STUDY OF THAI BENTONITE AS APPLIED IN PETROLEUM DRILLING

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การศึกษาศักยภาพเบนโทไนต์ในประเทศไทยเพื่อการขุดเจาะปิโตรเลียม

นางสาวเฉลิมลักษณ์ ภูวสวัสดิ์

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิศวกรรมศาสตรมหาบัณฑิต
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STUDY OF THAI BENTONITE AS APPLIED IN PETROLEUM DRILLING

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

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เฉลิมลักษณ์ ภูวสวัสดิ์ : การศึกษาศักยภาพเบนโทไนต์ในประเทศไทยเพื่อการขุดเจาะปิโตรเลียม (STUDY OF THAI BENTONITE AS APPLIED IN PETROLEUM DRILLING) อาจารย์ที่ปรึกษา : ผู้ช่วยศาสตราจารย์ ดร.บัณฑิตา ธีระกุลสถิตย์, 132 หน้า.

วัตถุประสงค์ของงานวิจัยครั้งนี้คือเพื่อศึกษาและเปรียบเทียบประสิทธิภาพเบนโทไนต์ของลพบุรี สระบุรี และกาญจนบุรี กับเบนโทไนต์สหรัฐอเมริกา ในน้ำโคลนขุดเจาะ ซึ่งได้ทำการทดสอบคุณสมบัติทางกายภาพและทางเคมีของน้ำโคลนที่ผสมด้วยเบนโทไนต์ในแต่ละแหล่ง โดยทำการทดสอบที่อุณหภูมิ 30 60 และ 90 องศาเซลเซียส การวิเคราะห์คุณสมบัติทางเคมีของเบนโทไนต์และน้ำโคลนขุดเจาะที่ผสมเบนโทไนต์ในแต่ละแหล่ง ได้หาองค์ประกอบของธาตุและแร่โดยใช้เครื่องมือเอ็กเรย์ฟลูออเรสเซนต์ (XRF) และเครื่องมือเอ็กเรย์ดิฟแฟรคชั่น (XRD) ตามลำดับ ผลของการวิเคราะห์ทางเคมีพบว่าธาตุประกอบหลักของเบนโทไนต์ ส่วนใหญ่ประกอบด้วย แมกนีเซียมออกไซด์, อลูมิเนียมออกไซด์, ซิลิกอนไดออกไซด์, แคลเซียมออกไซด์ และ ไอรอนออกไซด์ ซึ่งธาตุเหล่านี้สัมพันธ์กับแร่ประกอบ โดยแร่ประกอบหลักของเบนโทไนต์สหรัฐอเมริกา ประกอบด้วยแร่ไมโครคลายน์ เคโอลิไนต์ ทัลก์ และซิลิกา เบนโทไนต์ลพบุรีมีแร่ทัลก์ และเคโอลิไนต์ เบนโทไนต์สระบุรีมีแร่ซิลิกาและไมโครคลายน์ และเบนโทไนต์กาญจนบุรีมีแร่ไมโครคลาย์และทัลก์ ซึ่งส่วนประกอบเคมีนี้ขึ้นอยู่กับปริมาณของส่วนผสมของเบนโทไนต์และแบไรต์ จากผลการวิเคราะห์โครงสร้างและรูปร่างของผลึกโดยกล้องอิเล็กตรอนแบบส่องกราด (SEM) พบว่าลักษณะพื้นผิวของตัวอย่างมีความขรุขระ มีการจับตัวกันแน่นของส่วนประกอบ อุณหภูมิไม่มีผลต่อการเปลี่ยนแปลงของธาตุและแร่ประกอบ และโครงสร้างและรูปร่างของผลึก การทดสอบคุณสมบัติทางกายภาพโดยใช้วิธีการศึกษาคุณสมบัติทางวิทยากระแสของน้ำโคลนขุดเจาะที่ผสมด้วยเบนโทไนต์แต่ละแหล่ง ตามแบบจำลองบิงแฮมและเพาเวอร์ลอว์ การทดสอบการซึมผ่าน ความหนาแน่น ความเป็นกรด-ด่าง ความต้านทานไฟฟ้า ปริมาณของแข็งและปริมาณทราย โดยได้ทำการทดสอบตามขั้นตอนมาตรฐาน API RP 13B-1 จากผลการทดสอบความหนืดปรากฏ จุดคราก และความแข็งของเจลมีค่าเพิ่มขึ้น ขณะที่ความหนืดพลาสติก มีค่าลดลงเล็กน้อยเมื่ออุณหภูมิเพิ่มขึ้น ส่วนค่าการซึมผ่าน อยู่ในช่วง 13.5 ถึง 195 มิลลิลิตร โดยค่าปริมาณการสูญเสียน้ำในน้ำโคลนขุดเจาะที่ผสมเบนโทไนต์จากทุกแหล่งมีความคล้ายคลึงกันคือ มีค่าเพิ่มขึ้นตามอุณหภูมิ ประสิทธิภาพของการสูญเสียน้ำโคลนของเบนโทไนต์ลพบุรีดีกว่าเบนโทไนต์สระบุรีและกาญจนบุรี แต่มีประสิทธิภาพต่ำกว่าเบนโทไนต์อเมริกา ในส่วนของความหนาแผ่นโคลนมีค่าอยู่ระหว่าง 1.96 ถึง 6.7 มิลลิเมตร ซึ่งสัมพันธ์โดยตรงกับปริมาณการสูญเสียน้ำของน้ำโคลน ผลของน้ำโคลนขุดเจาะที่ผสมเบนโทไนต์จากประเทศไทยมีประสิทธิภาพที่ต่ำกว่าเบนโทไนต์

สหรัฐอเมริกา ซึ่งประกอบด้วย ค่าความหนาแน่น (1.06 ถึง 1.10 กรัมต่อลูกบาศก์เซนติเมตร) ค่าความเป็นกรด-ด่าง (7.48 ถึง 9.95) ปริมาณของแข็ง (ร้อยละ 2 ถึง 9) ปริมาณทราย (ร้อยละ 0.2 ถึง 0.6) และค่าความต้านทานไฟฟ้า (4.43 ถึง 18.29 โอห์ม-เมตร) จากผลการวิเคราะห์พบว่าน้ำโคลนขุดเจาะที่ผสมด้วยเบนโทไนต์ลพบุรี เหมาะสำหรับการนำมาใช้ในการป้องกันการสูญเสียน้ำได้ แต่เบนโทไนต์กาญจนบุรีและสระบุรี ไม่เหมาะแก่การนำไปใช้ในคุณสมบัตินี้ การเปรียบเทียบราคาของเบนโทไนต์ พบว่า เบนโทไนต์ของประเทศไทยสามารถช่วยลดค่าใช้จ่ายในการนำเข้าเบนโทไนต์จากต่างประเทศได้ แต่คุณภาพและประสิทธิภาพอาจไม่เทียบเท่ากับเบนโทไนต์ของสหรัฐอเมริกา โดยคุณสมบัติของเบนโทไนต์ของจังหวัดลพบุรีใกล้เคียงกับเบนโทไนต์ของประเทศอินเดีย ประสิทธิภาพของเบนโทไนต์สระบุรี ลพบุรี และกาญจนบุรี สามารถใช้ทดแทนเบนโทไนต์จากต่างประเทศได้ โดยเฉพาะเหมาะกับสภาวะของหลุมที่ไม่ลึกมาก

สาขาวิชา เทคโนโลยีธรณี ลายมือชื่อนักศึกษา ____________________

ปีการศึกษา 2559 ลายมือชื่ออาจารย์ที่ปรึกษา ____________________

CHALERMLUCK PHOOVASAWAT : STUDY OF THAI BENTONITE AS APPLIED IN PETROLEUM DRILLING. THESIS ADVISOR : ASST. PROF. BANTITA TERAKULSATIT, Ph.D., 132 PP.

DRILLING MUD / BENTONITE / LOPBURI / SARABURI / KANCHANABURI

The purpose of this study is to study and compare an efficiency of Lopburi, Saraburi and Kanchanaburi bentonite with the America bentonite used in drilling mud. The study investigates the physical and chemical properties of the drilling mud mixed with each bentonite at 30, 60 and 90°C. The chemical properties of the bentonite and drilling mud are determined in terms of the elemental and mineral compositions by X-ray fluorescence (XRF) and X-ray diffraction (XRD), respectively. The elemental compositions mainly consisting of MgO, Al_2O_3, SiO_2, CaO and Fe_2O_3. These elements relate to the mineral compositions of each bentonite. Mineral compositions of America bentonite mainly comprise microcline, kaolinite, talc, and silica. Lopburi has talc and kaolinite, Saraburi has silica and microcline, and Kanchanaburi has microcline and talc. These chemical compositions depend on the contents of bentonite and barite. Crystal structures and morphologies are analyzed by scanning electron microscope (SEM), showing a roughly, tightly packed from the composition. The temperature does not affect of the variation of elemental and mineral compositions, and crystal structure and morphology. The physical property is analyzed in terms of the rheological properties using Bingham and Power Law model, filtration, density, pH, resistivity, solid and sand content according to API RP 13B-1 standard. Results of the apparent viscosity, yield point and gel strength of drilling mud mixed with all bentonite have increased as temperature rises, while the plastic viscosity slightly decreases as increasing temperature. The filtration ranges from 13.5 to 195 ml, which the filtration loss of drilling mud mixed with all bentonite are similar values that high as rising temperature. The filtration loss performance of Lopburi is better than that of the Kanchaburi and Saraburi, which are lower than the America bentonite. Mud cake thickness ranges from 1.96 to 6.7 ml, which directly relates to the filtration loss. Results from the drilling mud mixed with bentonite from Thailand has slightly lowered efficiency than America bentonite including density (1.06 to 1.10 g/cm^3), pH (7.48 to 9.95), solid content (2.0 to 9.0%), sand content (0.2 to 0.6%), and resistivity (4.43 to 18.29 Ω.m). Drilling mud mixed with Lopburi bentonite is suitable for utilization of filtration loss control, but Kanchanaburi and Saraburi are unqualified for this property. The comparative price of bentonite shows that the bentonite from Thailand could reduce the cost of imported bentonite from aboard. However, the quality and performance could not be comparable to America bentonite. Performance of bentonite from Saraburi, Lopburi and Kanchanaburi could be used to replace the bentonite from aboard, which is applicable for the shallow holes.

School of Geotechnology Student's Signature______________

Academic Year 2016 Advisor's Signature______________

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I would like to express my sincere thanks to my thesis advisor, Asst. Prof. Dr. Bantita Terakulsatit for her invaluable help and constant encouragement throughout the course of this research. I am most grateful for her teaching and advice, not only the research methodologies but also many other methodologies in life. I would not have achieved this far and this thesis would not have been completed without all the support that I have always received from her.

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Finally, I most gratefully acknowledge my parents and my friends for all their support throughout the period of this research.

Chalermluck Phoovasawat

TABLE OF CONTENTS

Page

TABLE OF CONTENTS (Continued)

Page

TABLE OF CONTENTS (Continued)

Page

TABLE OF CONTENTS (Continued)

Page

TABLE OF CONTENTS (Continued)

Page

LIST OF TABLES

Table **Page**

LIST OF TABLES (Continued)

Table **Page**

LIST OF FIGURES

Figure **Page**

LIST OF FIGURES (Continued)

Figure **Page**

LIST OF FIGURES (Continued)

Figure **Page**

LIST OF FIGURES (Continued)

Figure **Page**

LIST OF FIGURES (Continued)

Figure **Page**

SYMBOLS AND ABBREVIATIONS

ROMAN ABBREVIATIONS:

Gel_{10}	=	10 minutes gel strength
Gel_{in}	=	initial gel strength
gm	=	gram
k	=	fluid consistency index
N	=	range extension factor of the torque spring of the VG meter
n	=	flow behavior index
rpm	=	rotational speed
Temp.	=	temperature

GREEK ABBREVIATIONS:

γ	=	shear rate
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
μ_a	=	apparent viscosity
μ_p	=	plastic viscosity
τ	=	shear stress
τ_0	=	yield stress

CHAPTER I

INTRODUCTION

1.1 Background of problems and significance of the study

Bentonite and water are the main ingredients to mix in water based mud. It could be used in the drilling process and rotary drilling. The property of bentonite can absorb the water and which can be swelling about 15-20%. This will have high viscosity and prevent the fluid passing through better. The purpose of bentonite in drilling facility could fill up bentonite into drilling mud for improving the lubricant of drilling bit, bring the cutting up to the surface, reduce the fluid lost, control the bottom hole pressure and also equalize the pressure in the well to protect the formation collapse. The bentonite in drilling facility follows the American Petroleum Institute (API) standard. Normally, the bentonite in Thailand have been imported from worldwide such as the United states of America (USA), Greece, Germany, Japan, China, and Indonesia, etc. The properties of physical and chemical of bentonite from each country are different under the requirement for the purpose of use, grade and cost. The result of the import of an expensive bentonite makes Thailand's trade deficits with others countries. Generally, the source of bentonite in Thailand found in Lopburi, Saraburi and Kanchanaburi provinces. The bentonite had been used more in an industrial as bleach the color or chemical absorption, filler for the increase amount of substance, adjust the viscosity for inks and paint industries, absorbs odor from the waste of animal, improve soil quality for planting, etc. The drilling exploration will use bentonite from Thailand less than the other country. However, the bentonite product from Thailand to API standard. Therefore, the purpose of this research to compare the physical and chemical properties of bentonite from Thailand and other countries, and to compare the efficiency of drilling mud by vary with temperature and improve the property of bentonite by fill up the additive into the drilling mud to increase the efficiency of drilling mud according to API standard.

1.2 Research objectives

The main aim of this research is to enhance the efficiency of drilling mud. Some more objectives are comprised of (1) to compare an efficiency of Lopburi, Saraburi and Kanchanaburi bentonite with the America bentonite used in drilling mud, (2) study the effect of temperature on the properties of drilling mud mixing with bentonite from Thailand and (3) to reduce the costs of import bentonite in the industry of petroleum exploration and production.

1.3 Scope and limitation of the study

This research aims to study the chemical and physical properties of water-based drilling mud mixed with bentonite when the bentonite concentration and temperature were changed. The bentonite sample was collected from Lopburi, Saraburi and Kanchanaburi provinces, Thailand. The physical and chemical properties, and rheological tests are operated at laboratory of Suranaree University of Technology. The chemical properties of additives are analyzed both before and after mixed with drilling mud for determine the components, elemental and mineral crystals of samples by using X-ray diffractometer (XRD), X-ray fluorescence spectrometer (XRF) and Scanning

Electron Microscope (SEM). The physical properties test is followed (API 13B-1, 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 13B-1, 1997). Economists wealthiest of bentonite will compare with bentonite in each country after mixed with drilling mud, which follow Department of Primary Industries and Mines (Department of Primary Industries and Mines, 2014).

1.4 Thesis contents

Chapter I introduces the thesis by briefly describing the background of the 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

The researcher studies the journal, report and literature about the comparison of performance on bentonite from Thailand and that imported from foreign country in drilling mud. The correlation of drilling mud mixed with bentonite from each source. Including to improve the performance of bentonite for the advantage in various industries. The results are summarized as follows.

2.2 Functions of drilling fluid

In rotary drilling there are a variety of functions and characteristics that are expected of drilling fluids. The drilling fluid is used in the process to (1) clean the rock fragments from beneath the bit and carry them to separating at the surface, (2) exert sufficient hydrostatic pressure against subsurface formations to prevent inflow fluids into the well, (3) keep the newly drilled borehole open until steel casing can be cemented in the hole, and (4) cool and lubricate the rotating drillstring and bit (Bourgoyne et al., 1986). In addition to serving these functions, the drilling fluid should not (1) have properties detrimental to use of planned formation evaluation techniques, (2) cause any adverse effects upon the formation penetrated, or (3) cause any corrosion of the drilling equipment and subsurface tubulars. The bentonite used in drilling fluid is monmorillonite clay (Chilingarian et al., 1983). It is added to fresh water to (1) increase the hole cleaning properties, (2) reduce water seepage or filtration into stability in poorly cemented formation, and (5) avoid or overcome loss of circulation. The added bentonite is sometimes unable to provide satisfactory those properties that required for optimum performance in an oil well drilling. Therefore the polymers are added to achieve desired result.

2.3 Source and physical and chemical properties of bentonite

Hensen and Smit (2002) and Petroleum Support (2013) concluded about the property of montmorillonite. It is named in France. The group of minerals is phyllosilicate that typically form in microscopic crystals. It is a member of the smectite group, the character of these minerals is a 2:1 of clay, which means it is two tetrahedral sheets sandwiching with a central octahedral sheet (Figure 2.1). The particles are plate-shaped with an average diameter around 1 µm.

The characters of montmorillonite are have octahedral charge greater than 50%; its cation exchange capacity is due to isomorphous substitution of Mg for Al in the gibbsitic plane. In contrast, beidellite is smectite with tetrahedral charge greater than 50%. That is originating from isomorphous substitution of aluminum for silica in the quartz sheet.

The water content of montmorillonite is varies greatly in volume when it absorbs water. Chemically, it is hydrated with sodium, calcium aluminium, magnesium silicate hydroxide $(Na, Ca)_{0.33}(Al, Mg)_2(Si_4O_{10})(OH)_2 \cdot nH_2O$. Potassium, iron, and other cations are common substitutes, and the exact ratio of cations varies by source. It often occurs intermixed with chlorite, muscovite, illite, cookeite, and kaolinite.

Penn and Zhang (2013) describes that the montmorillonite is used in the oil-drilling industry such as a component of drilling mud, making the mud slurry viscous, which helps in keeping the drill bit coolant and removing drilled solids. It is also used as an additive to hold soil water in drought-prone soils, to the construction of earthen dams and levees, and used to prevent the leakage of fluids. It is also used as a component of foundry sand and as a desiccant to remove moisture from air and gases.

Lloyd (2011) This swelling property makes montmorillonite-containing bentonite useful also as an annular seal or plug for water wells and as a protective liner for landfills. Other uses include as an anticaking agent in animal feed, in paper making to minimize deposit formation, and as a retention and drainage aid component. Montmorillonite has also been used in cosmetics.

Sodium montmorillonite is also used as the base of some cat litter products, due to its adsorbent and clumping properties.

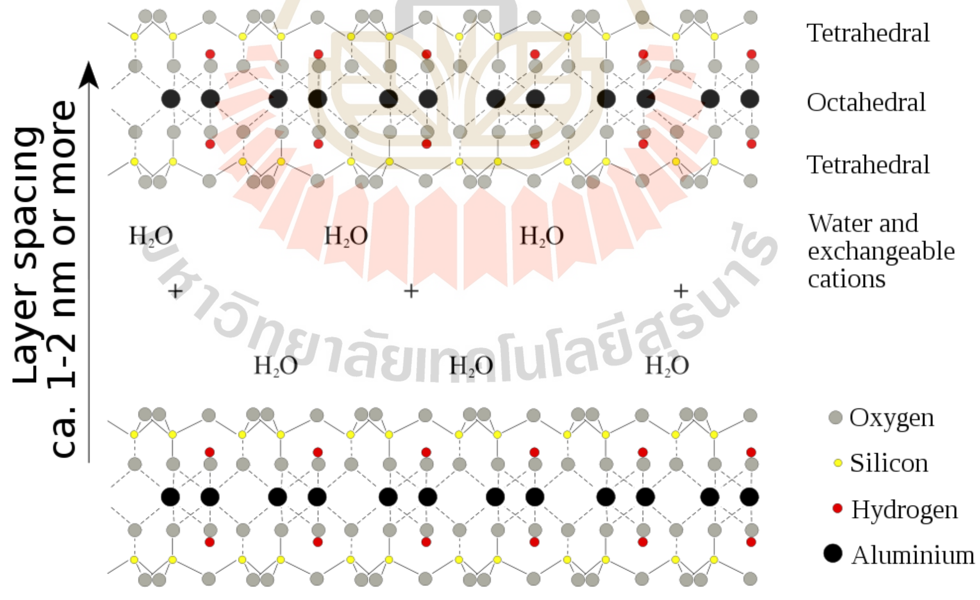

Figure 2.1 Structure of montmorillonite (Lloyd, 2011).

Table 2.1 Adsorption properties of clay (Oliveira et al., 2003).

Type of solid	meq/100g of solids
Attapulgite clay	15 – 25
Chlorite clay	10 – 40
Gumbo shale	20 – 40
Illite clay	10 – 40
Kaoline clay	3 – 15
Montmorillonite clay	80 – 150

Department of Mineral Resources (2013) investigated the properties of bentonite in as follows:

Physical properties of crystal monoclinic system. Normal manner as soil texture or grain dust or small details like dust. It has colors as follows white gray yellow, green, pink and shiny blue soil. The hardness classification is about 1-2 so it is very soft. The specific gravity is about 2-3 lightweight opaque because very small particles.

Properties of chemical formula $(Na, Ca)_{0.33}(Al, Mg)_2(Si_4O_{10})(OH)_2 \cdot nH_2O$ can absorb molecules of water into the structure resulting from inflationary growth is sure enough. Mineral soil resembles a fine-grain smooth feel to make lightweight properties. X-ray and chemical exposure.

Mostly occurrence of bentonite derive from the secondary mineral, which rock conditions change from volcanic rocks. Moreover, montmorillonite also found in sedimentary rock and metamorphic rock dust. This mineral is the one of thermal mineral water with illite, halloysite, kaolinite and quartz.

Sources of bentonite in Thailand are in varying location, including Uttaradit, Lampang, Chiang Rai, Chanthaburi, Prachinburi, Nakhon Sawan, Lopburi, Saraburi, Chachoengsao, Udon Thani, and Kamphaeng Phet provinces.

The important source of bentonite in the world was located Wyoming, USA. The secondary source had located at the Commonwealth of Independent States (CIS), Greece, Germany, Japan and Turkey. The 84% of the production in the world should be produce from there in 1995 and the previous survey could define the reserve of bentonite estimated 1,452 million tons. While the average of demand around 9.8 million tons per year. In 1997-1998, the price of bentonite estimate 98 USD per ton, and the capital of product estimate 50 to 250 USD per ton. From the according should be depended on the properties, volume and demand of bentonite.

Department of Mineral Resources (2013) defines the two sources of bentonite in Chaibadhan District, Lopburi Province and another source in Kanchanaburi province. The detail of each source shows as below:

1) The source of bentonite in Lumnarai Sub-District had found at Pa-Khon Mountain. That should be an extensive area estimate 12.64 square kilometers. The source of bentonite at Pa-Khon Mountain had reserve estimated 290 million tons. Currently, this source has been operated by Sinthanan Ltd., Company.

2) The source of bentonite in Snake Mountain, Huayhin Sub-district and Pluak-Lon Mountain, Lumnarai Sub-District had the extensive area estimate 2.736 square kilometers. That had the reserve estimate 23 million tons.

From the highest reserve and Thailand can produce the bentonite. We can use bentonite from Thailand if its quality and performance is better than the one imported from foreign countries. Bentonite is a key ingredient in drilling mud in order to use in petroleum and groundwater industry and construction purpose. Using local bentonite can reduce the number of imported substance results in a better financial issue. Also, they can make the valuation of resource and take the benefits of this mineral.

2.4 Bentonite

Department of Primary Industries and Mines (2007) concludes the specification of bentonite in physical and chemical properties as follows:

2.4.1 American Petroleum Institute of bentonite specification

The American Petroleum Institute Standard of bentonite specification use for drilling fluids showing in Table 2.2.

Table 2.2 American Petroleum Institute defines bentonite specifications to use for drilling fluids (API Specification 13A, 2010).

Requirement	Specification
Suspension properties:	
Viscometer dial reading at 600 rpm	30, minimum
Yield point/plastic viscosity ratio	3, minimum
Filtrate volume 15.0 cm	4.0 wt. percent or 13.5 ml, maximum
Residue greater than 75 micrometers	2.5 wt. percent, maximum
Moisture	10.0 wt. percent, maximum
Yield	91.8 bbls/ton

2.4.2 Specification of bentonite for oil companies materials

The Oil Companies Materials Association Bentonite Specification (OCMA) is the standard property of drilling fluid after mixed with bentonite, showing in Table 2.3.

Table 2.3 Oil Companies Materials Association Bentonite Specification standard property of drilling fluid after mixed with bentonite (API Specification 13A, 2010).

Requirements	Specification
Suspension properties:	
Viscometer dial reading at 600 rpm	30 cP, minimum
Yield point, lb/100 ft^2	6 times plastic viscosity, maximum
Filtrate-relative 30 minutes	16.0 cm^3, maximum
Residue greater than 75 micrometers	2.5% wt., maximum

2.4.3 Chemical composition of bentonite

The different of physical property and chemical composition using X-ray fluorescent of bentonite from USA, China, Indonesia and Thailand represent in Table 2.4 and 2.5, respectively.

Table 2.4 The variation of physical property of bentonite from USA, China, Indonesia and Thailand (Department of Primary Industries and Mines, 2007).

Minerals	**Contents**			
	Wyoming, USA	**China**	**Indonesia**	**Lopburi, Thailand**
Ferrous oxide (FeO)	NA	0.63%	NA	0.37%
Zinc Oxide (ZnO)	NA	NA	0.003	NA
Barium oxide (BaO)	NA	NA	0.84	NA
Moisture	7.8%	10%	NA	4.8%
pH	8.3-9.1	8.0-9.5	NA	8.0-9.0

Table 2.5 The variation of chemical composition using X-ray fluorescent of bentonite from USA, China, Indonesia and Thailand (Department of Primary Industries and Mines, 2007).

Minerals	**Contents**			
	Wyoming, USA (%)	**China (%)**	**Indonesia (%)**	**Lopburi, Thailand (%)**
Silica (Si_2O)	61.4	67.13	54.80	71.62
Alumina (Al_2O_3)	18.1	14.27	17.20	15.22
Ferric oxide (Fe_2O_3)	3.5	1.84	6.55	1.96
Titanium dioxide (TiO_2)	0.02	0.13	1.67	0.36
Calcium oxide (CaO)	0.04	1.99	4.05	0.61
Sodium oxide (Na_2O)	2.3	1.85	0.004	1.41
Magnesium hydroxide (MgO)	1.7	2.69	3.89	1.66
Potassium oxide (K_2O)	0.01	1.38	0.40	1.00

Table 2.6 The result of chemical composition of bentonite comparison between from the SUT laboratory with American Colloid Company (Horpibulsuk, 2011).

