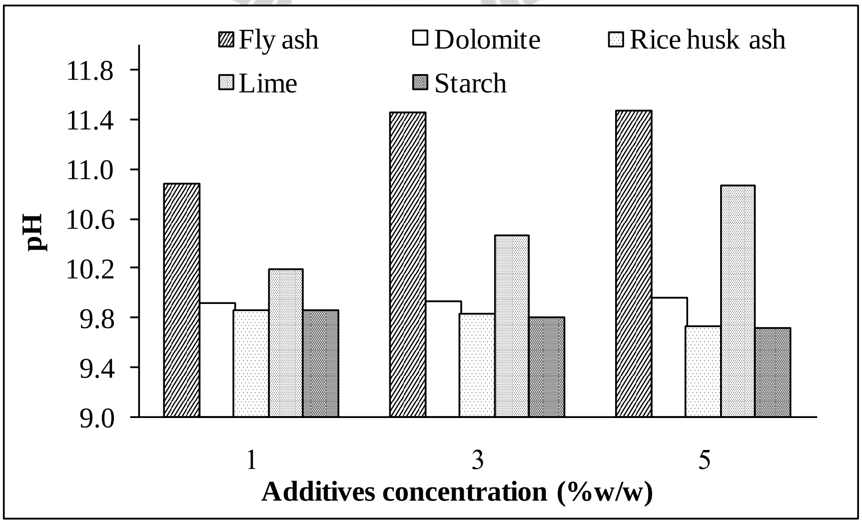

Figure 4.42 pH of drilling mud mixed additives at 30°C.

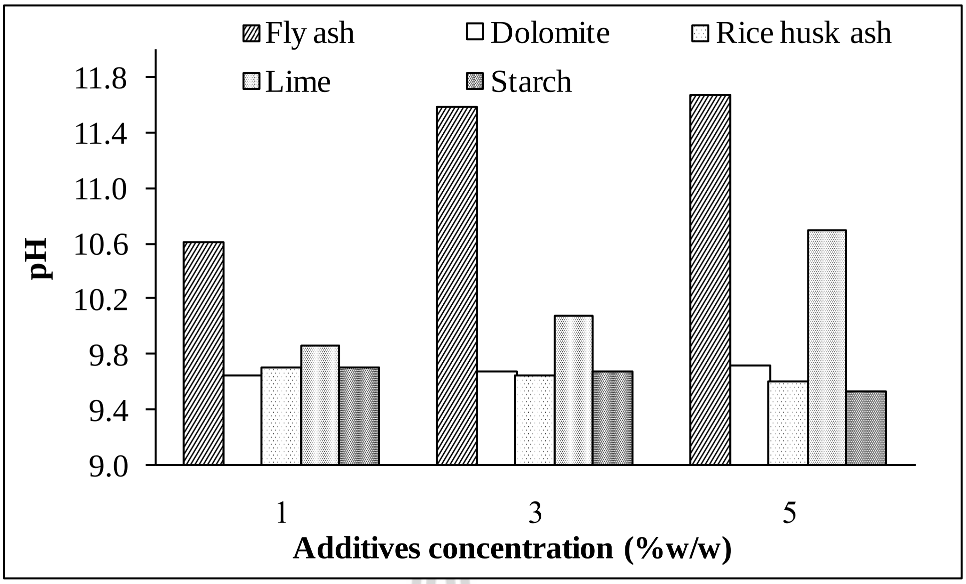

Figure 4.43 pH of mud filtrate for additives containing mud at 30°C.

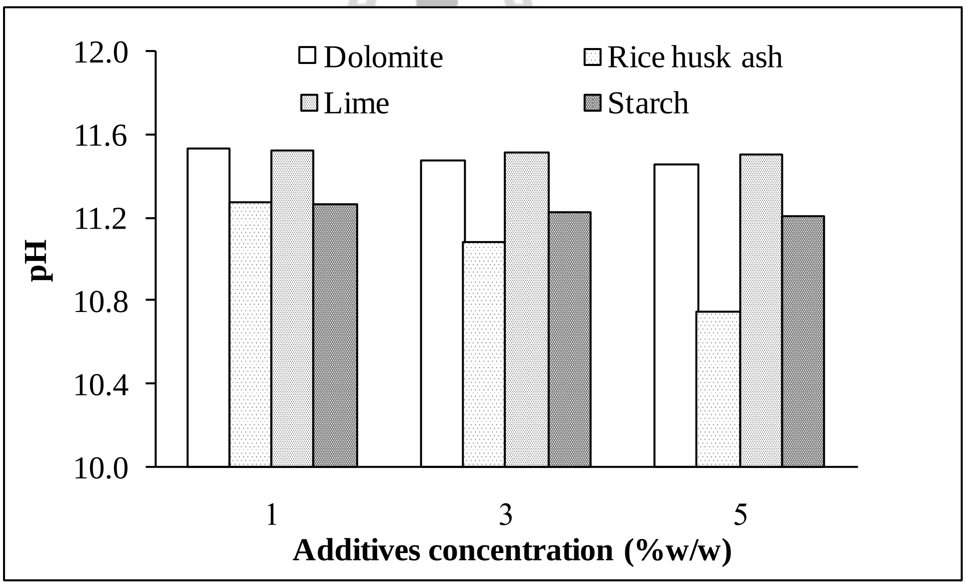

Figure 4.44 pH of new-base mud mixed additives at 30°C.

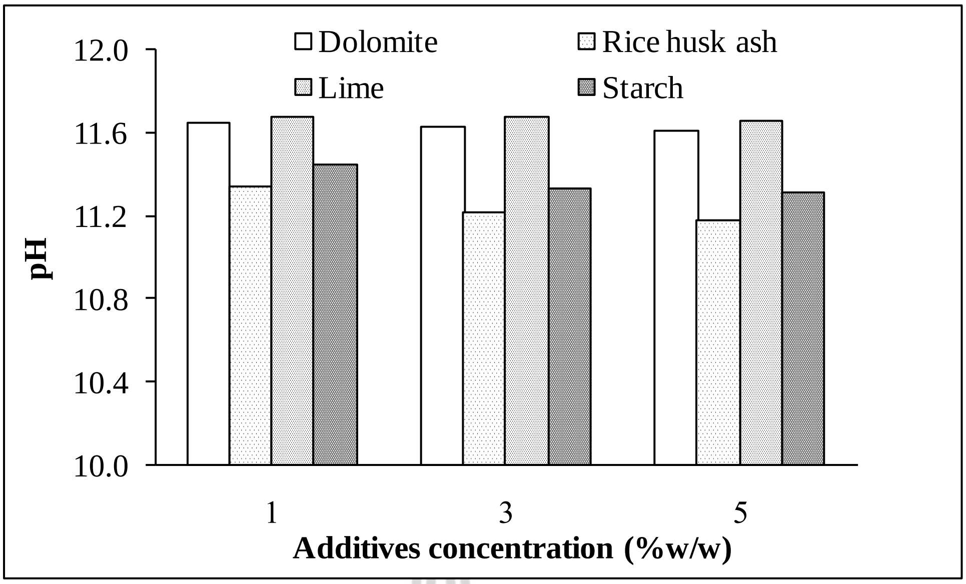

Figure 4.45 pH of mud filtrate for additives containing mud at 30^{o}C.

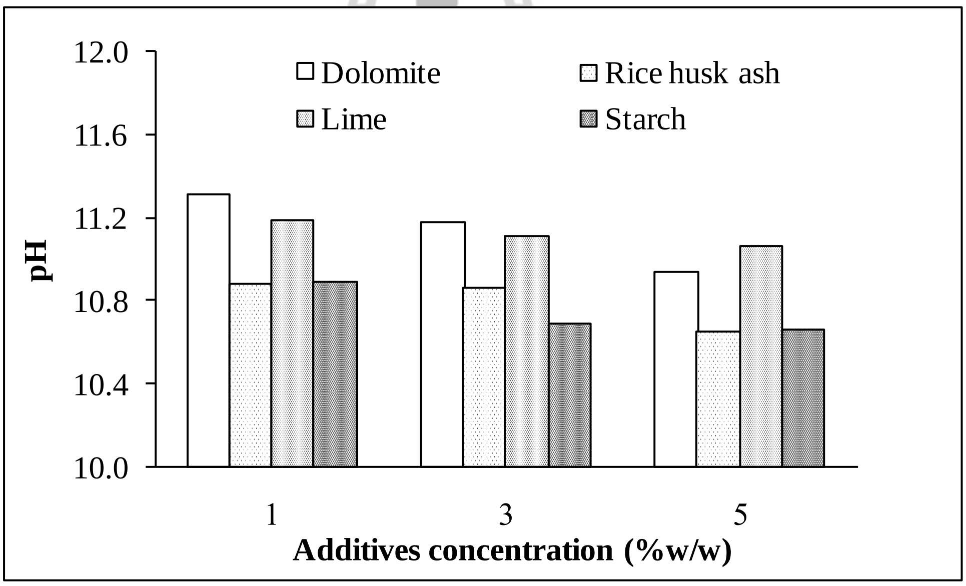

Figure 4.46 pH of new-base mud mixed additives at 60^{o}C.

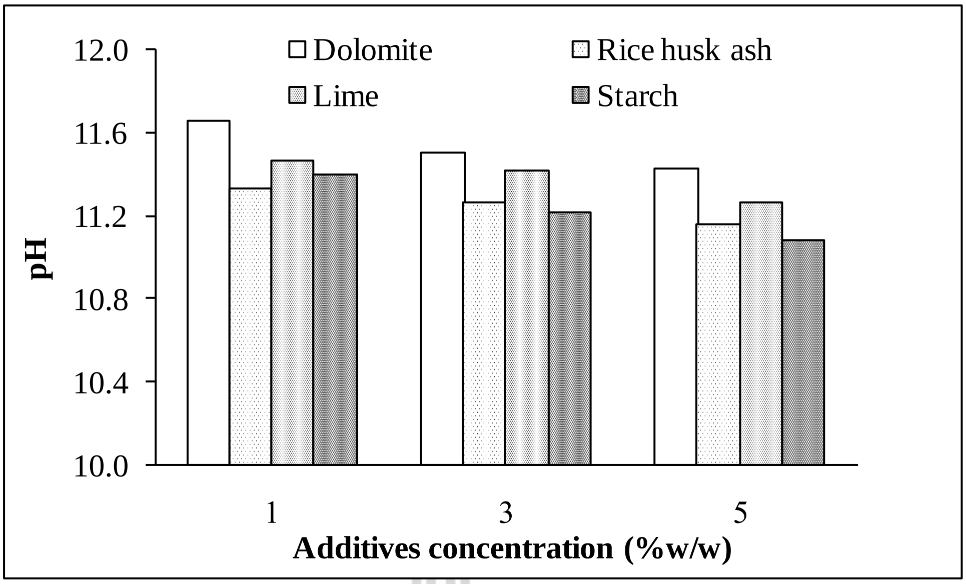

Figure 4.47 pH of mud filtrate for additives containing mud at 60^{o}C.

The result indicates that the pH increased as the increasing concentration of fly ash and lime, but the pH is slightly decreased when the dolomite, rice husk ash and starch concentration increased. Temperature effect to the pH value by the increasing of temperature causes the pH decreasing. The pH of the filtrate for filtration test is more than the pH of drilling mud.

4.3.6 Solid content in drilling mud

Solids are usually classified as high gravity solid (HGS) that referred to barite and other weighting agents. Low gravity solid (LGS) consists of clays, polymers and bridging materials deliberately put in the mud, plus drilled solids from dispersed cuttings and ground rock. The amount and type of solids in the mud affect a number of drilling mud properties. The results of solid content describe in Figures 4.48 through 4.51.

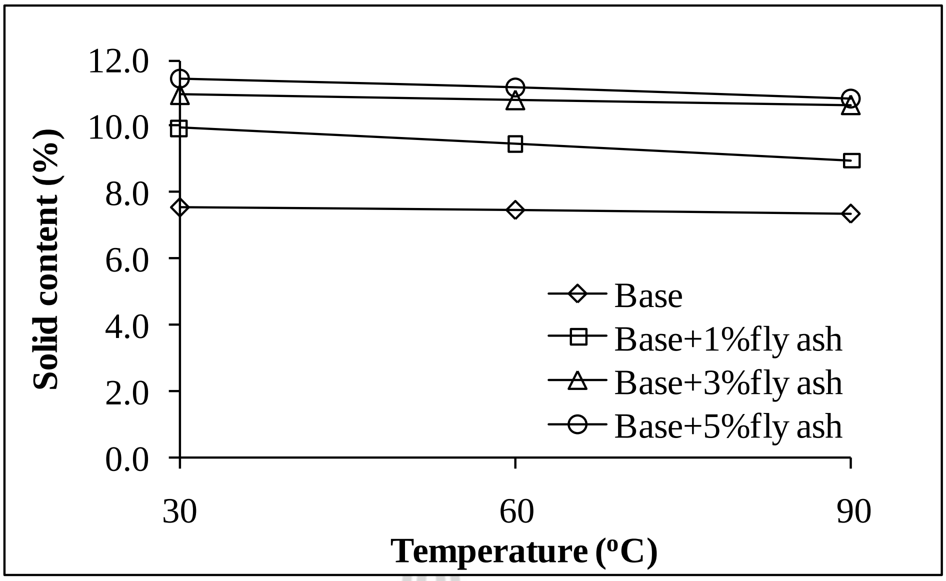

Figure 4.48 Solid content of drilling mud mixed with fly ash at 30, 60 and 90^{o}C.

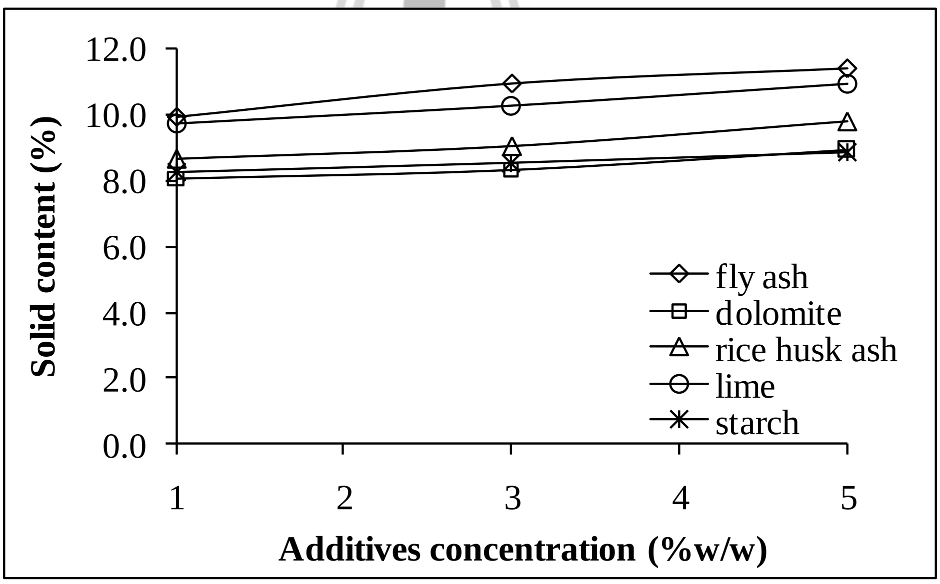

Figure 4.49 Solid content of drilling mud mixed with additives at 30^{o}C.

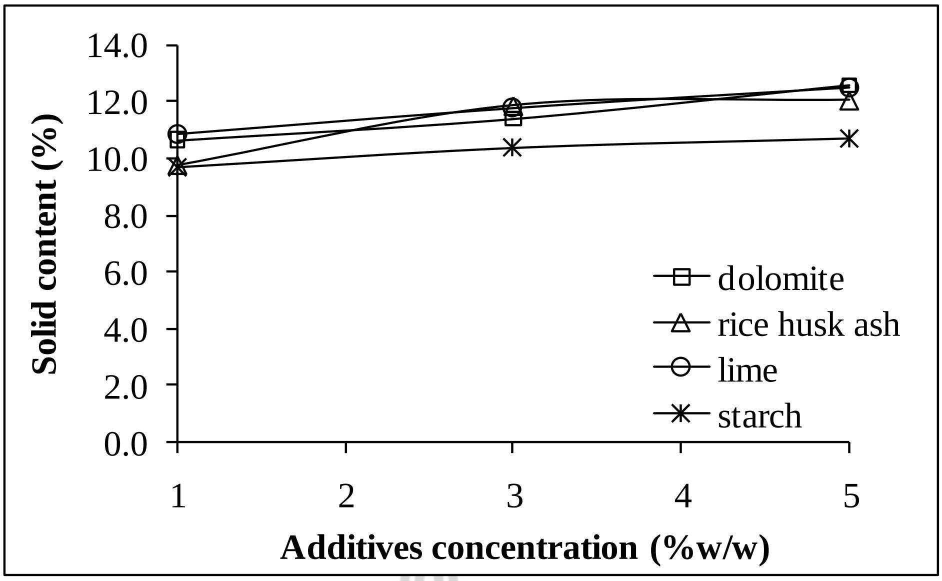

Figure 4.50 Solid content of new-base mud mixed with additives at 30^{o}C.

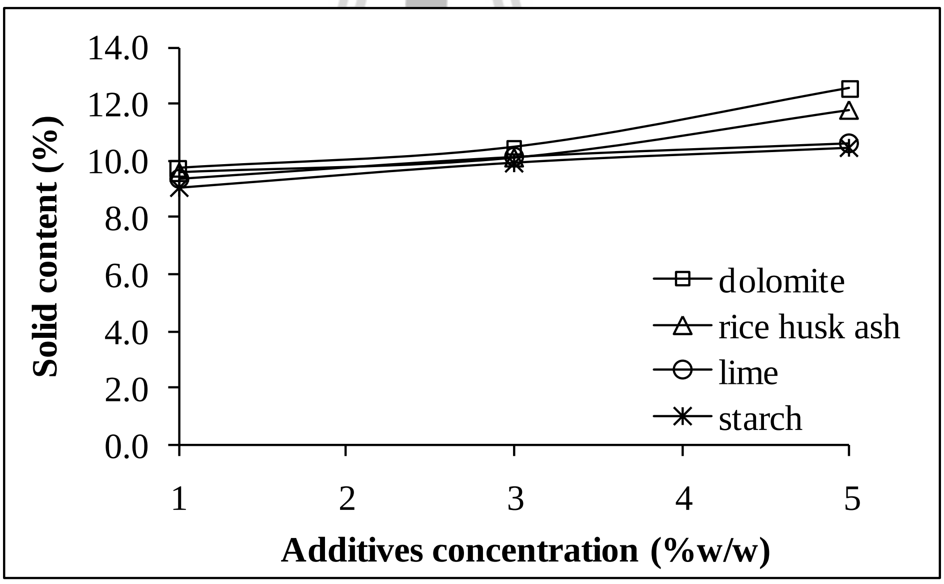

Figure 4.51 Solid content of new-base mud mixed with additives at 60^{o}C.

High solids content (HGS) will increase plastic viscosity and gel strength. High solids muds have much thicker filter cakes and slower drilling rates. Analysis of results represents to the adding additives to water-based drilling mud led to the increasing the solids. However, the increasing of temperature effect to the solid content decreased. Moreover, the starch is an LGS improving rheological properties of drilling mud.

4.3.7 Sand content of drilling mud

Large particles of sand in the mud cause abrasion on the pump parts, tubular, measurement while drilling equipment and downhole motors. The drilling mud should not have sand content more than 0.3 percentages. The Sand content must be more than 0.075 millimeters or 200-mesh. The results illustrate by Figures 4.52 through 4.55 show relationship between sand content with concentration of additives to add in base and new-base drilling mud. The sand contents are value more than 0.3 percentages; nevertheless, the water-based drilling mud is used to standard that is 0.5 percentages. The ranges of sand content are 0.5 to 2 percentages; expect the rice husk ash is 1.5 to 10 percentages. It is sieved through No.200-mesh, thus particle of rice husk ash equals the screen of sand content set and sand size. Therefore, the rice husk ash is a high sand content. The sand content increase when the temperature increased.

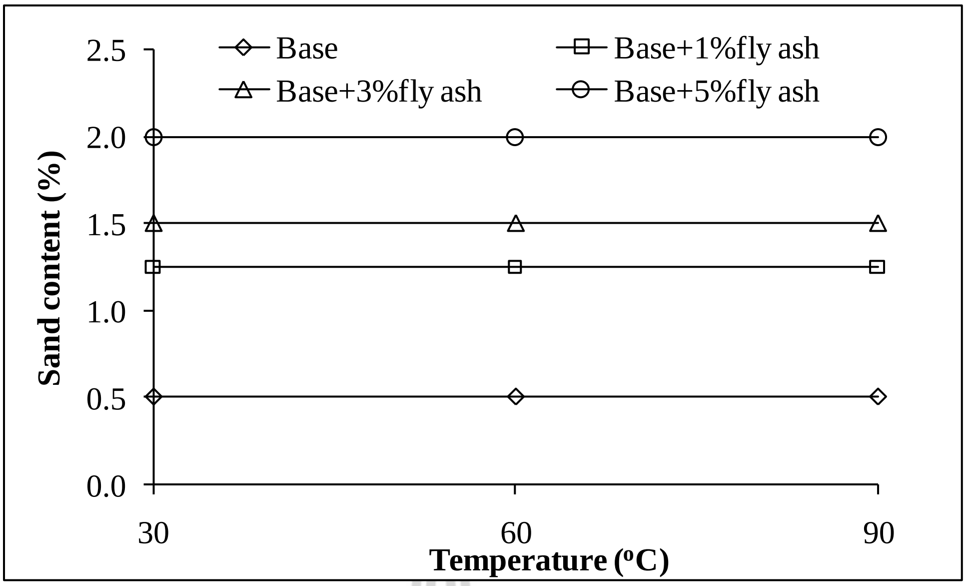

Figure 4.52 Sand content of drilling mud mixed with fly ash at 30, 60 and 90°C.

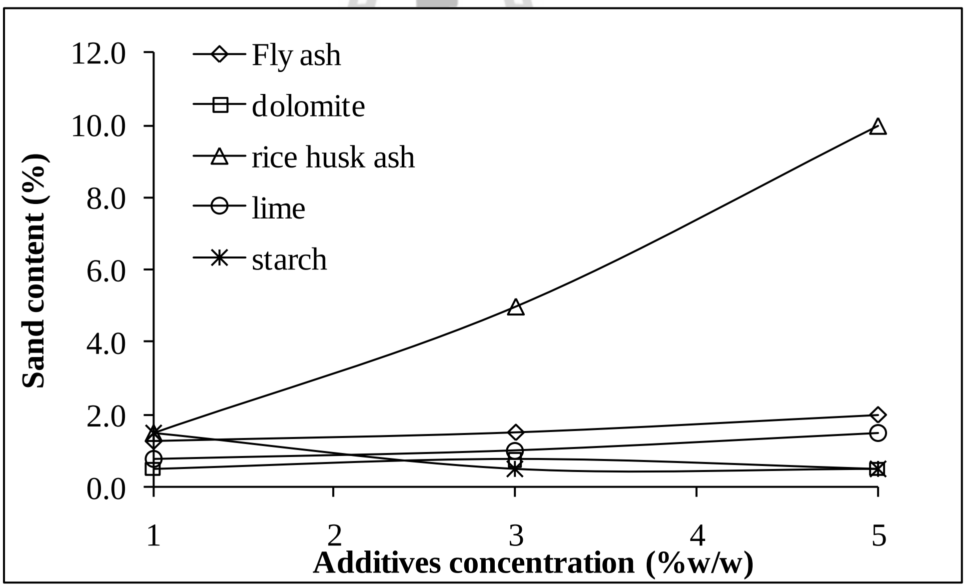

Figure 4.53 Sand content of drilling mud mixed with additives at 30°C.

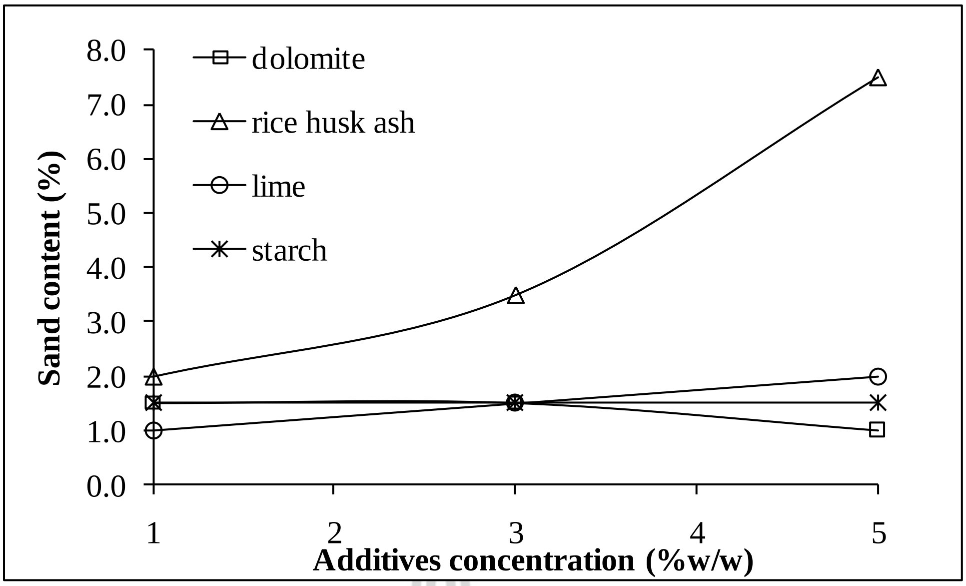

Figure 4.54 Sand content of new-base mud mixed with additives at 30^{o}C.