Oxide	**Concentration (%wt.)**	
	SUT Lab	**American Colloid Co.**
SiO_2	61.93	61.30
Al_2O_3	19.85	19.80
Fe_2O_3	4.45	3.90
Na_2O	1.63	2.20
MgO	2.44	1.30
CaO	1.27	0.60
K_2O	0.44	0.40
TiO_2	0.19	0.10
P_2O_5	0.05	-
SO_3	1.27	-
Cl	-	-
V_2O_5	-	-
Cr_2O_3	-	-
MnO	0.02	-
CuO	0.01	-
Rb_2O	-	-
SrO	0.03	-

Table 2.6 The result of chemical composition of bentonite comparison between from the SUT laboratory with American Colloid Company (Horpibulsuk, 2011). (Continued).

Oxide	**Concentration (%wt.)**	
	SUT Lab	**American Colloid Co.**
Y_2O_3	0.01	-
ZrO_2	0.03	-
Nb_2O_5	0.01	-
BaO	0.03	-
CeO_2	0.04	-
LOI.at 1025 °C	6.29	-
Total	100.00	89

2.5 Type of drilling mud

Department of Mineral Resources (2013) summarize a type of drilling mud in water based mud as shown in Table 2.7.

Table 2.7 Type of drilling mud in water based muds (Department of Mineral Resources, 2013)

Straight bentonite mud			
Average composition ($/m^3$)	**Characteristics**	**Stability to ward contaminants**	**Area of use**
Bentonite: 40 to 60 kg CMC: 0 to 5 kg Caustic for pH: 8.5 to 9	Low initial density: 1.03 to 1.05	Slight	- Spud mud - Few contamination problems
Bentonite mud with tanning extracts			
Bentonite: 40 to 60 kg Tannin: 2 to 4 kg CMC: 1 to 5 kg Caustic: 0.5 to 1 kg	pH < 11 Filtrate: 2 to 4 cm^3	Average Ca^{++} < 300 mg/l Cl^- < 20 g/l	- Depth < 3000 m - Low contamination zones (gypsum, anhydrite, shales)
Full Container Load (FCL) / Less Container Load (LCL) bentonite mud			
Bentonite: 50 to 60 kg FCL: 20 to 40 kg Caustic: 2 to 4 kg CMC: 0.5 kg Possibly with LC: 10 to 20kg	pH < 9 Holds up well to 200 °C	Good Cl^- from 50 to 70 g/l	- Depth: 5000 to 6000 m - Wide area of use: concentrations adjusted according to contamination (gypsum, anhydrite, shales)

Table 2.7 Type of drilling mud in water based muds (Department of Mineral Resources, 2013) (Continued).

Gypsum mud			
Average composition (/m^3)	**Characteristics**	**Stability to ward contaminants**	**Area of use**
Bentonite: 50 to 70 kg FCL: 12 to 15 kg Caustic: 3 to 4 kg CMC: 0.5 kg Possibly with LC: 10 to 20 kg	pH < 9 Holds up well to 200 °C	Good Cl^- from 60 to 70 g/l	- Gypsum or anhydrite section - Shaly sections - Slightly salt-bearing sections
Salt – saturated mud with inorganic thinners			
Salt: 300 kg Clay: 50 kg (specific for salt-water mud) Starch: 30 to 40 kg Lime: 0 to 10 kg	d > 1.20 Holds up moderately to temperature, 130 to 140 °C	Good with gypsum and anhydrite section Fair with shales	- Salt bearing sections - Zones with slightly or moderately dispersing shales

2.6 Improvement the performance of bentonite for using in each industrial

SIEP (2003) the physical properties of mud for using in the application (Table 2.8) and concluded the character and the physical properties of mud in drilling application (Table 2.9) as below:

Table 2.8 The physical properties of mud for using in the application (SIEP, 2003).

Drilling mud type	Advantages of using drilling mud	General properties
Prehydrated bentonite (mixed with water)	- Increase viscosity and reduce amount of solid - Control fluid loss - Thin and hard Mud cake	- Addition bentonite 75-100 kg/m^3 - Hydrate estimate 8-10 hours - Adjusted pH = 9 by caustic soda addition
Spud mud	- Clean the well - Increase viscosity - Increase rate of drilling	- Addition bentonite 40-60 kg/m3 in fresh water - Adjust pH = 9-10 by caustic soda addition - Sometime add CMC-HV polymer to increase viscosity ± 20 - Fluid loss ±30 mlAPI
Bentonite/ Lignosulphonate	- Added bentonite for increase yield point and gel strength - Added lignosulphonate to decrease mud loss, yield point and gel strength	- Density <1.2 kg/l - Viscosity (Plastic viscosity, PV) ± 20 - Yield point (YP) 8-12 - Gels 2/4 - pH 9.5-10.5

Table 2.8 The physical properties of mud for using in the application (SIEP, 2003). (Continued).

Drilling mud type	**Advantages of using drilling mud**	**General properties**
Gypsum/ Lignosulphonate	- Added Gypsum for drill in clay formation - Prevented swelling of shale formation or melting of salt formation - Added lignosulphonate to reduce mud loss, yield point gel strength and viscosity	- Density <1.3 kg/l - PV ± 20 - YP 10-15 - Gels 8/12 - pH 9.5-10.5 - Ca^{++} 600-1200 ppm
Salt drilling mud	- Mud in salt formation application - Property of salt is plastic	- Added Starch instead the Synthetic polymers

Table 2.9 Character and the physical properties of mud in drilling application. (SIEP, 2003).

Function	**Relevant properties**	**Effect of properties on penetration rate**	**Chemicals for control of water based drilling fluid**
Controlled the pressure in formation	Drilling fluid density	- Increased density of mud - Reduced rate of drilling	- Barite addition - Reduced by water addition (Then verify the viscosity)
Cuttings	Plastic viscosity	- Increased viscosity of mud - Decreased rate of drilling	- Reduced by water addition (Then verify the density) or (Thinner)

Table 2.9 Character and the physical properties of mud in drilling application (SIEP, 2003) (Continued).

Function	Relevant properties	Effect of properties on penetration rate	Chemicals for control of water based drilling fluid
Cuttings	Yield point	- Increased yield point and gel strength - Reduced rate of drilling	- Increased by bentonite or XC-polymer addition - Reduced the dilution
	Gel strength		- Reduced by fill up thinner - Increased by fill up fresh water
Prevented and relieved the well by mud cake that could reduce the contaminated in formation	Fluid loss	- Reduced mud loss - Reduced a little bit rate of drilling	- Reduced by CMC or starch addition - Increased by fill up fresh water
	Solid content	- Increased solid content - Reduced rate of drilling	- Tried to reduce each values by restricted clay, silt, sand and cutting

Mutturee et al. (2012) had experiment about an effect of temperature on efficacy of bentonite to adsorb aflatoxin B1. By comparison adsorb performance under each temperature we found that bentonite had adsorbed aflatoxin B1 in high temperature better than bentonite in low temperature then the appropriate temperature for absorb efficiently was 600^{o}C.

Dewu et al. (2011) had experiment for adjustment the properties of rheology or vary of physical properties and flow character of bentonite from The northeast of Nigeria by using Sodium carbonate and the increased viscosity synthetic substance that called Drispac. By the experiment they found when filled up Sodium carbonate and Drispac estimate 0.2-1 gram in the bentonite sample that sample had better than when compared with the standard of bentonite in petroleum drilling application.

Apugo-Nwosu et al. (2011) had studied the property of bentonite from Nigeria (Ubagala) for using in petroleum drilling exploration compared with Wyoming bentonite then that was the standard for used in petroleum drilling. By comparison the property of sediment distribution exchange ion and property of rheology. Conclusion the study property of bentonite from Nigeria had the better performance when mixed with Carboxymethyl cellulose (CMC) Poly Anionic Cellulose-Regular (PAC-R) and Sodium Carbonate (Na_2CO_3; Soda Ash) but the best property and close to Wyoming bentonite property was the mixed Ubanala bentonite 24.5 grams with fresh water 350 ml, CMC 2 grams and Na_2CO_3 1.5 grams.

Al-Homadhi (2013) had experiment to improve the performance of bentonite in Saudiarabia instead of imported bentonite from the other countries to use in drilling. The improvement property of bentonite in drilling for API standard by bentonite should be increased viscosity and reduce mud loss in formation until lifting cutting. That experiment had adjusted the property of bentonite by cheap addition that could increase viscosity and reduced mud loss such as CMC polymer, Caustic soda etc. They founded the caustic soda addition 5% of intensity and filled Polymer as Drispac addition low intensity estimate 0.5% mixed with bentonite. The result of viscosity and mud loss estimate 8% by the weight of bentonite mixed with Caustic soda and polymer that result closed to drilling mud mixed with imported bentonite. The viscosity and mud loss estimate 7% by weight of addition in bentonite.

Lyons (2009) had experiment by improve bentonite in drilling mud and take a little period to settling mud after mixed. Drilling mud will mix bentonite 75-100 kg/m^3 or 25-35 ppb in fresh water by filled soda ash and caustic soda. The Soda ash in drilling mud will improve restrict calcium in water, improved pH and restrict Calcium Sulfate ($CaSO_4$) in mud that could improve high viscosity, yield point and gel strength however the amount of solid and mud loss should be decreased and mud cake had thin and hard. The simple mud in drilling will have a period to settling estimate 6-12 hours after mixed.

CHAPTER III

METHODOLOGY

3.1 Introduction

The objective of the experiment in the laboratory is to test the chemical property of bentonite from Thailand and the information in this unit is compound of drilling mud sample preparation for the experiment, devices and the equipment used in the experiment and the method of experiment.

3.2 Research methodology

The research methodology is comprised five steps as shown in Figure 3.1, 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:

3.2.1 Literature review

The relevant literatures are studied to improve understanding drilling mud properties by differential bentonite sources according to American Petroleum Institute standard (API), It had compose of reviewing and studying water-based drilling mud and application, It will use the bentonite additive from the other sources in Thailand such as Saraburi, Lopburi and Kanchanaburi sources in drilling mud and the sources of information were from journals, researches, dissertation and books concerned.

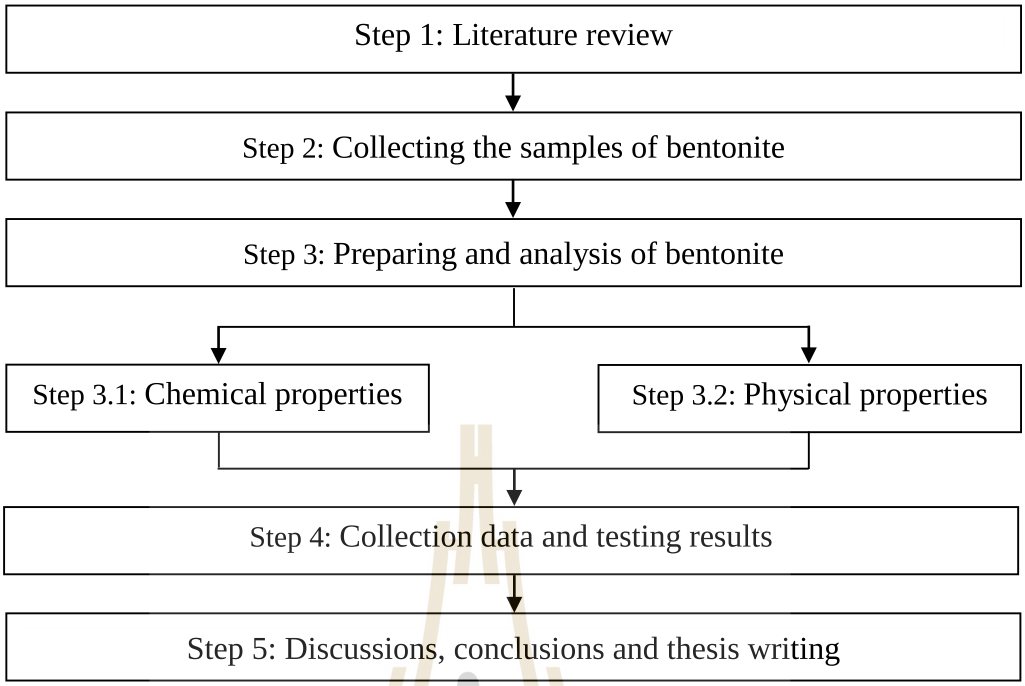

Figure 3.1 Research plan

3.2.2 Collecting the samples of bentonite

Bentonite samples are collected from Saraburi, Lopburi and Kanchanaburi provinces, Thailand and America bentonite.

3.2.3 Preparing and analysis of bentonite

The samples will be prepared and tested at laboratory of Suranaree University of Technology. Bentonite will be sieved in size less than 75 micrometers (mesh No. 200) prior to store in zip lock bags. These samples will be divided into 2 parts for chemical properties testing and physical properties testing after mixed with drilling mud.

3.2.3.1 Chemical property tests

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

3.2.3.2 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), including of density, viscosity, API filtration, pH, sand content, resistivity, solid content of drilling mud mix with bentonite from America, Saraburi, Lopburi and Kanchanaburi provinces and Scanning Electron Microscope (SEM) at temperatures ranging from 30, 60 to 90°C.

3.2.4 Collecting data and testing results

The research results are analyzed to optimize the drilling mud mix bentonite with drilling mud will be compared between before and after mixed with drilling mud for determine components and properties of bentonite were added in drilling mud and efficiency of drilling mud which varies in different temperatures

3.2.5 Conclusion, discussion and thesis writing

The laboratory results of measurements in terms of plastic viscosity, yield point, gel strength, filtrate volume, mud cake thickness and pH, have compared those results from water-based mud and water-based mud mixing with bentonite from Saraburi, Lopburi and Kanchanaburi provinces. 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-based mud mixing with bentonite in onshore and offshore well in Thailand was also considered.

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

3.3 Sample collection

The bentonite from Lopburi province is supported from Thai Nippon Chemical Industry Co., Ltd. Bentonite Saraburi, Kanchanaburi province are purchased from a store, Thailand. Barite was assisted from Weatherford International Thailand Company.

3.4 Sample preparation

The drilling mud sample composition use in the experiment compose of bentonite in Thailand such as Saraburi, Lopburi and Kanchanaburi sources and bentonite from USA. In the experiment was lead bentonite from sieve size 75 micrometer (No. 200) for analyzed the chemical property. That was analyzed elemental and mineral composition by X-ray diffraction (XRD), X-ray fluorescence (XRF) and Scanning Electron Microscope (SEM) test respectively.

Table 3.1 Compositions of drilling mud samples.

Composition of mud	Bentonite mud (grams)
Water	1000
Barite	100
America bentonite (Base)	60
Saraburi bentonite	60
Lopburi bentonite	60
Kanchanaburi bentonite	60

3.5 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 3.2 demonstrates the composition and nature of common drilling muds. The curves show the increasing of viscosity with percentage of bentonite solids.

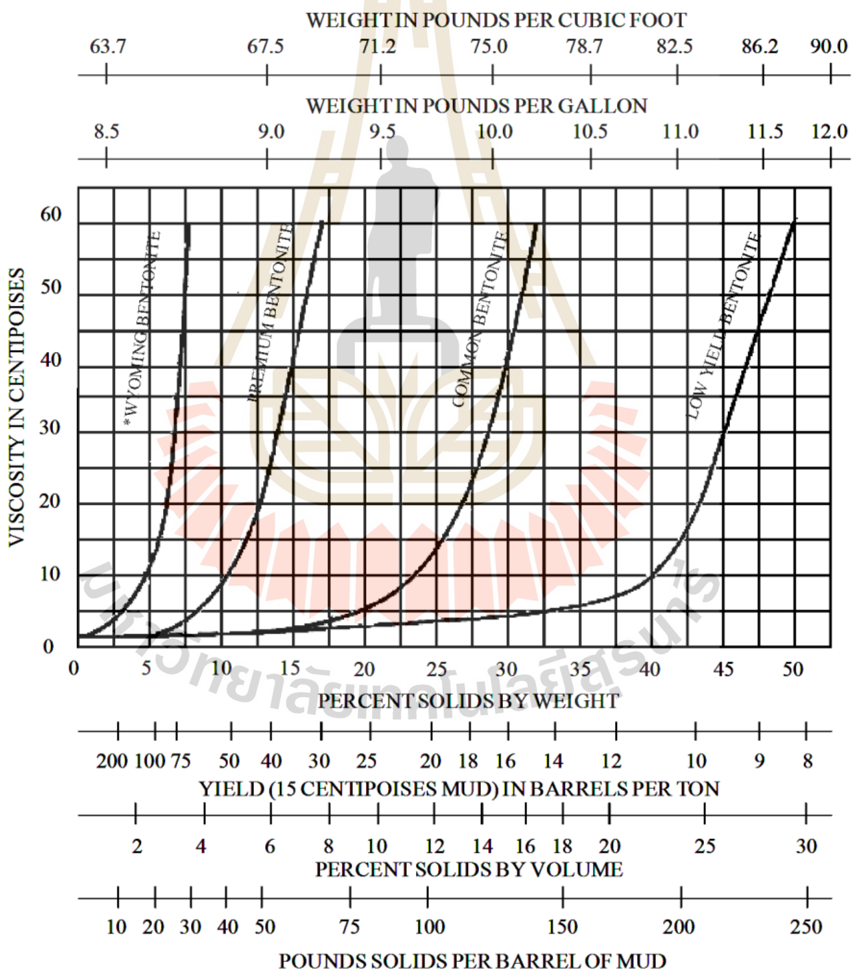

Figure 3.2 Yield curve for typical clays (modified from Gatlin, 1960).

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 based 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 3.3). 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 3.1.

Figure 3.3 Mud balance.

3.6 Chemical properties tests

The objective of chemical property testing is to determine the components, elemental and mineral crystals of samples by using X-ray diffractometer (XRD) and

X-ray fluorescence spectrometer (XRF). Sample preparations were sieved by the mesh No. 200 (0.075 mm) and was dried at 60°C in the oven for 24 hours.

3.6.1 X-ray fluorescence

X-ray Fluorescence analysis using Horiba XGT-5200 spectrometers was a commonly used technique for the identification and quantification of the element in a substance (Figure 3.4). Place the sample approximately 0.5 to 1.0 grams in the sample holder. Load the sample holder into the ED-XRF, analysis probe is set with vacuum, making it possible to analyze the sample at normal atmospheric pressure. The X-ray excitation sources used in wavelength and energy-dispersive XRF provides adequate analytical sensitivity for quantitative analysis across the element sodium to uranium. Typically, all elements from sodium through to uranium can be detected simultaneously, with good quality spectra obtained in 100 seconds per sample. Results are analyzed in the spectrum, including Rayleigh and Compton scattered characteristic line from the X-ray generator, a peak caused by X-ray diffraction, and sum/escape peak. The quantitative XRF analysis of unknown samples is usually performed using calibrations with matrix-matched standards. The XRF results are presented as the percentage of major elements.

Figure 3.4 Horiba (XGT-5200) X-ray fluorescence.

3.6.2 X-ray diffraction

X-ray Diffraction analysis using Bruker-D2 Phaser was an essential technique in the material characterization analysis to obtain qualitative and quantitative mineralogical characterization (Figure 3.5). Load the prepared samples approximately 0.5 to 1.0 grams into the sample holder. Pull down the spherical handle of the stage and place onto sample holder into the sample position of the stage. Lift the sample back into the sample measurement position by pulling up the spherical handle of the stage and slide down the instrument door and spent time 10 minutes per sample. The X-ray beam is diffracted by innumerous crystallites in specific 2 Theta directions and the intensity of diffracted X-rays is continuously recorded as the sample. Data is recorded the exact 2 Theta positions a narrow slit in front of a point detector is required. A peak in intensity occurs when the mineral contains lattice planes with d-spacings appropriate to diffract X-rays at that value of θ. Conditions of analysis include a Cu standard ceramic sealed tube (0.4x12 mm), X-ray generation (30 kV, 10 mA), angular range analysis (2θ, 5º to 80º) and accuracy (±0.02º throughout the entire measuring range). Results are presented as peak positions at 2θ and X-ray counts (intensity) in the form of a table or an x-y plot and 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 by software TOPAS.

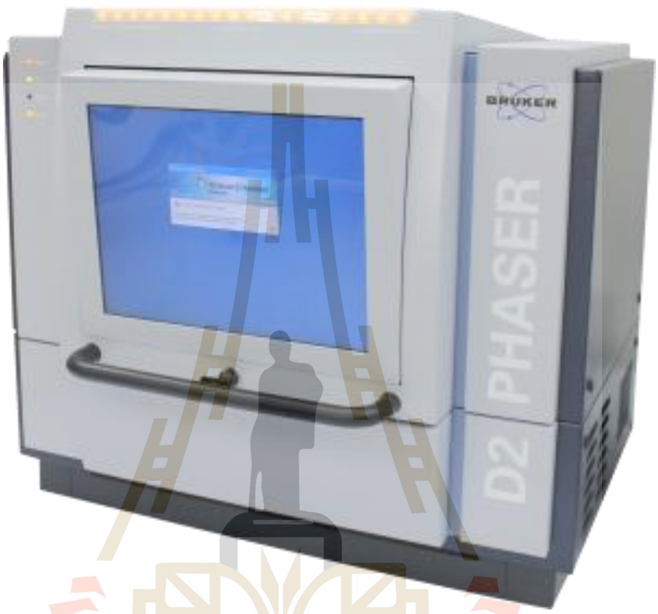

Figure 3.5 Bruker (D2 Phaser) X-ray diffractometer.

3.7 Physical properties tests

The physical properties consist of density, rheology, filtration, hydrogen ion, resistivity, solid content, sand content and scanning electron microscope (SEM). They are determined following API standard.

3.7.1 Rheological tests

The rheology of drilling mud, was conducted by rotational viscometer (Fann model 35SA viscometer) was used to directly measure the viscosity of the drilling mud (Figure 3.6). Rheology is the study of how matter deformation and flows. It is primarily concerned with the relationship of shear stress and shear rate, temperature and the impact these have on flow characteristics inside tubulars and annular spaces. The rheological property was monitored to assist in optimizing the drilling process. The rheological parameters of water based drilling mud were investigated and calculated.

Figure 3.6 Fann model 35SA viscometer.

Direct indicated viscometers are rotational types of instruments powered by an electric motor. Drilling mud is contained in the annular space between two concentric cylinders. The outer cylinder or rotor sleeve is driven at a constant RPM (rotational velocity); its rotation of the rotor sleeve in the drilling mud produces a torque on the inner cylinder or bob. A torsion spring restrains the movement of the bob, and a dial attached to the bob indicates its displacement on a direct reading scale. The rheological calculation, it is appropriate to discuss some basic drilling mud flow properties, determination of rheological parameters that describe the flow behavior of a fluid.

The effective viscosity is sometimes referred to as the apparent viscosity (AV). Apparent viscosity is a rheological property calculated from rheometer readings. It measures the shear rate of drilling mud 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 is reported as either the mud viscometer reading at 300 RPM (θ_{300}) or one-half of the meter reading at 600 RPM (θ_{600}). It should be noted that both of these apparent viscosity values are consistent with the viscosity formula:

$$\text{AV or } \mu_a \text{ (cP)} = \frac{\theta_{600}}{2} \tag{3.1}$$

Plastic viscosity (PV) in centipoise (cP) is the shearing stress in excess of yield point that will induce a unit rate of shear. Plastic viscosity is usually described as that part of resistance to flow caused by mechanical friction. Primarily, it is affected by (1) solids concentration, (2) size and shape of solids, (3) viscosity of the fluid phase, (4) the presence of some long chain polymers, (5) the oil-to-water (O/W) or synthetic-to-water (S/W) ratio in invert emulsion fluids, (6) type of emulsifiers in invert emulsion fluids. The 600 dial reading (θ_{600}) minus the 300 dial reading (θ_{300}) gives the slope of the shear stress/shear rate curve. This is the plastic viscosity (see Figure 3.7) and its range value that are used in well drilling is shown in Figure 3.8.

$$\text{PV or } \mu_p \text{ (cP)} = \theta_{600} - \theta_{300} \tag{3.2}$$

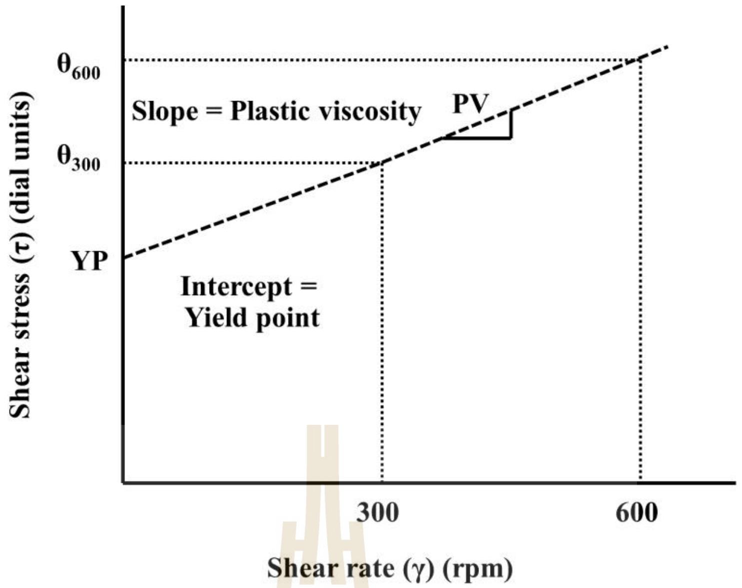

Figure 3.7 Plastic viscosity and yield point values from two measurements.

(modified from Baker Hughes, 2006)

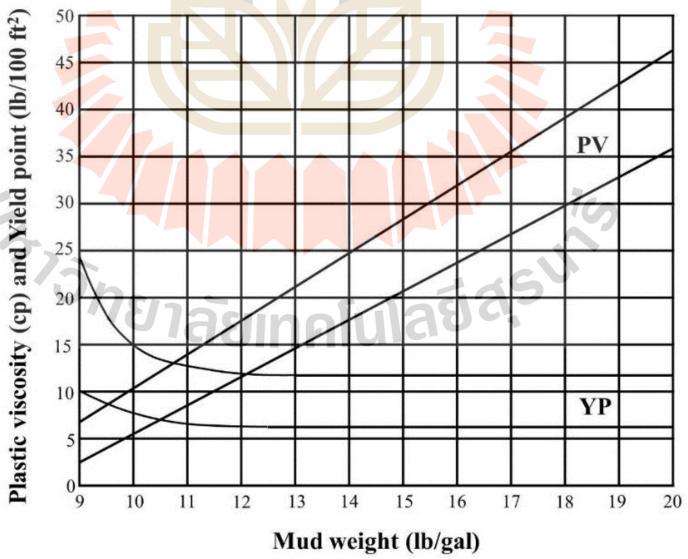

Figure 3.8 Plastic viscosity and yield point ranges for water based drilling mud.

(modified from MI-Swaco, 1998).

Yield point, the second component of resistance to flow in drilling mud. This parameter is also obtained from the viscometer. It is a measurement of the electro-chemical or attractive forces. These forces are a result of negative and positive charges located on or near the particle surfaces. Yield point is a measure of these forces under flow conditions and is dependent upon: (1) the surface properties of the mud solids, (2) the volume concentration of the solids, and (3) the electrical environment of these solids (concentration and types of ions in the fluid phase of the fluid). Yield point is that part of resistance to flow that may be controlled by proper chemical treatment. The yield point will decrease as the attractive forces are reduced by chemical treatment. Reduction of yield point will also decrease the apparent viscosity. The yield point in pounds per 100 square feet ($lb_f/100\ ft^2$) equals the 300 rpm reading minus the plastic viscosity, is the shear stress at zero shear rate (see Figure 3.8) and its range value that used in well drilling is also shown in Figure 3.8.

$$\text{YP or } \gamma_p\ (lb_f/100\ ft^2) = 2 \times \theta_{300} - \theta_{600} \tag{3.3}$$

$$\text{or YP or } \gamma_p\ (lb_f/100\ ft^2) = \theta_{300} - PV \tag{3.4}$$

Gel strength is a measure of the inter-particle forces and indicates the gelling that will occur when circulation is stopped. This property prevents the cuttings from setting in the hole. Similar to the yield point, gel strength is a measure of the electro-chemical attractive forces between solid particles. Gel strength is measured in units of $lb_f/100\ ft^2$. This reading is obtained by noting the maximum dial deflection when the rotational viscometer turned at a low rotor speed (3 rpm) after the mud has remained static for some period of time (10 seconds and 10 minutes). If the mud is allowed to remain static in the viscometer for a period of 10 seconds, the maximum dial deflection obtained when the viscometer is turned on is reported as the initial gel on the

API mud report form. If the mud is allowed to remain static for 10 minutes, the maximum dial deflection is reported as the 10 min gel. The strength of the gel formed is a function of the amount and type of solids in suspension, time, temperature and chemical treatment. In other words, anything promoting or preventing the linking of the particles will increase or decrease the gelation tendency of a fluid.

The other terms of viscosity can be described in terms of the ratio of the shear stress to the shear rate. By definition:

$$\mu = \frac{\tau}{\gamma} \tag{3.5}$$

where μ = viscosity, cP

τ = shear stress, $lb_f/100\ ft^2$

γ = shear rate, sec^{-1}

The drilling mud, was characterized by their shear rate and shear stress relationships. The shear rate and shear stress were calculated using the viscometer dial readings. The shear stress and shear rate equations are as follows:

$$\tau = 1.0678 \times \theta \tag{3.6}$$

$$\gamma = 1.703 \times \omega \tag{3.7}$$

where θ = mud viscometer dial readings

ω = mud viscometer RPM

The power law model parameter constants in term of flow behavior index (n) and consistency index (K) can be determined from any two sets of shear stress to shear rate data. Plotted on a log-log graph, a power law fluid shear stress to shear rate relationship forms a straight line, as shown on Figure 3.9. The “slope” of this line is “n.” “K’ is the intercept of this line were calculated from viscometer readings using following equations.

$$n = \frac{\log\left(\frac{\theta_{600}}{\theta_{300}}\right)}{\log\left(\frac{\omega_{600}}{\omega_{300}}\right)} \quad (3.8)$$

$$K = \frac{\theta_{300}}{\omega_{300}^{\ n}} \quad (3.9)$$

where n = flow behavior index

K = fluid consistency index

θ_{600} = mud viscometer dial readings at 600 rpm

θ_{300} = mud viscometer dial readings at 300 rpm

ω_{600} = mud viscometer RPM at 600 rpm

ω_{300} = mud viscometer RPM at 300 rpm

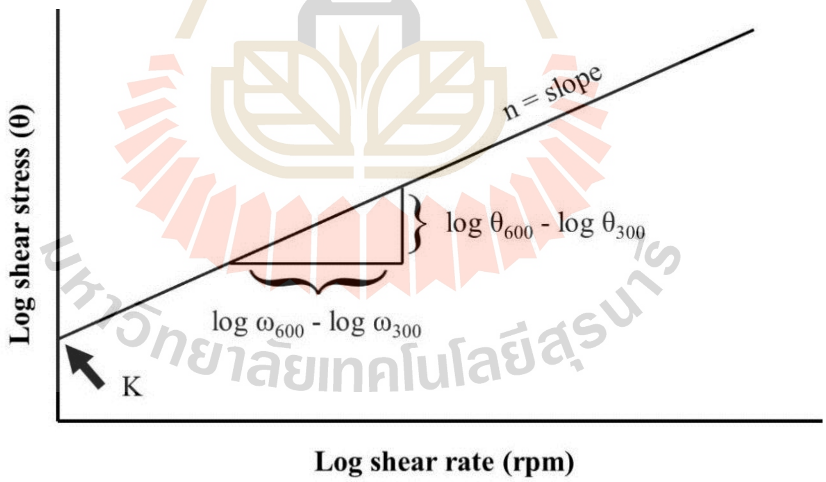

Figure 3.9 Log plot of power law models. (modified from Baker Hughes, 2006)

3.7.2 Static filtration tests

The filtration experiment was conducted by filter press API low pressure, low temperature (Fann series 300 API filter press) which used to determine the filtration loss of a drilling mud through standard filter paper and the mud filter cake building characteristics under static conditions (Figure 3.10). The filter press consists of a cylindrical mud chamber made of materials resistant to strongly alkaline solutions. A filter paper is placed on the bottom of the chamber just above a suitable support. Below the support is a drain tube for discharging the filtrate into a graduated cylinder. The entire assembly is supported by a pressurized nitrogen gas cylinder and stand so 100 psi (6.9 bars) pressure can be applied to the mud sample in the chamber. At the end of the 30 minute filtration time, the volume of filtrate is reported as API filtration in cubic centimeters (cm^3). Thickness of the residue deposited upon the filter paper washes the cake gently to remove excess mud. Measure the thickness of the mud filter cake and reported in millimeters (mm) by using a Vernier caliper. The properties of the mud filter cake were visually examined, and its consistency is record using such notations as texture, color, hardness, or flexibility.

Figure 3.10 Fann (series 300) filter press.

3.7.3 Hydrogen ion tests

The hydrogen ion concentration (pH) was conducted by using a glass electrode pH meter (Oakton pH 700 benchtop meters) to measure of drilling mud or mud filtrate pH and adjustments to the pH are fundamental to drilling mud control (Figure 3.11). Two methods are used for measurements the pH of water based drilling mud: a modified colorimetric method, using plastic backed test strips (sticks); and the potentiometric method, employing the glass electrode electronic pH meter. In this work used glass electrode pH meter, consists of a glass electrode, an electronic amplifier, and a meter calibrated in pH units. The electrode is composed of (1) the glass electrode, a thin walled bulb made of special glass within which is sealed a suitable electrolyte and an electrode, and (2) the reference electrode, which is a saturated calomel cell. Electrical connection with the mud is established through a saturated solution of potassium chloride contained in a tube surrounding the calomel cell. The electrical potential generated in the glass electrode system by the hydrogen ions in the drilling mud is amplified and operates the calibrated pH meter. Measurement and adjustments of pH are the fundament of drilling mud 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.

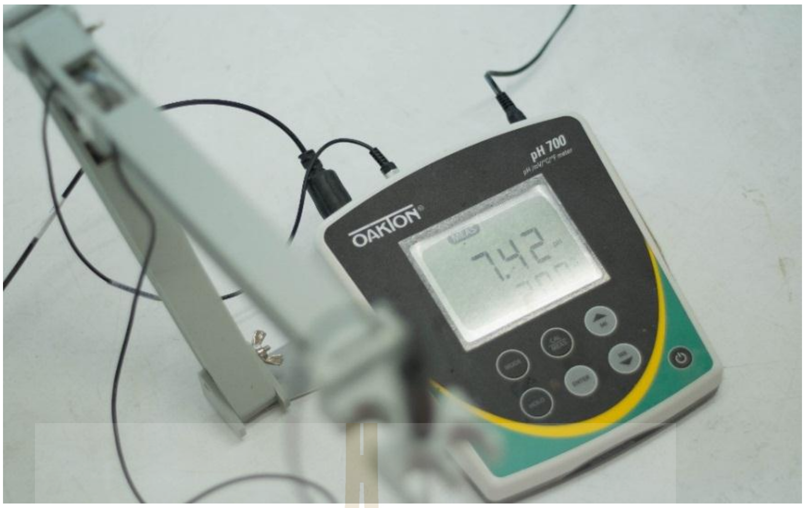

Figure 3.11 OAKTON (pH 700 model) pH meter.

3.7.4 Liquid and solid content tests

The liquid and solid contents were measured by retort kit (Fann retort oil and water 50 ml kit) which was direct-reading method for measuring volumes of water, and solids contained in drilling mud (Figure 3.12). Disassemble retort assembly and lubricate sample cup threads with high-temperature grease. Fill samples cup almost level full of the mud to be tested. Put the sample cup cover in place by rotating firmly, squeezing out excess fluid to obtain the exact volume 50 ml required. Clean spills from cover and threads. Pack fine steel wool into the upper expansion chamber, then screw sample cup into expansion chamber and heated at high temperature until the liquid components have been distilled off and vaporized. These vapors passed through a condenser and collected in a graduated cylinder that usually is graduated in percentage. Water volumes are read directly in percentage from the graduated cylinder. The solids, both suspended and dissolved, are determined by subtracting from 100% or by reading the void space at the top. Drilling mud retorts are generally designed to distill 50 ml sample volumes. The percentage by volume solids analysis, weight method (calculated by weight difference using conventional retort) was calculated following formulas from API standard.

Compute volume percentage solids:

$$\text{Fraction of solids} = \frac{(C - B) - SG_{MUD}\,x(C - D)}{C - B} \tag{3.10}$$

$$\%\ \text{solids} = 100 \text{ x volume fraction solids} \tag{3.11}$$

Measurements are taken:

A. Mud weight

B. Weight of retort (including steel wool and cup)

C. Weight of retort with whole mud

D. Weight of retort with mud solids

where mud density (g/cm^3); SG_{MUD} = mud weight (lb/gal) x 0.11994

grams of mud in retort: grams of mud = Value C - Value B

grams or cm^3 water distilled: Value C - Value D

Figure 3.12 Fann retort kit.

3.7.5 Sand content tests

Fann sand content set (Figure 3.13) 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 3.13 Fann sand content kit.

3.7.6 Resistivity tests

The resistivity of drilling mud, mud filtrate, and mud filter cake are measured by resistivity meter (Fann model 88c resistivity meter) to control of the resistivity of the drilling mud and mud filtrate while drilling may be desirable to permit enhanced evaluation of the formation characteristics from electric logs (Figure 3.14).

The determination of resistivity is essentially the measurement of the resistance to electrical current flow through a known sample configuration. Measured resistance is converted to resistivity by use of a cell constant. The cell constant is fixed by the configuration of the sample in the cell and is determined by calibration with standard solutions of known resistivity. Fill the clean, dry resistivity cell with freshly stirred drilling mud, mud filtrate, or mud filter cake and fill the cell to the correct volume according to the manufacturer's procedure. Connect the cell to the meter and measure the resistance in ohm-meters and temperature. The resistivity meter provides a direct digital readout of resistivity in three ranges; 2, 20, and 200 ohm-meters/meters². Instrument calibration uses salt solution and calculated the correction factor for accurate data.

Figure 3.14 Fann (88C model) resistivity meter.

3.7.7 Scanning Electron Microscope

Scanning electron microscope analysis using JEOL JSM-6010LV was utilized in imaging and chemical analysis (Figure 3.15). The sample was mounted on a sample holder using conductive carbon tapes and applies a thin gold film conductive coating to the sample that is effective in eliminating charging of non-conductive materials. Load sample holder on the bottom that fits over the raised circle in the center of the stage. Press and hold the EVAC button on the vacuum control until it starts flashing. It will take about 1 minute to evacuate to a pressure that is safe for the beam. The electrons are generated using the electron Gun. The electrons pass through the electromagnetic lenses (condenser lens) to make the electrons into an electron beam. The electron beam is adjusted by the objective lens to focus on the sample surface, make interaction with the sample reflected from the surface of the sample and to cause secondary electrons. The resulting electrons emitted from the sample are attracted and collected by a secondary electron detector and secondary electron signal translated into electronic signals into images in the three-dimensional display on the screen. Imaging in an SEM can be done using secondary electrons to obtain fine surface topographical features or with backscattered electrons which give contrast based on atomic number. Images are typically resolved in 5-3,000× magnification with a spot size of 20-30 and beam strength of 5-10 kV.

Figure 3.15 JEOL (JSM-6010LV) Scanning Electron Microscope.

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 described below.

4.2 Chemical property

The objectives of these tests are to determine the oxide compounds and minerals of drilling mud both before and after mixed with each country. The step of methods is the rheological and physical properties.

4.2.1 Chemical property of barite and each bentonite

The oxide compounds are determined by an X-ray fluorescence spectrometer. The minerals are measured by an X-ray diffractometer. Table 4.1 and Table 4.2 show the major oxide compounds and minerals of materials before mixing.

Table 4.1 shows the semi-quantity analysis result of barite and bentonite in each source by XRF as following:

Barite generally composes of BaO, SO_3, Rh_2O_3 and SiO_2 estimating 82.43%, 8.888%, 2.795% and 1.902%, respectively. The amounts of Al_2O_3, Fe_2O_3, SrO, K_2O and CaO are approximate 3.985%.

Generally, bentonite from America composes of SiO_2, Al_2O_3, MgO and SO_3 are approximate 69.83%, 21.97%, 3.93% and 1.14% respectively. The amount of K_2O, CaO, Fe_2O_3, SrO, Rh_2O_3, MnO_2 and TiO_2 are approximate 3.13%.

Bentonite from Saraburi comprises SiO_2, Al_2O_3, Fe_2O_3, and MgO are approximate 72.62%, 16.18%, 4.67% and 3.542% respectively. The amount of SO_3, K_2O, CaO, SrO, Rh_2O_3, MnO_2, TiO_2, ZnO and ZrO_2 are approximate 0.91%.

Bentonite from Lopburi comprises of SiO_2, Al_2O_3, Fe_2O and MgO estimate 69.29%, 18.29%, 5.32%, and 2.65% respectively. The amount of SO_3, K_2O, CaO, SrO, Rh_2O_3, MnO_2, TiO_2, ZnO and ZrO_2 is approximate 4.45%.

Bentonite from Kanchanaburi comprises of SiO_2, Al_2O_3, MgO, CaO and Fe_2O_3 are approximate 77.90%, 12.42%, 3.69%, 2.50% and 2.38% respectively. The amount of K_2O, SrO, Rh_2O_3 and MnO_2 is approximate 1.11%.

Oxide compounds of drilling mud before mixing included MgO, Al_2O_3, SiO_2, K_2O, CaO, Fe_2O_3, Rh_2O_3 and MnO_2. However, the content of SO_3 and TiO_2 is not shown in Kanchanaburi bentonite ZnO and ZrO_2 do not show in both America and Kanchanaburi bentonites.

Table 4.1 Major oxide compounds of bentonite in each country before mixing using X-ray fluorescence.

Major oxide compounds (weight %)	**Barite**	**Bentonite from**			
		America (Base)	**Saraburi**	**Lopburi**	**Kanchanaburi**
MgO	-	3.934	3.542	2.65	3.689
Al_2O_3	1.305	21.967	16.177	18.286	12.422
SiO_2	1.902	69.83	72.626	69.29	77.9
SO_3	8.888	1.14	0.16	1.26	-
K_2O	0.209	0.372	0.489	0.35	0.901
CaO	0.186	1.841	1.217	1.27	2.504
Fe_2O_3	1.454	0.747	4.669	5.32	2.377
SrO	0.831	0.073	0.005	0.049	0.029
Rh_2O_3	2.795	0.069	0.066	0.111	0.074
MnO_2	-	0.007	0.014	0.164	0.104
TiO_2	-	0.02	1.016	1.2	-
ZnO	-	-	0.003	0.017	-
ZrO_2	-	-	0.016	0.033	-
BaO	82.43	-	-	-	-
Total	100	100	100	100	100

Table 4.2 shows the result of XRD analysis from barite and bentonite in each source. Barite generally consists 77.3% barite, 21.3% quartz and 1.4% anhydrite respectively.

America bentonite is composed of 29.98% microcline, 18.13% talc, silica 14.96%, 5.93% anorthite, 3.67% calcite, 3.16% quartz, 2.94% choromite and 2.58% gypsum respectively.

Bentonite from Saraburi composes of 63.2% silica, 19.77% microcline, 7.32% kaolinite, 4.08% talc, 2.01% choromite, 1.47% calcite, 1.12% quartz, 0.65% gypsum, 0.29% anorthite and 0.09% hematite respectively.

Bentonite from Lopburi composes of 28.51% talc, 18.8% kaolinite, 18.63% calcite, 16.89% microcline, 11.95% silica, 2.06% chromite, 1.65% anorthite, 0.96% gypsum, 0.44% hematite and 0.11% quartz respectively.

Bentonite from Kanchanaburi composes of 40.21% microcline, 20.84% talc, 8.19% calcite, 8.18% kaolinite, 8.01% quartz, 5.77% anorthite, 4.19% silica, 3.13% gypsum, 1.4% choromite and 0.08% hematite respectively.

The major minerals of materials before mixing of all four materials included quartz, kaolinite, calcite, gypsum, anorthite, choromite, silica, talc and microcline. However, variation of specific mineral in drilling mud does not show the hematite in America bentonite.

Table 4.2 Minerals contents of bentonite mud in each country before mixing using X-ray diffraction.

Minerals (weight %)	Barite	Bentonite from			
		America (Base)	Saraburi	Lopburi	Kanchanaburi
Quartz	21.3	3.16	1.12	0.11	8.01
Kaolinite	-	18.65	7.32	18.8	8.18
Hematite	-	-	0.09	0.44	0.08
Calcite	-	3.67	1.47	18.63	8.19
Gypsum	-	2.58	0.65	0.96	3.13
Anorthite	-	5.93	0.29	1.65	5.77
Choromite	-	2.94	2.01	2.06	1.4
Silica	-	14.96	63.2	11.95	4.19
Talc	-	18.13	4.08	28.51	20.84
Microcline	-	29.98	19.77	16.89	40.21
Anhydrite	1.4	-	-	-	-
Barite	77.3	-	-	-	-
Total	100	100	100	100	100

4.2.2 Chemical property of drilling mud mixing with each bentonite

Drilling mud mixed with bentonite in each country and temperature are measured by the X-ray fluorescence and X-ray diffraction to determine the compositions of the oxide compounds and minerals. Tables 4.3 and 4.4 are display X-ray fluorescence and X-ray diffraction of drilling mud mixed with bentonite in each country.

Table 4.3 show the XRF analysis result from barite and bentonite in each sources. The major oxide compounds of each bentonite sources shows the highest amount including 77.84% SiO_2 (Kanchanaburi bentonite), 23.07% SO_3 (Lopburi bentonite), 13.96% Al_2O_3 (America bentonite), 5.03% Fe_2O_3 (Lopburi bentonite), 3.04% BaO (Kanchanaburi bentonite), 3.92% MgO (Lopburi bentonite), 3.06% CaO (Lopburi bentonite), 0.87% K_2O (Kanchanaburi bentonite), 0.53% SrO (Kanchanaburi bentonite) and 0.45% Rh_2O_3 (Kanchanaburi bentonite) respectively.

The major oxide compounds of drilling mud after mixed with bentonite from America, Saraburi, Lopburi, and Kanchanaburi consist of MgO, Al_2O_3, SiO_2, K_2O, CaO, Fe_2O_3, SrO, Rh_2O_3 and BaO. However, SO_3 does not show in Kanchanaburi bentonite.

Table 4.3 Oxide compounds of drilling mud mixed with bentonite in each country using X-ray fluorescence.

Sample No.	Temp. (ºC)	Bentonite from	Major oxide compounds (weight %)										
			MgO	Al_2O_3	SiO_2	SO_3	K_2O	CaO	Fe_2O_3	SrO	Rh_2O_3	BaO	Total
1	30	America (Base)	3.031	13.743	59.92	19.011	0.412	0.66	2.099	0.173	0.146	0.805	100
2	60		2.985	13.96	60.934	17.53	0.658	0.644	1.829	0.311	0.147	1.002	100
3	90		2.908	13.75	57.34	19.772	0.337	0.782	1.962	0.319	0.268	2.562	100
4	30	Saraburi	2.231	12.587	62.511	18.439	0.374	0.669	1.95	0.201	0.173	0.865	100
5	60		2.243	13.235	60.802	18.987	0.497	0.77	2.08	0.223	0.199	0.964	100
6	90		2.013	13.805	61.932	18.112	0.304	0.487	1.946	0.254	0.208	0.939	100
7	30	Lopburi	3.915	11.694	50.527	23.073	0.561	2.752	4.796	0.343	0.267	2.072	100
8	60		3.831	12.596	51.399	21.21	0.432	2.74	4.952	0.357	0.37	2.113	100
9	90		3.549	12.84	51.623	20.758	0.444	3.064	5.031	0.37	0.292	2.029	100
10	30	Kanchana buri	2.421	12.548	76.703	-	0.867	1.829	1.653	0.528	0.453	2.998	100
11	60		2.801	11.653	77.64	-	0.768	1.422	1.904	0.418	0.356	3.038	100
12	90		2.616	11.891	77.84	-	0.804	1.804	1.986	0.349	0.296	2.414	100

Table 4.4 show the XRD analysis result from bentonite in each source. The oxide compounds and minerals correlation result in drilling mud as follow: the element composition of BaO in barite form; the element composition of SiO_2 in quartz form as kaolinite, anortite, silica, talc and microcline the element composition of SO_3 in barite form and gypsum, element composition of Fe_2O_3 in hematite and chromite forms and element composition CaO in calcite form.

The minerals of drilling mud after mixed with bentonite from America, Saraburi, Lopburi, and Kanchanaburi consist of quartz, kaolinite, calcite, gypsum, anorthite, choromite, silica, talc, microcline and barite. However, variation of mineral in drilling mud represents does not show in hematite of America bentonite.

From research study represent that the chemical property of drilling mud mixed with all of study materials is not effect from temperature, due to the variation of temperature is not change the structure and content of oxide compounds and minerals of drilling mud. However, the chemical compositions of drilling mud depend on amount of bentonite and barite.

Table 4.4 Minerals contents of drilling mud mixed with bentonite in each country using X-ray diffraction.

Sample No.	Temp. (ºC)	Bentonite from	Minerals (weight %)											
			Qua.	**Kao.**	**Hem.**	**Cal.**	**Gyp.**	**Anor.**	**Chor.**	**Si.**	**Tal.**	**Micr.**	**Bar.**	**Total**
1	30	America (Base)	10.47	5.86	-	0.27	0.35	7.63	0.12	0.01	16	5.91	53.38	100
2	60		10.11	5.03	-	0.12	0.49	6.23	0.26	0.16	17.56	5.16	54.88	100
3	90		11.052	4.64	-	0.2	0.453	6.396	0.34	0.13	19.93	4.59	52.269	100
4	30	Saraburi	23.61	5.46	0.25	0.81	0.46	0.83	0.15	0.32	10.93	5.53	51.65	100
5	60		25.29	5.279	0.154	0.64	0.71	0.72	0.14	0.22	11.09	4.93	50.827	100
6	90		23.11	5.48	0.302	0.74	0.73	0.893	0.209	0.227	12.52	5.03	50.759	100
7	30	Lopburi	14.51	4.25	1.19	5.21	0.81	2.72	0.25	0.01	17.27	5.05	48.73	100
8	60		15.55	3.87	0.99	6.67	1.08	1.91	0.118	0.09	15.461	4.11	50.151	100
9	90		15.769	5.072	0.93	5.45	0.92	2.057	0.307	0.14	16.29	3.65	49.415	100
10	30	Kanchana buri	15.09	3.53	0.04	0.78	0.46	8.59	0.2	0.12	6.52	6.07	58.6	100
11	60		16.63	3.82	0.18	0.815	0.7	9.164	0.11	0.28	7.147	5.507	55.647	100
12	90		17.067	3.36	0.3	0.89	0.66	7.23	0.13	0.32	8.453	5.25	56.34	100

*Qua. = Quartz, Kao. = Kaolinite, Hem. = Hematite, Cal. = Calcite, Gyp. = Gypsum, Anor. = Anorthite, Chor. = Choromite, Si. = Silica, Tal. = Talc, Micr. = Microcline and Bar. = Barite

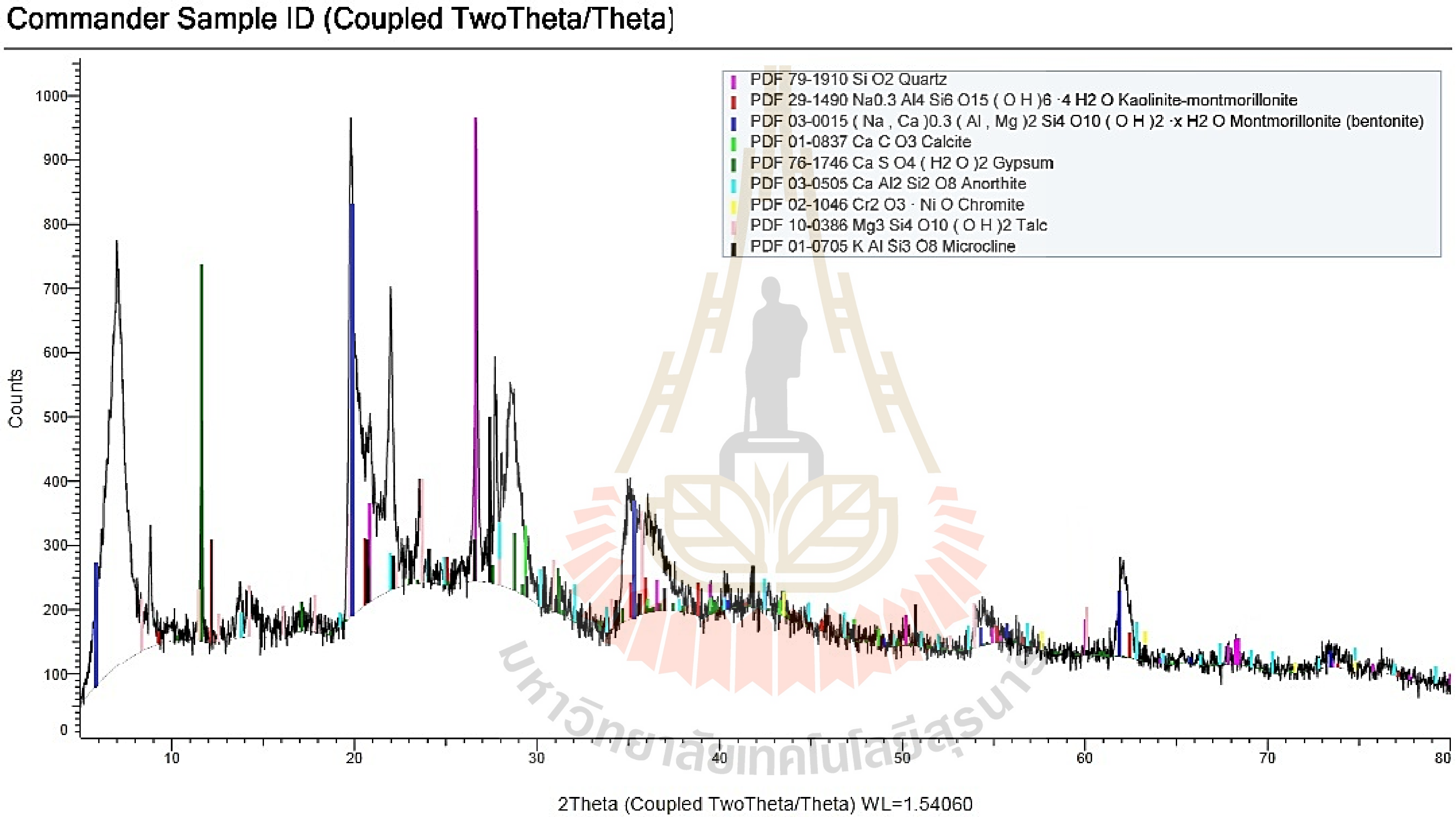

Figure 4.1 XRD of America bentonite.