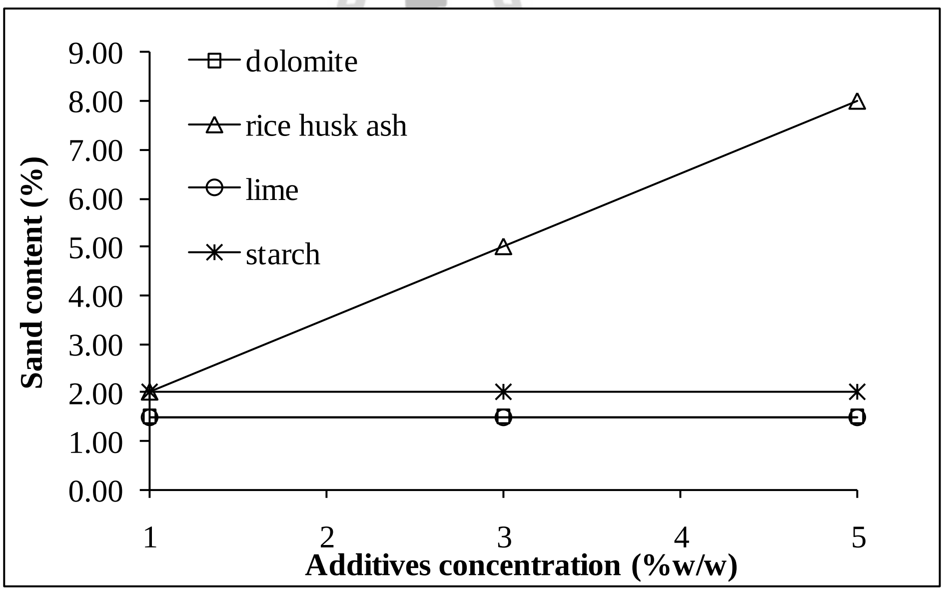

Figure 4.55 Sand content of new-base mud mixed with additives at 60^{o}C.

4.3.8 Resistivity of drilling mud

The results of resistivity are illustrated in Figures 4.56 through 4.63. Resistivity of drilling mud decreased as additive's concentration and temperature increased, excepted starch increased while resistivity increased. The resistivity of Mud filtrate is more than drilling mud and mud cake thickness, respectively.

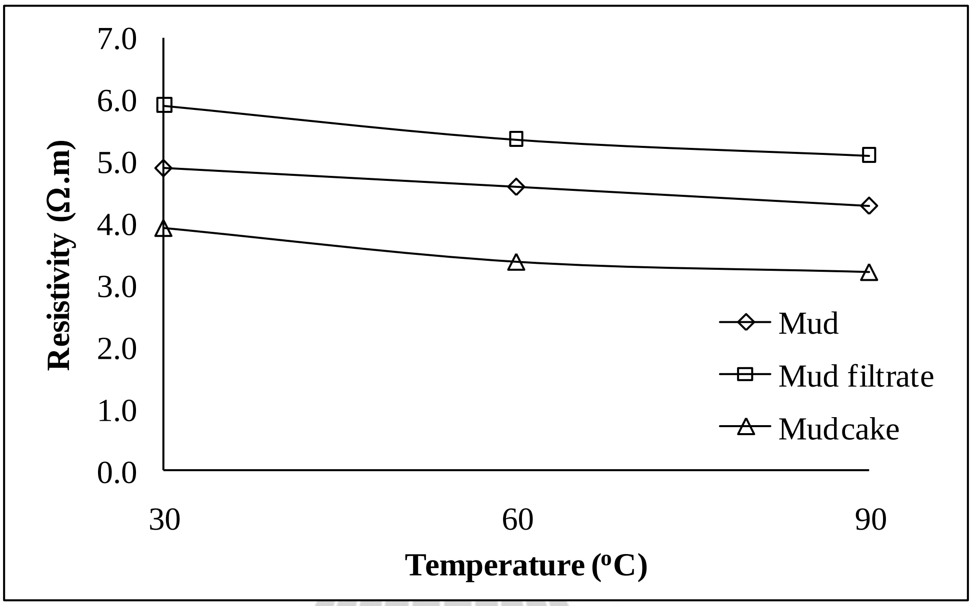

Figure 4.56 Resistivity of drilling mud at 30, 60 and 90^{o}C.

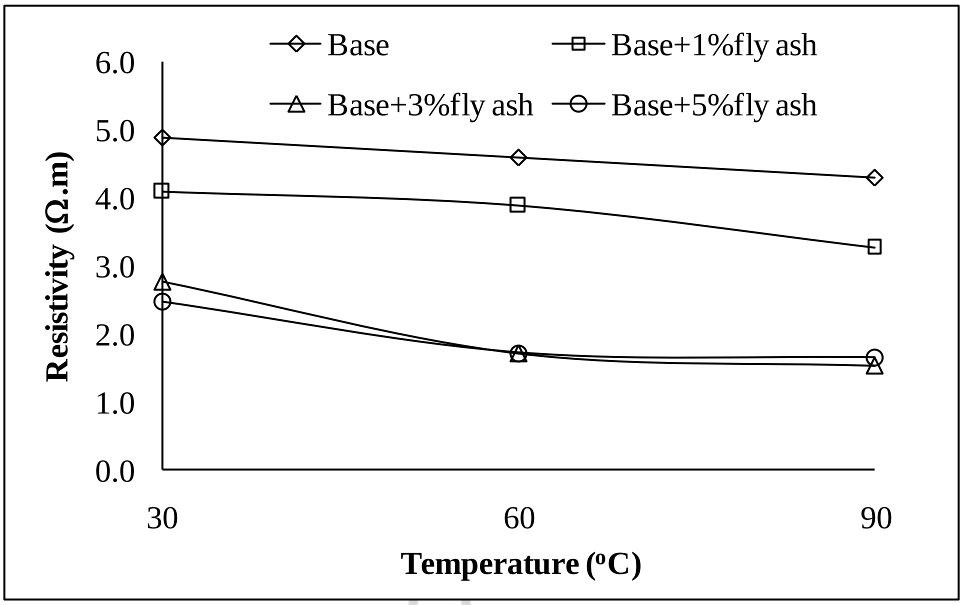

Figure 4.57 Resistivity of drilling mud mixed with fly ash at 30, 60 and 90^{o}C.

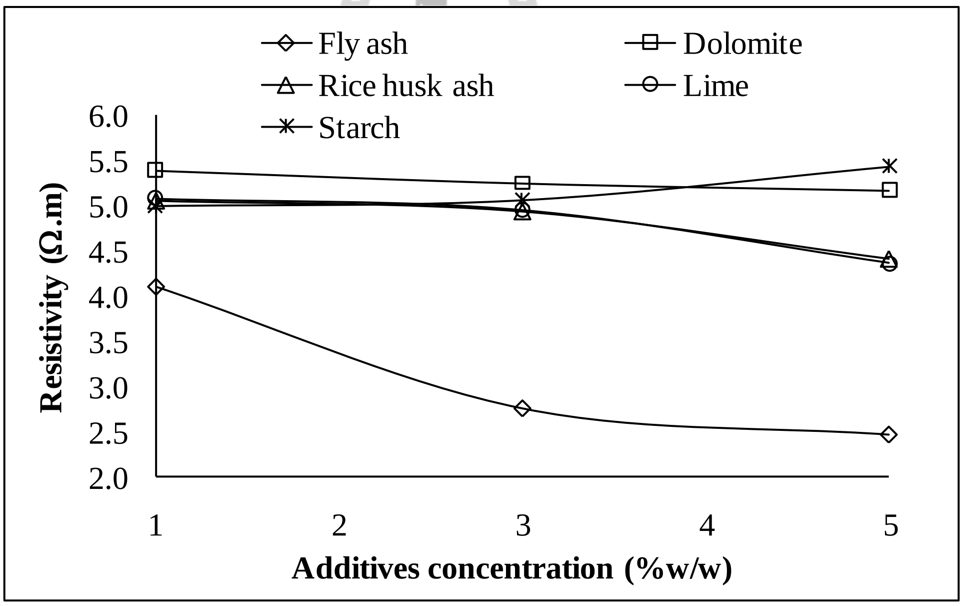

Figure 4.58 Resistivity of drilling mud mixed with additives at 30^{o}C.

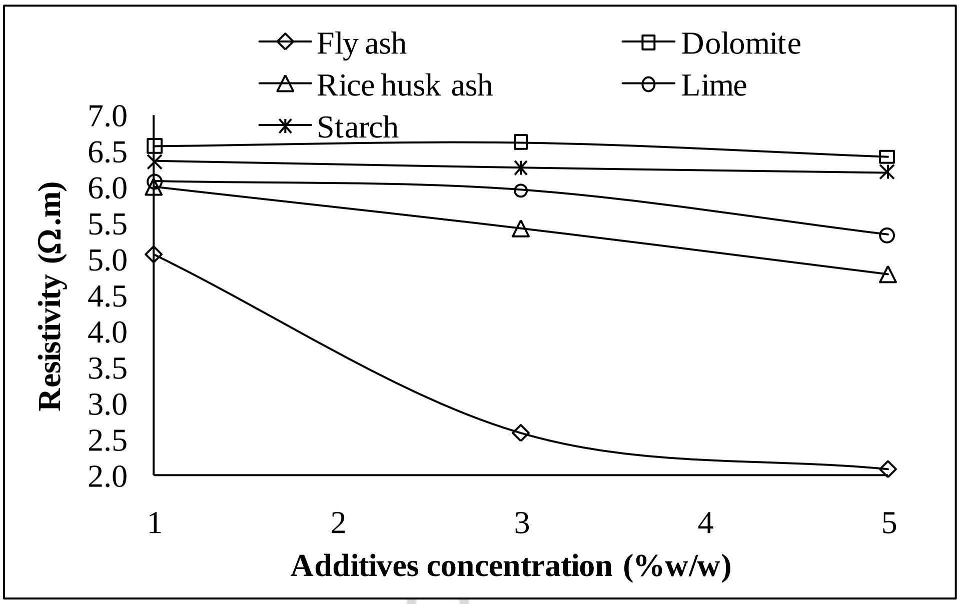

Figure 4.59 Resistivity of additives containing mud filtrate at 30^{o}C.

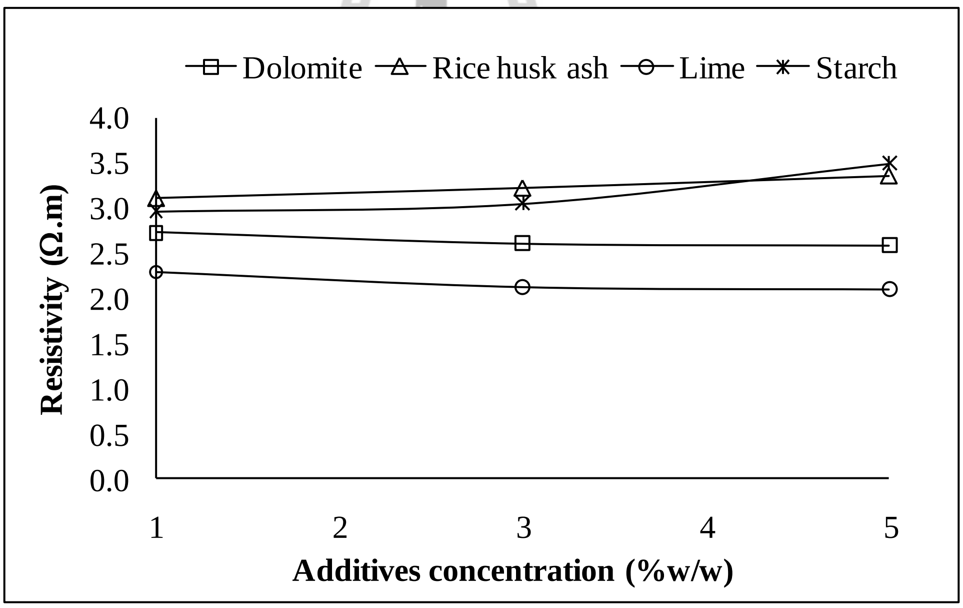

Figure 4.60 Resistivity of additives containing new-base mud at 30^{o}C.

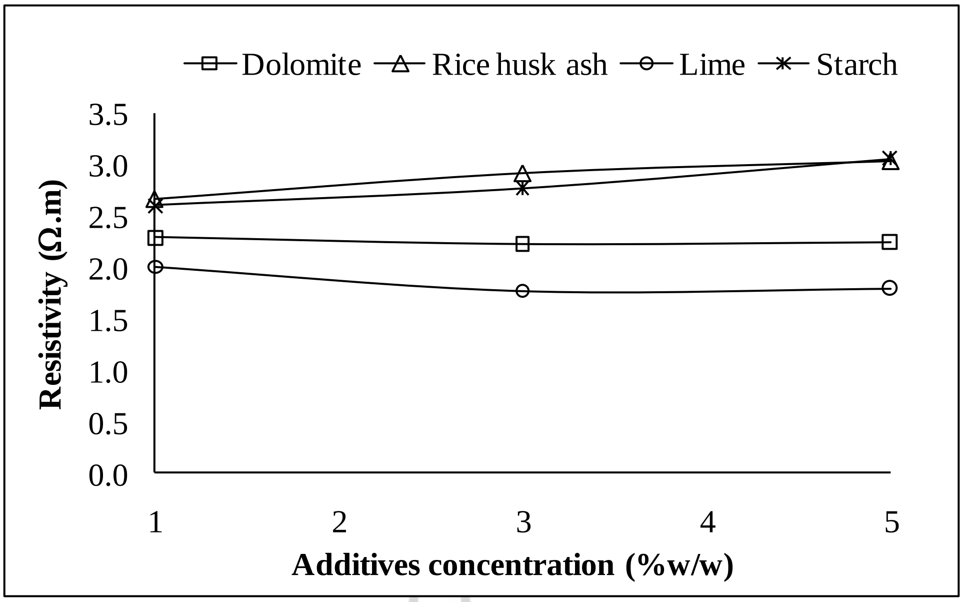

Figure 4.61 Resistivity of additives containing new-base mud filtrate at 30^{o}C.

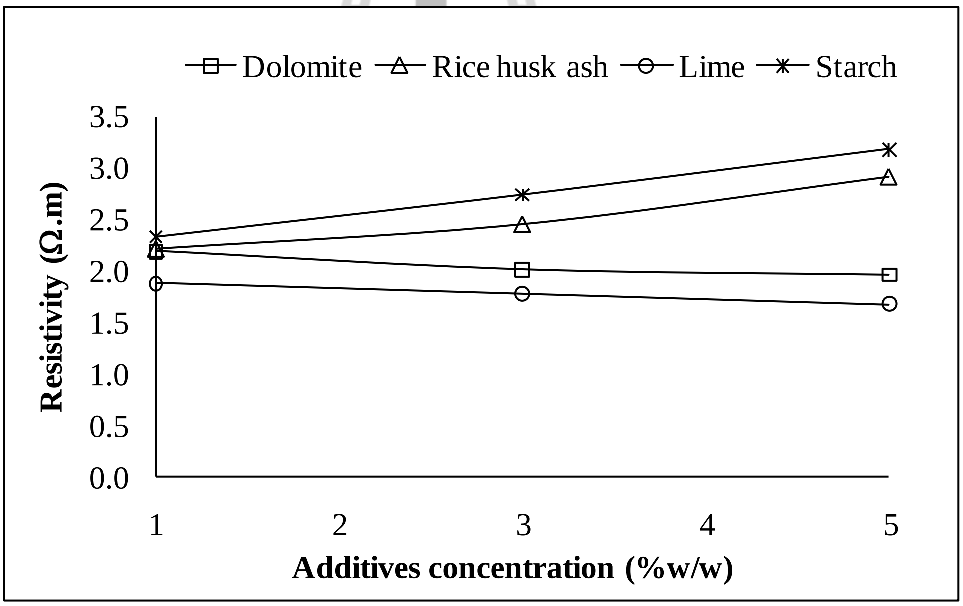

Figure 4.62 Resistivity of additives containing new-base mud at 60^{o}C.

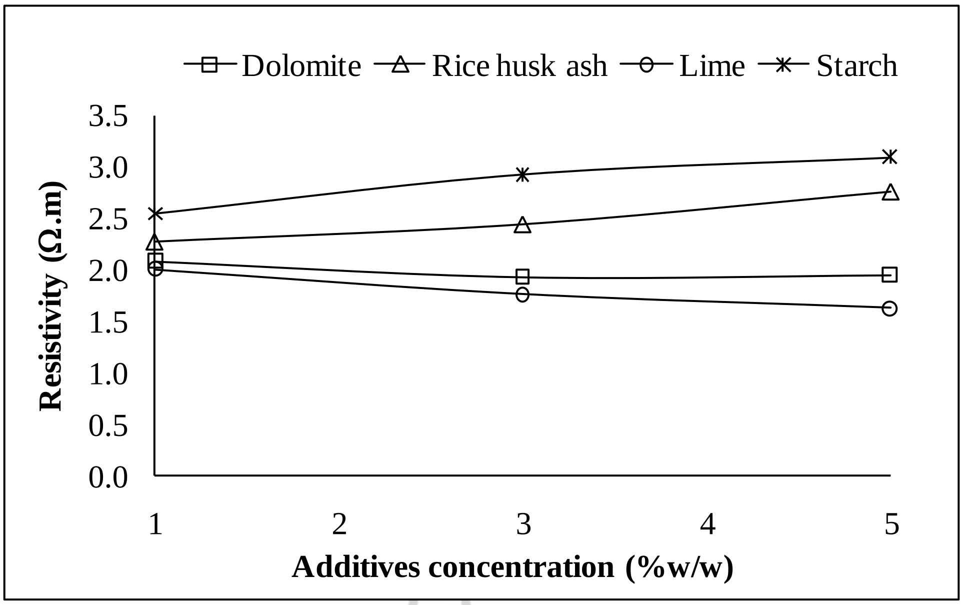

Figure 4.63 Resistivity of additives containing new-base mud filtrate at 60^{o}C.

4.4 Cost analysis

There are good reasons to improve drilling mud properties. Drilling mud may represent 5 to 15 percentages of drilling costs. Furthermore, increasing environmental concerns have limited the use of some of the most effective drilling muds and additives. At the same time, as part of the industry's drive for improved cost-effectiveness, drilling mud performance has come under ever scrutiny. Therefore, it is important to study and match the API standard, and the drilling mud mixed with fly ash. It is shown in Table 4.10. The drilling mud formula (70:10:20) includes barite: dolomite: fly ash and 3% bentonite (Petchote and Sikong, 2005).

Table 4.10 Comparison between the appropriate drilling mud formula and API standard.

Drilling mud Formula	**Viscosity (cP)**	**Density (g/cm^3)**	**pH**
Standard API	35-78	1.00-1.35	9.9-12
New-base + 3% starch	58.00	1.09	10.69
70:10:20	78.10	1.12	9.97

These drilling mud formulas above reach the drilling mud properties of API standard. Therefore, it is essential to compare them cost between the appropriate drilling mud formulas. Table 4.11 indicates the cost of each drilling mud formula.

Table 4.11 Cost of the appropriate drilling mud formula.

Drilling mud Formula	**Cost (Baht/Ton)**
New-base + 3% starch	3,879
70:10:20	2,343

Consequently, the cost of new-base drilling mud mixed with 3 percentages of starch that is a costly more than the drilling mud (70:10:20) formula.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

It is based on the results of drilling mud mixed with additives properties acquired from the previous chapter. The testing samples are divided into two parts that an additive containing mud and additives containing new-base mud. The conclusions of this study are as follows.

5.1.1 Chemical properties

The results of element and mineral analysis found that the temperature in the study is 30, 60 and 90^{o}C, which not change the structure of element and mineral of drilling mud. Hence, the drilling mud after mixed with additives are changed the content of elements and minerals that depended on the mixing ratio. The percentages of fly ash consist of silicon 34.90, aluminum 18.98, calcium 16.57, iron 15.51 and other elements 14.04. The percentages of major elements of drilling mud include silicon content range between 20.3 to 55.1, barium 4.8 to 31.9, sulfur 9.3 to 18.9, calcium 1.7 to 23.7, aluminum 7.5 to 13.5, iron 6.8 to 19.5 and other elements found a little.

The mineralogical composition of fly ash depends on the geological factors which related to the formation and deposition of coal. The percentages of dominate minerals of fly ash are quartz 24.26, anhydrite 14.28, hematite 20.46, calcite 15.33, mullite 17.23 and lime 8.44. The percentages of major minerals of the drilling mud consist of barite range between 31.65 to 43.47, montmorillonite 18.66 to 30.60, kaolinite 7.47 to 22.07, quartz 5.88 to 15.70, calcite 1.87 to 23.29, hematite 2.04 to 4.83, Gypsum 0.42 to 2.33, dolomite 0.03 to 0.53, anorthite 0.02 to 6.18 and anhydrite 0.06 to 1.19, respectively.

5.1.2 Physical properties

The drilling mud mixed with fly ash explicated the shear thinning fluid by giving flow behavior index less than one that indicated pseudo-plastic flow. The drilling mud mixed with three percentages of fly ash is the best composition to improve drilling mud properties and to use the new-base drilling mud. The appropriate additives containing new-base mud at 30 and 60^{o}C are described below.

The rheological properties of three percentages of starch containing in new-base mud are the appropriate mud properties that the plastic viscosity 58 centipoise, yield point 142 $lb_f/100ft^2$, gel strength 68 $lb_{f/}100ft^2$ in initial and 44 $lb_f/100ft^2$ in 10 minutes, respectively. These results reach the drilling mud properties of API standard.

There are 8.5 and 7.0 milliliters API static filtration of three and five percentages of starch mixing drilling mud, respectively. This concentration is suitable for control fluid loss at 60^{o}C. The mudcake thickness of them is 2.99 and 2.66 millimeters. The slickness and lubricity of mudcake relate to the lubricity of drilling string when drilling operation. API static filtration of 3 and 5 percentages starch mixing drilling mud, which are 8.5 and 7.0 ml. Thus, the suitable concentration is to control fluid loss at 60^{o}C. The mudcake thickness of them is 2.99 and 2.66 mm. The slickness and lubricity of mudcake that relate to lubricate drilling string when drilling operation.

The increasing density depends on the amount of weighting materials. The range of drilling mud mixed with additives is 1.10 to 1.14 g/cm^3 or 9.16 to 9.50 lb/gal. Hence, dolomite is a maximum weighting material. The dolomite optimizes to increase density nevertheless, the density decreases as temperature increases.

The pH range of drilling muds is 10.66 to 11.54. It can minimize corrosion problems of steel in drilling mud circulation process. The additives mixing drilling mud optimize all concentration at both 30 and 60^{o}C.

The high concentration of additives affected the increasing solid and sand contents. Standards of solid and sand contents are less than 10 and 0.3 percentages, respectively. The solid contents of one percentage of rice husk ash and starch mixing new-base drilling mud are in a range of standards, but sand content is overrated. Large particles of sand in the mud cause abrasion on pump parts, tubular, measurement while drilling equipment and downhole motors. Furthermore, the increasing solid content has the effect as differential sticking, slower drilling rates, circulation and surge and swab pressure.

The resistivity slightly decreased while temperature and concentration of additives increased, except rice husk ash and starch.

5.1.3 Cost analysis

The comparison between drilling muds mixed with fly ash that the formula of a new-base mixed with three percentages of starch has higher cost of the drilling mud including barite: dolomite: fly ash (70: 10: 20) formula. However, the fly ash can enhance the properties of drilling mud by using with other additives, which is quite suitable for using in drilling mud system.

5.2 Recommendations

The research investigation and results lead to recommendation area for further studies including that the drilling mud mixed additives should be investigated at elevated temperatures more than 60^{o}C and varied percentage of fly ash as a base composition. The additives should be sieved before mixed with water-based drilling mud, in order to reduce the solid and sand contents. The starch limits are to burn at high temperature (more than 70^{o}C) and to appear decomposition. Therefore, the fluid loss should be modified natural or synthetic polymer such as cellulose, CMC, polyacrylamide, etc.

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APPENDIX A

EXPERIMENTAL DATA

Fann viscometer data and parameters for all tested.

Table A1 Water-based drilling mud at 30°C (No.1).

RPM	Reading #1	Reading #2	Reading #3	Reading #4	Average reading	γ (sec^{-1})	τ (lb_f/ft^2)
600	44	46	47	48	46.3	1021.8	0.099
300	37	37	41	38	38.3	510.9	0.082
200	34	34	36	35	34.8	340.6	0.074
100	32	31	33	30	31.5	170.3	0.067
6	30	29	32	27	29.5	10.2	0.063
3	27	29	31	25	28.0	5.1	0.060
PV	7	9	6	10	8		
AV	22	23	23.5	24	23		
YP	30	28	35	28	30		
Gel_{in}	27						
Gel_{10}	31						

Table A2 Water-based drilling mud at 60°C (No.2).

RPM	Reading #1	Reading #2	Reading #3	Reading #4	Average reading	γ (sec^{-1})	τ (lb_f/ft^2)
600	65	63	61	59	62.0	1021.8	0.132
300	54	59	54	51	54.5	510.9	0.116
200	53	56	51	48	52.0	340.6	0.111
100	50	52	51	46	49.8	170.3	0.106
6	41	46	47	42	44.0	10.2	0.094
3	30	33	32	37	33.0	5.1	0.070
PV	11	4	7	8	8		
AV	32.5	31.5	30.5	29.5	31		
YP	43	55	47	43	47		
Gel_{in}	30						
Gel_{10}	32						

Table A3 Water-based drilling mud at 90^oC (No.3).

RPM	Reading #1	Reading #2	Reading #3	Reading #4	Average reading	γ (sec^{-1})	τ (lb_f/ft^2)
600	76	75	71	70	73.0	1021.8	0.156
300	74	70	66	63	68.3	510.9	0.146
200	74	68	70	60	68.0	340.6	0.145
100	70	65	67	57	64.8	170.3	0.138
6	52	51	57	46	51.5	10.2	0.110
3	37	39	42	37	38.8	5.1	0.083
PV	2	5	5	7	5		
AV	38	37.5	35.5	35	37		
YP	72	65	61	56	64		
Gel_{in}	37						
Gel_{10}	42						

Table A4 Water-based drilling mud mixed with 1 percent fly ash at 30^oC (No.4).

RPM	Reading #1	Reading #2	Reading #3	Reading #4	Average reading	γ (sec^{-1})	τ (lb_f/ft^2)
600	36	37	35	35	35.8	1021.8	0.076
300	26	27	28	27	27.0	510.9	0.058
200	25	24	25	22	24.0	340.6	0.051
100	21	19	22	19	20.3	170.3	0.043
6	20	18	22	20	20.0	10.2	0.043
3	19	23	26	18	21.5	5.1	0.046
PV	10	10	7	8	9		
AV	18	18.5	17.5	17.5	18		
YP	16	17	21	19	18		
Gel_{in}	19						
Gel_{10}	26						

Table A5 Water-based drilling mud mixed with 3 percent fly ash at 30°C (No.5).

RPM	Reading #1	Reading #2	Reading #3	Reading #4	Average reading	γ (sec^{-1})	τ (lb_f/ft^2)
600	78	78	76	79	77.8	1021.8	0.166
300	74	75	70	71	72.5	510.9	0.155
200	72	72	69	68	70.3	340.6	0.150
100	68	66	65	64	65.8	170.3	0.140
6	45	46	37	48	44.0	10.2	0.094
3	21	23	22	30	24.0	5.1	0.051
PV	4	3	6	8	5		
AV	39	39	38	39.5	39		
YP	70	72	64	63	67		
Gel_{in}	21						
Gel_{10}	22						

Table A6 Water-based drilling mud mixed with 5 percent fly ash at 30°C (No.6).

RPM	Reading #1	Reading #2	Reading #3	Reading #4	Average reading	γ (sec^{-1})	τ (lb_f/ft^2)
600	80	82	72	74	77.0	1021.8	0.164
300	75	73	64	66	69.5	510.9	0.148
200	72	69	63	59	65.8	340.6	0.140
100	67	60	60	52	59.8	170.3	0.127
6	41	35	32	30	34.5	10.2	0.074
3	22	22	19	18	20.3	5.1	0.043
PV	5	9	8	8	8		
AV	40	41	36	37	39		
YP	70	64	56	58	62		
Gel_{in}	22						
Gel_{10}	19						

Table A7 Water-based drilling mud mixed with 1 percent fly ash at 60°C (No.7).

RPM	Reading #1	Reading #2	Reading #3	Reading #4	Average reading	γ (sec^{-1})	τ (lb_f/ft^2)
600	36	37	37	31	35.3	1021.8	0.075
300	30	29	31	28	29.5	510.9	0.063
200	28	27	29	22	26.5	340.6	0.056
100	25	23	26	29	25.8	170.3	0.055
6	29	24	30	22	26.3	10.2	0.056
3	28	28	35	28	29.8	5.1	0.063
PV	6	8	6	3	6		
AV	18	18.5	18.5	15.5	18		
YP	24	21	25	25	24		
Gel_{in}	28						
Gel_{10}	35						

Table A8 Water-based drilling mud mixed with 3 percent fly ash at 60°C (No.8).

RPM	Reading #1	Reading #2	Reading #3	Reading #4	Average reading	γ (sec^{-1})	τ (lb_f/ft^2)
600	59	59	52	54	56.0	1021.8	0.119
300	54	52	46	51	50.0	510.9	0.107
200	50	49	44	48	47.8	340.6	0.102
100	47	44	40	44	43.8	170.3	0.093
6	16	16	15	17	16.0	10.2	0.034
3	10	10	13	11	11.0	5.1	0.023
PV	5	7	6	3	5		
AV	29.5	29.5	26	27	28		
YP	49	45	40	48	46		
Gel_{in}	10						
Gel_{10}	13						

Table A9 Water-based drilling mud mixed with 5 percent fly ash at 60^{o}C (No.9).

RPM	**Reading #1**	**Reading #2**	**Reading #3**	**Reading #4**	**Average reading**	**γ (sec^{-1})**	**τ (lb$_f$/ft^2)**
600	54	54	50	52	52.50	1021.8	0.112
300	49	50	45	50	48.50	510.9	0.103
200	46	47	42	47	45.50	340.6	0.097
100	42	43	38	43	41.50	170.3	0.088
6	15	17	16	17	16.25	10.2	0.035
3	12	12	10	12	11.50	5.1	0.025
PV	5	4	5	2	4		
AV	27	27	25	26	26		
YP	44	46	40	48	45		
Gel$_{in}$	12						
Gel$_{10}$	10						

Table A10 Water-based drilling mud mixed with 1 percent fly ash at 90^{o}C (No.10).

RPM	**Reading #1**	**Reading #2**	**Reading #3**	**Reading #4**	**Average reading**	**γ (sec^{-1})**	**τ (lb$_f$/ft^2)**
600	41	41	41	42	41.33	1021.8	0.088
300	38	34	35	34	35.33	510.9	0.075
200	37	33	34	31	33.67	340.6	0.072
100	36	30	31	28	31.33	170.3	0.067
6	35	30	32	31	32.00	10.2	0.068
3	27	34	32	35	32.00	5.1	0.068
PV	3	7	6	8	6		
AV	20.5	20.5	20.7	21	21		
YP	35	27	29.3	26	29		
Gel$_{in}$	27						
Gel$_{10}$	35						

Table A11 Water-based drilling mud mixed with 3 percent fly ash at 90°C (No.11).

RPM	Reading #1	Reading #2	Reading #3	Reading #4	Average reading	γ (sec^{-1})	τ (lb$_f$/ft^2)
600	57	57	56	57	56.75	1021.8	0.121
300	50	53	50	51	51.00	510.9	0.109
200	46	50	46	49	47.75	340.6	0.102
100	42	46	42	45	43.75	170.3	0.093
6	18	19	19	20	19.00	10.2	0.041
3	11	12	13	16	13.00	5.1	0.028
PV	7	4	6	6	6		
AV	28.5	28.5	28	28.5	28		
YP	43	49	44	45	45		
Gel$_{in}$	11						
Gel$_{10}$	13						

Table A12 Water-based drilling mud mixed with 5 percent fly ash at 90°C (No.12).

RPM	Reading #1	Reading #2	Reading #3	Reading #4	Average reading	γ (sec^{-1})	τ (lb$_f$/ft^2)
600	51	51	51	51	51.00	1021.8	0.109
300	38	48	43	47	44.00	510.9	0.094
200	36	44	38	45	40.75	340.6	0.087
100	33	42	35	41	37.75	170.3	0.080
6	14	17	18	19	17.00	10.2	0.036
3	5	10	10	11	9.00	5.1	0.019
PV	13	3	8	4	7		
AV	25.5	25.5	25.5	25.5	26		
YP	25	45	35	43	37		
Gel$_{in}$	5						
Gel$_{10}$	10						

Table A13 Water-based drilling mud mixed with 1 percent dolomite at 30°C (No.13).

RPM	Reading #1	Reading #2	Reading #3	Reading #4	Average reading	γ (sec^{-1})	τ (lb_f/ft^2)
600	46	46	48	48	47.00	1021.8	0.100
300	38	37	40	39	38.50	510.9	0.082
200	34	35	37	36	35.50	340.6	0.076
100	31	31	34	32	32.00	170.3	0.068
6	28	27	32	27	28.50	10.2	0.061
3	22	28	33	27	27.50	5.1	0.059
PV	8	9	8	9	9		
AV	23	23	24	24	24		
YP	30	28	32	30	30		
Gel_{in}	22						
Gel_{10}	33						

Table A14 Water-based drilling mud mixed with 3 percent dolomite at 30°C (No.14).

RPM	Reading #1	Reading #2	Reading #3	Reading #4	Average reading	γ (sec^{-1})	τ (lb_f/ft^2)
600	48	48	49	51	49.00	1021.8	0.104
300	39	39	41	41	40.00	510.9	0.085
200	36	36	37	37	36.50	340.6	0.078
100	33	32	35	33	33.25	170.3	0.071
6	31	31	34	30	31.50	10.2	0.067
3	28	31	38	32	32.25	5.1	0.069
PV	9	9	8	10	9		
AV	24	24	24.5	25.5	25		
YP	30	30	33	31	31		
Gel_{in}	28						
Gel_{10}	38						

Table A15 Water-based drilling mud mixed with 5 percent dolomite at 30^oC (No.15).

RPM	Reading #1	Reading #2	Reading #3	Reading #4	Average reading	γ (sec^{-1})	τ (lb_f/ft^2)
600	49	50	50	51	50.00	1021.8	0.107
300	42	42	42	43	42.25	510.9	0.090
200	39	38	40	40	39.25	340.6	0.084
100	35	35	36	35	35.25	170.3	0.075
6	34	34	37	32	34.25	10.2	0.073
3	33	33	37	33	34.00	5.1	0.072
PV	7	8	8	8	8		
AV	24.5	25	25	25.5	25		
YP	35	34	34	35	35		
Gel_{in}	33						
Gel_{10}	37						

Table A16 Water-based drilling mud mixed with 1 percent rice husk ash at 30^oC (No.16).

RPM	Reading #1	Reading #2	Reading #3	Reading #4	Average reading	γ (sec^{-1})	τ (lb_f/ft^2)
600	44	45	48	49	46.50	1021.8	0.099
300	35	36	40	42	38.25	510.9	0.082
200	32	33	36	36	34.25	340.6	0.073
100	29	29	32	32	30.50	170.3	0.065
6	25	26	30	25	26.50	10.2	0.056
3	22	25	28	24	24.75	5.1	0.053
PV	9	9	8	7	8		
AV	22	22.5	24	24.5	23		
YP	26	27	32	35	30		
Gel_{in}	22						
Gel_{10}	28						

Table A17 Water-based drilling mud mixed with 3 percent rice husk ash at 30°C (No.17).

RPM	Reading #1	Reading #2	Reading #3	Reading #4	Average reading	γ (sec^{-1})	τ (lb$_f$/ft^2)
600	40	40	40	41	40.25	1021.8	0.086
300	29	30	30	31	30.00	510.9	0.064
200	26	26	27	26	26.25	340.6	0.056
100	22	21	23	21	21.75	170.3	0.046
6	17	16	18	16	16.75	10.2	0.036
3	15	14	19	15	15.75	5.1	0.034
PV	11	10	10	10	10		
AV	20	20	20	20.5	20		
YP	18	20	20	21	20		
Gel$_{in}$	15						
Gel$_{10}$	19						

Table A18 Water-based drilling mud mixed with 5 percent rice husk ash at 30°C (No.18).

RPM	Reading #1	Reading #2	Reading #3	Reading #4	Average reading	γ (sec^{-1})	τ (lb$_f$/ft^2)
600	35	35	37	37	36.00	1021.8	0.077
300	25	25	26	26	25.50	510.9	0.054
200	21	20	22	21	21.00	340.6	0.045
100	17	16	17	16	16.50	170.3	0.035
6	11	11	14	11	11.75	10.2	0.025
3	9	10	9	9	9.25	5.1	0.020
PV	10	10	11	11	11		
AV	17.5	17.5	18.5	18.5	18		
YP	15	15	15	15	15		
Gel$_{in}$	9						
Gel$_{10}$	9						

Table A19 Water-based drilling mud mixed with 1 percent lime at 30°C (No.19).

RPM	**Reading #1**	**Reading #2**	**Reading #3**	**Reading #4**	**Average reading**	**γ (sec^{-1})**	**τ (lb_f/ft^2)**
600	41	43	50	49	45.75	1021.8	0.098
300	35	35	37	41	37.00	510.9	0.079
200	31	32	35	36	33.50	340.6	0.071
100	28	28	31	32	29.75	170.3	0.063
6	26	28	31	32	29.25	10.2	0.062
3	24	29	33	31	29.25	5.1	0.062
PV	6	8	13	8	9		
AV	20.5	21.5	25	24.5	23		
YP	29	27	24	33	28		
Gel_{in}	24						
Gel_{10}	33						

Table A20 Water-based drilling mud mixed with 3 percent lime at 30°C (No.20).

RPM	**Reading #1**	**Reading #2**	**Reading #3**	**Reading #4**	**Average reading**	**γ (sec^{-1})**	**τ (lb_f/ft^2)**
600	48	49	51	51	49.75	1021.8	0.106
300	41	41	42	41	41.25	510.9	0.088
200	38	37	38	37	37.50	340.6	0.080
100	34	33	37	32	34.00	170.3	0.072
6	32	33	37	31	33.25	10.2	0.071
3	31	33	40	33	34.25	5.1	0.073
PV	7	8	9	10	9		
AV	24	24.5	25.5	25.5	25		
YP	34	33	33	31	33		
Gel_{in}	31						
Gel_{10}	40						

Table A21 Water-based drilling mud mixed with 5 percent lime at 30°C (No.21).

RPM	Reading #1	Reading #2	Reading #3	Reading #4	Average reading	γ (sec^{-1})	τ (lb_f/ft^2)
600	43	44	47	47	45.25	1021.8	0.096
300	33	34	36	35	34.50	510.9	0.074
200	30	29	31	29	29.75	340.6	0.063
100	25	24	26	25	25.00	170.3	0.053
6	21	19	24	19	20.75	10.2	0.044
3	21	19	26	19	21.25	5.1	0.045
PV	10	10	11	12	11		
AV	21.5	22	23.5	23.5	23		
YP	23	24	25	23	24		
Gel_{in}	21						
Gel_{10}	26						

Table A22 Water-based drilling mud mixed with 1 percent starch at 30°C (No.22).

RPM	Reading #1	Reading #2	Reading #3	Reading #4	Average reading	γ (sec^{-1})	τ (lb_f/ft^2)
600	47	47	49	49	48.00	1021.8	0.102
300	38	37	42	38	38.75	510.9	0.083
200	35	35	40	36	36.50	340.6	0.078
100	32	32	36	33	33.25	170.3	0.071
6	29	27	35	31	30.50	10.2	0.065
3	26	27	35	31	29.75	5.1	0.063
PV	9	10	7	11	9		
AV	23.5	23.5	24.5	24.5	24		
YP	29	27	35	27	30		
Gel_{in}	26						
Gel_{10}	35						

Table A23 Water-based drilling mud mixed with 3 percent starch at 30°C (No.23).

RPM	**Reading #1**	**Reading #2**	**Reading #3**	**Reading #4**	**Average reading**	**γ (sec^{-1})**	**τ (lb$_f$/ft^2)**
600	51	52	54	55	53.00	1021.8	0.113
300	44	45	47	46	45.50	510.9	0.097
200	42	42	44	43	42.75	340.6	0.091
100	39	38	40	40	39.25	170.3	0.084
6	37	37	42	39	38.75	10.2	0.083
3	34	37	41	38	37.50	5.1	0.080
PV	7	7	7	9	8		
AV	25.5	26	27	27.5	27		
YP	37	38	40	37	38		
Gel$_{in}$	34						
Gel$_{10}$	41						

Table A24 Water-based drilling mud mixed with 5 percent starch at 30°C (No.24).

RPM	**Reading #1**	**Reading #2**	**Reading #3**	**Reading #4**	**Average reading**	**γ (sec^{-1})**	**τ (lb$_f$/ft^2)**
600	51	52	55	55	53.25	1021.8	0.114
300	45	45	48	46	46.00	510.9	0.098
200	42	42	44	43	42.75	340.6	0.091
100	38	39	41	39	39.25	170.3	0.084
6	35	36	40	34	36.25	10.2	0.077
3	32	35	40	34	35.25	5.1	0.075
PV	6	7	7	9	7		
AV	25.5	26	27.5	27.5	27		
YP	39	38	41	37	39		
Gel$_{in}$	32						
Gel$_{10}$	40						

Table A25 New-based drilling mud mixed with 1 percent dolomite at 30°C (No.25).

RPM	Reading #1	Reading #2	Reading #3	Reading #4	Average reading	γ (sec^{-1})	τ (lb_f/ft^2)
600	84	82	90	91	86.75	1021.8	0.185
300	78	78	84	85	81.25	510.9	0.173
200	75	74	79	80	77.00	340.6	0.164
100	70	71	75	75	72.75	170.3	0.155
6	48	47	48	42	46.25	10.2	0.099
3	32	26	18	28	26.00	5.1	0.055
PV	6	4	6	6	6		
AV	42	41	45	45.5	43		
YP	72	74	78	79	76		
Gel_{in}	32						
Gel_{10}	18						

Table A26 New-based drilling mud mixed with 3 percent dolomite at 30°C (No.26).

RPM	Reading #1	Reading #2	Reading #3	Reading #4	Average reading	γ (sec^{-1})	τ (lb_f/ft^2)
600	83	85	87	86	85.25	1021.8	0.182
300	79	81	78	80	79.50	510.9	0.169
200	77	77	73	74	75.25	340.6	0.160
100	66	72	66	70	68.50	170.3	0.146
6	43	45	37	43	42.00	10.2	0.090
3	31	40	34	37	35.50	5.1	0.076
PV	4	4	9	6	6		
AV	41.5	42.5	43.5	43	43		
YP	75	77	69	74	74		
Gel_{in}	31						
Gel_{10}	34						

Table A27 New-based drilling mud mixed with 5 percent dolomite at 30°C (No.27).

RPM	Reading #1	Reading #2	Reading #3	Reading #4	Average reading	γ (sec^{-1})	τ (lb_f/ft^2)
600	91	101	90	93	93.75	1021.8	0.200
300	79	90	84	85	84.50	510.9	0.180
200	73	87	80	81	80.25	340.6	0.171
100	65	77	74	75	72.75	170.3	0.155
6	40	46	42	48	44.00	10.2	0.094
3	24	37	25	37	30.75	5.1	0.066
PV	12	11	6	8	9		
AV	45.5	50.5	45	46.5	47		
YP	67	79	78	77	75		
Gel_{in}	24						
Gel_{10}	25						

Table A28 New-based drilling mud mixed with 1 percent dolomite at 60°C (No.28).

RPM	Reading #1	Reading #2	Reading #3	Reading #4	Average reading	γ (sec^{-1})	τ (lb_f/ft^2)
600	59	60	60	61	60.00	1021.8	0.128
300	56	55	53	55	54.75	510.9	0.117
200	55	52	50	52	52.25	340.6	0.111
100	52	45	45	48	47.50	170.3	0.101
6	28	23	19	25	23.75	10.2	0.051
3	20	12	8	13	13.25	5.1	0.028
PV	3	5	7	6	5		
AV	29.5	30	30	30.5	30		
YP	53	50	46	49	50		
Gel_{in}	20						
Gel_{10}	8						

Table A29 New-based drilling mud mixed with 3 percent dolomite at 60°C (No.29).

RPM	Reading #1	Reading #2	Reading #3	Reading #4	Average reading	γ (sec^{-1})	τ (lb_f/ft^2)
600	62	61	63	62	62.00	1021.8	0.132
300	56	57	56	57	56.50	510.9	0.120
200	53	54	52	54	53.25	340.6	0.114
100	51	50	47	49	49.25	170.3	0.105
6	28	28	29	28	28.25	10.2	0.060
3	20	21	17	20	19.50	5.1	0.042
PV	6	4	7	5	6		
AV	31	30.5	31.5	31	31		
YP	50	53	49	52	51		
Gel_{in}	20						
Gel_{10}	17						

Table A30 New-based drilling mud mixed with 5 percent dolomite at 60°C (No.30).

RPM	Reading #1	Reading #2	Reading #3	Reading #4	Average reading	γ (sec^{-1})	τ (lb_f/ft^2)
600	78	78	76	75	76.75	1021.8	0.164
300	73	73	68	68	70.50	510.9	0.150
200	70	68	62	65	66.25	340.6	0.141
100	67	63	59	60	62.25	170.3	0.133
6	29	27	19	28	25.75	10.2	0.055
3	26	11	9	10	14.00	5.1	0.030
PV	5	5	8	7	6		
AV	39	39	38	37.5	38		
YP	68	68	60	61	64		
Gel_{in}	26						
Gel_{10}	9						

Table A31 New-based drilling mud mixed with 1 percent rice husk ash at 30^oC (No.31).

RPM	Reading #1	Reading #2	Reading #3	Reading #4	Average reading	γ (sec^{-1})	τ (lb_f/ft^2)
600	72	70	70	69	70.25	1021.8	0.150
300	65	67	65	63	65.00	510.9	0.139
200	54	66	63	62	61.25	340.6	0.131
100	41	65	62	59	56.75	170.3	0.121
6	19	60	59	53	47.75	10.2	0.102
3	21	55	36	48	40.00	5.1	0.085
PV	7	3	5	6	5		
AV	36	35	35	34.5	35		
YP	58	64	60	57	60		
Gel_{in}	21						
Gel_{10}	36						

Table A32 New-based drilling mud mixed with 3 percent rice husk ash at 30^oC (No.32).

RPM	Reading #1	Reading #2	Reading #3	Reading #4	Average reading	γ (sec^{-1})	τ (lb_f/ft^2)
600	62	62	65	65	63.50	1021.8	0.135
300	55	57	61	62	58.75	510.9	0.125
200	51	56	58	62	56.75	340.6	0.121
100	49	55	54	61	54.75	170.3	0.117
6	45	54	49	55	50.75	10.2	0.108
3	31	42	34	42	37.25	5.1	0.079
PV	7	5	4	3	5		
AV	31	31	32.5	32.5	32		
YP	48	52	57	59	54		
Gel_{in}	31						
Gel_{10}	34						

Table A33 New-based drilling mud mixed with 5 percent rice husk ash at 30^oC (No.33).

RPM	Reading #1	Reading #2	Reading #3	Reading #4	Average reading	γ (sec^{-1})	τ (lb_f/ft^2)
600	36	36	45	45	40.50	1021.8	0.086
300	33	33	35	40	35.25	510.9	0.075
200	32	33	33	39	34.25	340.6	0.073
100	28	30	37	41	34.00	170.3	0.072
6	20	30	27	40	29.25	10.2	0.062
3	21	19	19	24	20.75	5.1	0.044
PV	3	3	10	5	5		
AV	18	18	22.5	22.5	20		
YP	30	30	25	35	30		
Gel_{in}	21						
Gel_{10}	19						

Table A34 New-based drilling mud mixed with 1 percent rice husk ash at 60^oC (No.34).

RPM	Reading #1	Reading #2	Reading #3	Reading #4	Average reading	γ (sec^{-1})	τ (lb_f/ft^2)
600	45	45	46	48	46.00	1021.8	0.098
300	39	41	37	43	40.00	510.9	0.085
200	35	38	35	39	36.75	340.6	0.078
100	33	35	33	33	33.50	170.3	0.071
6	19	14	13	9	13.75	10.2	0.029
3	24	9	10	7	12.50	5.1	0.027
PV	6	4	9	5	6		
AV	22.5	22.5	23	24	23		
YP	33	37	28	38	34		
Gel_{in}	24						
Gel_{10}	10						

Table A35 New-based drilling mud mixed with 3 percent rice husk ash at 60^{o}C (No.35).