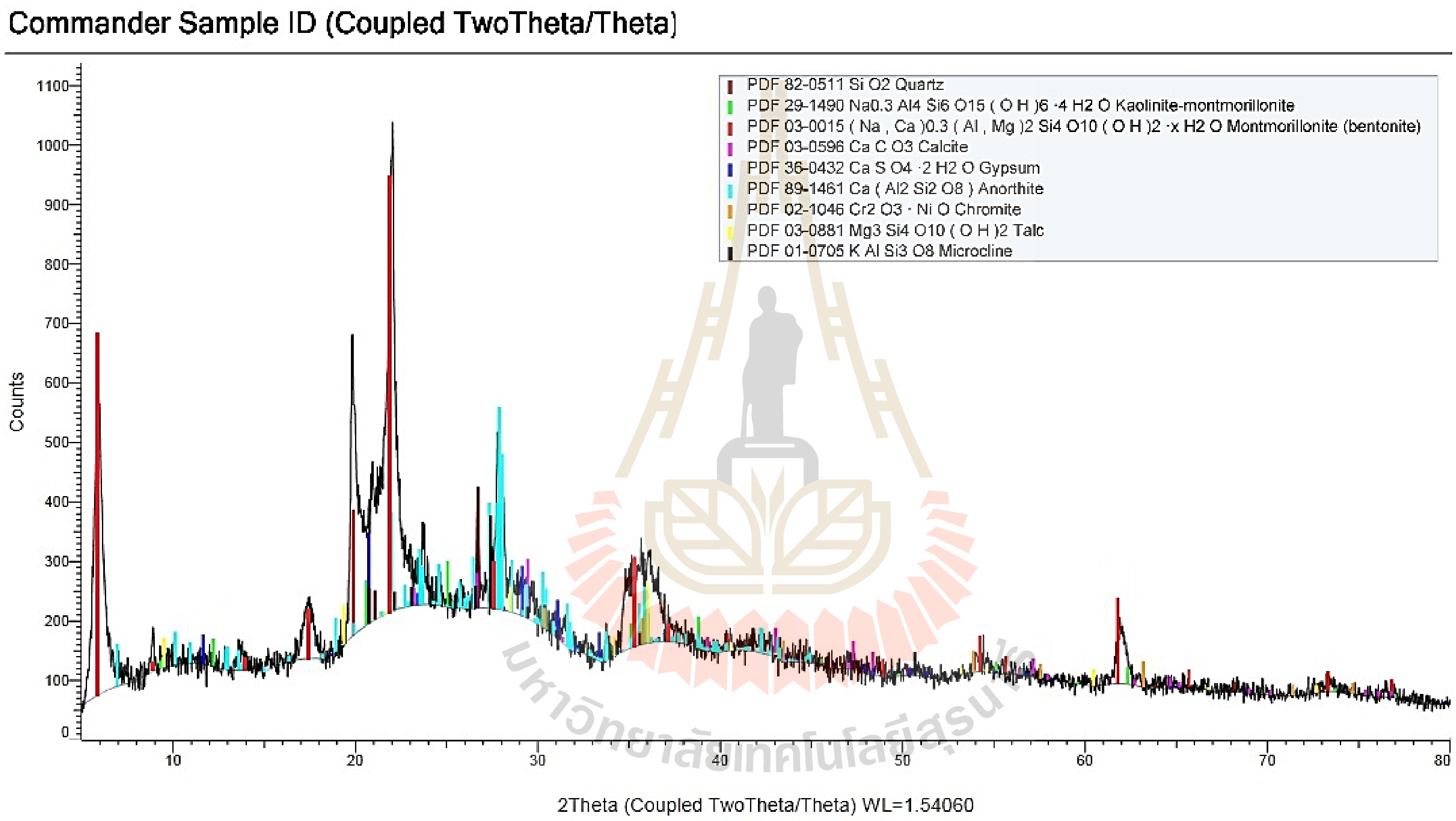

Figure 4.2 XRD of Saraburi bentonite.

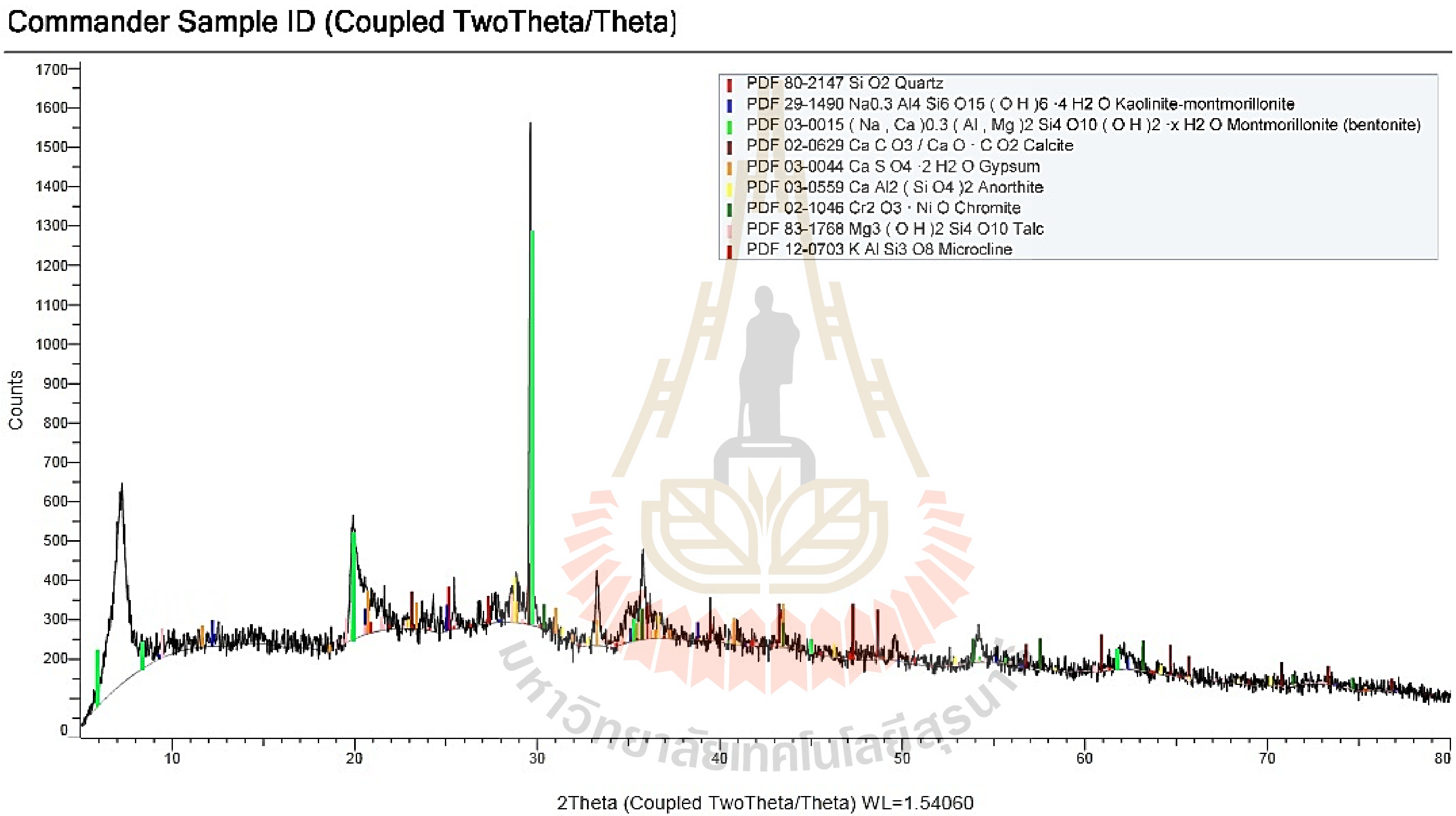

Figure 4.3 XRD of Lopburi bentonite.

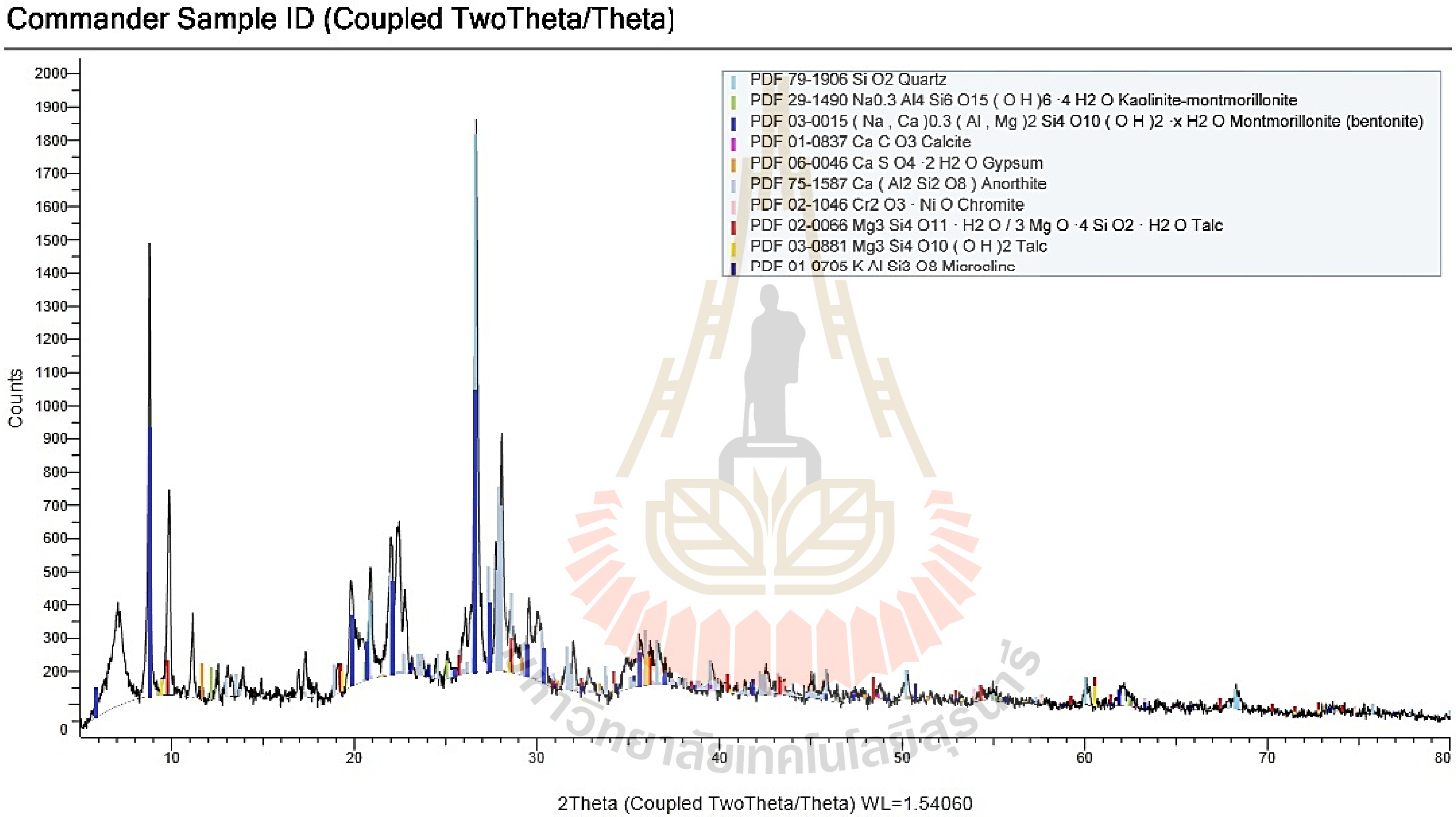

Figure 4.4 XRD of Kanchanaburi bentonite.

4.3 Physical property

The varied composition of drilling mud mixed with bentonite in each country are represented in Table 4.5 Base composition consists of 1,000 grams of water, 100 grams of barite and 60 grams of bentonite at temperature 30, 60 and 90°C.

Table 4.5 The compositions of drilling mud mixed with bentonite in each country.

Sample No.	Bentonite from	Temperature (°C)	Barite (gram)	Bentonite (gram)
1	America (Base)	30	100	60
2		60	100	60
3		90	100	60
4	Saraburi	30	100	60
5		60	100	60
6		90	100	60
7	Lopburi	30	100	60
8		60	100	60
9		90	100	60
10	Kanchanaburi	30	100	60
11		60	100	60
12		90	100	60

4.3.1 Rheological properties and parameters

The shear stress and shear rate calculated from the averages viscometer readings are following equations 3.4 and 3.5 in the previous chapter. Table 4.6 shows the values the shear stress and shear rate for all six viscometer readings of water-based drilling mud under temperature at 30°C. The calculated shear stresses were plotted against shear rates in order to choose the best-fit curve for the model. For example, Figure 4.5 shows the consistency plots for water-based drilling mud under temperature at 25°C, the Bingham plastic fluid plot curve was fitted with a linear correction and Figure 4.6 show the consistency plots for water-based drilling mud under temperature at 25°C, the Power Law fluid plot curve was fitted with a power correlation. From the two plots, the Bingham plastic fluids were better fitted with a linear correlation represented in Figure 4.5. Thus, the model can be inferred that the fluid tends to be a Bingham Plastic fluid.

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	41.50	1021.8	43.780
300	29.75	510.9	30.966
200	26.00	340.6	27.763
100	21.25	170.3	22.424
6	20.00	10.2	21.356
3	17.75	5.1	18.153

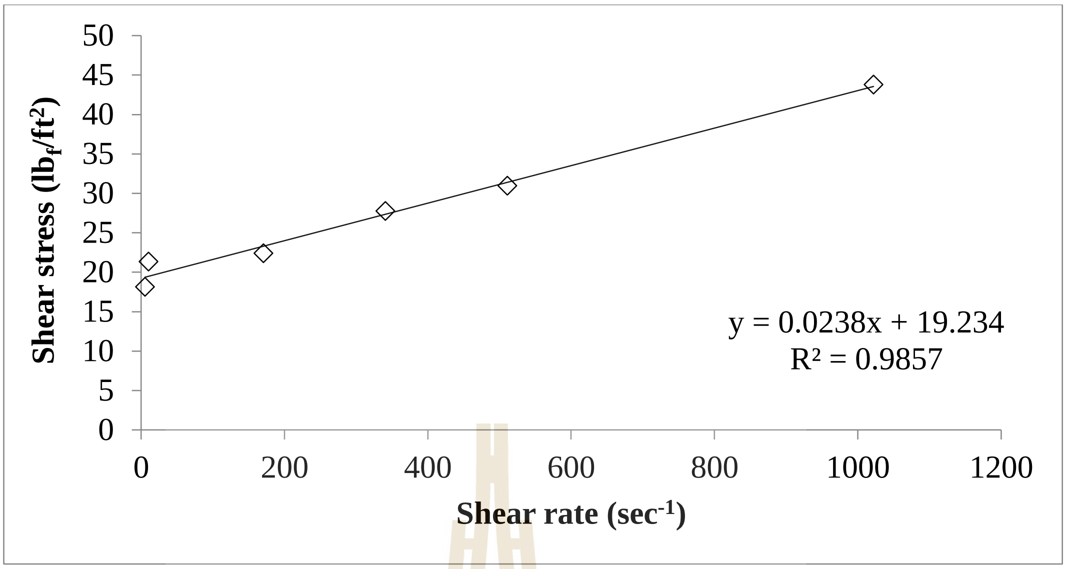

Figure 4.5 Consistency plot of water-based drilling mud with a linear correction.

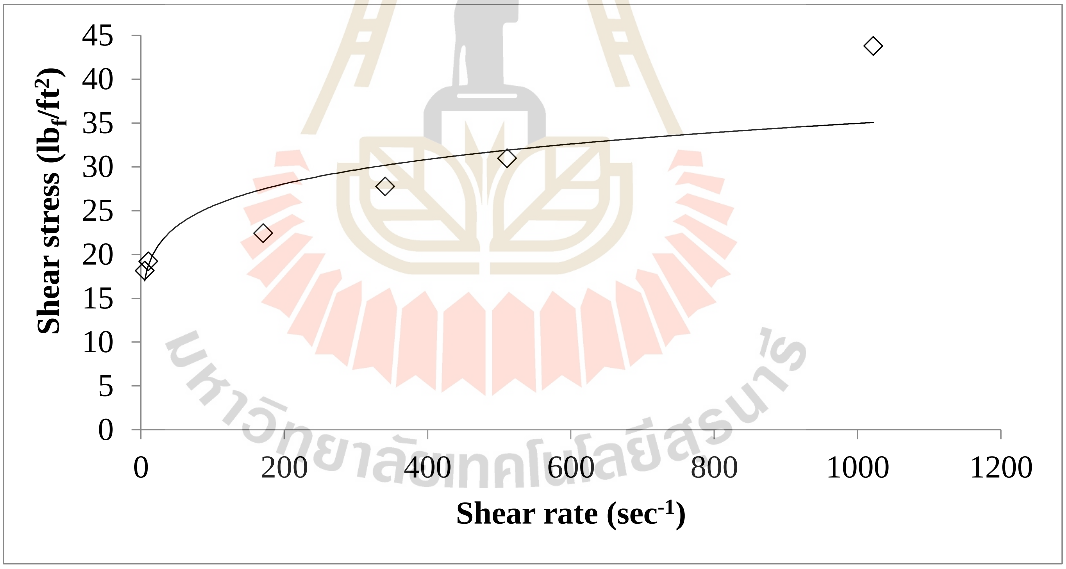

Figure 4.6 Consistency plot of water-based drilling mud with a power correction.

The appropriate rheological model for other drilling mud samples was calculated in likewise. The water based drilling mud samples were categorized into six groups of testes temperature (30, 60 and 90°C). Their consistency curves were plotted in Figure 4.7 to 4.10. Most of water based drilling mud sample demonstrates the flow behavior in between the Bingham Plastic model and the Power Law model. The rheological properties of each sample were calculated for both models. Both models were used for each fluid just for comparison purposes. The results of rheological calculation are shown in Table 4.7.

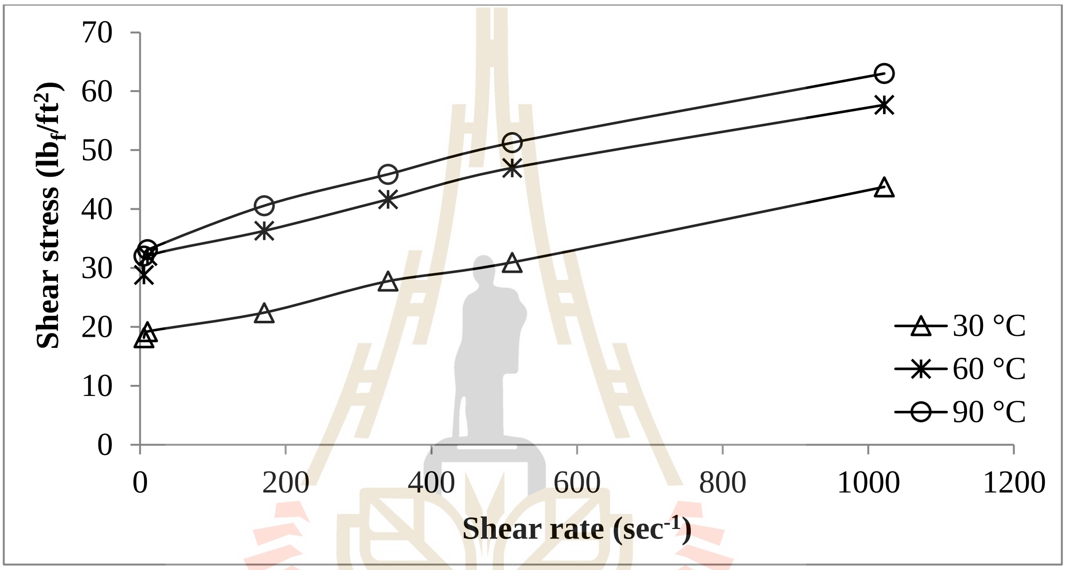

Figure 4.7 Consistency plot of drilling mixed with America bentonite (Base) at temperature 30, 60 and 90°C.

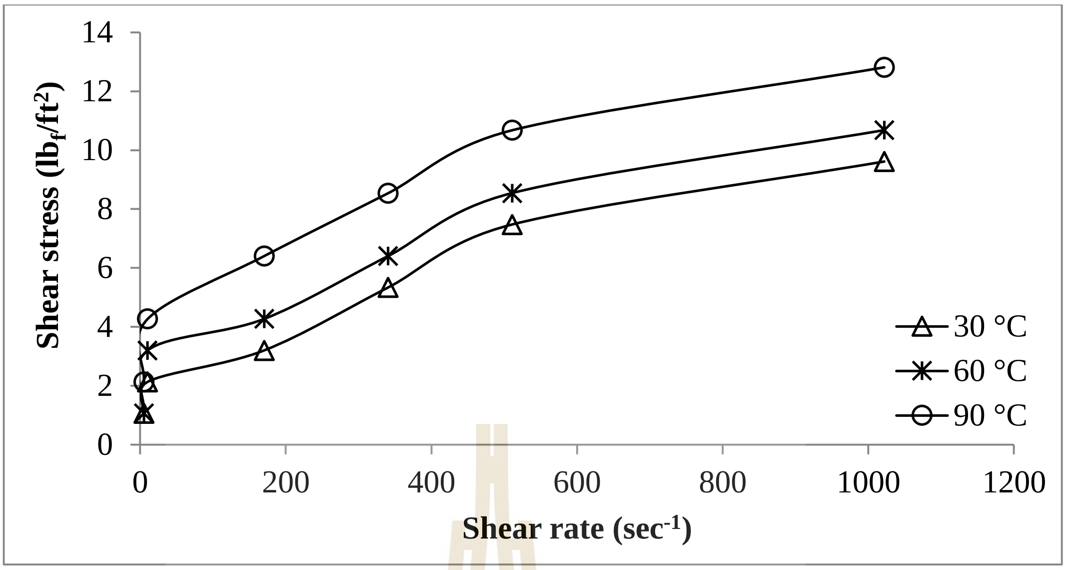

Figure 4.8 Consistency plot of drilling mixed with Saraburi bentonite at temperature 30, 60 and 90°C.

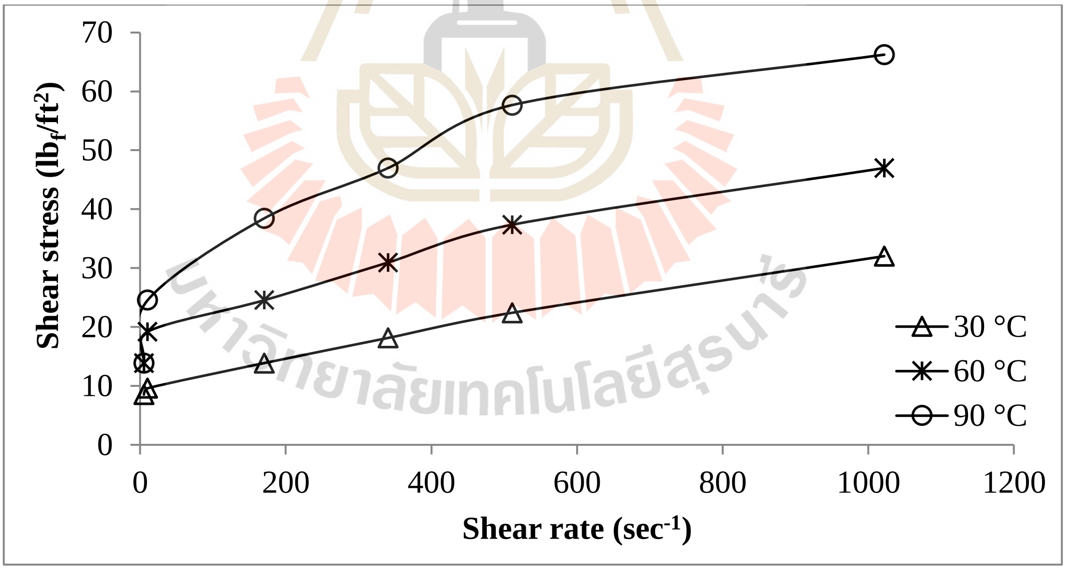

Figure 4.9 Consistency plot of drilling mixed with Lopburi bentonite at temperature 30, 60 and 90°C.