RPM	Reading #1	Reading #2	Reading #3	Reading #4	Average reading	γ (sec^{-1})	τ (lb$_f$/ft^2)
600	42	49	40	40	42.75	1021.8	0.091
300	41	44	37	34	39.00	510.9	0.083
200	40	41	37	33	37.75	340.6	0.080
100	40	41	39	31	37.75	170.3	0.080
6	38	36	38	27	34.75	10.2	0.074
3	32	33	32	24	30.25	5.1	0.064
PV	1	5	3	6	4		
AV	21	24.5	20	20	21		
YP	40	39	34	28	35		
Gel$_{in}$	32						
Gel$_{10}$	32						

Table A36 New-based drilling mud mixed with 5 percent rice husk ash at 60^{o}C (No.36).

RPM	Reading #1	Reading #2	Reading #3	Reading #4	Average reading	γ (sec^{-1})	τ (lb$_f$/ft^2)
600	70	68	70	69	69.25	1021.8	0.148
300	68	68	68	67	67.75	510.9	0.144
200	68	68	69	68	68.25	340.6	0.146
100	67	66	64	69	66.50	170.3	0.142
6	47	60	54	63	56.00	10.2	0.119
3	22	34	35	41	33.00	5.1	0.070
PV	2	0	2	2	2		
AV	35	34	35	34.5	35		
YP	66	68	66	65	66		
Gel$_{in}$	22						
Gel$_{10}$	35						

Table A37 New-based drilling mud mixed with 1 percent lime at 30^{o}C (No.37).

RPM	Reading #1	Reading #2	Reading #3	Reading #4	Average reading	γ (sec^{-1})	τ (lb_f/ft^2)
600	78	78	76	79	77.8	1021.8	0.166
300	74	75	70	71	72.5	510.9	0.155
200	72	72	69	68	70.3	340.6	0.150
100	68	66	65	64	65.8	170.3	0.140
6	45	46	37	48	44.0	10.2	0.094
3	21	23	22	30	24.0	5.1	0.051
PV	4	3	6	8	5.3		
AV	39	39	38	39.5	38.9		
YP	70	72	64	63	67.3		
Gel_{in}	21						
Gel_{10}	22						

Table A38 New-based drilling mud mixed with 3 percent lime at 30^{o}C (No.38).

RPM	Reading #1	Reading #2	Reading #3	Reading #4	Average reading	γ (sec^{-1})	τ (lb_f/ft^2)
600	104	111	100	96	102.75	1021.8	0.219
300	97	94	83	84	89.50	510.9	0.191
200	92	85	77	79	83.25	340.6	0.177
100	83	77	69	71	75.00	170.3	0.160
6	43	44	38	36	40.25	10.2	0.086
3	26	29	19	26	25.00	5.1	0.053
PV	7	17	17	12	13		
AV	52	55.5	50	48	51		
YP	90	77	66	72	76		
Gel_{in}	26						
Gel_{10}	19						

Table A39 New-based drilling mud mixed with 5 percent lime at 30^{o}C (No.39).

RPM	**Reading #1**	**Reading #2**	**Reading #3**	**Reading #4**	**Average reading**	**γ (sec^{-1})**	**τ (lb$_f$/ft^2)**
600	89	82	78	78	81.75	1021.8	0.174
300	81	73	65	69	72.00	510.9	0.154
200	67	67	60	65	64.75	340.6	0.138
100	62	61	50	58	57.75	170.3	0.123
6	32	36	28	38	33.50	10.2	0.071
3	11	19	18	23	17.75	5.1	0.038
PV	8	9	13	9	10		
AV	44.5	41	39	39	41		
YP	73	64	52	60	62		
Gel$_{in}$	11						
Gel$_{10}$	18						

Table A40 New-based drilling mud mixed with 1 percent lime at 60^{o}C (No.40).

RPM	**Reading #1**	**Reading #2**	**Reading #3**	**Reading #4**	**Average reading**	**γ (sec^{-1})**	**τ (lb$_f$/ft^2)**
600	65	65	69	68	66.75	1021.8	0.142
300	55	60	53	62	57.50	510.9	0.123
200	49	54	56	58	54.25	340.6	0.116
100	46	46	43	50	46.25	170.3	0.099
6	12	18	8	21	14.75	10.2	0.031
3	14	11	6	8	9.75	5.1	0.021
PV	10	5	16	6	9		
AV	32.5	32.5	34.5	34	33		
YP	45	55	37	56	48		
Gel$_{in}$	14						
Gel$_{10}$	6						

Table A41 New-based drilling mud mixed with 3 percent lime at 60^{o}C (No.41).

RPM	Reading #1	Reading #2	Reading #3	Reading #4	Average reading	γ (sec^{-1})	τ (lb_f/ft^2)
600	80	78	76	83	79.25	1021.8	0.169
300	70	70	67	77	71.00	510.9	0.151
200	65	66	60	72	65.75	340.6	0.140
100	60	60	54	66	60.00	170.3	0.128
6	32	33	28	40	33.25	10.2	0.071
3	15	19	18	20	18.00	5.1	0.038
PV	10	8	9	6	8		
AV	40	39	38	41.5	40		
YP	60	62	58	71	63		
Gel_{in}	15						
Gel_{10}	18						

Table A42 New-based drilling mud mixed with 5 percent lime at 60^{o}C (No.42).

RPM	Reading #1	Reading #2	Reading #3	Reading #4	Average reading	γ (sec^{-1})	τ (lb_f/ft^2)
600	70	69	65	64	67.00	1021.8	0.143
300	59	62	55	60	59.00	510.9	0.126
200	54	57	51	56	54.50	340.6	0.116
100	47	51	46	52	49.00	170.3	0.104
6	25	26	25	26	25.50	10.2	0.054
3	21	19	13	17	17.50	5.1	0.037
PV	11	7	10	4	8		
AV	35	34.5	32.5	32	34		
YP	48	55	45	56	51		
Gel_{in}	21						
Gel_{10}	13						

Table A43 New-based drilling mud mixed with 1 percent starch at 30^{o}C (No.43).

RPM	Reading #1	Reading #2	Reading #3	Reading #4	Average reading	γ (sec^{-1})	τ (lb_f/ft^2)
600	84	80	82	83	82.25	1021.8	0.175
300	81	77	77	79	78.50	510.9	0.167
200	80	75	74	86	78.75	340.6	0.168
100	78	69	69	76	73.00	170.3	0.156
6	50	49	35	55	47.25	10.2	0.101
3	31	16	15	15	19.25	5.1	0.041
PV	3	3	5	4	4		
AV	42	40	41	41.5	41		
YP	78	74	72	75	75		
Gel_{in}	31						
Gel_{10}	15						

Table A44 New-based drilling mud mixed with 3 percent starch at 30^{o}C (No.44).

RPM	Reading #1	Reading #2	Reading #3	Reading #4	Average reading	γ (sec^{-1})	τ (lb_f/ft^2)
600	77	76	81	83	79.25	1021.8	0.169
300	76	73	75	79	75.75	510.9	0.161
200	74	70	69	75	72.00	340.6	0.154
100	72	68	65	71	69.00	170.3	0.147
6	48	49	48	51	49.00	10.2	0.104
3	24	24	18	26	23.00	5.1	0.049
PV	1	3	6	4	4		
AV	38.5	38	40.5	41.5	40		
YP	75	70	69	75	72		
Gel_{in}	24						
Gel_{10}	18						

Table A45 New-based drilling mud mixed with 5 percent starch at 30^{o}C (No.45).

RPM	Reading #1	Reading #2	Reading #3	Reading #4	Average reading	γ (sec^{-1})	τ (lb_f/ft^2)
600	87	92	99	100	94.50	1021.8	0.201
300	82	88	90	94	88.50	510.9	0.189
200	80	86	86	90	85.50	340.6	0.182
100	74	82	74	85	78.75	170.3	0.168
6	57	62	56	59	58.50	10.2	0.125
3	26	24	19	27	24.00	5.1	0.051
PV	5	4	9	6	6		
AV	43.5	46	49.5	50	47		
YP	77	84	81	88	83		
Gel_{in}	26						
Gel_{10}	19						

Table A46 New-based drilling mud mixed with 1 percent starch at 60^{o}C (No.46).

RPM	Reading #1	Reading #2	Reading #3	Reading #4	Average reading	γ (sec^{-1})	τ (lb_f/ft^2)
600	100	103	102	102	101.75	1021.8	0.217
300	79	89	82	86	84.00	510.9	0.179
200	75	80	80	78	78.25	340.6	0.167
100	72	75	74	72	73.25	170.3	0.156
6	25	35	27	40	31.75	10.2	0.068
3	23	29	25	25	25.50	5.1	0.054
PV	21	14	20	16	18		
AV	50	51.5	51	51	51		
YP	58	75	62	70	66		
Gel_{in}	23						
Gel_{10}	25						

Table A47 New-based drilling mud mixed with 3 percent starch at 60°C (No.47).

RPM	Reading #1	Reading #2	Reading #3	Reading #4	Average reading	γ (sec^{-1})	τ (lb_f/ft^2)
600	266	268	252	249	258.75	1021.8	0.552
300	198	223	188	193	200.50	510.9	0.427
200	185	208	167	177	184.25	340.6	0.393
100	169	179	148	157	163.25	170.3	0.348
6	78	109	45	106	84.50	10.2	0.180
3	68	68	44	64	61.00	5.1	0.130
PV	68	45	64	56	58		
AV	133	134	126	124.5	129		
YP	130	178	124	137	142		
Gel_{in}	68						
Gel_{10}	44						

Table A48 New-based drilling mud mixed with 5 percent starch at 60°C (No.48).

RPM	Reading #1	Reading #2	Reading #3	Reading #4	Average reading	γ (sec^{-1})	τ (lb_f/ft^2)
600	304	304	304	304	304.00	1021.8	0.648
300	304	304	304	304	304.00	510.9	0.648
200	303	304	304	304	303.75	340.6	0.648
100	303	303	304	304	303.50	170.3	0.647
6	134	136	134	142	136.50	10.2	0.291
3	131	122	130	126	127.25	5.1	0.271
PV	0	0	0	0	0		
AV	152	152	152	152	152		
YP	304	304	304	304	304		
Gel_{in}	131						
Gel_{10}	130						

Mudcake thickness data for all fluids tested.

Table A49 Water-based drilling mud at 30, 60 and 90°C.

No.	Mudcake thickness (mm)			Average (mm)
	#1	#2	#3	
1	3.80	3.84	3.79	3.81
2	3.96	3.14	4.60	3.90
3	4.92	4.92	5.72	5.19

Table A50 Water-based drilling mud mixed with 1, 3 and 5 percent fly ash at 30°C.

No.	Mudcake thickness (mm)			Average (mm)
	#1	#2	#3	
4	5.10	4.50	6.92	5.51
5	10.10	11.68	10.16	10.65
6	10.80	10.12	12.42	11.11

Table A51 Water-based drilling mud mixed with 1, 3 and 5 percent fly ash at 60°C.

No.	Mudcake thickness (mm)			Average (mm)
	#1	#2	#3	
7	6.84	5.10	7.24	6.39
8	12.06	12.90	12.54	12.50
9	12.54	14.76	13.02	13.44

Table A52 Water-based drilling mud mixed with 1, 3 and 5 percent fly ash at 90°C.

No.	Mudcake thickness (mm)			Average (mm)
	#1	#2	#3	
10	9.70	8.34	10.90	9.65
11	15.70	20.00	15.28	16.99
12	18.90	21.28	18.84	19.67

Table A53 Water-based drilling mud mixed with 1, 3 and 5 percent dolomite at 30°C.

No.	Mudcake thickness (mm)			Average (mm)
	#1	#2	#3	
13	4.42	4.42	3.86	4.23
14	3.96	4.06	4.18	4.07
15	3.92	4.20	4.12	4.08

Table A54 Water-based drilling mud mixed with 1, 3 and 5 percent rice husk ash at 30°C.

No.	Mudcake thickness (mm)			Average (mm)
	#1	#2	#3	
16	3.82	3.96	3.81	3.86
17	4.38	4.34	3.98	4.23
18	4.48	4.36	4.08	4.31

Table A55 Water-based drilling mud mixed with 1, 3 and 5 percent lime at 30°C.

No.	Mudcake thickness (mm)			Average (mm)
	#1	#2	#3	
19	4.39	4.32	3.94	4.22
20	3.42	3.92	4.12	3.82
21	3.90	3.86	3.96	3.91

Table A56 Water-based drilling mud mixed with 1, 3 and 5 percent starch at 30°C.

No.	Mudcake thickness (mm)			Average (mm)
	#1	#2	#3	
22	4.00	4.12	4.52	4.21
23	3.52	3.67	4.20	3.80
24	3.36	2.94	3.00	3.10

Table A57 New-based drilling mud mixed with 1, 3 and 5 percent dolomite at 30°C.

No.	Mudcake thickness (mm)			Average (mm)
	#1	#2	#3	
25	7.94	9.92	9.92	9.26
26	10.32	10.22	10.20	10.25
27	11.24	10.32	9.37	10.31

Table A58 New-based drilling mud mixed with 1, 3 and 5 percent dolomite at 60°C.

No.	Mudcake thickness (mm)			Average (mm)
	#1	#2	#3	
28	13.62	13.52	14.42	13.85
29	16.82	17.68	17.88	17.46
30	17.80	18.10	17.98	17.96

Table A59 New-based drilling mud mixed with 1, 3 and 5 percent rice husk ash at 30°C.

No.	Mudcake thickness (mm)			Average (mm)
	#1	#2	#3	
31	9.22	7.98	9.98	9.06
32	7.30	8.22	8.84	8.12
33	7.14	6.88	7.56	7.19

Table A60 New-based drilling mud mixed with 1, 3 and 5 percent rice husk ash at 60°C.

No.	Mudcake thickness (mm)			Average (mm)
	#1	#2	#3	
34	13.68	13.64	12.90	13.41
35	12.32	12.16	12.56	12.35
36	11.48	12.24	11.46	11.73

Table A61 New-based drilling mud mixed with 1,3 and 5 percent lime at 30°C.

No.	Mudcake thickness (mm)			Average (mm)
	#1	#2	#3	
37	10.64	11.52	10.42	10.86
38	11.62	11.92	11.48	11.67
39	11.22	12.14	12.02	11.79

Table A62 New-based drilling mud mixed with 1, 3 and 5 percent lime at 60°C.

No.	Mudcake thickness (mm)			Average (mm)
	#1	#2	#3	
40	17.16	16.94	16.26	16.79
41	17.32	18.94	17.58	17.95
42	18.14	18.62	19.38	18.71

Table A63 New-based drilling mud mixed with 1, 3 and 5 percent starch at 30°C.

No.	Mudcake thickness (mm)			Average (mm)
	#1	#2	#3	
43	10.20	10.92	10.30	10.47
44	9.92	9.34	11.42	10.23
45	8.72	9.96	8.30	8.99

Table A64 New-based drilling mud mixed with 1, 3 and 5 percent starch at 60°C.

No.	Mudcake thickness (mm)			Average (mm)
	#1	#2	#3	
46	3.46	4.84	4.90	4.40
47	3.40	2.86	2.72	2.99
48	2.40	2.08	3.50	2.66

Resistivity data for all tested.

Table A65 Water-based drilling mud at 30°C (No.1).

Sample	Temp. (°F)	#1	#2	#3	Average (Ω.m)	Correct value (Ω.m)
		(Ω.m)				
Mud	77.7	5.06	4.98	4.98	5.01	4.90
Mud filtrate	75.9	6.15	6.01	5.98	6.05	5.91
Mud cake	79.0	4.02			4.02	3.93

Table A66 Water-based drilling mud at 60°C (No.2).

Sample	Temp. (°F)	#1	#2	#3	Average (Ω.m)	Correct value (Ω.m)
		(Ω.m)				
Mud	79.7	4.75	4.74	4.62	4.70	4.60
Mud filtrate	76.1	5.65	5.47	5.33	5.48	5.36
Mud cake	78.2	3.46			3.46	3.38

Table A67 Water-based drilling mud at 90°C (No.3).

Sample	Temp. (°F)	#1	#2	#3	Average (Ω.m)	Correct value (Ω.m)
		(Ω.m)				
Mud	79.3	4.42	4.39	4.38	4.40	4.30
Mud filtrate	76.5	5.19	5.22	5.24	5.22	5.10
Mud cake	79.5	3.29			3.29	3.22

Table A68 Water-based drilling mud mixed with 1 percent fly ash at 30°C (No.4).

Sample	Temp. (°F)	#1	#2	#3	Average (Ω.m)	Correct value (Ω.m)
		(Ω.m)				
Mud	78.2	4.28	4.18	4.13	4.20	4.10
Mud filtrate	76.2	5.20	5.00	5.29	5.16	5.05
Mud cake	78.4	3.40			3.40	3.33

Table A69 Water-based drilling mud mixed with 3 percent fly ash at 30°C (No.5).

Sample	Temp. (°F)	#1	#2	#3	Average (Ω.m)	Correct value (Ω.m)
		(Ω.m)				
Mud	76.4	2.80	2.83	2.83	2.82	2.76
Mud filtrate	76.1	2.66	2.61	2.62	2.63	2.57
Mud cake	77.5	2.47			2.47	2.42

Table A70 Water-based drilling mud mixed with 5 percent fly ash at 30°C (No.6).

Sample	Temp. (°F)	#1	#2	#3	Average (Ω.m)	Correct value (Ω.m)
		(Ω.m)				
Mud	73.8	2.57	2.59	2.41	2.52	2.47
Mud filtrate	72.3	2.14	2.12	2.09	2.12	2.07
Mud cake	75.2	2.28			2.28	2.23

Table A71 Water-based drilling mud mixed with 1 percent fly ash at 60°C (No.7).

Sample	Temp. (°F)	#1	#2	#3	Average (Ω.m)	Correct value (Ω.m)
		(Ω.m)				
Mud	78.5	4.16	3.95	3.85	3.99	3.90
Mud filtrate	74.7	5.03	4.90	4.83	4.92	4.81
Mud cake	78.4	3.59			3.59	3.51

Table A72 Water-based drilling mud mixed with 3 percent fly ash at 60°C (No.8).

Sample	Temp. (°F)	#1	#2	#3	Average (Ω.m)	Correct value (Ω.m)
		(Ω.m)				
Mud	80.6	1.82	1.75	1.68	1.75	1.71
Mud filtrate	78.8	2.10	2.15	1.67	1.97	1.93
Mud cake	79.5	2.18			2.18	2.13

Table A73 Water-based drilling mud mixed with 5 percent fly ash at 60°C (No.9).

Sample	Temp. (°F)	#1	#2	#3	Average (Ω.m)	Correct value (Ω.m)
		(Ω.m)				
Mud	80.3	1.79	1.76	1.72	1.76	1.72
Mud filtrate	79.0	1.69	1.66	1.65	1.67	1.63
Mud cake	79.5	2.88			2.88	2.82

Table A74 Water-based drilling mud mixed with 1 percent fly ash at 90°C (No.10).

Sample	Temp. (°F)	#1	#2	#3	Average (Ω.m)	Correct value (Ω.m)
		(Ω.m)				
Mud	85.9	3.33	3.35	3.38	3.35	3.28
Mud filtrate	77.9	4.53	4.40	4.35	4.43	4.33
Mud cake	79.5	3.72			3.72	3.64

Table A75 Water-based drilling mud mixed with 3 percent fly ash at 90°C (No.11).

Sample	Temp. (°F)	#1	#2	#3	Average (Ω.m)	Correct value (Ω.m)
		(Ω.m)				
Mud	82.6	1.58	1.55	1.57	1.57	1.53
Mud filtrate	78.7	1.63	1.58	1.57	1.59	1.56
Mud cake	79.0	2.25			2.25	2.20

Table A76 Water-based drilling mud mixed with 5 percent fly ash at 90°C (No.12).

Sample	Temp. (°F)	#1	#2	#3	Average (Ω.m)	Correct value (Ω.m)
		(Ω.m)				
Mud	81.9	1.69	1.68	1.68	1.68	1.65
Mud filtrate	81.1	1.61	1.60	1.61	1.61	1.57
Mud cake	78.9	2.13			2.13	2.08

Table A77 Water-based drilling mud mixed with 1 percent dolomite at 30°C (No.13).

Sample	Temp. (°F)	#1	#2	#3	Average (Ω.m)	Correct value (Ω.m)
		(Ω.m)				
Mud	72.7	5.70	5.47	5.38	5.52	5.40
Mud filtrate	71.6	6.80	6.71	6.66	6.72	6.58
Mud cake	73.5	4.33			4.33	4.23

Table A78 Water-based drilling mud mixed with 3 percent dolomite at 30°C (No.14).

Sample	Temp. (°F)	#1	#2	#3	Average (Ω.m)	Correct value (Ω.m)
		(Ω.m)				
Mud	77.2	5.45	5.33	5.33	5.37	5.25
Mud filtrate	74.8	6.78	6.77	6.78	6.78	6.63
Mud cake	76.6	4.58			4.58	4.48

Table A79 Water-based drilling mud mixed with 5 percent dolomite at 30°C (No.15).

Sample	Temp. (°F)	#1	#2	#3	Average (Ω.m)	Correct value (Ω.m)
		(Ω.m)				
Mud	77.2	5.30	5.28	5.28	5.29	5.17
Mud filtrate	76.9	6.69	6.53	6.46	6.56	6.42
Mud cake	79.4	4.45			4.45	4.35

Table A80 Water-based drilling mud mixed with 1 percent rice husk ash at 30°C (No.16).

Sample	Temp. (°F)	#1	#2	#3	Average (Ω.m)	Correct value (Ω.m)
		(Ω.m)				
Mud	73.5	5.23	5.12	5.17	5.17	5.06
Mud filtrate	71.2	6.18	6.14	6.06	6.13	5.99
Mud cake	75.0	4.21			4.21	4.12

Table A81 Water-based drilling mud mixed with 3 percent rice husk ash at 30^{o}C (No.17).

Sample	Temp. (^{o}F)	#1	#2	#3	Average (Ω.m)	Correct value (Ω.m)
		(Ω.m)				
Mud	74.0	5.09	5.03	5.03	5.05	4.94
Mud filtrate	75.9	5.60	5.52	5.50	5.54	5.42
Mud cake	78.1	4.04			4.04	3.95

Table A82 Water-based drilling mud mixed with 5 percent rice husk ash at 30^{o}C (No.18).

Sample	Temp. (^{o}F)	#1	#2	#3	Average (Ω.m)	Correct value (Ω.m)
		(Ω.m)				
Mud	78.5	4.53	4.51	4.48	4.51	4.41
Mud filtrate	78.0	4.95	4.88	4.85	4.89	4.79
Mud cake	79.7	3.72			3.72	3.64

Table A83 Water-based drilling mud mixed with 1 percent lime at 30^{o}C (No.19).

Sample	Temp. (^{o}F)	#1	#2	#3	Average (Ω.m)	Correct value (Ω.m)
		(Ω.m)				
Mud	75.3	5.32	5.19	5.08	5.20	5.08
Mud filtrate	76.3	6.26	6.20	6.17	6.21	6.07
Mud cake	80.0	4.10			4.10	4.01

Table A84 Water-based drilling mud mixed with 3 percent lime at 30^{o}C (No.20).

Sample	Temp. (^{o}F)	#1	#2	#3	Average (Ω.m)	Correct value (Ω.m)
		(Ω.m)				
Mud	75.8	5.01	5.04	5.15	5.07	4.96
Mud filtrate	76.5	6.20	6.06	6.00	6.09	5.95
Mud cake	79.0	4.28			4.28	4.19

Table A85 Water-based drilling mud mixed with 5 percent lime at 30°C (No.21).

Sample	Temp. (°F)	#1	#2	#3	Average (Ω.m)	Correct value (Ω.m)
		(Ω.m)				
Mud	78.1	4.64	4.43	4.32	4.46	4.37
Mud filtrate	77.1	5.52	5.41	5.42	5.45	5.33
Mud cake	79.2	3.33			3.33	3.26

Table A86 Water-based drilling mud mixed with 1 percent starch at 30°C (No.22).

Sample	Temp. (°F)	#1	#2	#3	Average (Ω.m)	Correct value (Ω.m)
		(Ω.m)				
Mud	79.6	5.20	5.13	5.01	5.11	5.00
Mud filtrate	77.1	6.59	6.53	6.37	6.50	6.35
Mud cake	79.4	3.33			3.33	3.26

Table A87 Water-based drilling mud mixed with 3 percent starch at 30°C (No.23).

Sample	Temp. (°F)	#1	#2	#3	Average (Ω.m)	Correct value (Ω.m)
		(Ω.m)				
Mud	77.8	5.26	5.14	5.14	5.18	5.07
Mud filtrate	75.1	6.45	6.39	6.39	6.41	6.27
Mud cake	77.3	4.63			4.63	4.53

Table A88 Water-based drilling mud mixed with 5 percent starch at 30°C (No.24).

Sample	Temp. (°F)	#1	#2	#3	Average (Ω.m)	Correct value (Ω.m)
		(Ω.m)				
Mud	76.7	5.62	5.58	5.48	5.56	5.44
Mud filtrate	74.3	6.51	6.25	6.27	6.34	6.20
Mud cake	77.9	5.05			5.05	4.94

Table A89 New-based drilling mud mixed with 1 percent dolomite at 30°C (No.25).