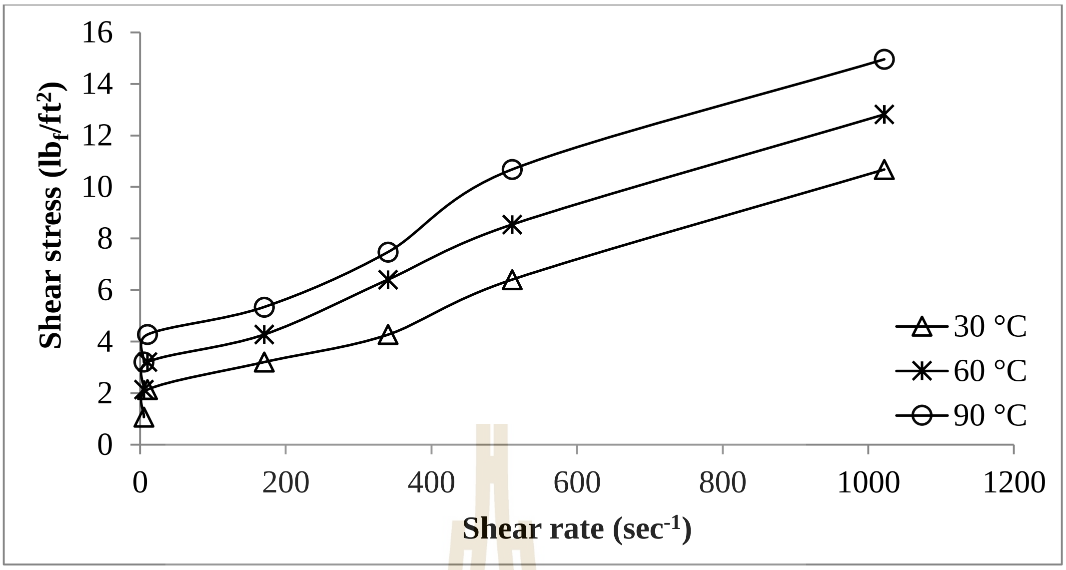

Figure 4.10 Consistency plot of drilling mixed with Kanchanaburi bentonite at temperature 30, 60 and 90^{o}C.

Table 4.7 Rheological parameters of drilling mud mixed with bentonite in each country.

Test 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	1	America (Base)	20.6	11.8	17.8	0.4996	1.6784	17	19
	4	Saraburi	4.8	2.5	4.5	0.3626	0.8851	1	2
	7	Lopburi	15.3	9.5	11.5	0.5146	1.1157	8	10
	10	Kanchanaburi	5.4	4.8	1.3	0.7370	0.0897	1	2
60	2	America (Base)	27.4	11.3	32.3	0.2955	8.1578	26	28
	5	Saraburi	5.4	2.0	6.8	0.3219	1.2754	2	3
	8	Lopburi	22.0	8.3	27.5	0.3301	5.3241	13	14
	11	Kanchanaburi	6.4	4.0	4.8	0.5850	0.2845	2	3
90	3	America (Base)	29.6	11.0	37.3	0.2977	8.7872	29	32
	6	Saraburi	6.0	2.0	8.0	0.2630	2.2307	4	5
	9	Lopburi	31.4	8.0	46.8	0.1993	17.3253	14	15
	12	Kanchanaburi	7.3	3.8	7.0	0.4854	0.6274	3	4

Gel_{in}** is initial gel strength and *Gel_{10}** is 10 minutes gel strength of drilling mud.

4.3.2 Rheological behavior of drilling mud

The rheological parameters of water-based drilling mud and drilling mud mixed with bentonite in each country samples are summarized in Table 4.7. The rheological data of total test are shown in Appendix A. The Power Law model parameters in the term of flow behavior index (n) and consistency (K) were calculated by equation 3.6 and 3.7 as showed in previous chapter. The index n indicated that all mud samples exhibited pseudoplastic flow with n less than 1. As mentioned above, the flow behavior of typical drilling mud usually acted between the Bingham Plastic and the Power Law model which was called pseudoplastic fluid. The consistency factors of mud sample clearly increased. The constant was analogous to the apparent viscosity of the fluid that described the thickness of the fluid. The power Law model did not describe the behavior or drilling fluids exactly but the constant n and K normally desirable in the interest of hydraulic horsepower utilization which was used in hydraulic calculations. (Baker Hughes, 2006).

Figure 4.11 through 4.15 are the plots of the rheological parameters obtained from the calculation drilling mud mixed with bentonite in each country.

The influence of temperature on the apparent viscosity is shown in Figure 4.11. It clearly sees that for all of drilling mud compositions, the apparent viscosity increase with increasing temperature. The consequence of temperature increase interaction energy of mud system (Luckham and Rossi, 1999). It induces more inter-particle attractive force between solid particlesand so the clay particles come into contact with another and agglomerate which is known as flocculation.

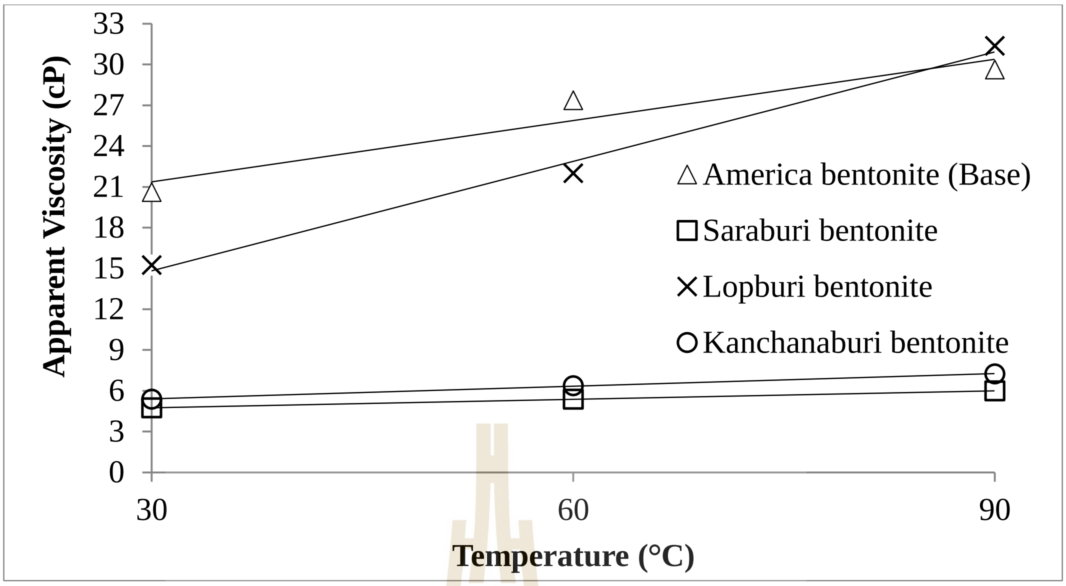

Figure 4.11 Apparent viscosity of drilling mud with bentonite in each country at temperature 30, 60 and 90^{o}C.

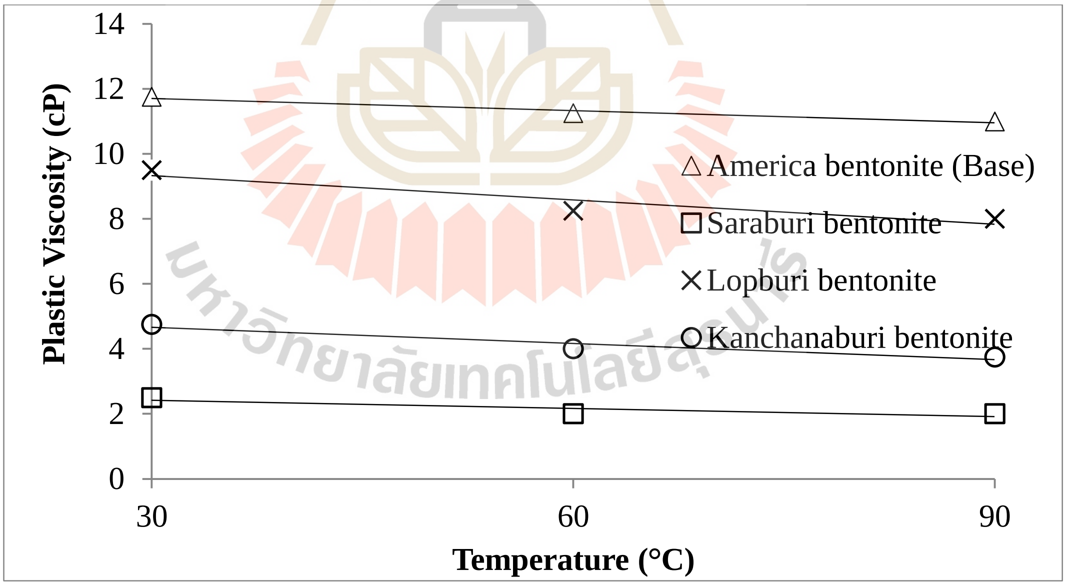

Figure 4.12 Plastic viscosity of drilling mud with bentonite in each country at temperature 30, 60 and 90^{o}C.

The yield point of drilling mud was plotted as function of drilling mud with bentonite in each country and temperature as showed in Figure 4.13. For all tested temperature, the result indicated that the yield stress clearly containing mud increasing. This is because large amount of solid in mud sample tend to agglomerate and result in increasing yield stress. The yield stress increased with elevated temperature. Rising of temperature increases interaction energy of clay system that leads bentonite suspension become thickened. From the experiment, it can be concluded that the presence of temperature increase yield strength of mud which enhance carrying capacity of drilling fluid while drilling circulation periods.

The initial and 10 minutes gel strength of drilling mud sample were investigated and their result was plotted as function of drilling mud with bentonite in each country and temperature as showed in Figure 4.14 through 4.15. The result showed insignificant improvement of gel strength with an increasing drilling mud with bentonite in each country and temperature. Considering drilling mud at 30 and 60^{o}C tested temperatures (Table 4.7), the 10 minutes gel strength was greater than initial gel strength. This is because of more undisturbed mud standing time would lead mud to form stronger gel structure compared to less undisturbed time. Considering drilling mud at 90^{o}C tested temperatures, the 10 minutes gel strength tended to became less than initial gel strength. The result indicated that the great temperature drop occurred while 10 minutes standing time period, which in turn, led to the lower of 10 minutes gel strength. This can be noted that gel strength is strongly influenced by time and temperature. From the experiment, it can be concluded that the presence of drilling mud increase gel strength of mud which enhance hole cleaning efficiency of drilling fluid by suspend cutting and weighting material when circulation is ceased.

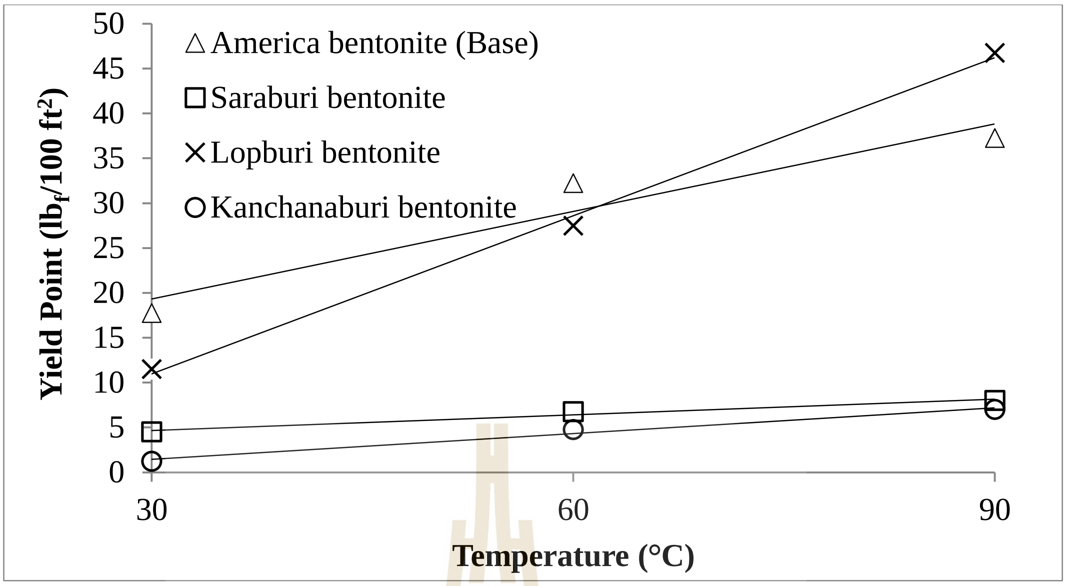

Figure 4.13 Yield point of drilling mud with bentonite in each country at temperature 30, 60 and 90°C.

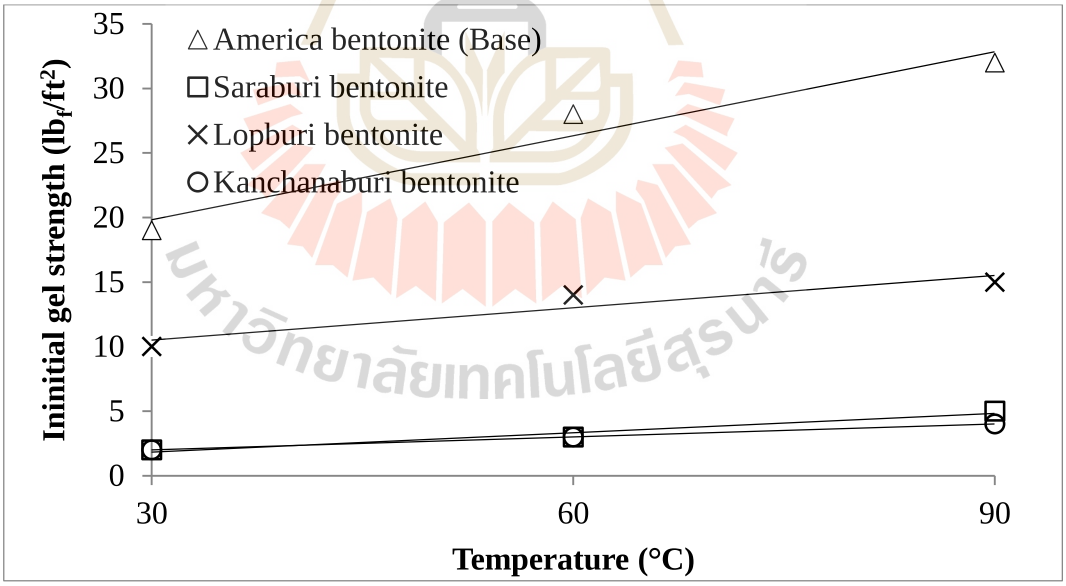

Figure 4.14 Initial gel strength of drilling mud with bentonite in each country at temperature 30, 60 and 90°C.

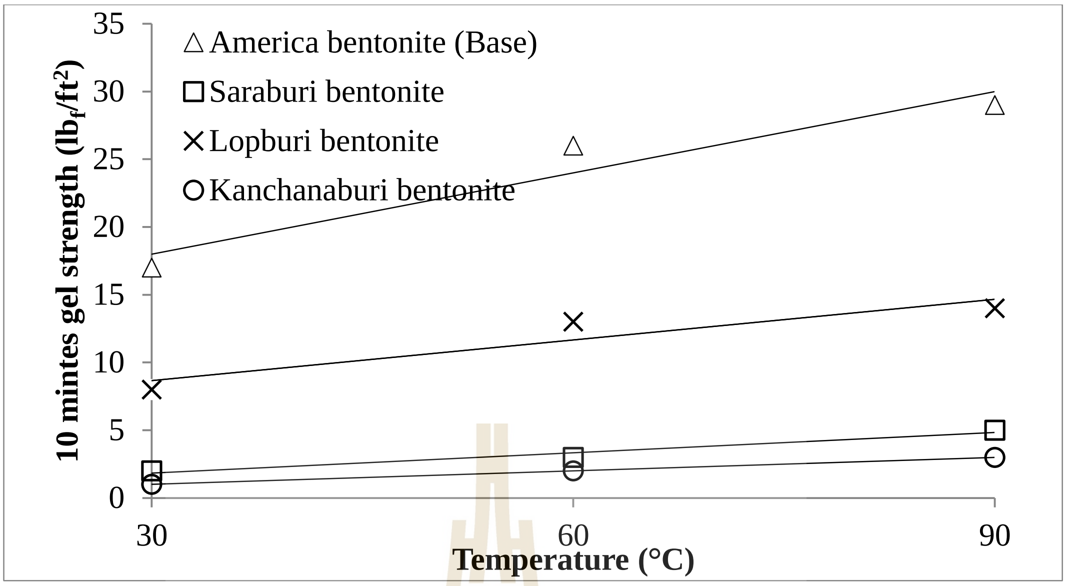

Figure 4.15 10 minutes gel strength of drilling mud with bentonite in each country at temperature 30, 60 and 90°C.

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 bentonite in each country. 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 4.16). The filtration properties of drilling mud mixed with bentonite in each country are shown in Figures 4.16 through 4.19.

These graphs show time-dependent filtration behavior of water-base drilling mud and indicate that the fluid loss exponentially increases as the time increase. The decreasing of filtrate volume is resulted from continuous mud cake deposition and compactions until the formation of a constant thickness and stable mud cakes have been formed completely.

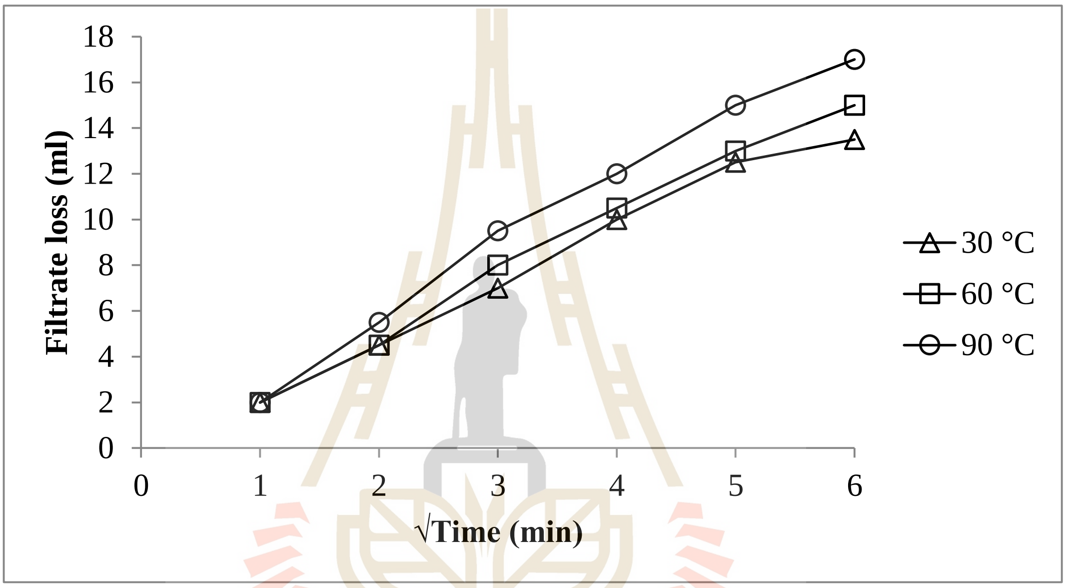

Figure 4.16 Static filtration and time of water-based drilling mud mixed with America bentonite (Base) at temperature 30, 60 and 90°C.

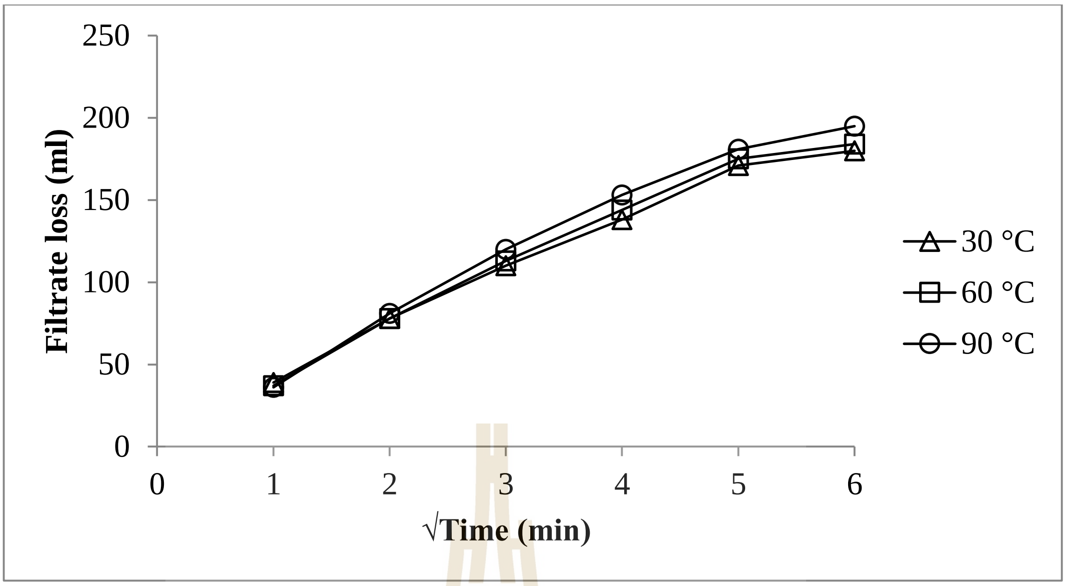

Figure 4.17 Static filtration and time of water-based drilling mud mixed with Saraburi bentonite at temperature 30, 60 and 90°C.

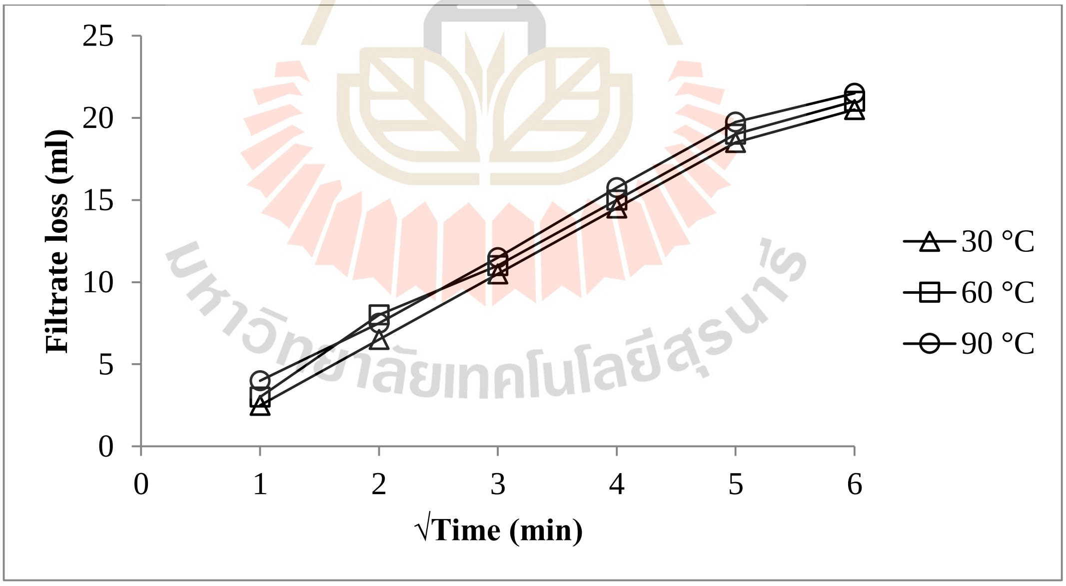

Figure 4.18 Static filtration and time of water-based drilling mud mixed with Lopburi bentonite at temperature 30, 60 and 90°C.

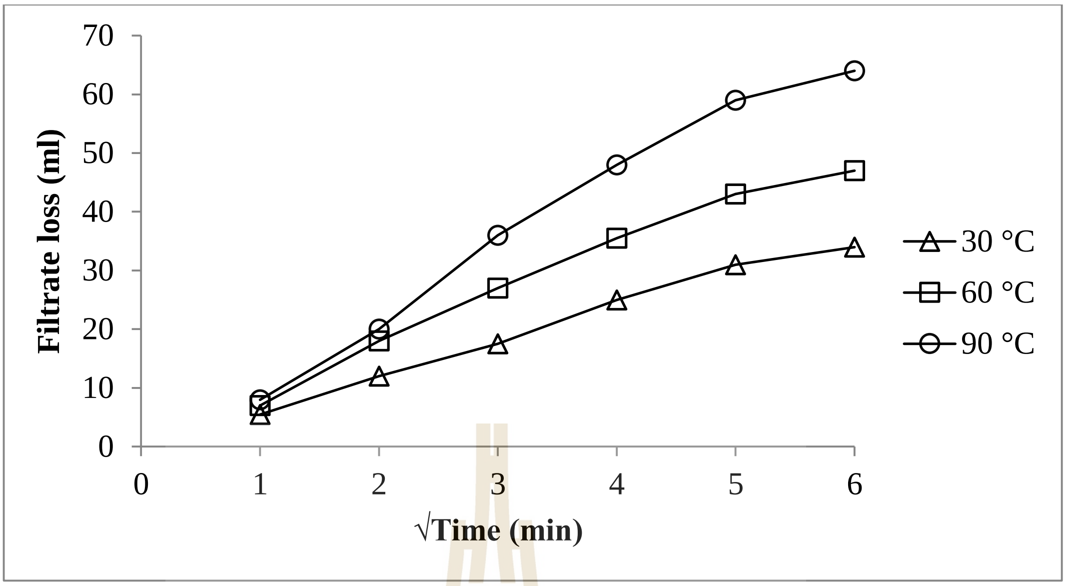

Figure 4.19 Static filtration and time of drilling mud mixed with Kanchanaburi bentonite at temperature 30, 60 and 90°C.

The mud filtrate analytical from drilling mud shows the filtrate loss in drilling mud according to API standard. When the temperature up to 90°C. The filtrate loss in drilling mud from each source were increasing as the temperature. The result of the experiment is found the filtrate loss in drilling mud mixed America bentonite (Base) was lowest. The filtrate loss of Lopburi bentonite is close to based drilling mud, but the bentonite of Kanchanaburi and Saraburi are higher than base, which Saraburi bentonite mixed in drilling mud had the highest filtrate loss (Figure 4.20).

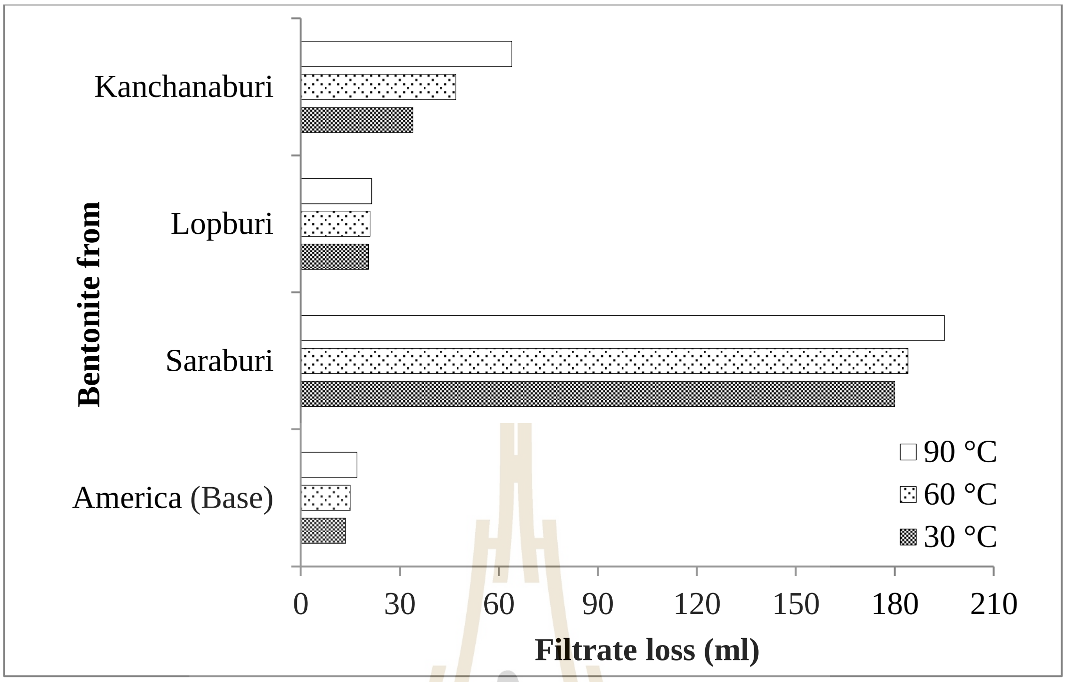

Figure 4.20 API filtrate loss at 30 minutes of drilling mud mixed with bentonite in each country at temperature 30, 60 and 90°C.

Mud Cake had the direct correlation with drilling fluid filtration loss. Then the temperature had effect of filtration. The fluid has the lowest viscosity and settling, which effect occurring mud cake was increasing. The thin layer mud cake is reduced drilling string stack, and the resistant between drilling string and formation.

Result of thickness of mud cake is shown in Figure 4.21, representing that the mud cake thickness of drilling mud mixed with each bentonite is increase as the temperature increasing. The mud cake of drilling mud mixed with America bentonite is a thin layer of mud cake that value ranges from 1.96 to 2.56 mm. The mud cake of drilling mud mixed with Lopburi bentonite ranges from 2.3 to 2.72 mm., drilling mud mixed with Kanchanaburi bentonite ranges from 2.96 to 3.28 mm., and drilling mud mixed with Saraburi bentonite is a thick layer of mud cake ranges from 5.1 to 6.21 mm, respectively.

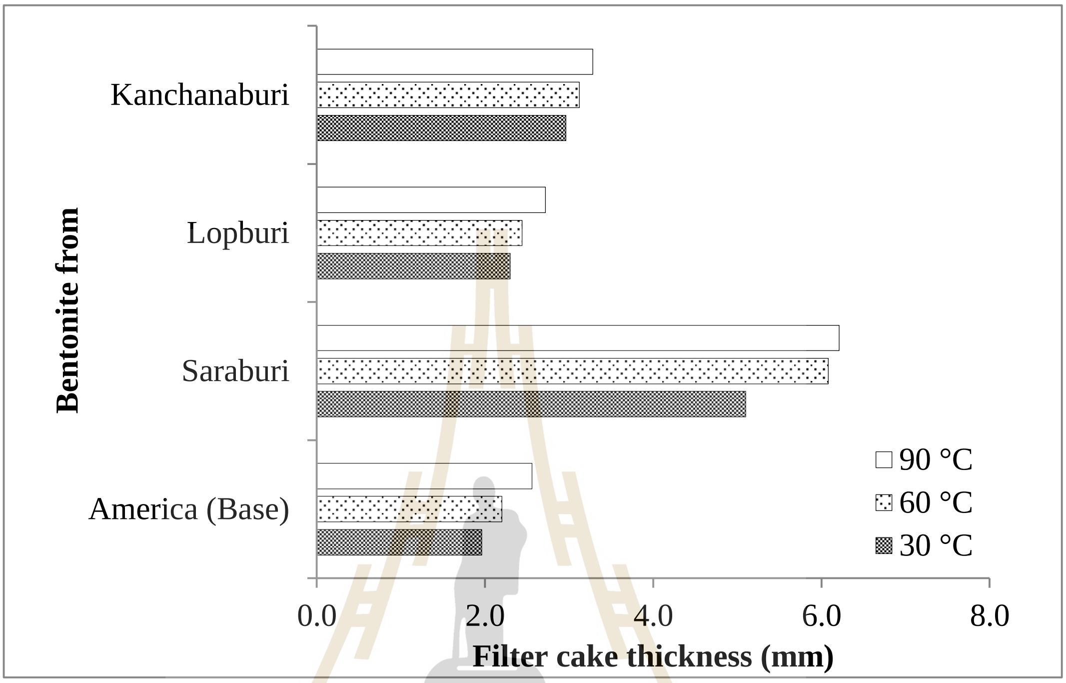

Figure 4.21 Mud filter cake thickness drilling mud mixed with bentonite in each country at temperature 30, 60 and 90°C.

4.3.4 Density of drilling mud

Hydrostatic pressure is the pressure for protect the formation from cave, hole and formation fluid through into drilling well. The drilling mud density is enhanced for a control the pressure in the well, which it has the density ranges from 1.06 to 2.16 g/cm^3 or 8.85 to 18 lb/gal (MI-Swaco, 1998).

Density of drilling mud mixed with each bentonite is shown in Figure 4.22. The density was decreasing when the temperature was increasing. The density of drilling mud mixed with Saraburi bentonite has a low density ranges from 1.06 to 1.067

g/cm^3. The density of drilling mud mixed with Kanchanaburi bentonite ranges from 1.07 to 1.075 g/cm^3. The density of drilling mud mixed with Lopburi bentonite ranges from 1.092 to 1.098 g/cm^3, and the drilling mud mixed with America bentonite is the highest density ranging from 1.095 to 1.1 g/cm^3.

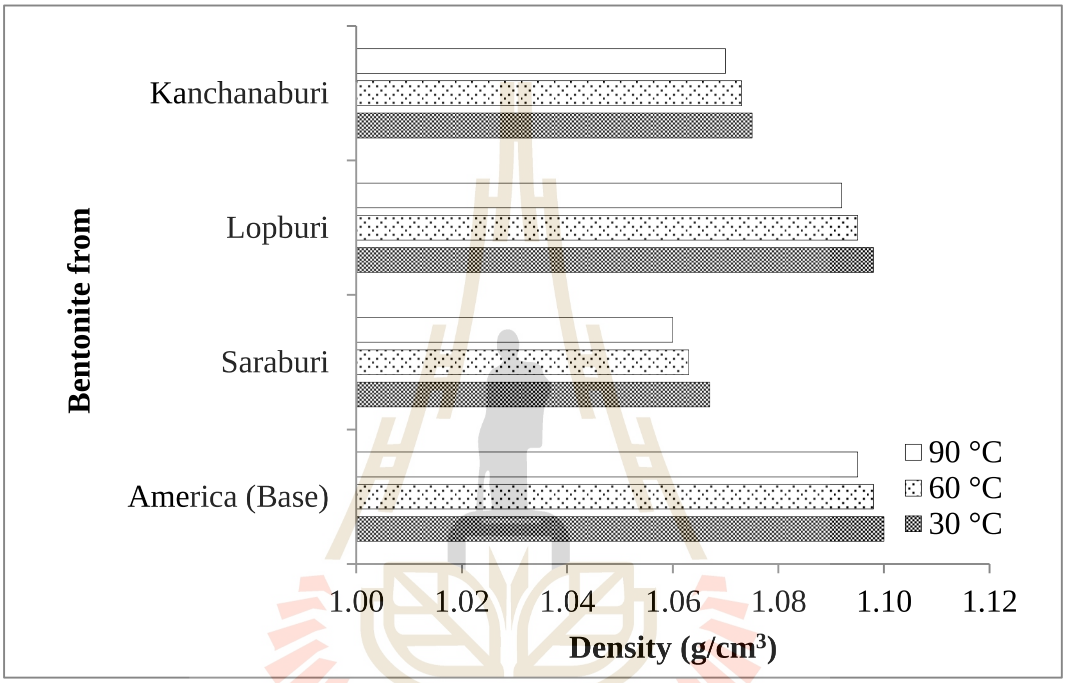

Figure 4.22 Density of drilling mud mixed with bentonite in each country at temperature 30, 60 and 90^{o}C

4.3.5 pH of drilling mud

Figure 4.23 through 4.25 summarize the test results on the pH of drilling mud before and after mixing bentonite in each country at 30, 60 and 90^{o}C. They describe the pH of mud and mud filtrates for filtration test. Total data testing pH of drilling mud mixed with bentonite in each country are displayed in Appendix A.

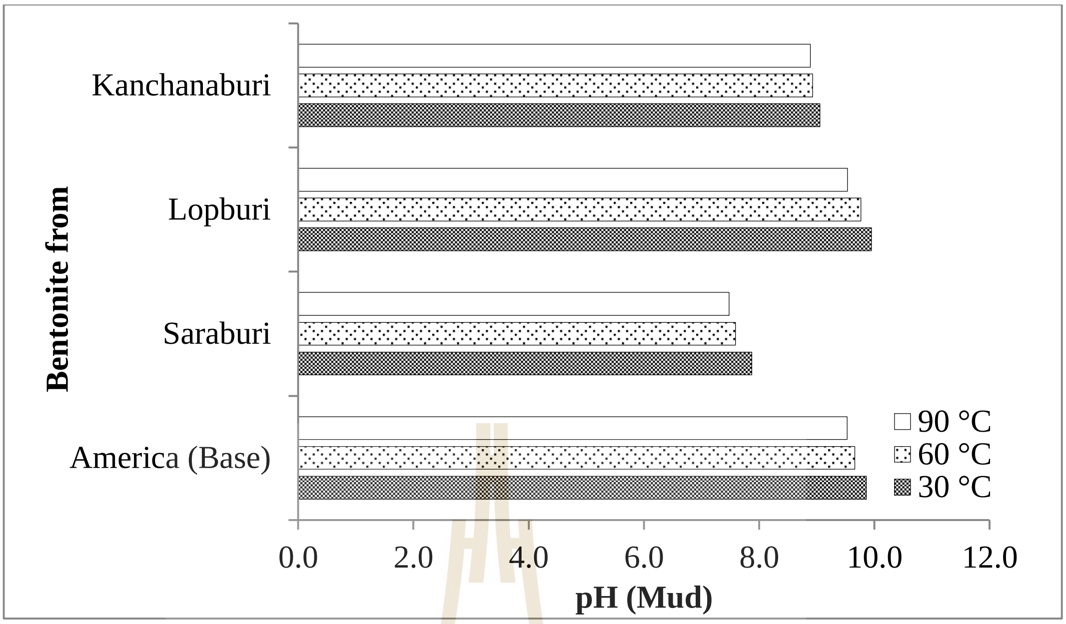

Figure 4.23 pH of water-based drilling mud with bentonite in each country at temperature 30, 60 and 90°C.

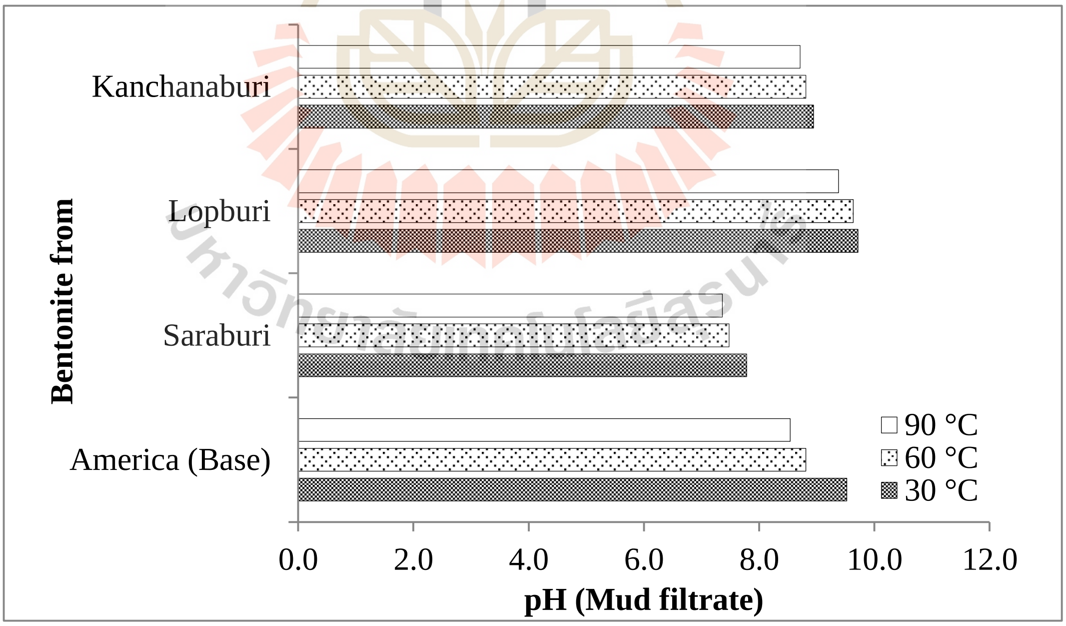

Figure 4.24 pH of mud filtrate drilling mud with bentonite in each country at temperature 30, 60 and 90°C.

Figure 4.23 and 4.24 showed the pH value of drilling mud mixed with each bentonite and mud filtrate, representing the pH decrease when the increasing of temperature. Result of the pH value of drilling mud mixed with Saraburi bentonite was the lowest pH value ranges from 48 to 7.80. The pH value of drilling mud mixed with America bentonite ranges from 8.67 to 8.86, drilling mud mixed with Kanchanaburi bentonite was pH value ranges from 8.89 to 9.03, and drilling mud mixed with Lopburi bentonite is the highest pH value ranging from 9.53 to 9.95 (Figure 4.23).

The pH of mud filtration on drilling mud mixed with Saraburi bentonite was the lowest pH value ranges from 7.36 to 7.78. The pH of mud filtrate on drilling mud mixed with America bentonite ranges from 8.54 to 8.77, the mud filtrate on drilling mud mixed with Kanchanaburi bentonite pH value ranges from 8.79 to 8.94, and mud filtrate on drilling mud mixed with Lopburi bentonite is the highest pH ranging from 9.38 to 9.72 (Figure 4.24).

Figure 4.25 showed that the pH of the filtrate of filtration test is more than the pH value of drilling mud. Both pH value of drilling mud and mud filtrate decrease as increasing of temperature.

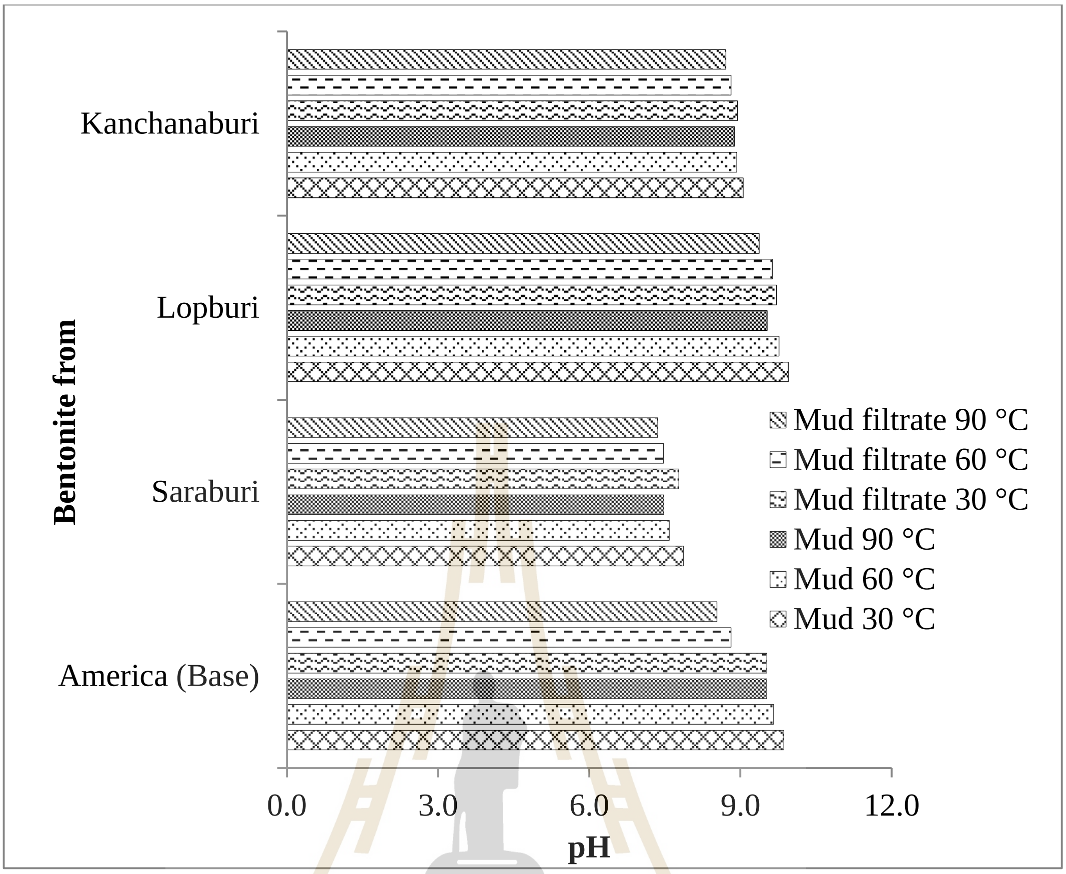

Figure 4.25 pH mud and mud filtrate of drilling mud with bentonite in each country at temperature 30, 60 and 90ºC.

4.3.6 Solid content in drilling mud

Solids usually classifies 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 result of solid content are illustrated in Figure 4.26 representing the solid content increased as the increasing temperature. The solid content of drilling mud mixed with America bentonite is the lowest value, ranging from 6 to 9%. Drilling mud mixed with Kanchanaburi bentonite has solid content ranges from 8 to 9%, Saraburi bentonite ranges from 2 to 4%, and Lopburi bentonite ranges from 7 to 9%, respectively.

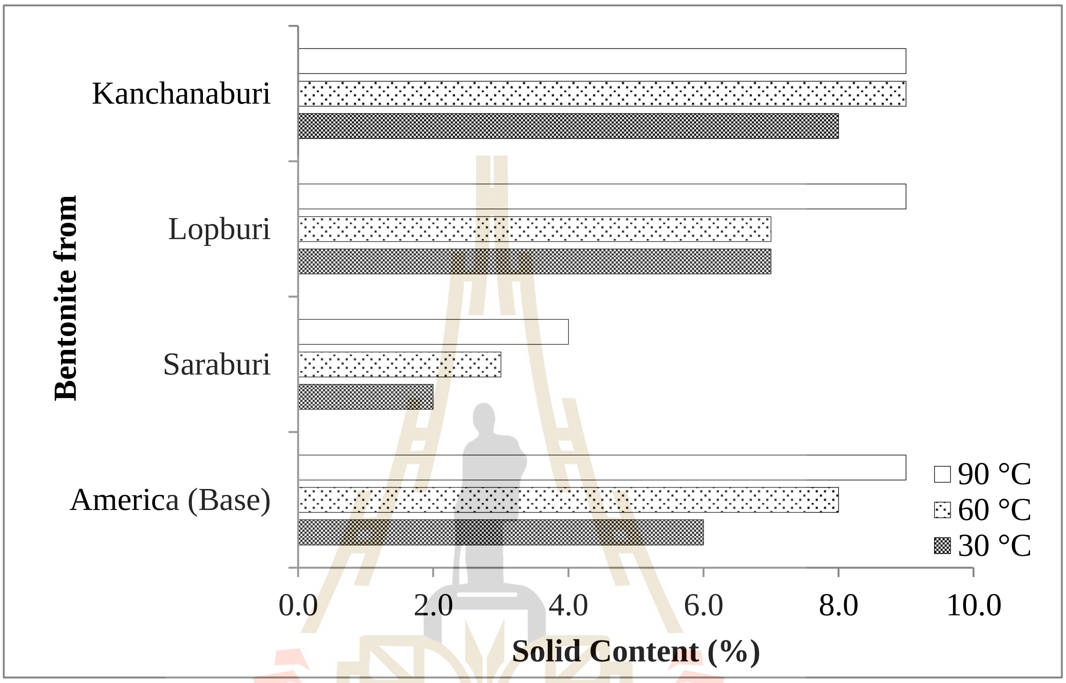

Figure 4.26 Solid content of drilling mud mixed with bentonite in each country at temperature 30, 60 and 90°C.

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%. The Sand content must be more than 0.075 millimeters or 200-mesh.

The sand content result of drilling mud mixed with each bentonite is illustrated in Figure 4.27, representing the sand content increase when the temperature was increased. The sand content of drilling mud mixed with Lopburi bentonite ranges from 0.2 to 0.3 %, America bentonite ranges from 0.25 to 0.26 %, Saraburi bentonite ranges from 0.5 to 0.6 %, Kanchanaburi bentonite ranges from 0.5 to 0.58 %, respectively.

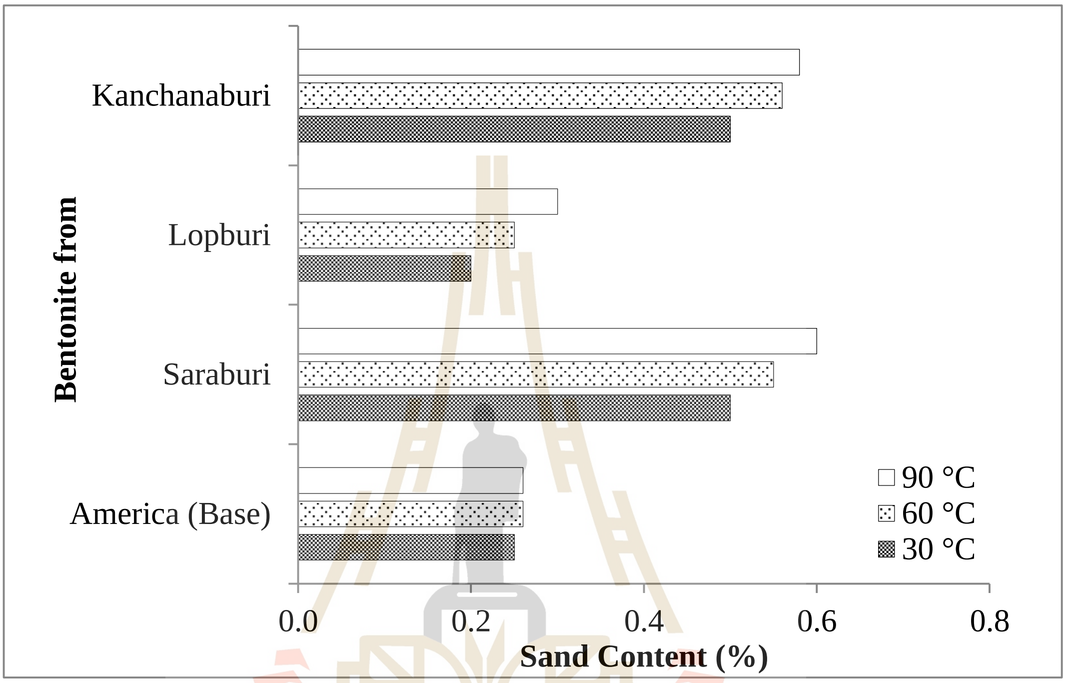

Figure 4.27 Sand content of drilling mud mixed with bentonite in each country at temperature 30, 60 and 90°C.

4.3.8 Resistivity of drilling mud

The results of resistivity drilling mud and mud filtrate are shown in the Figure 4.28 though 4.34. Drilling mud mixed with bentonite in each country, mud filtrate and mud cake were decreased resistivity when the temperature was increased. The resistivity on drilling mud was more than mud filter and mud cake, respectively.

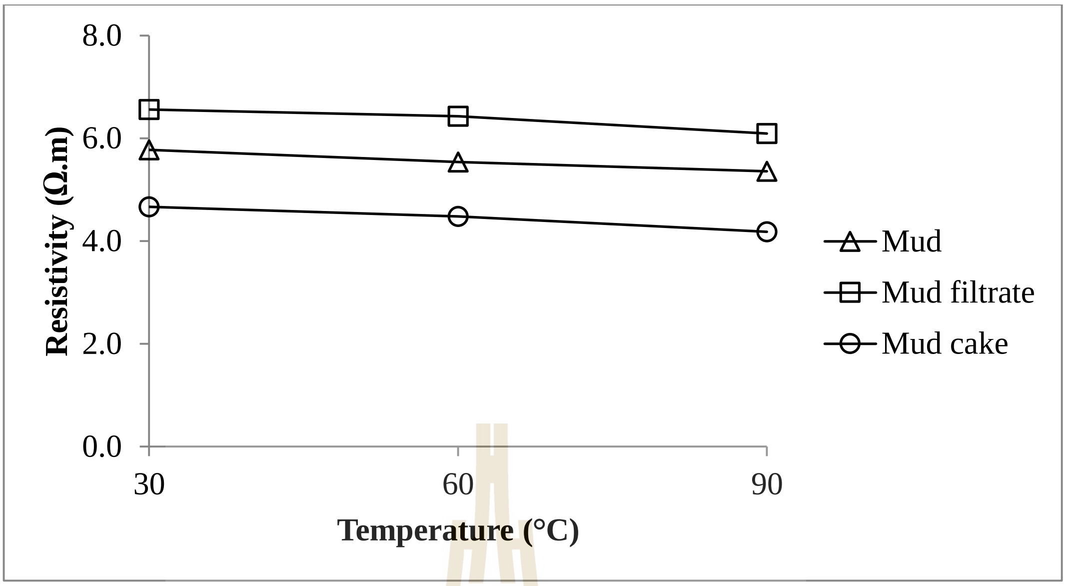

Figure 4.28 Resistivity of drilling mud mixed with America bentonite (Base) at temperature 30, 60 and 90°C.