Sample	Temp. (°F)	#1	#2	#3	Average (Ω.m)	Correct value (Ω.m)
		(Ω.m)				
Mud	73.6	2.80	2.79	2.77	2.79	2.73
Mud filtrate	74.6	2.33	2.39	2.32	2.35	2.30
Mud cake	77.6	2.57			2.57	2.51

Table A90 New-based drilling mud mixed with 3 percent dolomite at 30°C (No.26).

Sample	Temp. (°F)	#1	#2	#3	Average (Ω.m)	Correct value (Ω.m)
		(Ω.m)				
Mud	75.6	2.72	2.67	2.60	2.66	2.60
Mud filtrate	72.4	2.30	2.28	2.26	2.28	2.23
Mud cake	75.9	2.62			2.62	2.56

Table A91 New-based drilling mud mixed with 5 percent dolomite at 30°C (No.27).

Sample	Temp. (°F)	#1	#2	#3	Average (Ω.m)	Correct value (Ω.m)
		(Ω.m)				
Mud	75.4	2.68	2.63	2.62	2.64	2.59
Mud filtrate	70.2	2.32	2.29	2.28	2.30	2.25
Mud cake	74.3	2.58			2.58	2.52

Table A92 New-based drilling mud mixed with 1 percent dolomite at 60°C (No.28).

Sample	Temp. (°F)	#1	#2	#3	Average (Ω.m)	Correct value (Ω.m)
		(Ω.m)				
Mud	75.3	2.35	2.24	2.11	2.23	2.18
Mud filtrate	69.0	2.13	2.12	2.14	2.13	2.08
Mud cake	77.8	2.40			2.40	2.35

Table A93 New-based drilling mud mixed with 3 percent dolomite at 60^oC (No.29)

Sample	Temp. (^oF)	#1	#2	#3	Average (Ω.m)	Correct value (Ω.m)
		(Ω.m)				
Mud	81.5	2.09	2.05	2.02	2.05	2.01
Mud filtrate	77.5	1.96	1.97	1.98	1.97	1.93
Mud cake	78.2	2.23			2.23	2.18

Table A94 New-based drilling mud mixed with 5 percent dolomite at 60^oC (No.30).

Sample	Temp. (^oF)	#1	#2	#3	Average (Ω.m)	Correct value (Ω.m)
		(Ω.m)				
Mud	82.0	2.01	2.01	1.98	2.00	1.96
Mud filtrate	78.0	2.01	1.99	1.97	1.99	1.95
Mud cake	77.1	2.78			2.78	2.72

Table A95 New-based drilling mud mixed with 1 percent rice husk ash at 30^oC (No.31).

Sample	Temp. (^oF)	#1	#2	#3	Average (Ω.m)	Correct value (Ω.m)
		(Ω.m)				
Mud	76.8	3.24	3.16	3.11	3.17	3.10
Mud filtrate	77.3	2.77	2.72	2.71	2.73	2.67
Mud cake	78.4	3.25			3.25	3.18

Table A96 New-based drilling mud mixed with 3 percent rice husk ash at 30^oC (No.32).

Sample	Temp. (^oF)	#1	#2	#3	Average (Ω.m)	Correct value (Ω.m)
		(Ω.m)				
Mud	78.1	3.36	3.27	3.24	3.29	3.22
Mud filtrate	77.5	3.02	2.98	2.97	2.99	2.92
Mud cake	77.9	3.08			3.08	3.01

Table A97 New-based drilling mud mixed with 5 percent rice husk ash at 30^oC (No.33).

Sample	Temp. (^oF)	#1	#2	#3	Average (Ω.m)	Correct value (Ω.m)
		(Ω.m)				
Mud	78.3	3.40	3.46	3.44	3.43	3.36
Mud filtrate	77.0	3.17	3.11	3.15	3.14	3.07
Mud cake	77.3	3.32			3.32	3.25

Table A98 New-based drilling mud mixed with 1 percent rice husk ash at 60°C (No.34).

Sample	Temp. (°F)	#1	#2	#3	Average (Ω.m)	Correct value (Ω.m)
		(Ω.m)				
Mud	82.7	2.28	2.26	2.22	2.25	2.20
Mud filtrate	77.7	2.36	2.30	2.29	2.32	2.27
Mud cake	79.3	2.57			2.57	2.51

Table A99 New-based drilling mud mixed with 3 percent rice husk ash at 60°C (No.35).

Sample	Temp. (°F)	#1	#2	#3	Average (Ω.m)	Correct value (Ω.m)
		(Ω.m)				
Mud	82.7	2.55	2.50	2.45	2.50	2.45
Mud filtrate	77.1	2.52	2.48	2.47	2.49	2.44
Mud cake	78.5	3.15			3.15	3.08

Table A100 New-based drilling mud mixed with 5 percent rice husk ash at 60°C (No.36).

Sample	Temp. (°F)	#1	#2	#3	Average (Ω.m)	Correct value (Ω.m)
		(Ω.m)				
Mud	79.0	3.03	2.96	2.94	2.98	2.91
Mud filtrate	75.2	2.87	2.80	2.78	2.82	2.75
Mud cake	75.2	3.55			3.55	3.47

Table A101 New-based drilling mud mixed with 1 percent lime at 30°C (No.37).

Sample	Temp. (°F)	#1	#2	#3	Average (Ω.m)	Correct value (Ω.m)
		(Ω.m)				
Mud	77.4	2.40	2.33	2.30	2.34	2.29
Mud filtrate	74.2	2.05	2.06	2.06	2.06	2.01
Mud cake	76.4	2.25			2.25	2.20

Table A102 New-based drilling mud mixed with 3 percent lime at 30°C (No.38).

Sample	Temp. (°F)	#1	#2	#3	Average (Ω.m)	Correct value (Ω.m)
		(Ω.m)				
Mud	73.3	2.21	2.16	2.15	2.17	2.13
Mud filtrate	71.9	1.85	1.81	1.79	1.82	1.78
Mud cake	74.5	2.05			2.05	2.00

Table A103 New-based drilling mud mixed with 5 percent lime at 30°C (No.39).

Sample	Temp. (°F)	#1	#2	#3	Average (Ω.m)	Correct value (Ω.m)
		(Ω.m)				
Mud	72.5	2.16	2.11	2.17	2.15	2.10
Mud filtrate	71.7	1.85	1.83	1.84	1.84	1.80
Mud cake	73.8	2.27			2.27	2.22

Table A104 New-based drilling mud mixed with 1 percent lime at 60°C (No.40).

Sample	Temp. (°F)	#1	#2	#3	Average (Ω.m)	Correct value (Ω.m)
		(Ω.m)				
Mud	81.0	1.92	1.90	1.92	1.91	1.87
Mud filtrate	77.1	2.09	2.02	2.03	2.05	2.00
Mud cake	77.9	2.43			2.43	2.38

Table A105 New-based drilling mud mixed with 3 percent lime at 60°C (No.41).

Sample	Temp. (°F)	#1	#2	#3	Average (Ω.m)	Correct value (Ω.m)
		(Ω.m)				
Mud	81.0	1.83	1.82	1.79	1.81	1.77
Mud filtrate	77.7	1.82	1.79	1.78	1.80	1.76
Mud cake	77.6	1.98			1.98	1.94

Table A106 New-based drilling mud mixed with 5 percent lime at 60°C (No.42).

Sample	Temp. (°F)	#1	#2	#3	Average (Ω.m)	Correct value (Ω.m)
		(Ω.m)				
Mud	80.2	1.79	1.69	1.66	1.71	1.68
Mud filtrate	75.2	1.68	1.65	1.64	1.66	1.62
Mud cake	75.8	2.20			2.20	2.15

Table A107 New-based drilling mud mixed with 1 percent starch at 30°C (No.43).

Sample	Temp. (°F)	#1	#2	#3	Average (Ω.m)	Correct value (Ω.m)
		(Ω.m)				
Mud	76.6	3.13	3.02	2.95	3.03	2.97
Mud filtrate	74.5	2.70	2.66	2.63	2.66	2.60
Mud cake	77.4	2.68			2.68	2.62

Table A108 New-based drilling mud mixed with 3 percent starch at 30^{o}C (No.44).

Sample	Temp. (^{o}F)	#1	#2	#3	Average (Ω.m)	Correct value (Ω.m)
		(Ω.m)				
Mud	76.1	3.14	3.11	3.11	3.12	3.05
Mud filtrate	73.1	2.89	2.82	2.79	2.83	2.77
Mud cake	79.0	3.01			3.01	2.94

Table A109 New-based drilling mud mixed with 5 percent starch at 30^{o}C (No.45).

Sample	Temp. (^{o}F)	#1	#2	#3	Average (Ω.m)	Correct value (Ω.m)
		(Ω.m)				
Mud	73.4	3.62	3.55	3.55	3.57	3.49
Mud filtrate	69.9	3.20	3.11	3.09	3.13	3.06
Mud cake	74.9	3.28			3.28	3.21

Table A110 New-based drilling mud mixed with 1 percent starch at 60^{o}C (No.46).

Sample	Temp. (^{o}F)	#1	#2	#3	Average (Ω.m)	Correct value (Ω.m)
		(Ω.m)				
Mud	81.8	2.33	2.42	2.38	2.38	2.32
Mud filtrate	76.7	2.65	2.59	2.55	2.60	2.54
Mud cake	7.9	2.42			2.42	2.37

Table A111 New-based drilling mud mixed with 3 percent starch at 60^{o}C (No.47).

Sample	Temp. (^{o}F)	#1	#2	#3	Average (Ω.m)	Correct value (Ω.m)
		(Ω.m)				
Mud	53.1	2.81	2.81	2.76	2.79	2.73
Mud filtrate	74.3	3.03	2.98	2.96	2.99	2.92
Mud cake	76.9	2.93			2.93	2.87

Table A112 New-based drilling mud mixed with 5 percent starch at 60^{o}C (No.48).

Sample	Temp. (^{o}F)	#1	#2	#3	Average (Ω.m)	Correct value (Ω.m)
		(Ω.m)				
Mud	77.4	3.25	3.20	3.29	3.25	3.18
Mud filtrate	76.2	3.23	3.13	3.12	3.16	3.09
Mud cake	72.9	3.08			3.08	3.01

Solid and sand contents data for all fluids tested.

Table A113 Solid and sand contents all drilling mud.

No.	Average solid content		Average sand content (%)
	Water (ml)	Solid (%)	
1	49.0	7.6	0.50
2	48.0	7.5	0.58
3	48.0	7.4	0.58
4	48.0	9.9	1.25
5	47.0	10.9	1.50
6	48.0	11.4	2.00
7	47.5	9.5	1.25
8	46.0	10.8	1.50
9	39.0	11.2	2.00
10	45.0	9.0	1.25
11	48.5	10.7	1.50
12	45.5	10.8	2.00
13	48.0	8.1	0.50
14	48.0	8.3	0.75
15	47.5	8.9	0.50
16	47.0	8.7	1.50
17	47.0	9.0	5.00
18	46.5	9.8	10.00
19	45.5	9.8	0.75
20	45.0	10.3	1.00
21	39.5	10.9	1.50
22	48.0	8.3	0.83
23	47.5	8.5	0.50
24	47.0	8.9	0.50
25	47.0	10.6	1.50
26	46.0	11.4	1.50
27	45.5	12.6	1.00
28	47.0	9.7	1.50
29	47.5	10.5	1.50
30	47.5	12.5	1.50
31	47.0	9.8	2.00
32	47.0	11.9	3.50

Table A113 Solid and sand contents all drilling mud (continued).

No.	Average solid content		Average sand content
	Water (ml)	Solid (%)	
33	47.5	12.0	7.50
34	47.0	9.6	2.00
35	46.5	10.1	5.00
36	45.5	11.8	8.00
37	47.0	10.8	1.00
38	46.0	11.8	1.50
39	47.0	12.5	2.00
40	47.5	9.4	1.50
41	46.0	10.1	1.50
42	47.5	10.6	1.50
43	47.0	9.7	1.50
44	46.0	10.4	1.50
45	45.0	10.7	1.50
46	47.5	9.0	2.00
47	47.0	9.9	2.00
48	31.0	10.4	2.00

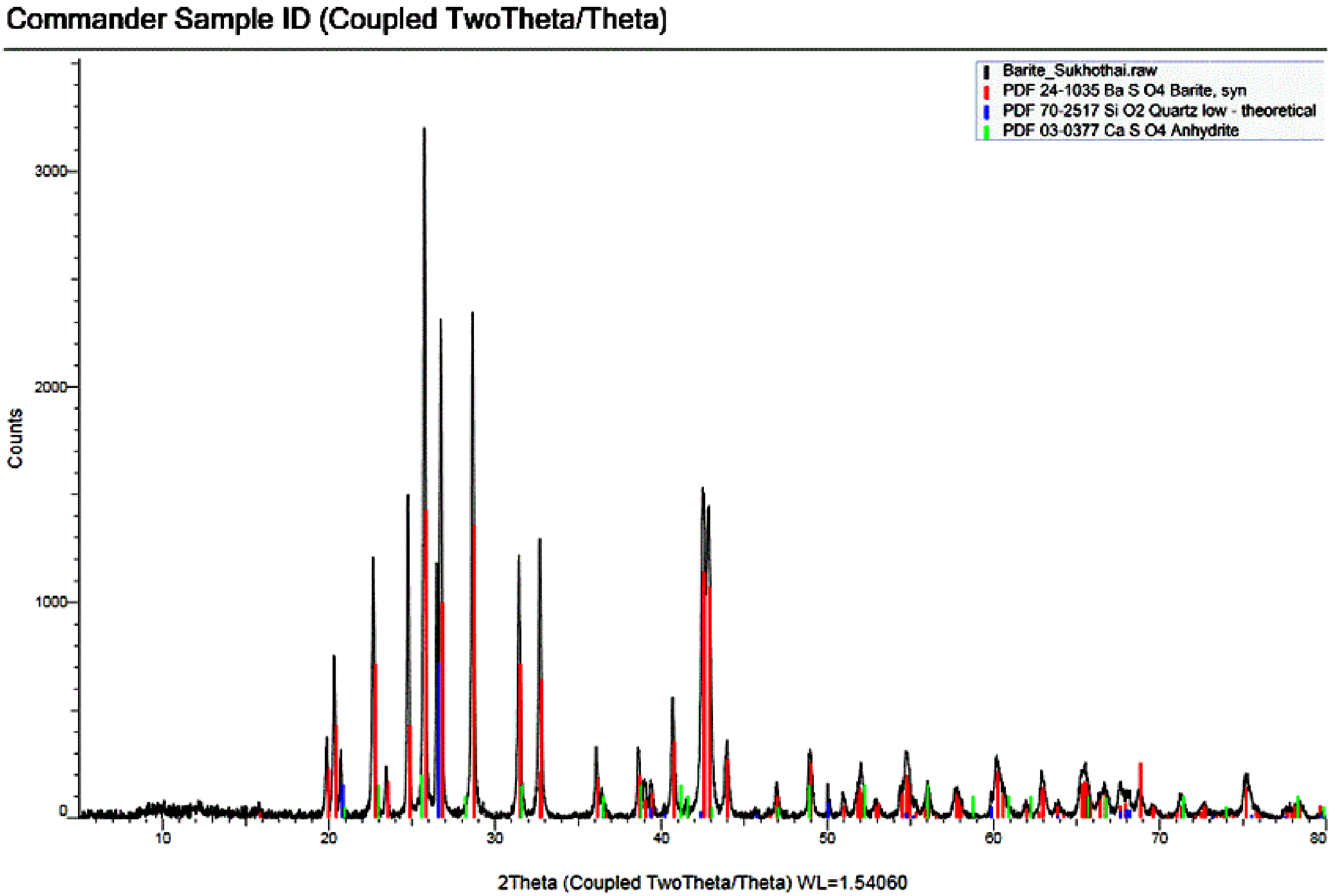

Figure A1. XRD of barite.

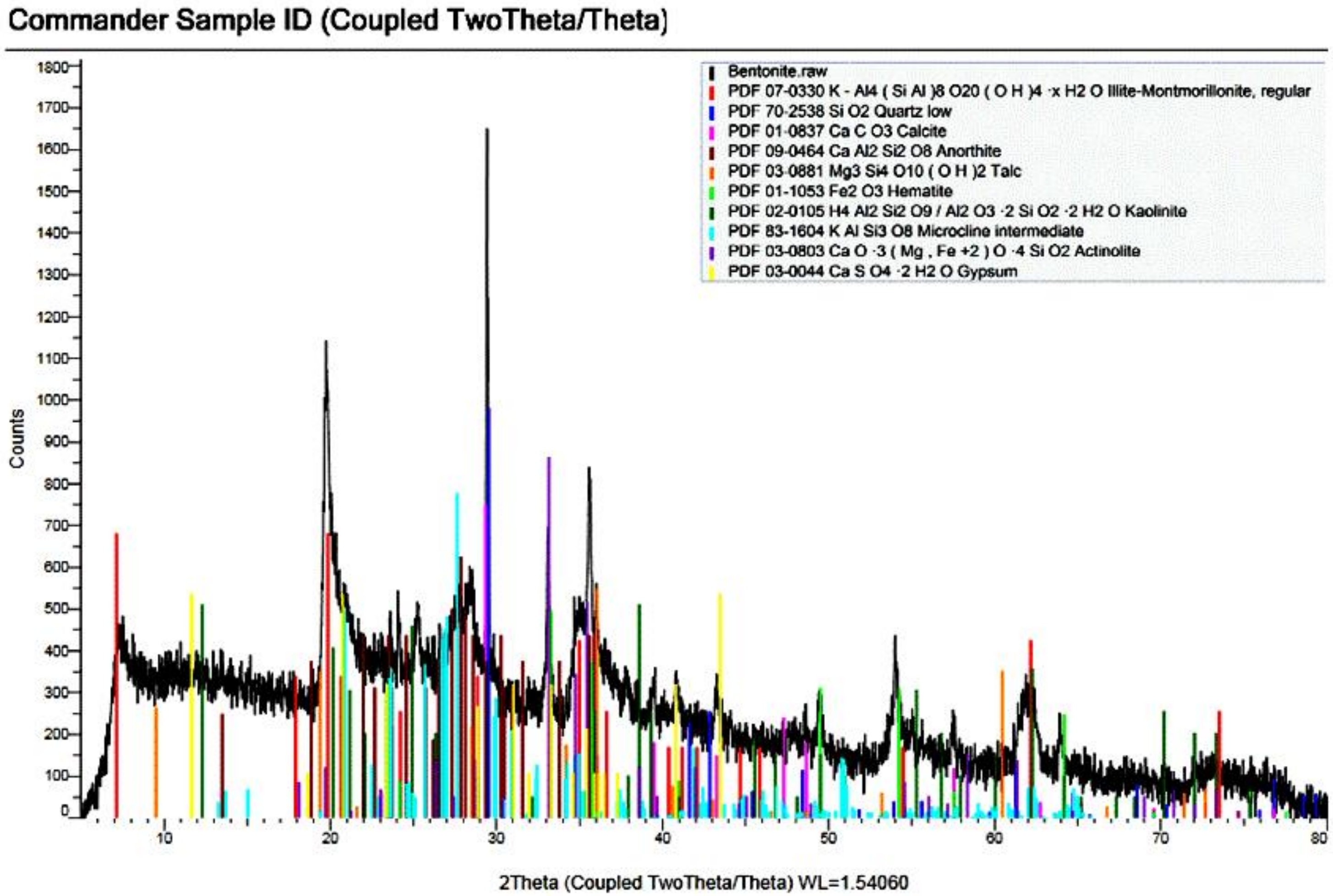

Figure A2. XRD of bentonite.

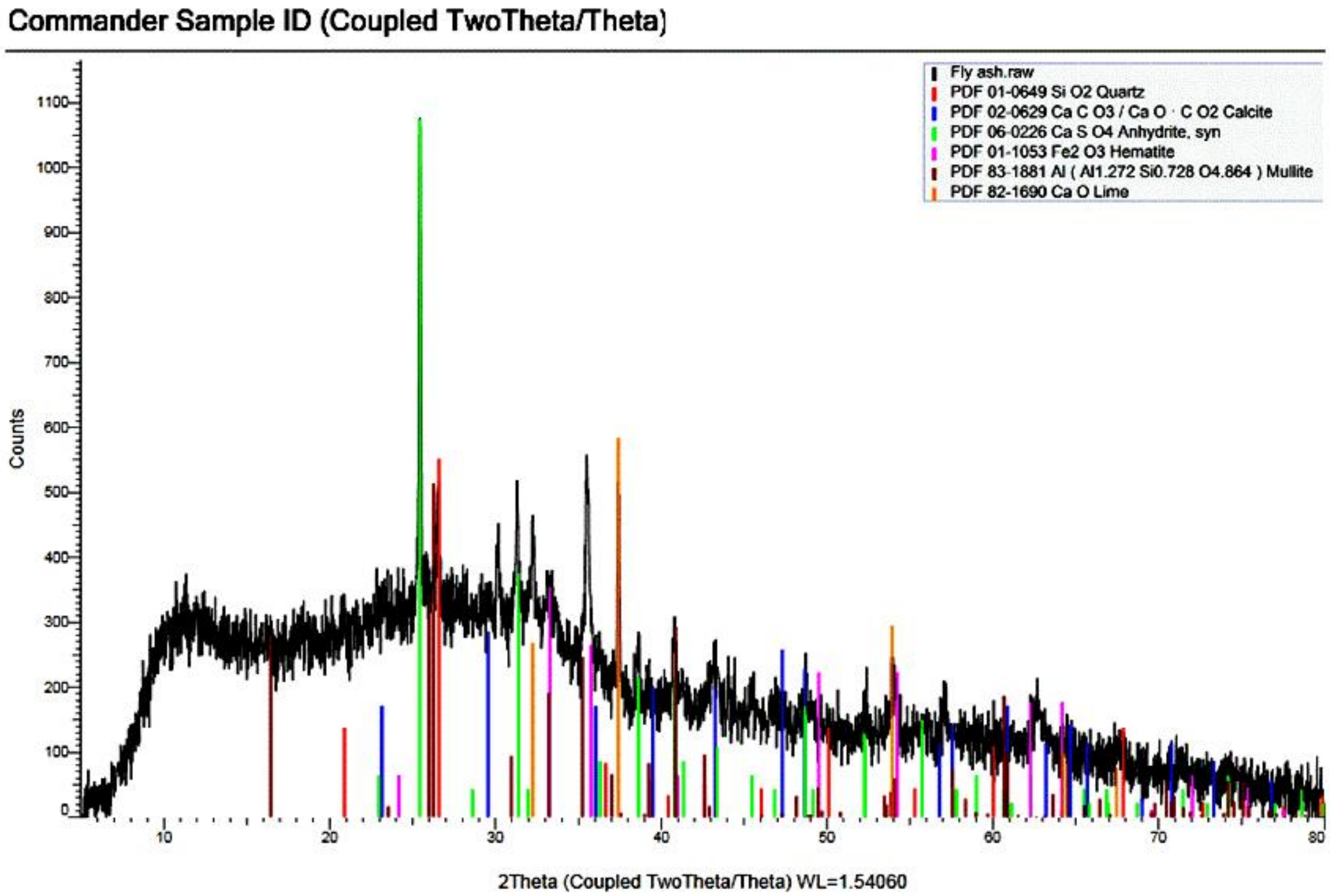

Figure A3. XRD of fly ash.