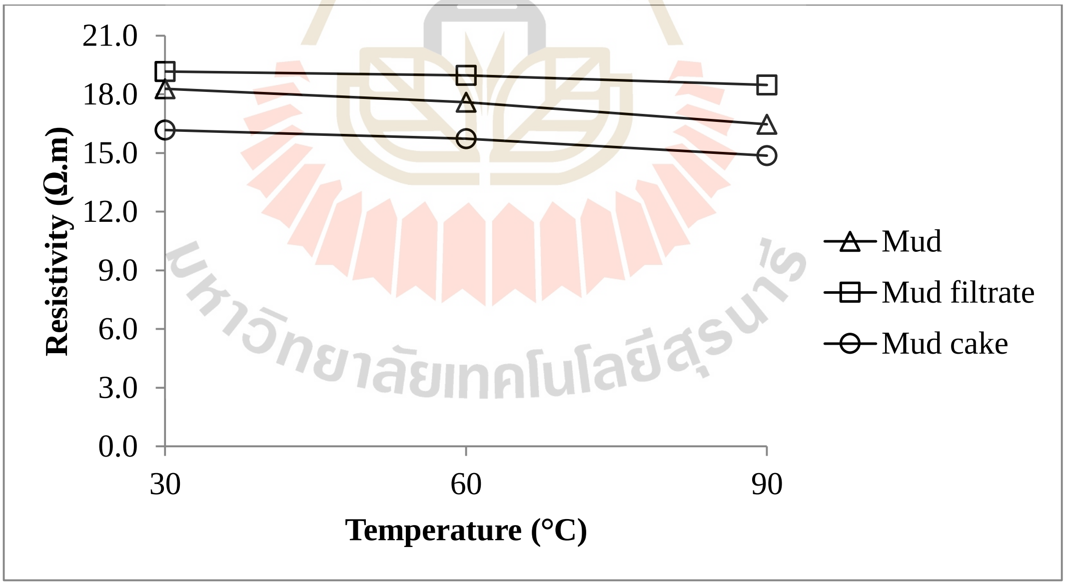

Figure 4.29 Resistivity of drilling mud mixed with Saraburi bentonite at temperature 30, 60 and 90°C.

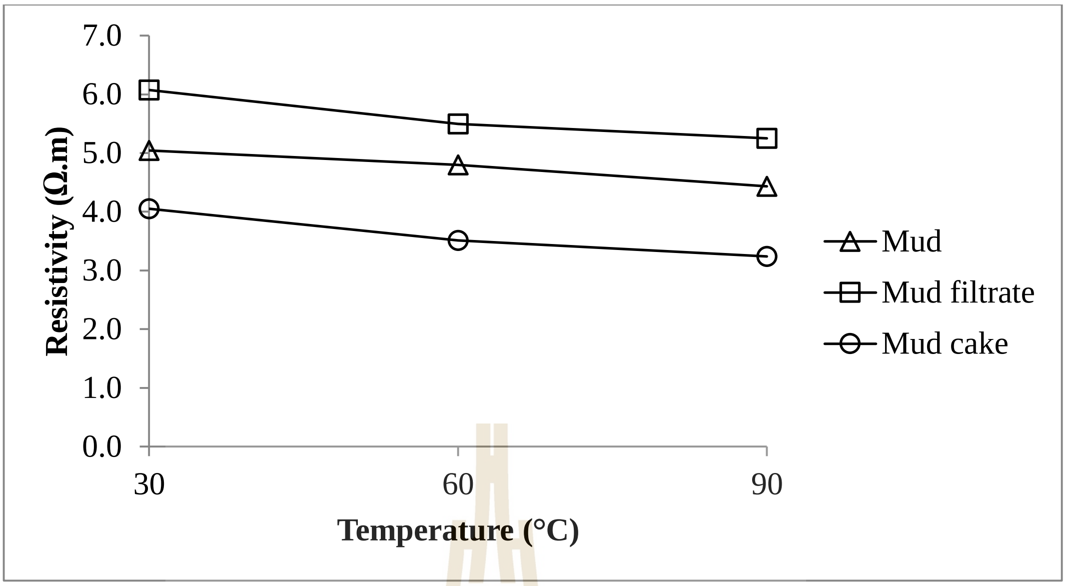

Figure 4.30 Resistivity of drilling mud mixed with Lopburi bentonite at temperature 30, 60 and 90°C.

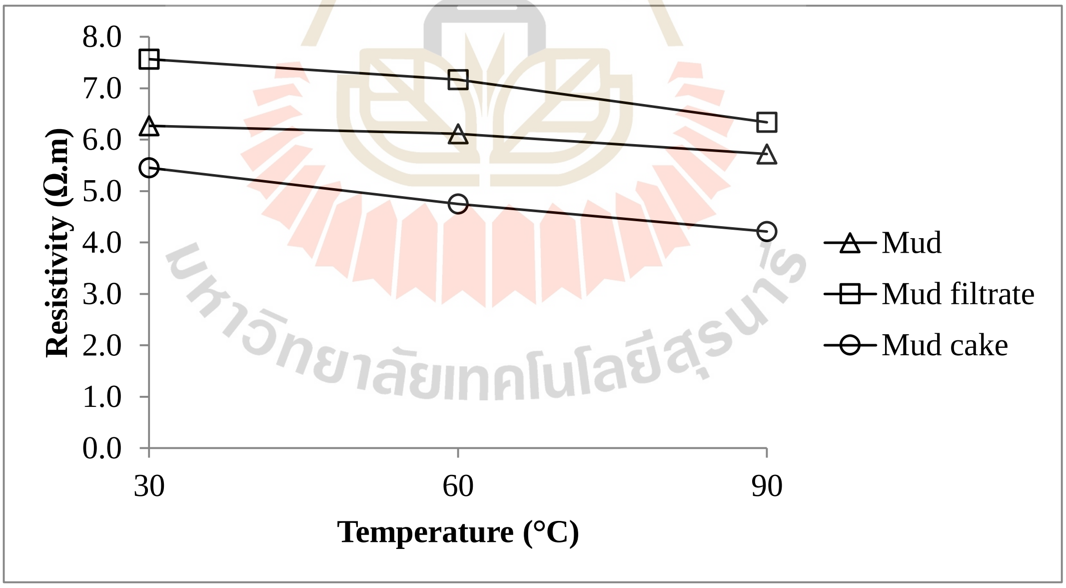

Figure 4.31 Resistivity of drilling mud mixed with Kanchanaburi bentonite at temperature 30, 60 and 90°C.

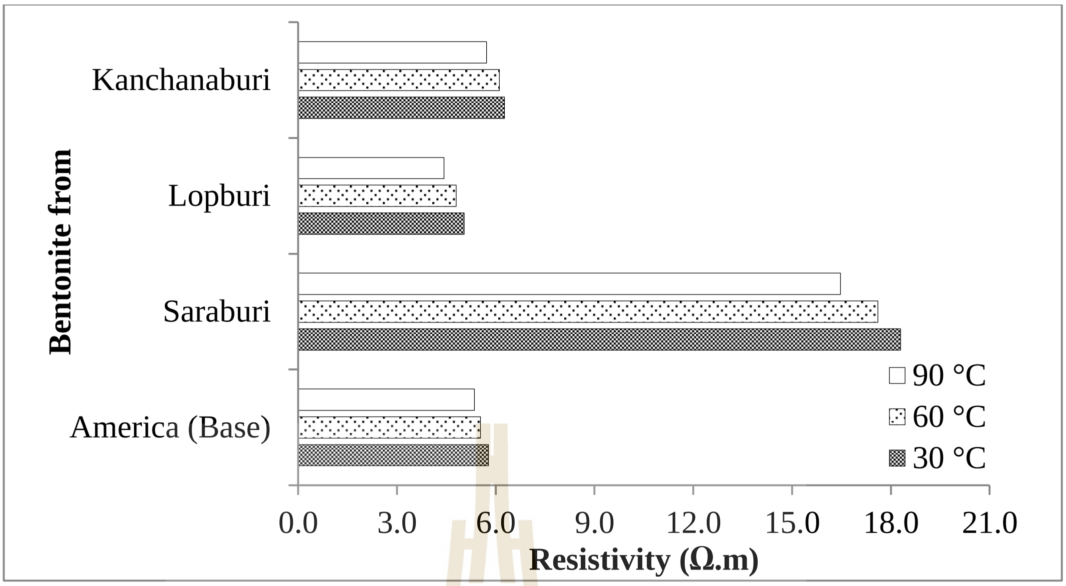

Figure 4.32 Resistivity of drilling mud mixed with bentonite in each country at temperature 30, 60 and 90°C.

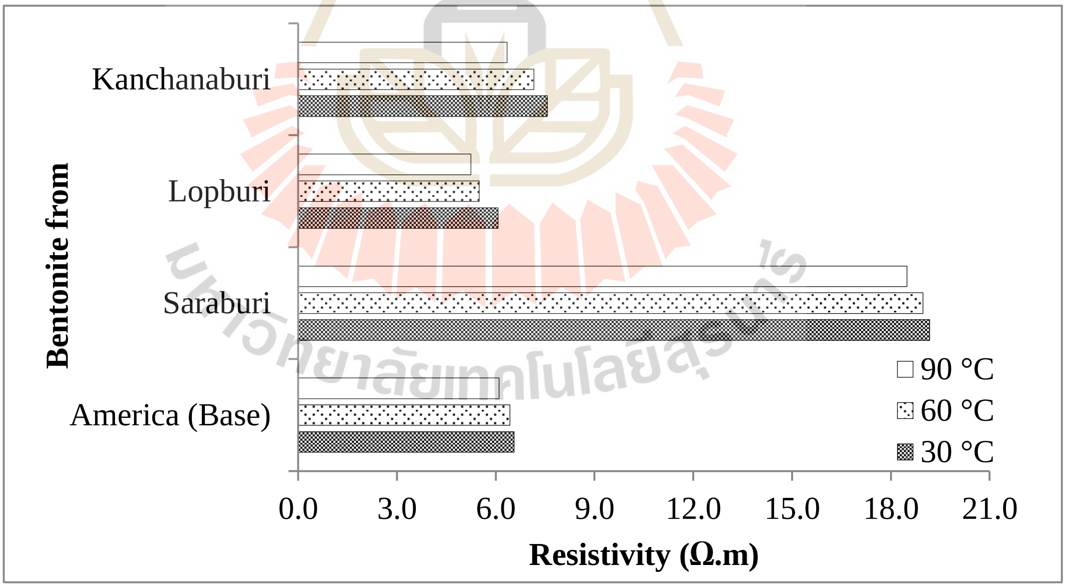

Figure 4.33 Resistivity of drilling mud filtrate mixed with bentonite in each country at temperature 30, 60 and 90°C.

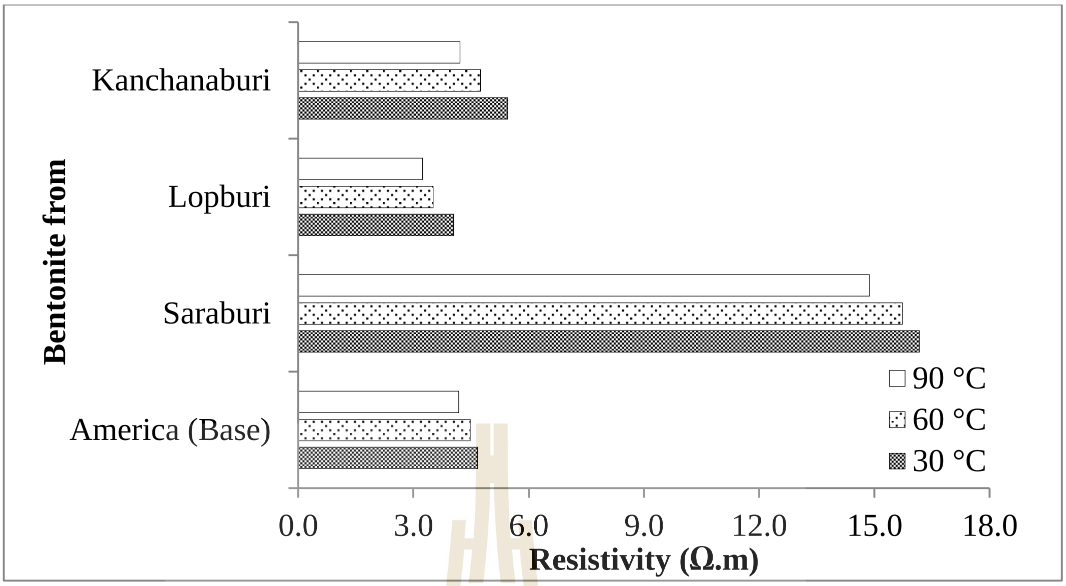

Figure 4.34 Resistivity of drilling mud cake mixed with bentonite in each country at temperature 30, 60 and 90^{o}C.

Figure 4.35 shows that the resistivity on the drilling mud reduced when the temperature was increased. The resistivity of drilling mud mixed with Lopburi bentonite is the lowest as between 4.43 to 5.04 Ω.m. The drilling mud mixed with America bentonite had a resistivity between 5.36 to 5.78 Ω.m, Kanchaburi bentonite ranges from 5.72 to 6.27 Ω.m, and Saraburi bentonite ranges from 16.47 to 18.29 Ω.m, which is the highest value.

The resistivity of mud filtrate from drilling mud mixed with Lopburi bentonite is the lowest value ranging from 5.25 to 6.07 Ω.m, America bentonite ranges from 6.1 to 6.56 Ω.m, Kanchaburi bentonite ranges from 6.34 to 7.56 Ω.m, and Saraburi bentonite ranges from 18.49 to 19.18 Ω.m, which is the highest value.

The resistivity of mud cake from drilling mud mixed with Lopburi bentonite is lowest ranging from 3.24 to 4.05 Ω.m, America bentonite ranges from 4.18

to 4.67 Ω.m, Kanchanaburi bentonite ranges from 4.21 to 5.45 Ω.m, and Saraburi bentonite is the highest ranging from 14.87 to 16.17 Ω.m respectively.

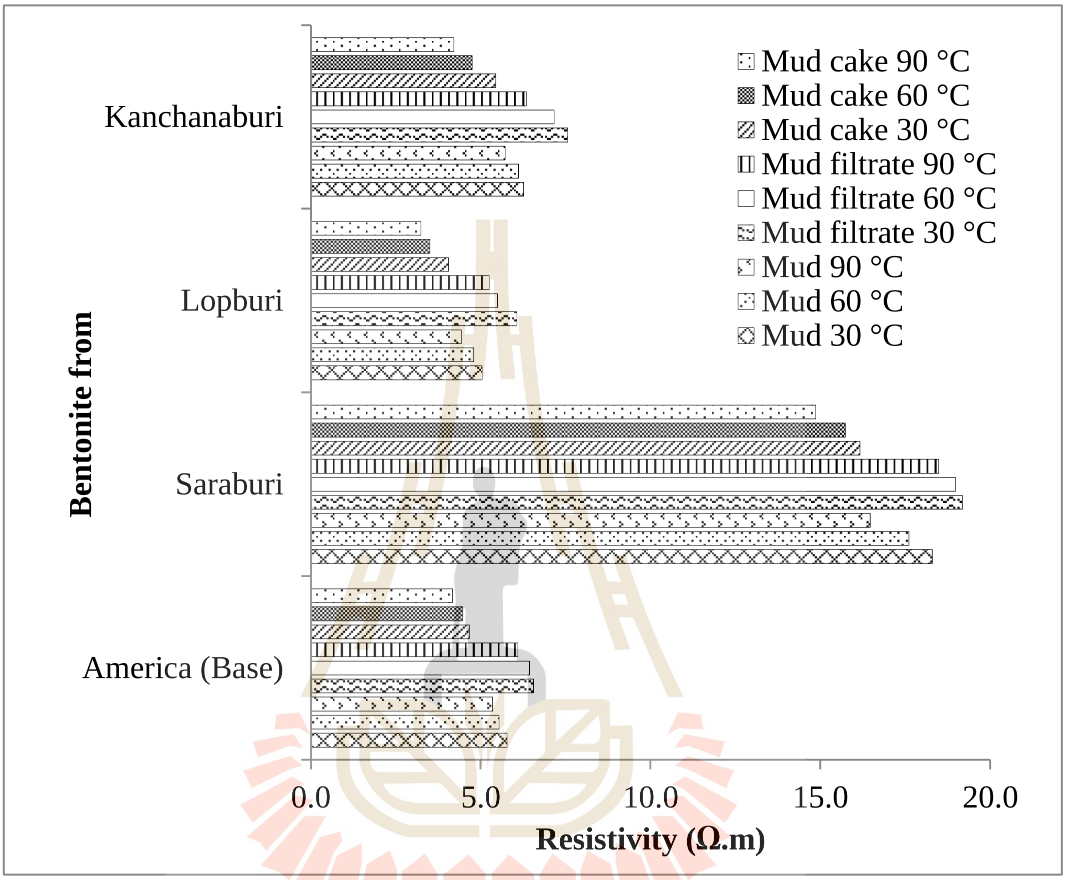

Figure 4.35 Resistivity on mud cake, mud filtrate and drilling mud mixed with bentonite in each country at the temperature 30, 60 and 90^{o}C.

4.3.9 Scanning Electron Microscope (SEM)

Morphology and texture of materials are analyzed by JEOL (model JSM-6010LV) to determine the value of the energy used in photography, which use the system at 20 kV and a vacuum (High Vacuum Mode). The result came as a magnification set, and analyze the texture of each bentonite source both before and after mixed drilling mud as following:

4.3.9.1 SEM of barite and each bentonite

Figures 4.36 to 4.40 show the surface mud filter cake of the base mud shows uneven, thin sheet of bentonite clay larger and smaller particles of barite with the compactness of individual grains and remains of the grains of the material is even though heating at 60 and 90°C.

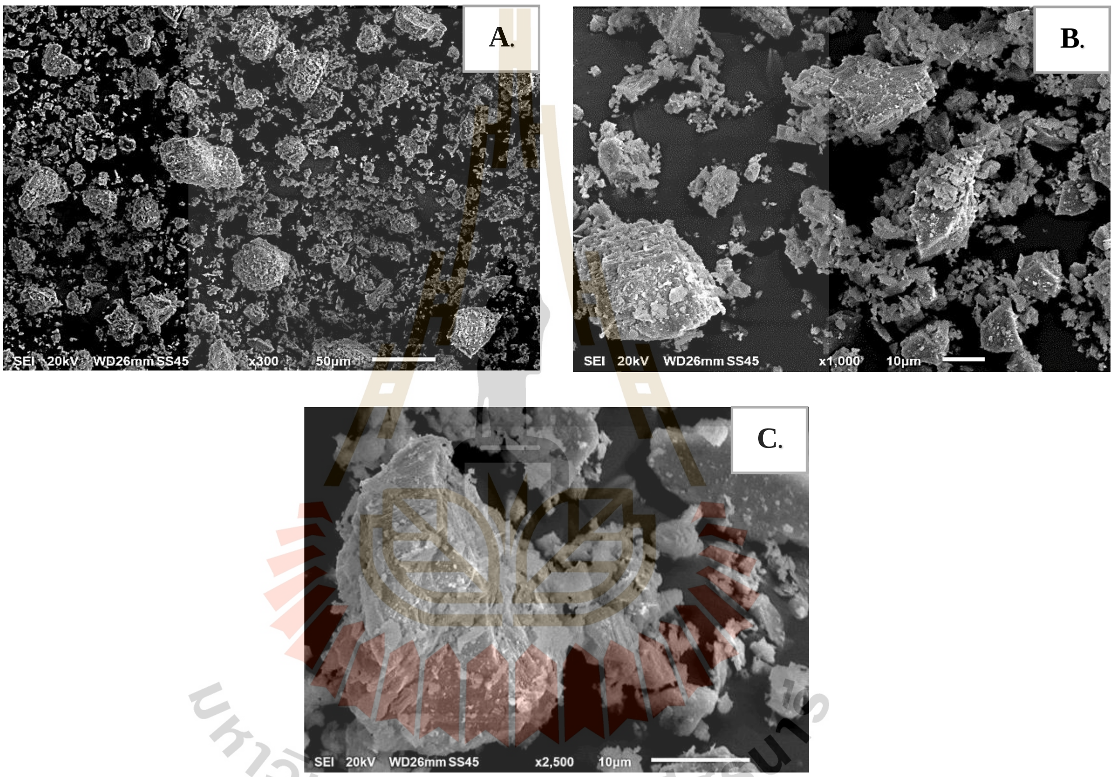

Figure 4.36 Characterize the distribution and size of the surface of the barite before mixing (A) and (B). The surface characteristics of the barite square texture will be angular and the pieces of the fragment size 10 µm (C).

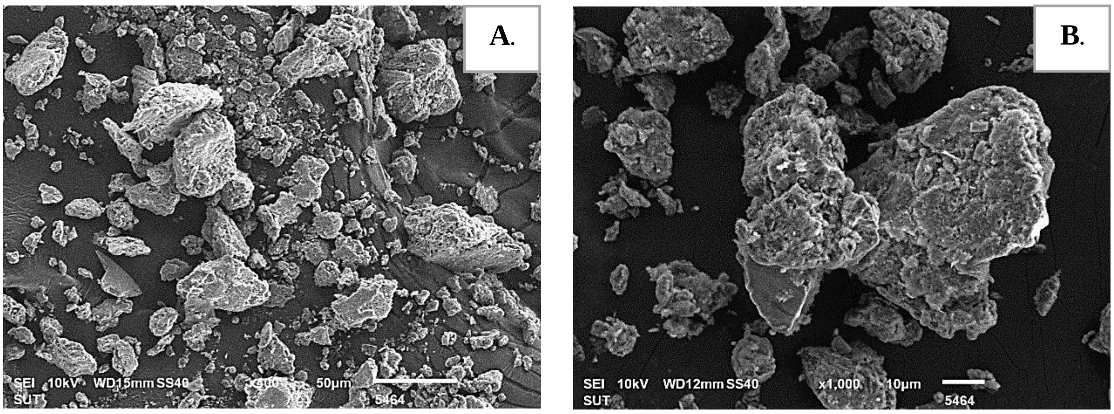

Figure 4.37 Characterize the distribution and size of the surface of America (Base) bentonite before mixing : (A) shows the size of bentonite and distribution (size 50 µm), and (B) shows the bentonite texture was sub-angular (size 10 µm).

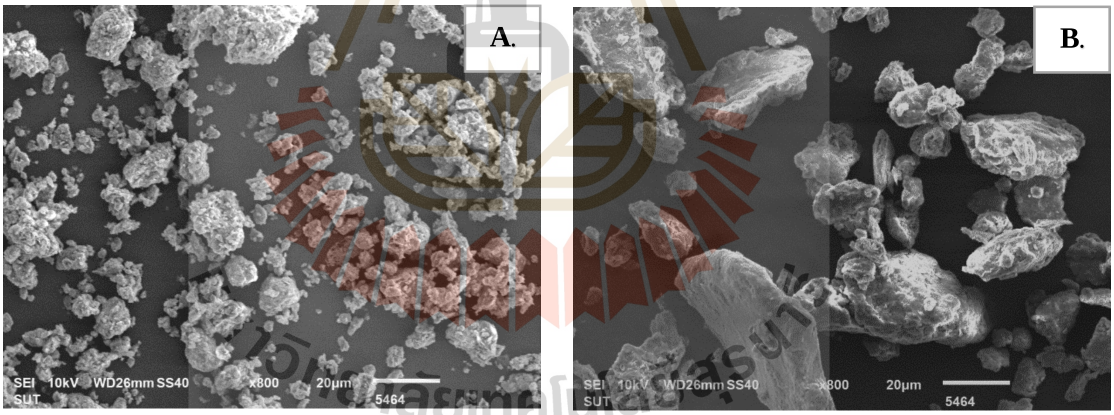

Figure 4.38 Characterize the distribution and size of the surface of Saraburi bentonite before mixing. (A) shows the size of bentonite and distribution (size 20 µm), and (B) shows the texture was sub-angular (size 20 µm).

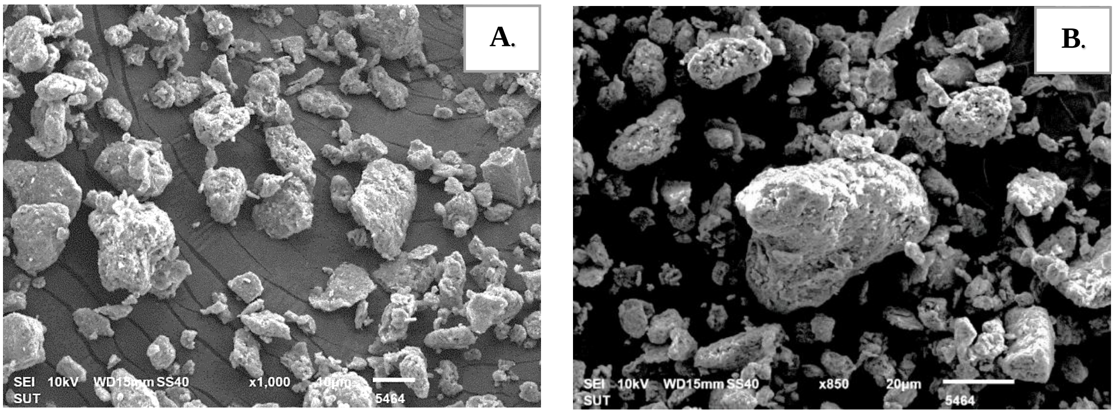

Figure 4.39 Characterize the distribution and size of the surface of Lopburi bentonite before mixing. (A) shows the size of bentonite and distribution (size 10 µm), and (B) shows the texture was sub-angular (size 20 µm).

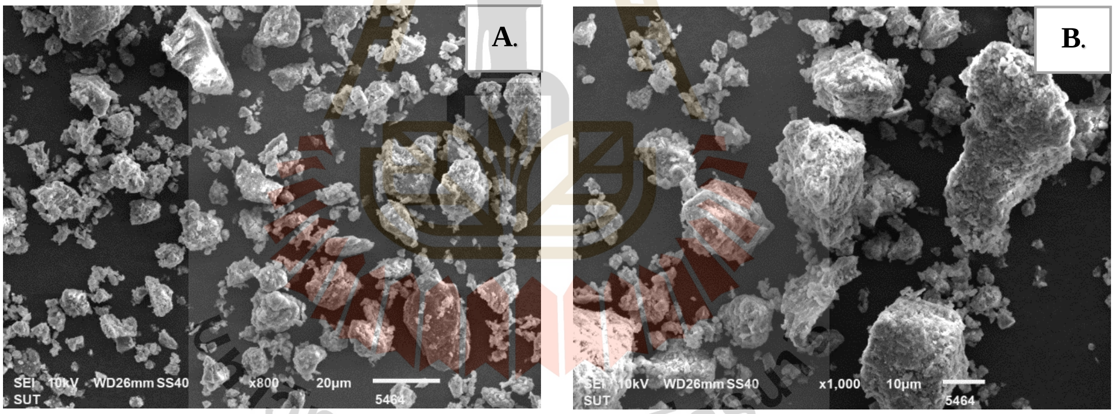

Figure 4.40 Characterize the distribution and size of the surface of Kanchanaburi bentonite before mixing. (A) shows the size of bentonite and distribution (size 20 µm), and (B) shows the texture was sub-angular (size 10 µm).