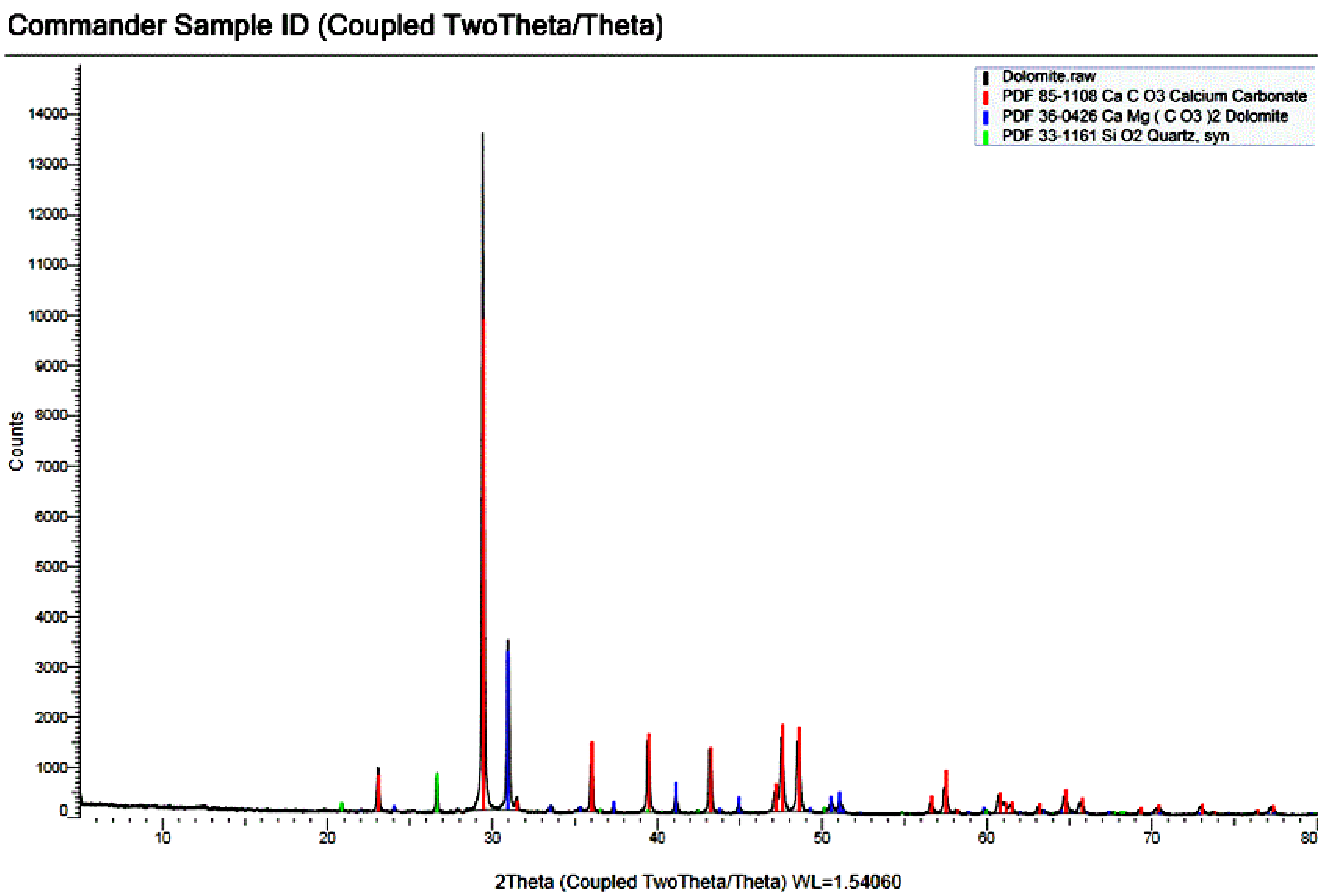

Figure A4. XRD of dolomite.

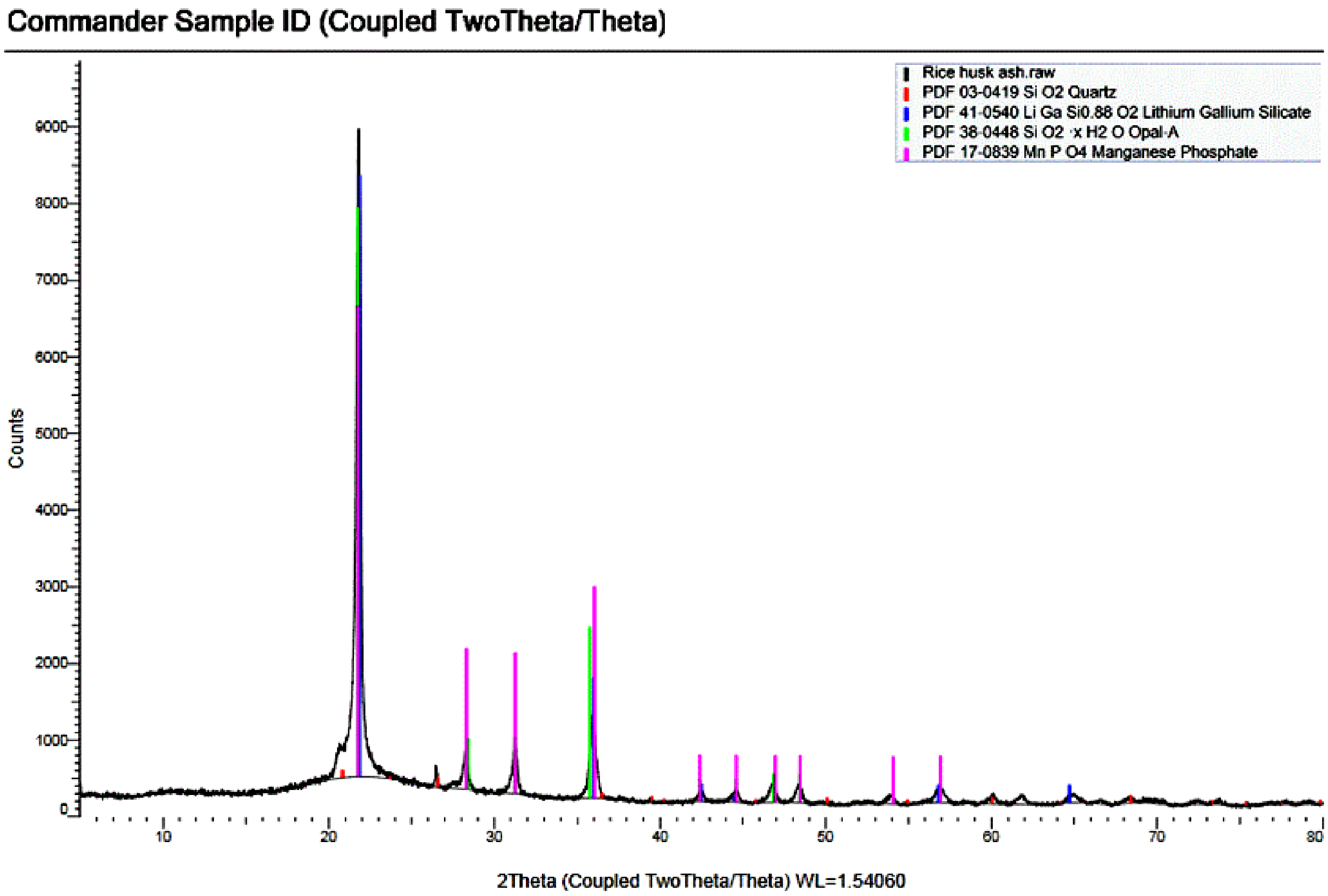

Figure A5. XRD of rice husk ash.

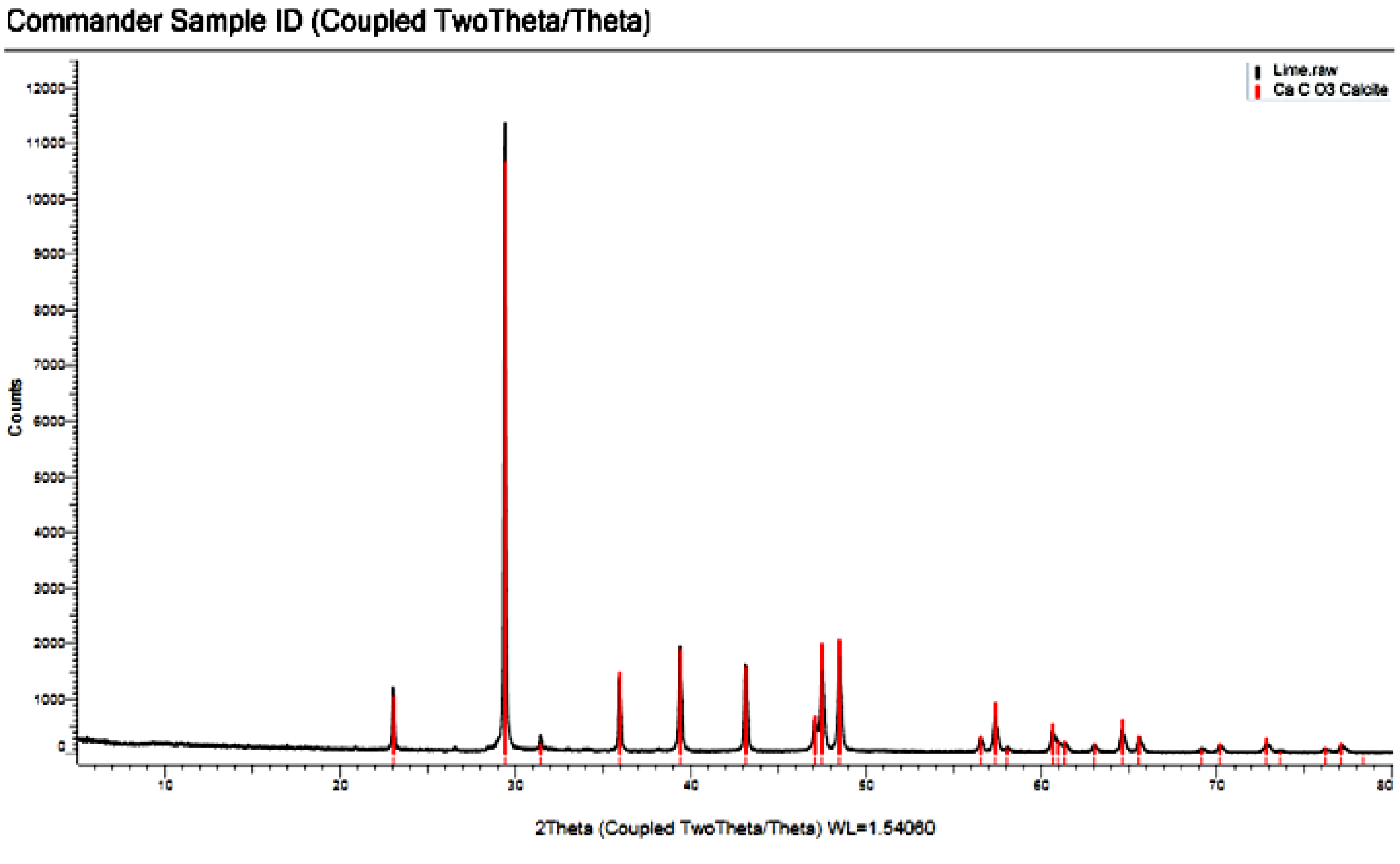

Figure A6. XRD of lime.

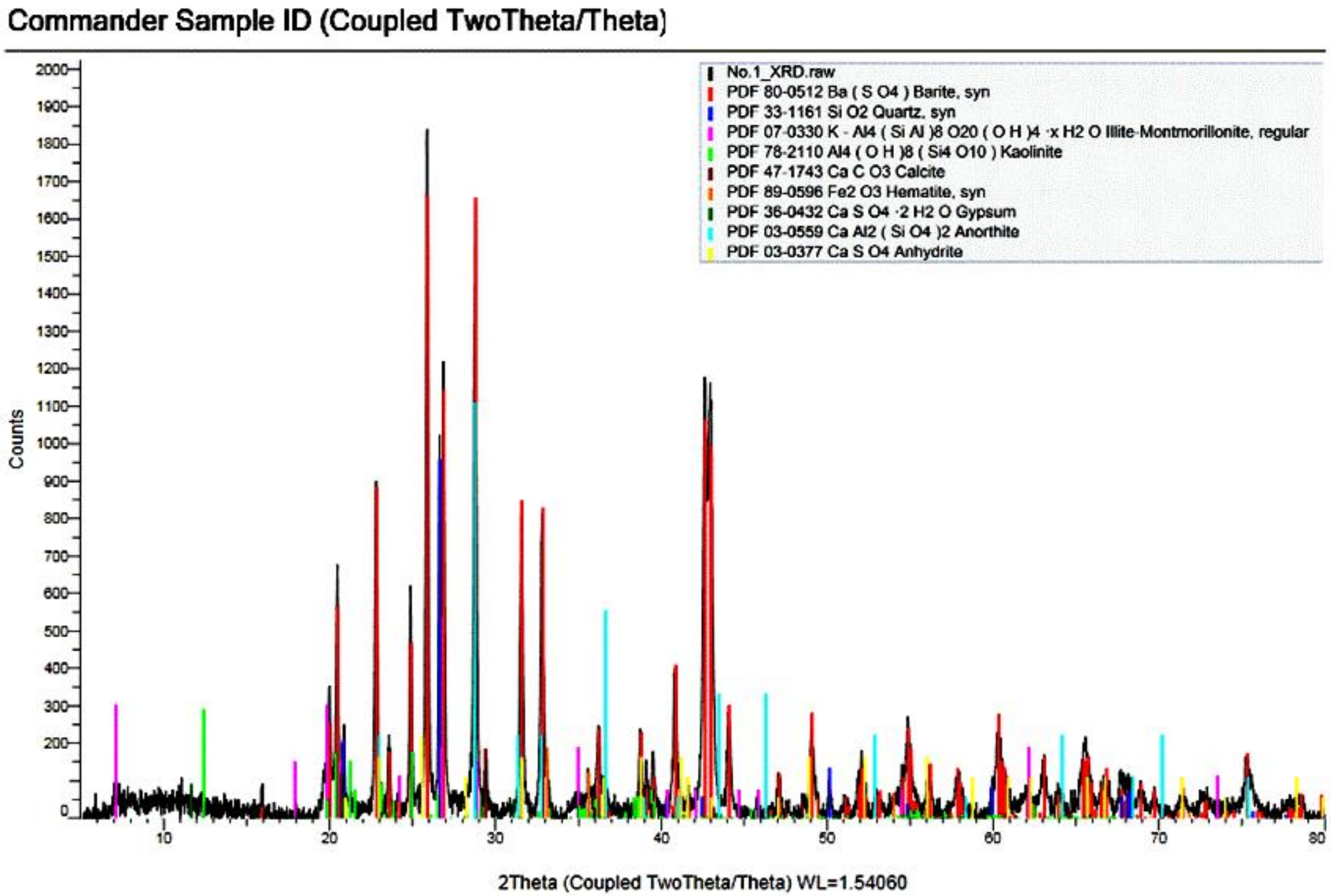

Figure A7. XRD of water-based drilling mud at 30^{o}C (No.1).

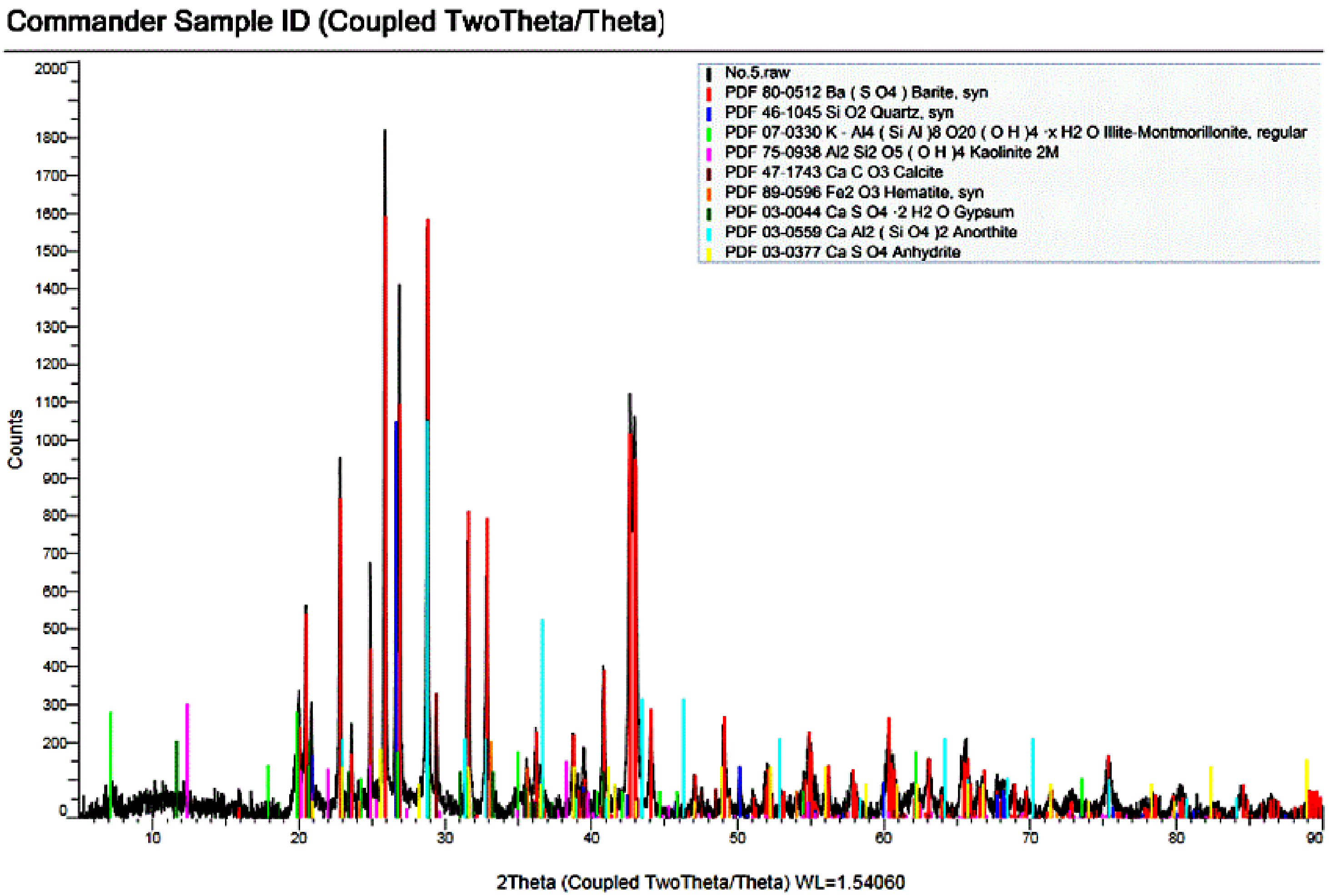

Figure A8. XRD of water-based drilling mud mixed with 3 percentage of fly ash at 30^{o}C (No.5).

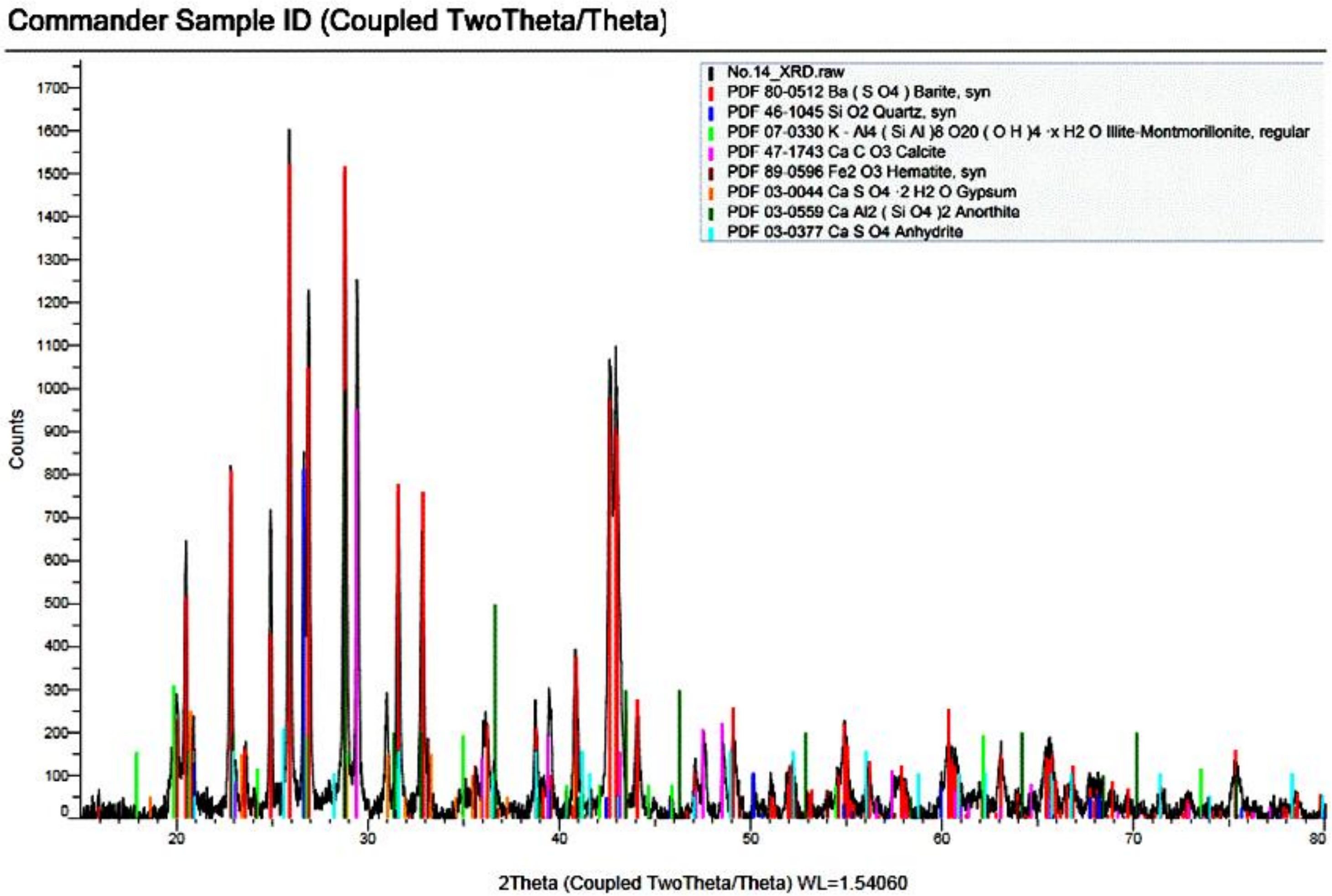

Figure A9. XRD of water-based drilling mud mixed with 3 percentage of dolomite at 30^{o}C (No.14).

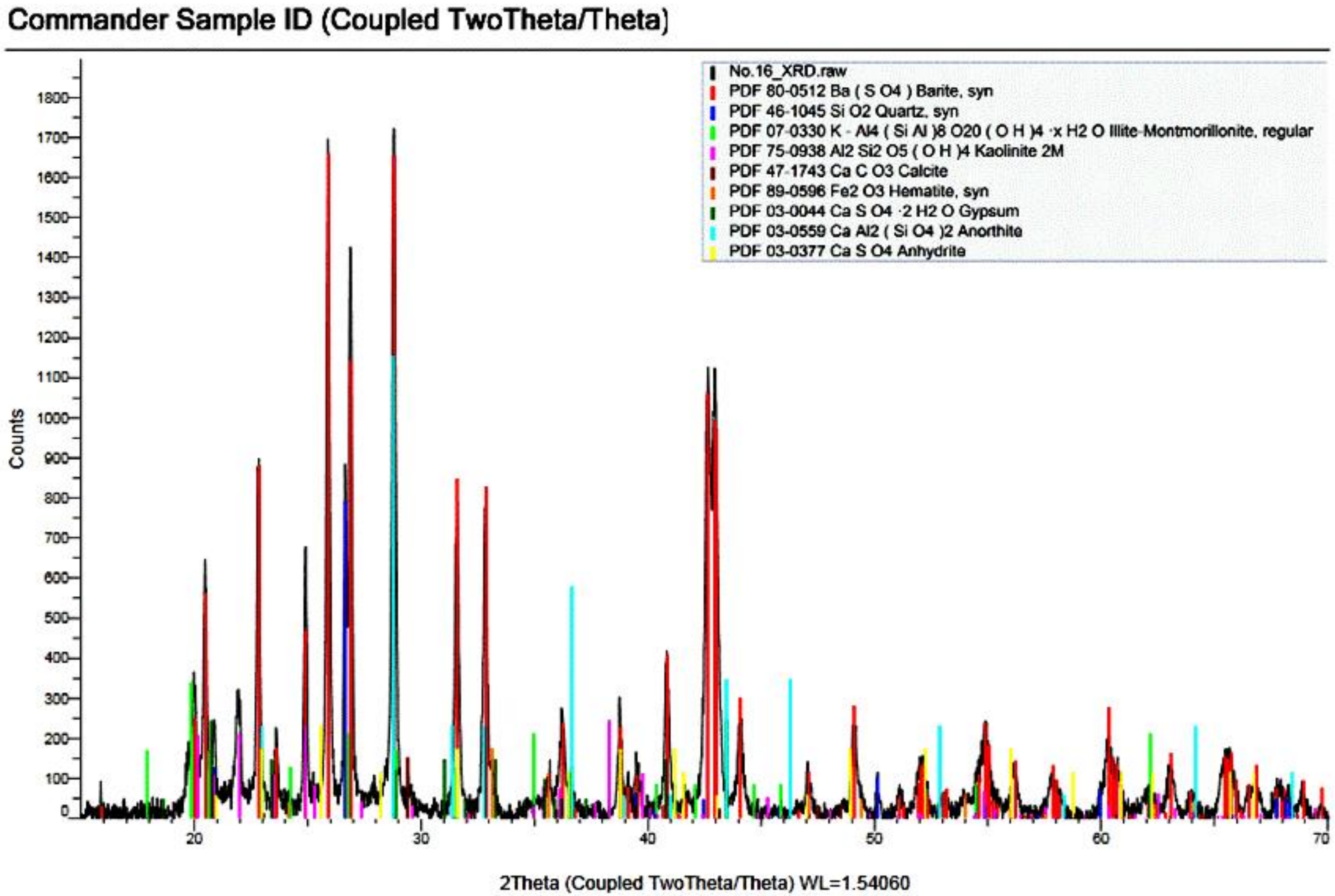

Figure A10. XRD of water-based drilling mud mixed with 1 percentage of rice husk ash at 30°C (No.16).

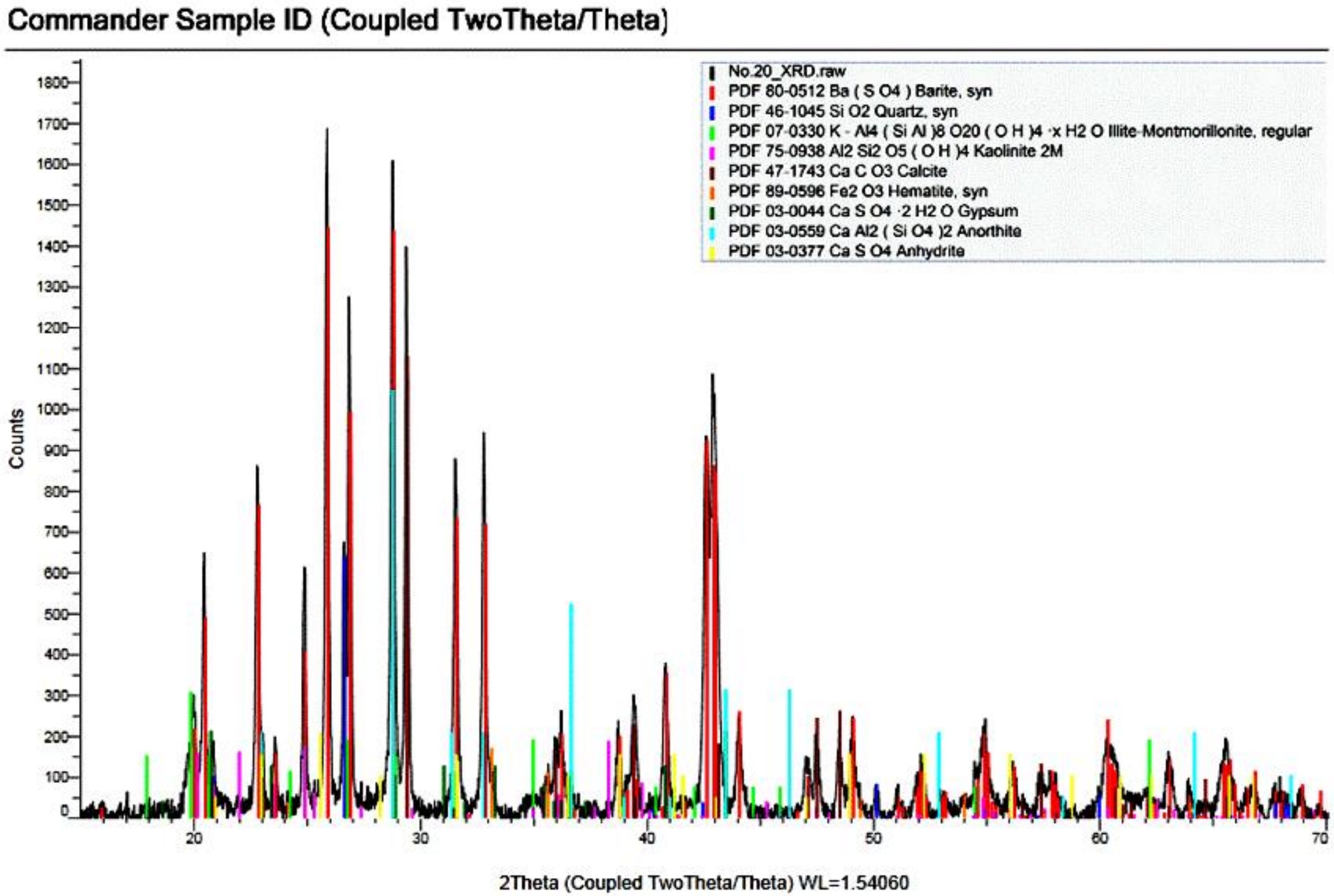

Figure A11. XRD of water-based drilling mud mixed with 3 percentage of lime at 30°C (No.20).

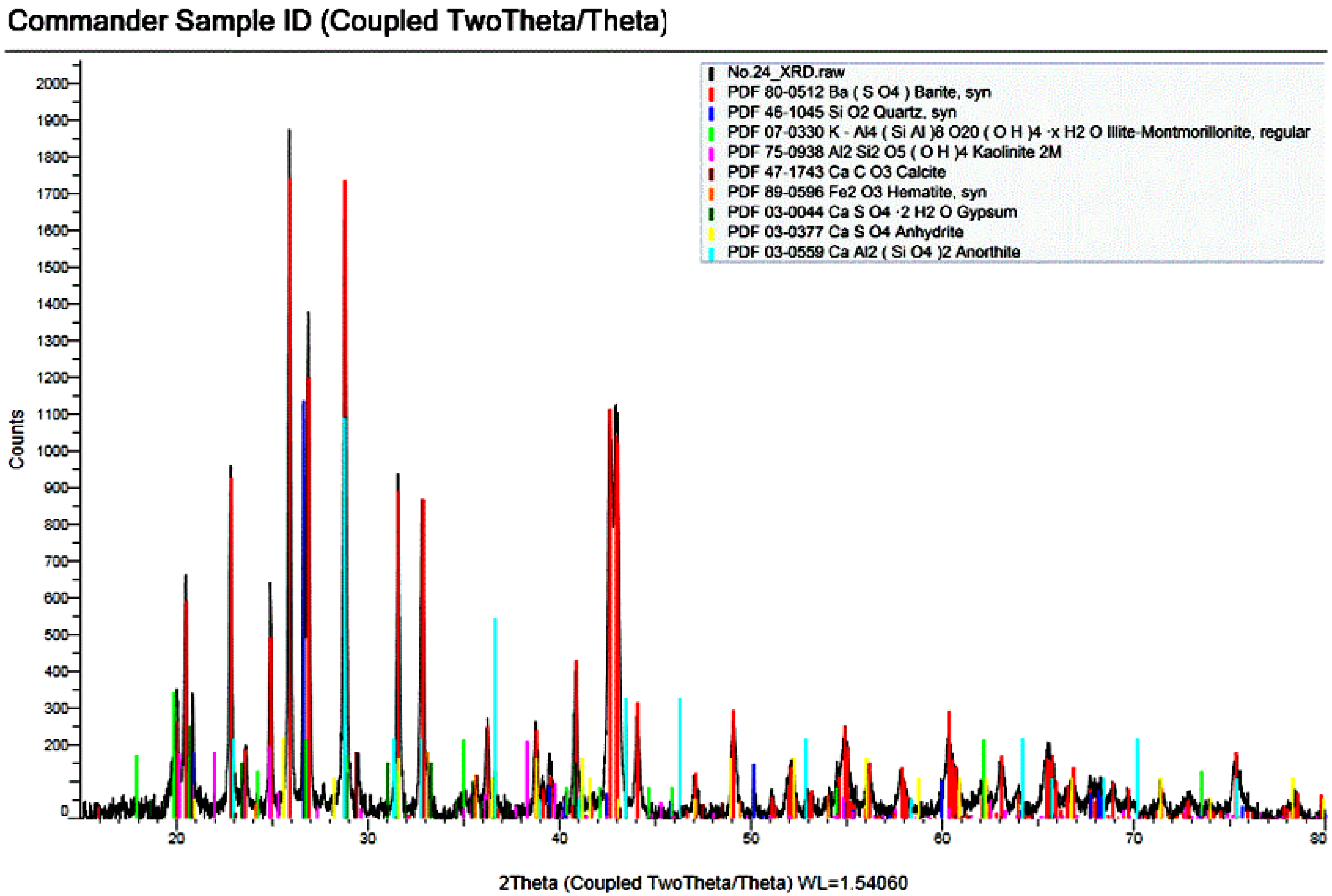

Figure A12. XRD of water-based drilling mud mixed with 5 percentage of starch at 30^{o}C (No.24).

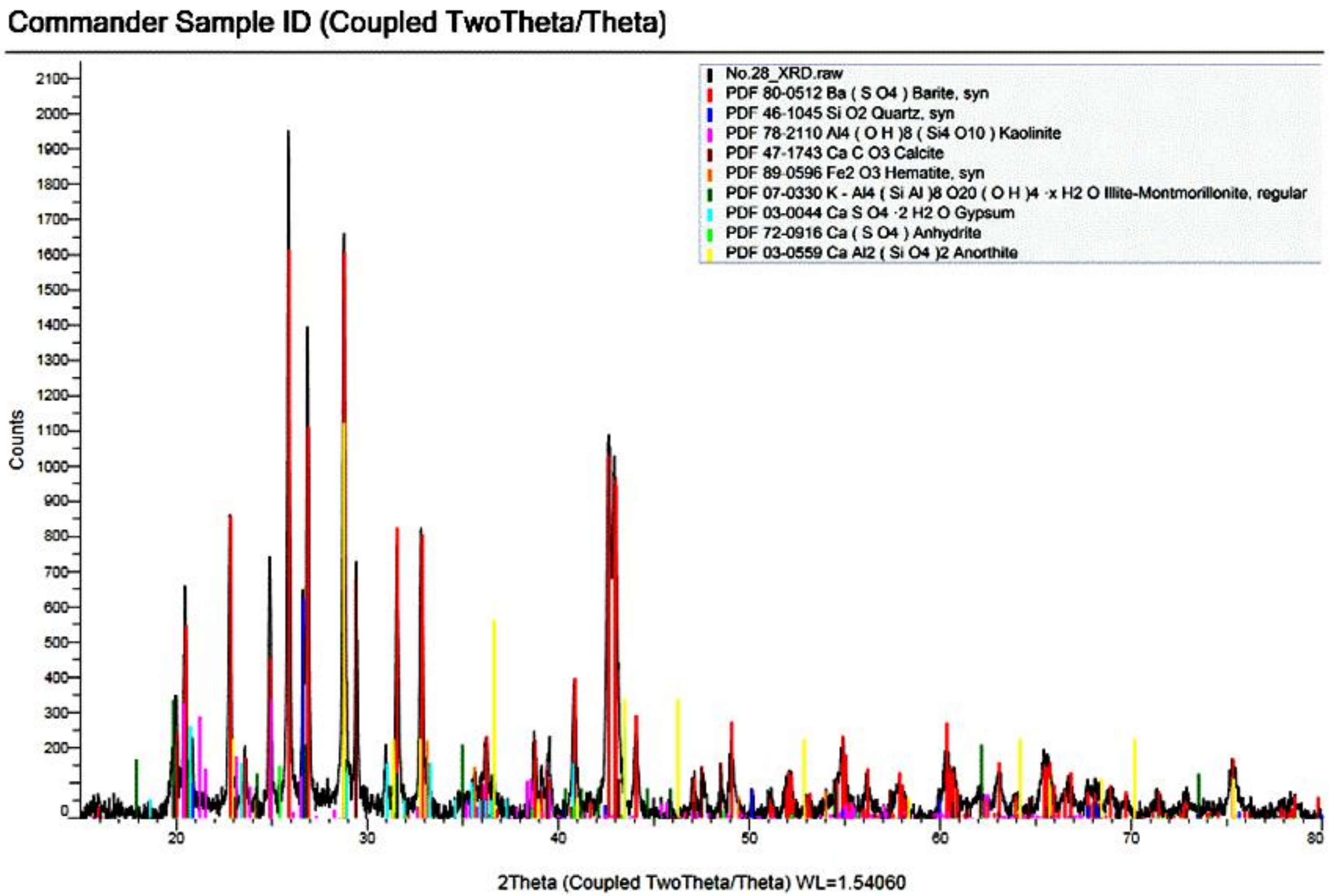

Figure A13. XRD of new-based drilling mud mixed with 1 percentage of dolomite at 60^{o}C (No.28).

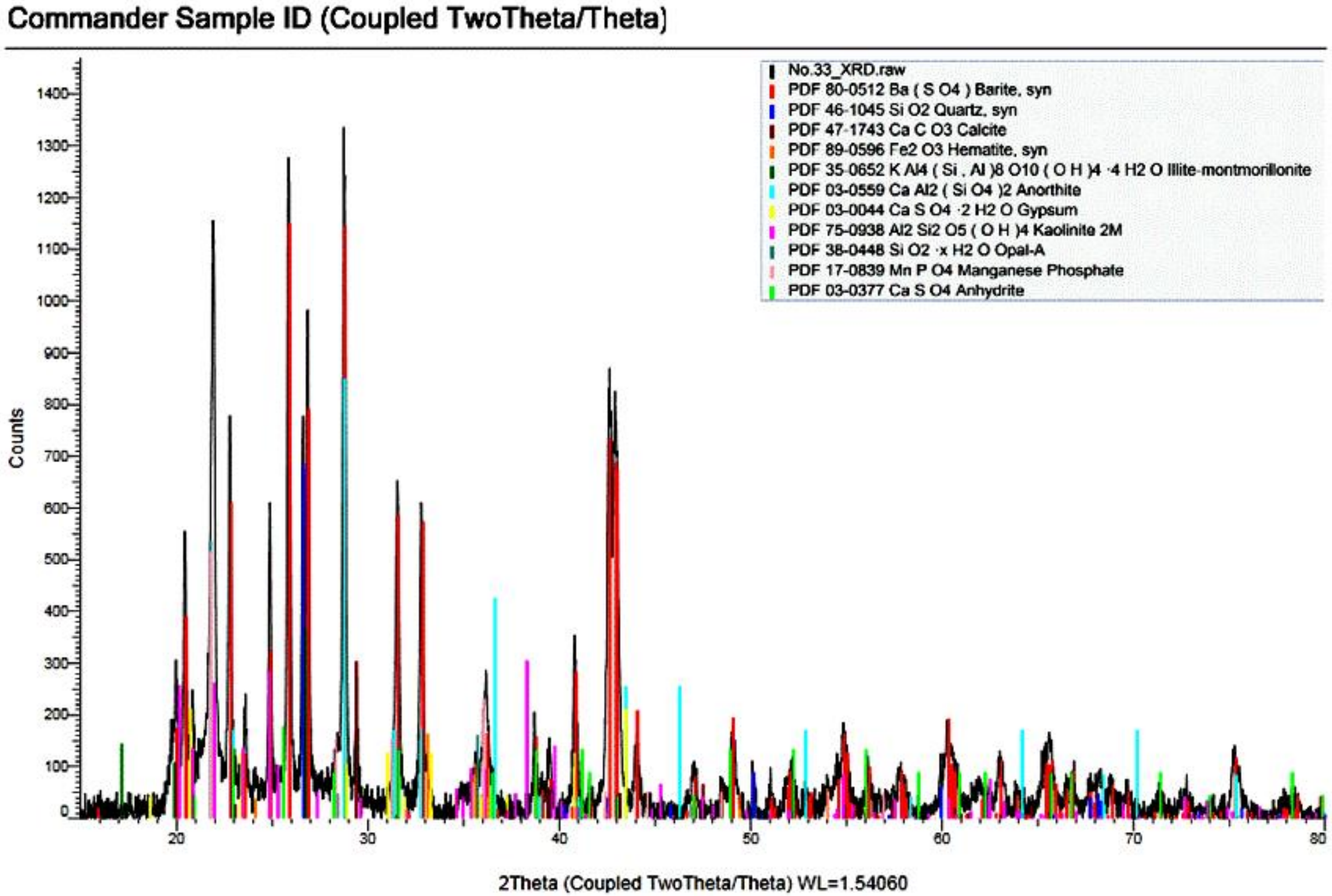

Figure A14. XRD of new-based drilling mud mixed with 5 percentage of rice husk ash at 30°C (No.33).

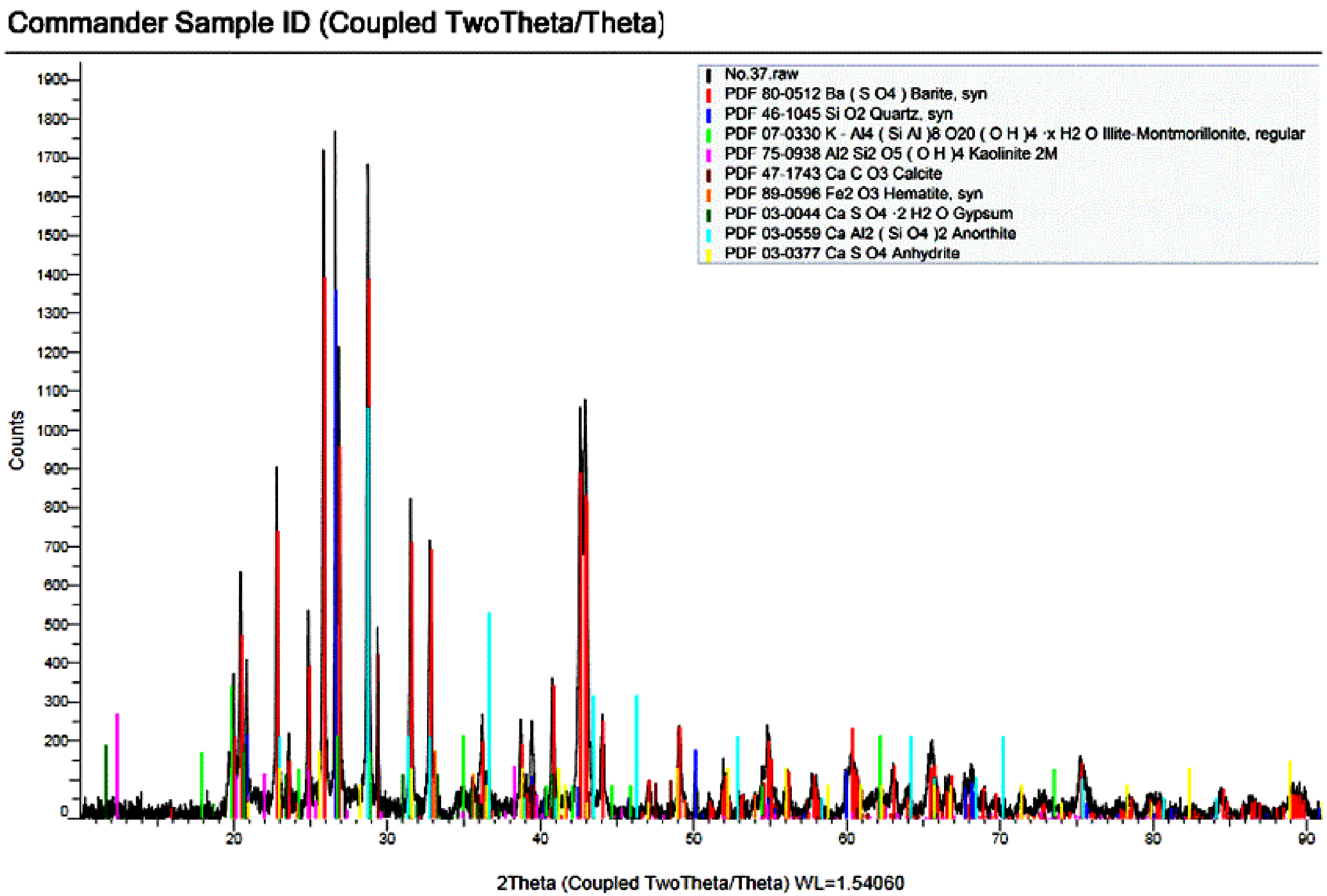

Figure A15. XRD of new-based drilling mud mixed with 1 percentage of lime at 30°C (No.37).

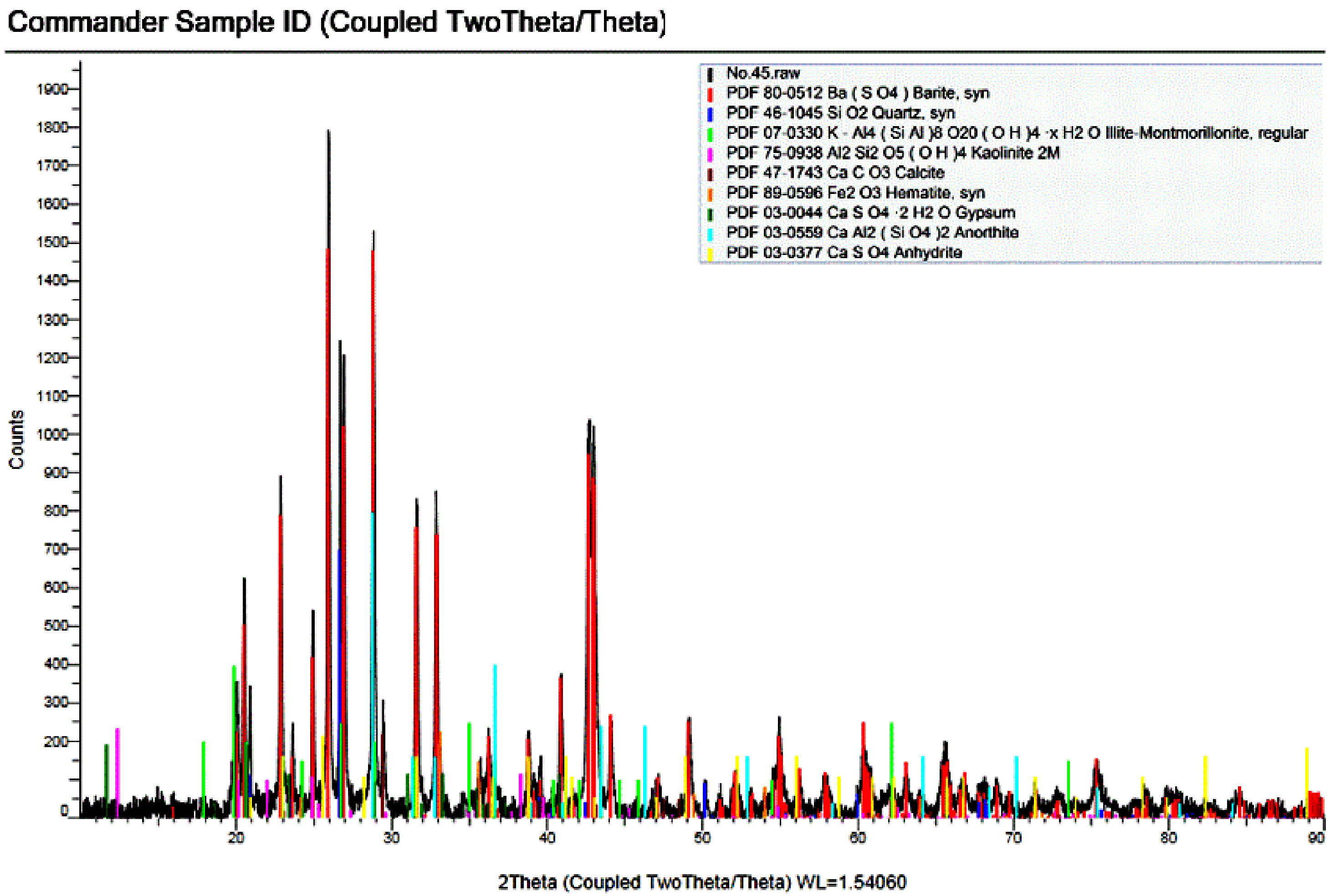

Figure A16. XRD of new-based drilling mud mixed with 5 percentage of starch at 30^{o}C (No.45).

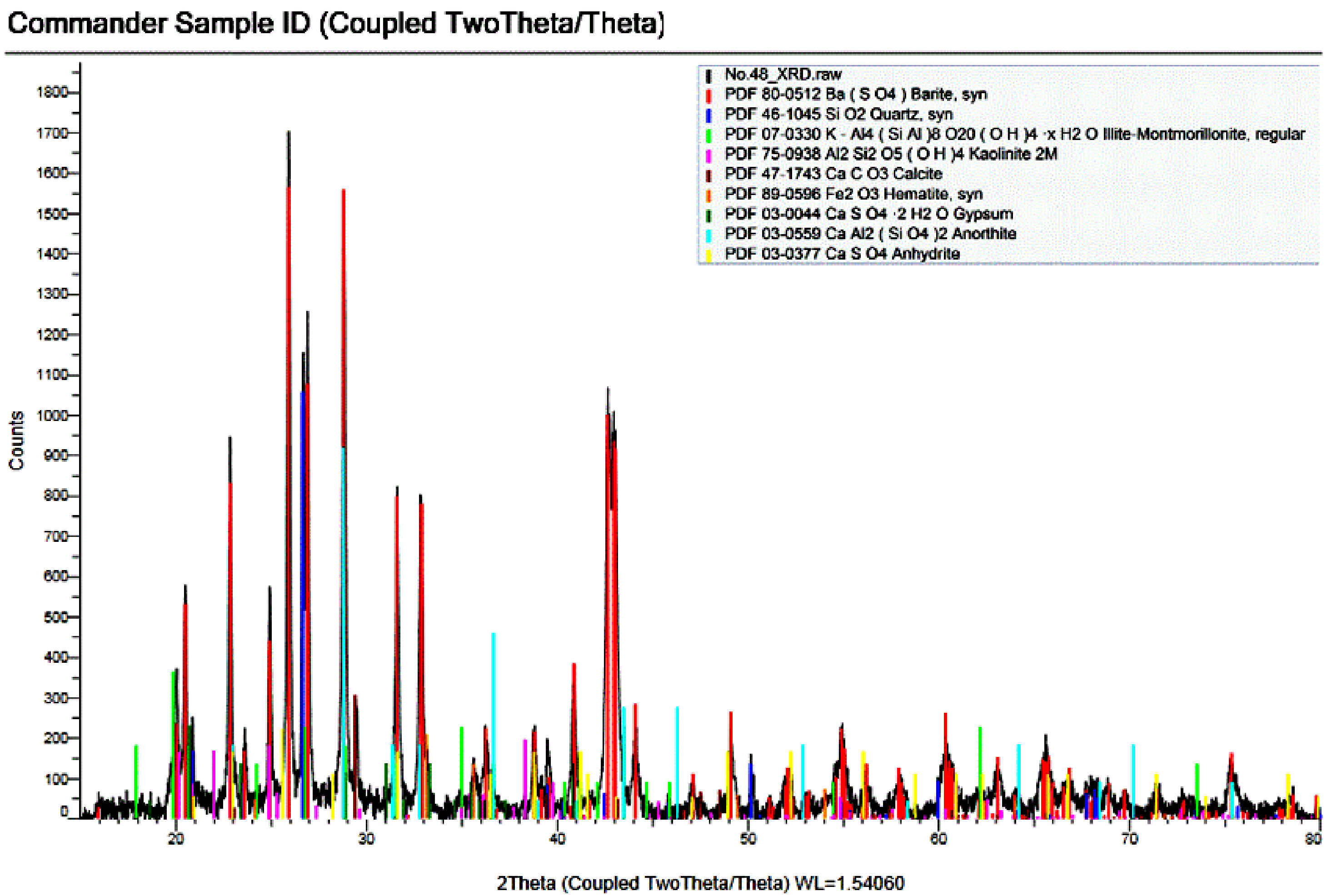

Figure A17. XRD of new-based drilling mud mixed with 5 percentage of starch at 60^{o}C (No.48).

APPENDIX B

PUBLICATION

List of Publication

Korsinwattana, P., and Terakulsatit, B., (2014). Efficiency enhancement of drilling mud by using fly ash as an additive. **In Proceedings of Advances in Civil Engineering for Sustainable Development 2014**, 27-29 August 2014, Nakhon Ratchasima, Thailand, pp. 531-536.

International Conference on Advances in Civil Engineering for Sustainable Development
Suranaree University of Technology
27-29 August 2014

Efficiency Enhancement of Drilling Mud by Using Fly Ash as an Additive

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ABSTRACT: The objective of this study to investigate the properties of drilling mud mixed with fly ash in order to enhance the formula of drilling mud. The drilling mud was mixed with concentration of various fly ashes in 3, 5 and 7% w/v and was examined based on the API RP13B-1 standard such as density, viscosity, filtration, resistivity, pH and sand content. This mud was tested their rheological properties at 30, 60 and 90°C using Bingham-Plastic model. Analysis of result indicates that the rheological properties of drilling mud mixing 3% fly ash are enhanced in apparent viscosity (18-21cP), yield point (27-30 lbf/100 ft^2), gel strength (6-13 lbf/100 ft^2) and pH (11-12), while the plastic viscosity and density slightly decreased with increasing temperature. These results represent that the fly ash containing mud showed insignificant increasing in the potential for rheological after elevated test at 90°C without thermal gradient and corrosive problem. The increasing of apparent viscosity and low plastic viscosity of the drilling mud can prevent the borehole problems such as surge and swab pressure, differential sticking and slow rate of penetration. The gel strength increasing can enhance the suspending of cutting and weighting materials when the circulation is ceased, and the increasing of yield point can improve the carrying capacity of drilling mud while drilling circulation periods. From the result of the API filtration tests represent that the increasing of the filtrate loss and mud cake thickness with increasing in percentage of fly ash and temperature, the sand content is also increased by adding a percentage of fly ash, which resulting the fluid loss and the smaller borehole size. In conclusion, the drilling mud mixed with 3% fly ash at temperature to 30°C testing is a high potential additive for enhancement the rheological properties of water-base drilling mud, especially in the increasing of apparent viscosity, yield point, gel strength, pH, and high efficiency of resistivity reduction. However, the high concentration of fly ash affects to the increasing of the filtrate loss, mud cake thickness and sand content.

1 INTRODUCTION

Drilling mud is important to petroleum production due to its use for protecting a lost circulation, controlling hydrostatic pressure in the well bore, minimizing fluid loss across permeable formations, and transporting rock cuttings to the surface. The drilling mud composition is a bentonite and barite with the base, and other additive such as cement, lime, starch, graphite, lignite, and sodium carboxymethyl cellulose (Benchabane and Bekkour, 2006).These additives are a high cost and could be imported from aboard. Fly ash (a mixture of mineral oxides) is a pozzolanic material and is considered as a major environmental pollutant in the 'recent-past'. Coal thermal power plant produces a huge amount of fly ash that creates severe waste disposal and environmental problems. In this regard, a good deal of work has been undertaken worldwide for the efficient utilization of fly ash. Utilization of fly ash as a resource material has been studied extensively in many areas such as extraction of valuable minerals, water pollution control, and production of ceramic products, composite materials, agriculture, building materials, paint, and plastic industries. Many investigators have also been carried out towards effective utilization of fly ash with understanding the potential environmental pollution and health impacts associated with the disposal of fly ash by land filling. More recently, the details of fly ash utilization as resource materials have been reviewed by (Ahmaruzzaman, 2010). In oil well drilling applications, fly ash is commonly used for the stabilization of drilling fluid wastes to avoid ground water contamination (Deeley et al., 1987; Thompson, 1994). It is also used as a foamable drilling fluid for deep water offshore drilling operations (Totten et al., 1997).

Therefore, using of fly ash in order to avert an increasing toxic threat to the environment, or disposal by making them more affordable. An economically viable solution to this problem should include utilization of fly ash for additive in the drilling mud. Petroleum industries have been used drilling mud for (1) clean the rock fragment from beneath the bit and carry them to the surface, (2) exert sufficient hydrostatic pressure against subsurface formations to prevent formation fluids from flowing into the well, (3) keep the newly drilled borehole open until the steel casing can be cemented in the hole, and (4) cool and lubricate the rotating drill string and bit. Thus, using fly ash is additive in the drilling mud

The objective of this paper is to study the efficiency enhancement of drilling mud mixed with fly ash on rheological properties of various temperatures. According to the Bingham - plastic model, the rheological properties are to investigate the apparent viscosity (AV), plastic viscosity (PV), yield point (YP) and gel strength.

2 MATERIALS AND EXPERIMENTAL METHODS

2.1 *Materials*

The Fly ash is obtained from Mae Moh Power Plant of Lampang province. Bentonite supports from Thai Nippon Chemical Industry Co., Ltd. Barite is assisted from Weatherford International Company, Thailand.

Generally, the ranges of the drilling mud density of typical well drilling are 1.5 to 8.5 %w/v of bentonite, mud weight varies around 8.85 to 18ppg(1.06 to 2.16 g/cm^3) depended on graded bentonite and drilled formations (MI-Swaco,1998). The previous literature of specific gravity of the materials is including a barite of 4.24 g/cm^3 and bentonite of 2.37 g/cm^3(Petchode and Sikong, 2003). In the Figure 1 demonstrates the composition and nature of common drilling mud. The curve shows the increasing of viscosity with a percentage of bentonite solids (Gatlin, 1960).

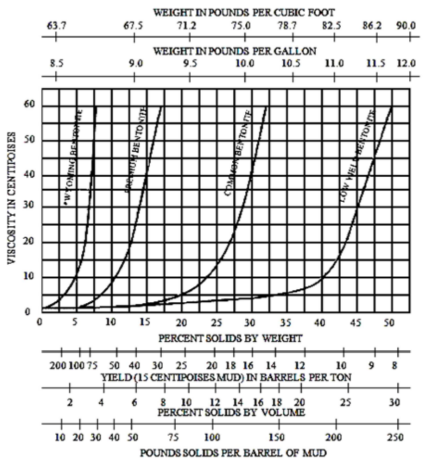

Figure 1. Yield curve for typical clays(after Gatlin, 1960).

Since the grade of bentonite that use in the experiment is not Wyoming grade. It is necessary to find the appropriate amount of bentonite that meet the viscosity requirement for typical well drilling. Table 1 shows bentonite water-based suspension at 2, 4, 6, and 8 %w/v of bentonite at 30oC. Therefore, the experiment was selected 4%w/v of bentonite as a base composition.

Table 1. Bentonite water-base suspension .

Bentonite %w/v	Average apparent viscosity (AV) cP
2	6.0
4	12.5
6	21.5
8	39.0

2.2 *Experimental methods*

2.2.1 *Sample preparation*

The materials are divided into two parts for chemical properties test by sieving size less than 75 micrometers (mesh No.200) for x-ray diffraction (XRD) and x-ray fluorescence (XRF) testing. Physical properties test by mixing with water-based drilling mud. A water-based drilling mud suspension is prepared using 40 grams of bentonite per liter of water; 120 grams of barite per liter of water and various con-centrations of fly ashes in 3, 5 and 7% w/v are added to mixing water-based drilling mud. The components are mixed for 15 minutes by using the high-speed mixture. During mixing, the fly ash is added slowly to agitated base fluid to avoid a lump occurring within mud system. The mud weight is measured by mud balance which is an API standard instrument for the testing mud weight. Various concentrations of fly ash are added to perform as a mud additive. These systems are prepared to compare the properties of the mud. Table 2 shows the formula of the drilling mud.

Table 2. Composition of drilling mud testing.

Composition	Water ml	Barite g	Bentonite g	Fly ash g
Mud	1,000	120	40	-
Mud+3%fly ash	1,000	120	40	31
Mud+5%fly ash	1,000	120	40	52
Mud+7%fly ash	1,000	120	40	73

2.2.2 *Rheological tests*

Drilling mud is tested for the rheological properties at 30, 60 and 90°C. The Rheology testing is carried out by a Fann 35Sa model Viscometer and measure by use six rotational speeds (3, 6, 100, 200, 300 and 600 rpm) for the viscosity, yield point and gel strength that relate to flow properties of drilling mud. The apparent viscosity, plastic viscosity and yield point are calculated from 300 and 600 rpm reading following formulas from API (API Recommended Practice, 1997).

$$\mu_a = \phi_{600}/2 \quad (1)$$

$$\mu_p = \phi_{600}/\phi_{300} \quad (2)$$

$$\gamma_p = \phi_{300}/\mu_p \quad (3)$$

where μ_a = apparent viscosity (cP); μ_p= plastic viscosity (cP); γ_p = Yield point ($lb_f/100\ ft^2$).

Filtration is tested by using Baroid standard filter press rig laboratory model 821 which determines the API filtrate loss through standard filter paper and the filter cake thickness under static conditions. It consists of fluid cup support by a frame, a filtering medium and a pressurized nitrogen gas cylinder and regulator. A graduated cylinder is used to measure the discharged filtrate. The 100 psig is applied to a column of fluid for the 30 minute period, which filtrate volume and filter cake thickness, are measured and recorded.

2.3 *Hydrogen ion tests*

The hydrogen ion (pH) measurements of the fluids are conducted using the Metrohm 713 modelglass electrode pH meter. The instrument determines the pH of an aqueous solution by measuring the electropotential generated between a glass electrode and a reference electrode. Measurement 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 the control of acidic and sulfide corrosion processes.

2.4 *Resistivity tests*

The Fann resistivity meter model 88 is measuredthe drilling mud, filtrate and mud cake.The resistivity meter provides a direct digital reading of resistivity in three ranges 2, 20, and 200 Ω/m^2 and direct measurement of the sample temperature in the transparent cell. Instrument calibrationis using salt solution and calculated the correction factor for accurate data.

2.5 *Sand content tests*

Baroid sand content set determines the account of sand and defined as the percentage by volume of solids in the drilling mud that retainedon75 micrometers (No.200mesh) sieve. The excessive sand makes a filter cake thickness with increasing;because abrasive wear of pump parts, bit and pipeand may settlewhen circulation is stopped and interfere with pipe movement or the setting of the casing.

3 RESULTS

3.1 *Characterization of fly ash*

The composition of fly ash is determined by XGT-5200 X-ray fluorescence microscope (XRF) at room temperature and the composition of fly ash result is shown in Table 3. The main elements include Si, Ca, Fe, S, K and Mg. X-ray diffraction (XRD) is used to study the structure of fly ash and the result is shown in Figure 2.

Table 3. Composition of fly ash.

Component	%
Si	38.60
Ca	23.32
Fe	21.70
S	10.49
K	2.41
Mg	2.36
Ti	0.57
Others	0.56

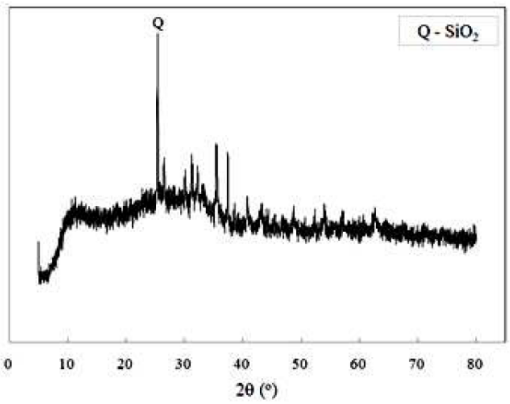

Figure 2. X-ray diffraction patterns of fly ash.

3.2 *Influence of fly ash on rheological properties of water-base drilling mud*

The effects of fly ash on rheological properties of water-base drilling mud, drilling mud is added into fly ash at different concentrations (3, 5 and 7%w/v respectively, i.e. 3%w/v means 3 g of fly ash is introduced into 100 ml of water-base drilling mud at 3g/100 ml). The rheological property results are shown in Figure 3-5. The viscosity is explained in Figure 3, including appearance viscosity (AV) and plastic viscosity (PV), which can analyze the flowability of drilling mud.The previous literatures, the AV reflect the flowability of drilling mud and is related to the rate of penetration, and the PV caused by the friction between the suspended particles and influenced by the viscosity of the base liquid (Falode et al., 2008). From the Figure 3(a), the AV of drilling mud amalgamate fly ash increase gradually as the addition of fly ash enlarge, which illustrate that the drilling mud mixed with fly ash has the better flowability and can prevent the borehole problem such as surge, swab pressure,differential stick and slow rate of penetration, nevertheless, the effect of temperatures are increased on viscosity.

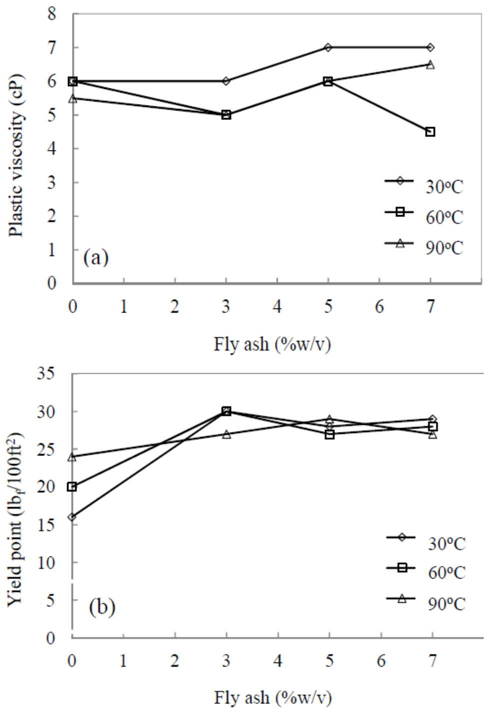

Figure 3. Viscosity of drilling mud mixed with fly ash:
(a) Appearance viscosity (AV); (b) Plastic viscosity (PV).

Yield point (YP) is important in determining pump capacity and the amount of pressure is applied to flow the mud from static positions. Figure 4 describe the YP of mud with various fly ash concentrations. The YP increases when the addition of fly ash into drilling mud but concentration of fly ash and temperature are not significant for yield point.

The initial and 10 minutes gel strength of drilling mud mixed with fly ash are investigated and the results are plotted as function of fly ash concentration and temperature as shown in Figure 5.

The results showed the 10 minutes gel strength is greater than initial gel strength because of more undisturbed mud, standing time would lead mud to from stronger gel structure compared to less undisturbed time.

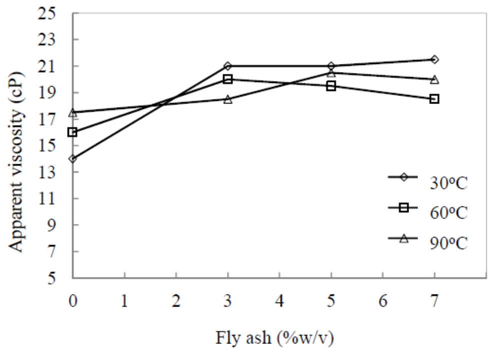

Figure 4. Yield point of drilling mud mixed with fly ash.

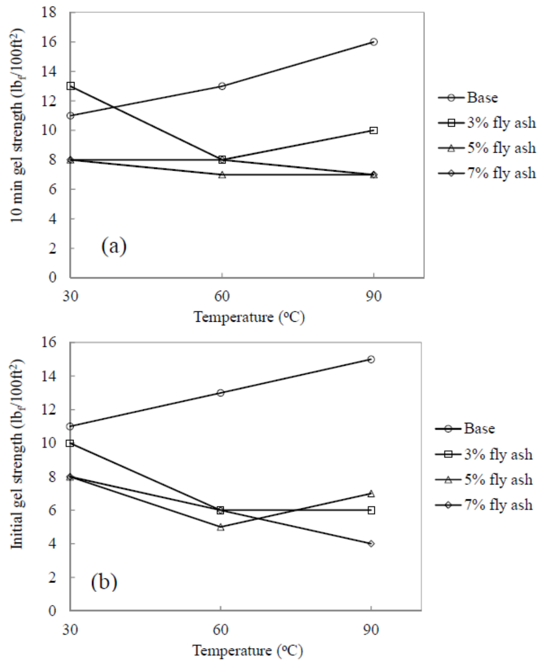

Figure 5. Gel strength of drilling mud mixed with fly ash:
(a) Initial gel strength; (b) 10 minutes gel strength.

API static filtrate loss and filter cake thickness within 30 minutes of drilling mud mixed with fly ash at the other temperatures are shown in Figure 6. The plot of the filtration properties of drilling mud that measured at 30, 60 and 90°C. Both of the graphs show time-dependent filtration behavior of drilling mud and indicate that the fluid loss exponentially increase as the time and temperature increase. The thickness of the filter cake deposited from the drilling mud on filter paper. The graph exhibits the thickness as the fly ash concentration and temperature increasing. As reported, the fluid loss of bentonite dispersions with carbon ash increased obviously. As carbon ash was added, the change of surface charge of bentonite particles weakened the capacity of bonding water (Xianghai et al, 2014). It refers more solid materials settled on formation wall, easier to collapse and the hole becomes smaller.

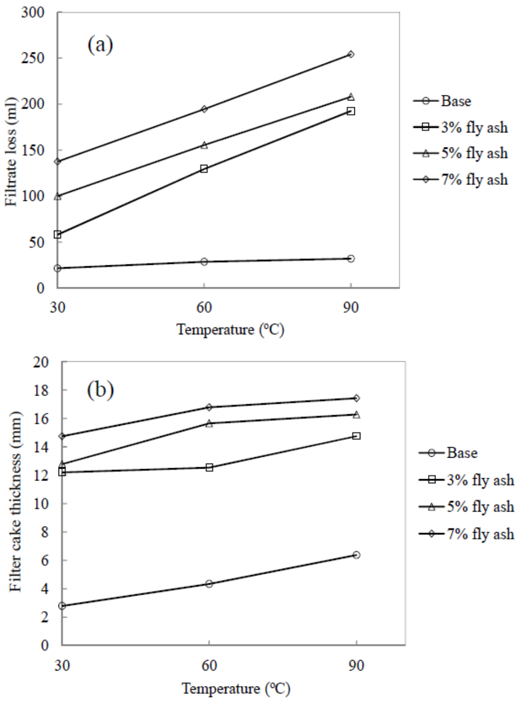

Figure 6. Filtration of drilling mud mixed with fly ash:
(a) Filtrate loss; (b) filter cake thickness.

3.3 *The effect of fly ash density, pH and resistivity of water-base drilling mud*

Mud density slightly decreased with increasing temperature. However, the density of drilling mud is increased by adding fly ash content with increasing. The relative of density, temperature and fly ash content are shown in Figure 7.

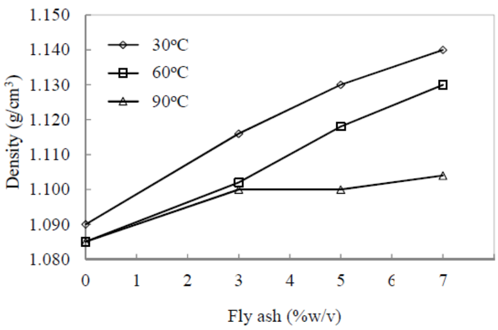

Figure 7. Density of drilling mud mixed with fly ash.

At ambient temperatures, as the pH increases, corrosion rates rapidly decrease. Rates are much slower in alkaline fluids than in acidic fluids. Little reduction in corrosion rate is obtained as pH is increased above 10.5(Baker Hughes, 1999). However, the pH decreased as the temperature increased.

A hydrogen ion (pH) of drilling mud mixed with fly ash is indicated in Figure 8. The pH increased as the fly ash concentration increased. It is implied that the greater of fly ash presence, the more mud alkalinity. Generally, corrosion rate decreases as pH increases.

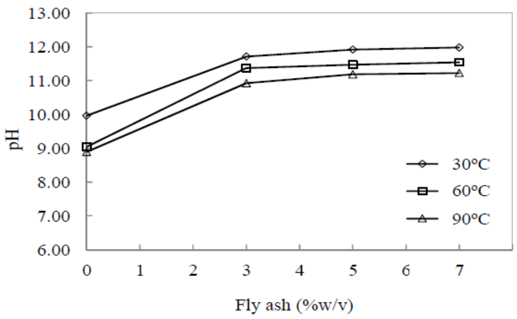

Figure 8. pH of drilling mud mixed with fly ash.

The results of resistivity are illustrated Figure 9. The resistivity of a mud decreased as fly ash concentration and temperature increased. However, control of the resistivity of a mud and mud filtrate may be desirable to better evaluate formation characteristics from electric logs (APIRecommended Practice, 1997).

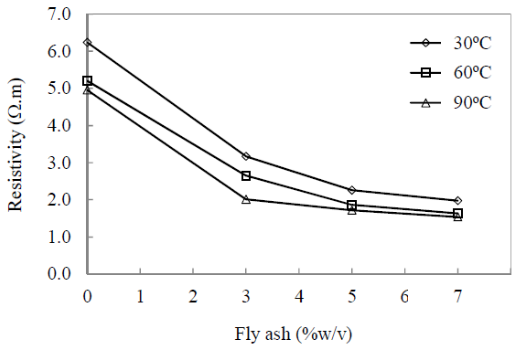

Figure 9. Resistivity of drilling mud mixed with fly ash.

3.4 *Stability of fly ash on sand content of water-base drilling mud*

The sand content is also increased by adding the 3, 5 and 7 percentage of fly ash on drilling mud. The results are 1, 1.5 and 2.5 percentages of sand content, respectively. However influence of temperatures is unaffected to the sand content.

4 CONCLUSIONS AND DISCUSSION

From the result of the drilling mud mixed with concentration of various fly ashes in 3, 5 and 7%w/v that measured at 30, 60 and 90°C, represent that the drilling mud mixed with 3%w/v of the fly ash at 30°C testing is a high potential additive for enhancement the rheological properties of water-base drilling mud, especially in the increasing of apparentviscosity, yield point, gel strength and pH, and high efficiency of resistivity reduction. However, the high concentration of fly ash affects to the increasing of the filtrate loss, mud cake thickness and sand content.

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BIOGRAPHY

Miss. Pornthip Korsinwattana was born on the 21st of September 1989 in Ubon ratchathani province. She earned her high school diploma in science-math from Benchama Maharat School in 2007 and her bachelor's degree in Science (Geotechnology) in 2011. The degree is from the Khon Kaen University (KKU). She continued to study with her master's degree in Petroleum Engineering Program at School of Geotechnology, Institute of Engineering at Suranaree University of Technology (SUT) in 2014. In 2013, she served in position of teacher and research assistant at SUT. Since 2012, she has a part-time teacher laboratory at SUT. She has a good knowledge in areas of oil field chemicals and drilling fluids processing.