4.3.9.2 SEM of drilling mud mixing with each bentonite

From the sample after mixed analytical by the image from SEM at the magnification extend from 100 to 10,000. These experiments have used a mud filter cake for testing, then found the sample texture is shown uneven, bentonite from each source are familiar a thin sheet. The bentonite clay larger and smaller particles of barite with compactness of individual grains and remains of the surface roughness, compactness and the texture are sub-angular and the porous distributed around. The grain is even though heating at 60 and 90°C. Some sample after mixed drilling mud is shown in Figure 4.41 to 4.44.

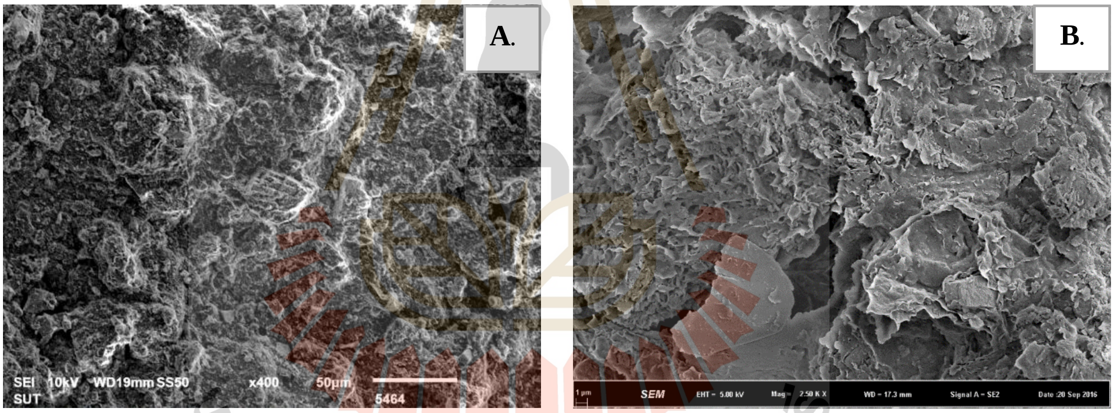

Figure 4.41 Characterize the distribution and size of the surface of sample No. 1 America bentonite or base (A) after mixed (size 50 μm).

(B) shows compactness of rough texture of the composition (size 1 μm).

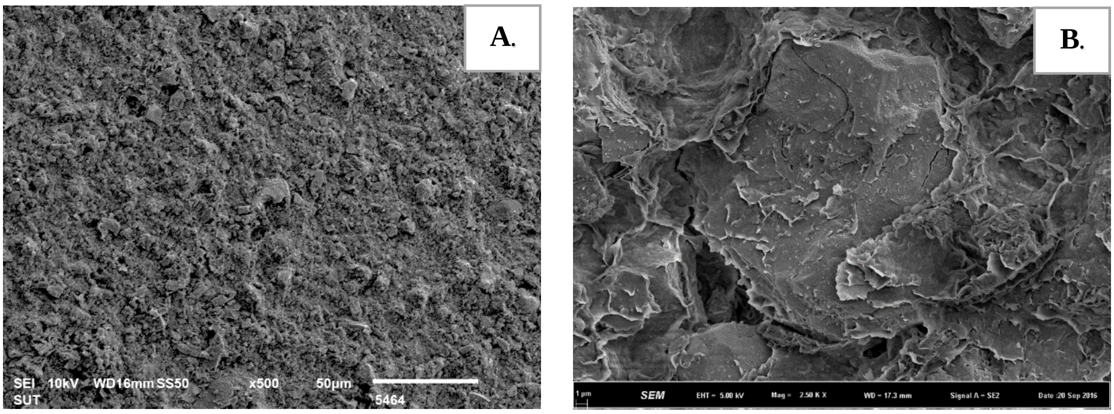

Figure 4.42 Characterize the distribution and size of the surface of sample No.4 (Saraburi bentonite) (A) after mixed (size 50 µm). (B) shows compactness of rough texture of the composition (size 1 µm).

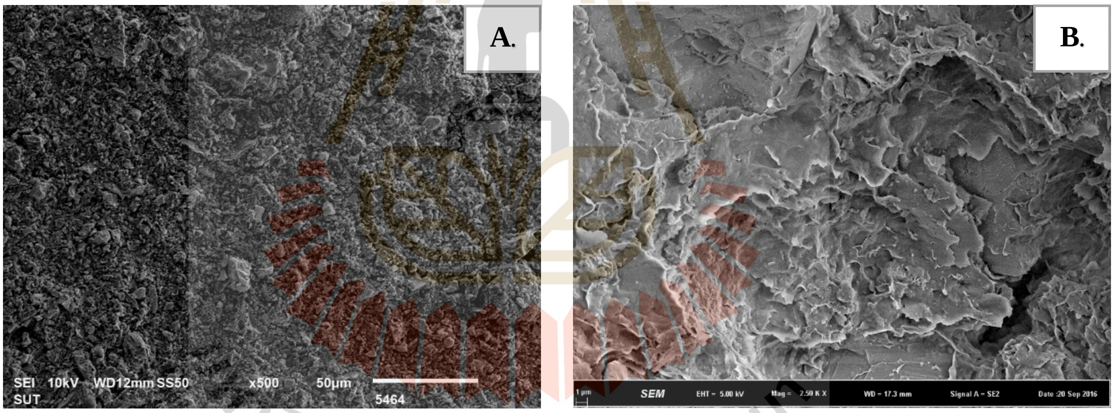

Figure 4.43 Characterize the distribution and size of the surface of sample No. 7 (Lopburi bentonite) (A) after mixed (size 50 µm). (B) shows compactness of rough texture of the composition (size 1 µm).

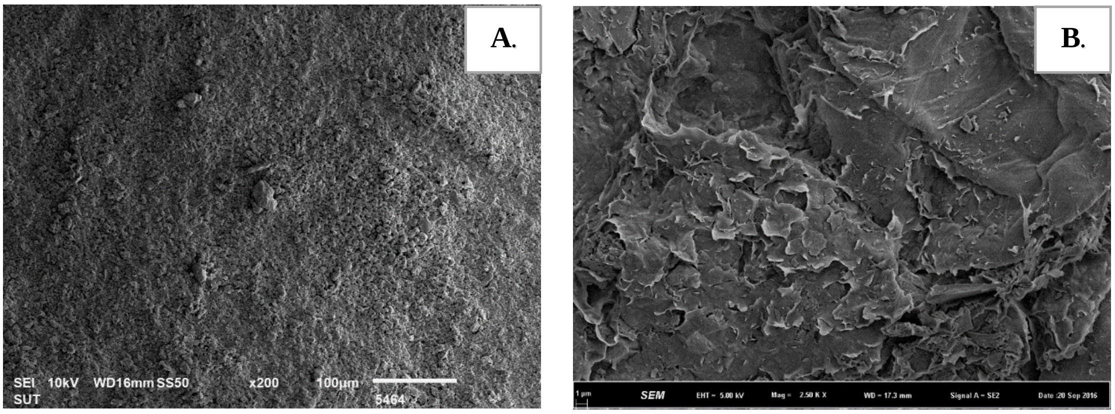

Figure 4.44 Characterize the distribution and size of the surface of sample No. 10 (Kanchanaburi bentonite) (A) after mixed (size 100 µm). (B) shows compactness of rough texture of the composition (size 1 µm).

4.4 Cost analysis

Generally, the drilling mud cost is higher due to the mixture of chemical and materials are imported from foreign countries. Therefore, it has to be analyzed and summarized the economic value of drilling mud from the Table 4.8, which shows the comparison of bentonite cost from each source then used to mix the drilling mud. From the result of comparison of higher bentonite cost (America bentonite) to lower bentonite cost from the local (Thailand) such as Saraburi, Lopburi and Kanchanaburi sources. The comparison of bentonite cost is found bentonite from the local (Thailand) could be reduce the cost from imported bentonite from foreign countries. However, the qualitative and performance is less than America bentonite. The bentonite from Thailand (Saraburi, Lopburi and Kanchanaburi) sources could be used instead of imported bentonite in the shallow well condition.

Table 4.8 Cost of chemical in drilling mud.

Chemical	Cost (Baht)	Unit (Kg)	Cost/Unit (Baht/ Kg)
Barite	5,000	1,000	5
America bentonite (Base)*	11,400	1,000	11.4
Saraburi bentonite*	6,000	1,000	6
Lopburi bentonite*	8,000	1,000	8
Kanchanaburi bentonite*	7,500	1,000	7.5
PAC Polymer	72,000	25	2,880
Guar Gum	350	1	350
Xanthan Gum	320	1	320
CMC HV	200,000	1,000	200

* Bentonite in each country were the ex-factory cost. It does not include a cost of the process materials, materials handling and storage, packaging, transport and other indirect materials.

4.5 Summary of chemical and physical properties and cost analysis

Result analysis of bentonite from America, Lopburi, Saraburi and Kanchanaburi sources can be summarized the chemical, physical properties and cost analysis in Table 4.9.

In terms of chemical composition, water base drilling mud, was dominantly filled with silica, followed by aluminum oxide, iron oxide, magnesium oxide, barium oxide and a slight other chemical was found. The physical properties associated with the chemical properties related to the same direction with the effect of analysis XRD, XRF and SEM.

The comparative price of bentonite represented that the bentonite from Thailand could reduce the expense better than importation bentonite from aboard. However, the quality and performance could not be comparable to America bentonite. Therefore, bentonite from Saraburi, Lopburi and Kanchanaburi could be instead of imported bentonite from aboard, which especially use in a shallow well condition.

Table 4.9 Summarized comparison of the chemical property, physical property and cost analysis in America, Saraburi, Lopburi and Kanchanaburi bentonites.

Bentonite from	Temperature (°C)	Chemical property		Physical property												Cost analysis (Baht/tons)	Remarks
		XRF	XRD	Density	Viscosity					Filtrate loss	pH	Resistivity	Solid content	Sand content	SEM		
					AV	PV	YP	n	K								
America (Base)	30	SiO_2 = 59.92 Al_2O_3 = 13.7 MgO = 3.03 Fe_2O_3 = 2.1 BaO = 0.81	Bar = 53.38 Tal = 16.00 Qua = 10.47 Kao = 5.86 Cal = 0.27	1.1	20.6	11.8	17.8	0.5	1.68	13.5	9.86	5.78	6	0.25	Surface mud filter cake of the base mud shows uneven, thin sheet of bentonite clay larger and smaller particles of barite with compactness of individual grains and remains of the grains of the material is even though heating at 60 and 90°C.	Prices of bentonite from America is the high cost but the cost of bentonite from the local in Thailand is less than foreign countries.	API Standrad
	60	SiO_2 = 60.93 Al_2O_3 = 13.9 MgO = 2.99 Fe_2O_3 = 1.83 BaO = 1.002	Bar = 54.88 Tal = 17.56 Qua = 10.11 Kao = 5.03 Cal = 0.12	1.098	27.4	11.3	32.3	0.3	8.16	15	9.66	5.54	8	0.26			
	90	SiO_2 = 57.34 Al_2O_3 = 13.7 MgO = 2.91 Fe_2O_3 = 1.96 BaO = 2.56	Bar = 52.27 Tal = 19.93 Qua = 11.05 Kao = 4.64 Cal = 0.20	1.095	29.6	11.0	37.3	0.3	8.78	17	9.53	5.36	9	0.26			

Table 4.9 Summarized comparison of the chemical property, physical property and cost analysis in America, Saraburi, Lopburi and Kanchanaburi bentonites (Continued).

Bentonite from	**Temperature (°C)**	**Chemical property**		**Physical property**												**Cost analysis** (Baht/tons)	**Remarks**
		XRF	XRD	Density	Viscosity					Filtrate loss	pH	Resistivity	Solid content	Sand content	SEM		
					AV	PV	YP	n	K								
Saraburi	30	SiO_2 = 62.51 Al_2O_3 = 12.59 MgO = 2.23 Fe_2O_3 = 1.95 BaO = 0.87	Bar = 51.65 Tal = 10.93 Qua = 23.61 Kao = 5.46 Cal = 0.81	↑	↓	↓	↓	↓	↓	↓	↓	↓	↑	↓	Surface mud filter cake of the Saraburi bentonite shows uneven, thin sheet of bentonite clay larger and smaller particles of barite with compactness and remains of the surface roughness, compactness and the porous distributed around.	Prices of bentonite from Saraburi is cheaper than bentonite from America.	Bentonite from Saraburi have the density and solid content is in the standard. So, this bentonite is appropriate to use.
	60	SiO_2 = 60.80 Al_2O_3 = 13.24 MgO = 2.243 Fe_2O_3 = 2.08 BaO = 0.96	Bar = 50.88 Tal = 11.09 Qua = 25.29 Kao = 5.28 Cal = 0.64	↑	↓	↓	↓	↓	↓	↓	↓	↓	↑	↓			
	90	SiO_2 = 61.93 Al_2O_3 = 13.81 MgO = 2.01 Fe_2O_3 = 1.95 BaO = 0.94	Bar = 50.76 Tal = 12.52 Qua = 23.11 Kao = 5.48 Cal = 0.74	↑	↓	↓	↓	↓	↓	↓	↓	↓	↑	↓			

Table 4.9 Summarized comparison of the chemical property, physical property and cost analysis in America, Saraburi, Lopburi and Kanchanaburi bentonites (Continued).

Bentonite from	**Temperature (°C)**	**Chemical property**		**Physical property**												**Cost analysis** (Baht/tons)	**Remarks**
		XRF	XRD	Density	Viscosity AV	PV	YP	n	K	Filtrate loss	pH	Resistivity	Solid content	Sand content	SEM		
Lopburi	30	SiO_2 = 50.527 Al_2O_3 = 11.69 MgO = 3.915 Fe_2O_3 = 4.80 BaO = 2.07	Bar = 48.73 Tal = 17.27 Qua = 14.51 Kao = 4.25 Cal = 5.21	↑	↓	↓	↓	↓	↓	↓	↑	↓	↑	↑	Surface mud filter cake of the Lopburi bentonite shows uneven, thin sheet of bentonite clay larger and smaller particles of barite with compactness and remains of the surface roughness, compactness and the porous distributed around.	Prices of bentonite from Lopburi is cheaper than bentonite from America.	Bentonite from Lopburi have the density, pH, solid content and sand content value according to the standard. So, this is appropriate to use.
	60	SiO_2 = 51.399 Al_2O_3 = 12.60 MgO = 3.83 Fe_2O_3 = 4.95 BaO = 2.11	Bar = 50.15 Tal = 15.46 Qua = 15.55 Kao = 3.87 Cal = 6.67	↑	↓	↓	↓	↓	↓	↓	↑	↓	↑	↑			
	90	SiO_2 = 51.62 Al_2O_3 = 12.84 MgO = 3.55 Fe_2O_3 = 5.03 BaO = 2.03	Bar = 49.42 Tal = 16.29 Qua = 15.77 Kao = 5.072 Cal = 5.45	↑	↓	↓	↓	↓	↓	↓	-	↓	↑	↑			

Table 4.9 Summarized comparison of the chemical property, physical property and cost analysis in America, Saraburi, Lopburi and Kanchanaburi bentonites (Continued).

Bentonite from	**Temperature (°C)**	**Chemical property**		**Physical property**												**Cost analysis** (Baht/tons)	**Remarks**
		XRF	XRD	Density	Viscosity					Filtrate loss	pH	Resistivity	Solid content	Sand content	SEM		
					AV	PV	YP	n	K								
Kancha naburi	30	SiO_2 = 76.70 Al_2O_3 = 12.55 MgO = 2.421 Fe_2O_3 = 1.65 BaO = 2.998	Bar = 58.60 Tal = 6.52 Qua = 15.09 Kao = 3.53 Cal = 0.78	↑	↓	↓	↓	↓	↓	↓	↓	↓	↑	↓	Surface mud filter cake of the Kanchanaburi bentonite shows uneven, thin sheet of bentonite clay larger and smaller particles of barite with compactness and remains of the surface roughness, compactness and the porous distributed around.	Prices of bentonite from Kancha naburi is cheaper than bentonite from America.	Bentonite from Kanchana buri have the density, solid content value according to the standard. So, this is appropriate to use.
	60	SiO_2 = 77.640 Al_2O_3 = 11.65 MgO = 2.801 Fe_2O_3 = 1.90 BaO = 3.04	Bar = 55.65 Tal = 7.147 Qua = 16.63 Kao = 3.82 Cal = 0.82	↑	↓	↓	↓	↓	↓	↓	↓	↓	↑	↓			
	90	SiO_2 = 77.84 Al_2O_3 = 11.89 MgO = 2.616 Fe_2O_3 = 1.99 BaO = 2.414	Bar = 56.34 Tal = 8.45 Qua = 17.07 Kao = 3.36 Cal = 0.89	↑	↓	↓	↓	↓	↓	↓	↓	↓	↑	↓			

↑ = Better, ↓ = Worse, **-** = Unaltered

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

This chapter is divided into two parts, which are conclusions and recommendations. In conclusion part, it presents the conclusion from two main sections (I) chemical property of drilling mud mixed with bentonite from various sources, and (II) physical property of drilling mud mixed with bentonite from various sources, respectively. In recommendation part, it consists of some recommendations for the future study.

5.2 Conclusions

This chapter will analyze the result and compare the price of bentonite from each source and the conclusion from the experiment and guideline for study in the future.

5.2.1 Chemical property

In terms of chemical composition, water based drilling mud, was dominantly filled with silica, followed by aluminum oxide, iron oxide, magnesium oxide, barium oxide and a slight other chemical was found. The major elements of water based drilling mud include barite, talc, quartz, calcite, kaolinite, and microcline.

The microstructure of water based drilling by using mud filter cake is characterized shows uneven, thin sheet of bentonite clay larger and smaller particles of barite with compactness of individual grains.

The element and mineral result are found that the temperatures for the study are 30, 60 and 90^{o}C, that can't change the element and mineral structure in drilling mud. Hence, the element composition result is found the mixing in drilling mud such as barite, America, Saraburi, Lopburi and Kanchanaburi bentonite. that have the element composition follow as: barite compose of BaO 82.43%. America bentonite is compose of 69.83% SiO_2, 21.97% Al_2O_3 and 3.93% MgO. Saraburi bentonite is compose of 72.62% SiO_2 and 16.18% Al_2O_3. Lopburi bentonite is compose of 69.29% SiO_2, 18.29% Al_2O_3 and 5.32% Fe_2O_3. Kanchanaburi bentonite is compose of 77.90% SiO_2 and 12.42%. Al_2O_3.

The analysis from each bentonite sources was found the SO_3 element composition except for Kanchanaburi bentonite. The element composition of TiO_2 isn't found in Kanchanaburi bentonite. The element composition of ZnO and ZrO_2 isn't found in America and Kanchanaburi bentonite.

The element composition result is found the additive mix in drilling mud. That element composition has similarity such as: Barite is compose of Barite 77.3%. America bentonite is compose of 29.98% microcline, 18.65% kaolinite, 18.13% talc and 14.96% silica. Saraburi bentonite is compose of Silica 63.2% and microcline 19.77%. Lopburi bentonite is compose of 28.51% talc, 18.8% kaolinite and 18.63% calcite. Kanchanaburi bentonite is compose of 40.21% microcline and 20.84% talc.

Drilling mud mixing with each bentonite was found the mineral and main element composition in appropriate drilling mud as follows:

The amount of SiO_2 is highest ranging from 50.53 to 77.84%. The secondary elements include SO_3, Al_2O_3, Fe_2O_3, BaO, MgO, CaO, K_2O, SrO and Rh_2O_3 contents range from 0 to 23.07%, 11.65 to 13.96%, 1.65 to 5.03%, 0.81 to 3.04%, 2.01 to 3.92%, 0.49% to 3.07%, 0.30% to 0.87%, 0.17% to 0.53% and 0.15% to 0.45%, respectively.

Mineral compositions in drilling mud mixed with each bentonite comprise of various mineral content, which range from 48.73 to 56.34% barite, 6.52 to 19.93% talc, 10.11 to 25.29% quartz, 0.72 to 9.16% anorthite, 0.12 to 6.67% calcite, 3.65 to 5.91% microcline, 3.53 to 5.86% kaolinite, 0 to 1.19% hematite, 0.35 to 1.08% gypsum, 0.11to 0.34% choromite and 0.01 to 0.32% silica. Hematite appears in all bentonite sample from Thailand, but it is invisible in America bentonite.

The correlation study of mineral and element compositions in drilling mud shows that the element composition of BaO relate to barite, The element composition of SiO_2 in quartz form as kaolinite, anorthite, silica, talc and microcline, The element composition of SO_3 in barite and gypsum form and The element composition of Fe_2O_3 in hematite and choromite. The changing of element composition and structure of mineral depend on the proportion of element and mineral compositions, but it not effects from temperature.

Texture and distribution analysis of barite and bentonite samples on the magnification at 100 to 10,000 represent that the barite texture is triangle and a fragment around the roughly grain size between 10 to 50 micrometers, and the bentonite texture from each sources represent a sub-angular texture and good porosity distribute around the grain.

5.2.2 Physical property

Summary of the rheological properties on drilling mud mixed with bentonite from each source when the temperature is 90^{o}C as follows:

Apparent viscosity is between 4.8 cP to 31.4 cP, plastic viscosity is between 2.0 cP to 11.8 cP, yield point is between 1.3 $lb_f/100ft^2$ to 46.8 $lb_f/100ft^2$, initial gel strength is between 1 $lb_f/100ft^2$ to 29 $lb_f/100ft^2$ and gel strength at 10 minute is between 2 $lb_f/100ft^2$ to 32 $lb_f/100ft^2$.

Result of rheological on drilling mud with each bentonite sources show both Bingham Plastic model and Power Law model. At 30, 60 and 90^{o}C, the Bingham Plastic model of drilling mud with Lopburi bentonite is closer to America bentonite (Based) than bentonite from Saraburi and Kanchanaburi. The Power Law model (Pseudo-plastic flow) due to the index n and consistency (k) are less than indicated that all drilling mud from each source exhibited pseudo-plastic flow. The drilling mud with Lopburi bentonite has the constant n and k is nearby America bentonite, which these constant n and k normally describe in the interest of hydraulic utilization using for hydraulic calculations. Therefore, rheological property of bentonite from Lopburi is better than Saraburi and Kanchanburi due to the Bingham Plastic and Power Law Model is close to America bentonite (Based). When changing the temperature from 30 to 90^{o}C, the apparent viscosity, yield point and gel strength of drilling mud mixed with these bentonite increased with increasing temperature, while the plastic viscosity slightly decreased with increasing temperature. The drilling mud mixed with America bentonite and Lopburi bentonite in all ranges tested the temperature; give appropriate rheological properties for water based drilling mud. Viscosity is found bentonite from Thailand source is less than the standard. Therefore, this bentonite is inappropriate to use. In case of improving the efficiency of Thailand bentonite to equivalent America bentonite performance should be added CMC additive to improve viscosity efficiency.

Result of filtration according to API standard the filtration value is less than 13.5 ml. When the temperature is increased to 90°C that filtration loss from drilling mud mixed with each bentonite depending on the temperature. From the experiment is found filtration loss from America bentonite is lowest, secondary is Lopburi bentonite and Kanchanaburi bentonite, Saraburi bentonite are the highest filtration loss, respectively. The amount of filtration loss from the experiment is between 13.5 ml. to 195 ml. For the prevention of filtration loss from drilling mud mixed with Kanchanaburi bentonite and Saraburi bentonite inappropriate to use in drilling facility. For the mud cake thickness is a correlation with filtration loss from drilling mud, then qualitative of mud cake depending on shape, size and chemical contamination in drilling mud. The thin mud cake is enhancing drill string stuck and resistance between the drill string and formation. The thickness of mud cake is between 1.96 ml. to 6.21 ml. filtration loss from Thailand bentonite mixed in drilling mud is less than the standard. Thus, the bentonite from Thailand is inappropriate to use. In case of improving the efficiency of Thailand bentonite to equivalent America bentonite performance should be added CMC additive to decrease the filtration loss.

Result of drilling mud density, the hydrostatic pressure is protected the drilling formation from cave or hole and fluid from the formation into the well. Usually, the density of drilling mud will enhance to control the pressure in the well.

Density standard value is between 1.06 to 2.16 g/cm^3 then is found drilling mud from the experiment is between 1.06 to 1.10 g/cm^3 or 8.846 to 9.18 lb/gal. The result of the viscosity of each bentonite has decreased when the temperature is increased. Density from Thailand bentonite mixed in drilling mud is found the bentonite from Thailand has the value as the standard. This is appropriate to use.

Result of pH has the intensity of hydrogen ion in gram/liter unit. Usually, pH of water-based drilling mud is between 9.5 to 10.5. That pH of drilling mud is between 7.48 to 9.95. From the experiment is found pH is decreasing when the temperature is increasing and pH on mud filtrate from drilling mud is between 7.36 to 9.72. It can decrease corrosion problems of steel in the drilling mud circulation process. The pH value of bentonite from Lopburi has the value as the standard. This is appropriate to use in drilling mud.

Resistivity result represents that the resistivity on drilling mud ranges from 4.43 to 18.29 Ω.m. The resistivity on mud filtrate ranges from 5.25 to 19.18 Ω.m. and the resistivity on mud cake is between 3.24 to 16.17 Ω.m. The resistivity is decreased when the temperature is increased. Resistivity is found the bentonite from Saraburi and Kanchanaburi has the value as the standard. This is appropriate to use.

Solid content result of drilling mud mixed with bentonite in each country range from 2 to 9%, which increase depending on the temperature. The result of solid content each country is still according with the standard is less than 10%. Solid content is found the bentonite from Thailand source has the value as the standard. So, this is appropriate to use.

Result of sand content from the experiment depending on increasing temperature ranging from 0.2 to 0.58%. Normally, the standard of sand content in drilling mud is less than 0.3%. The sand content of bentonite from America, Lopburi range from 0.2 to 0.3% according to the standard, but bentonite from Kanchanaburi has between 0.5 to 0.58% and Saraburi has between 0.5 to 0.6% that are not according to the standard. So, this is inappropriate to use.

The microstructure on mud filter cake from drilling mud is show an uneven characteristic, the thin sheet on bentonite , larger clay and smaller particles of barite are compactness grains. The SEM image of drilling mud mixed with each bentonite, that can be show the rougher texture. that component is tightly packed and remain of the grain although the sample is heat in high temperature. The result from chemical, mineral and morphology analysis is found that the temperature in the study is 30, 60 and 90°C, that cannot change the chemical and mineral structure in drilling mud.

5.2.3 Cost comparison

The result of bentonite valuation in each country mixed in drilling mud is found that the cost on bentonite in each country ascending from Saraburi bentonite, Kanchanaburi bentonite, Lopburi bentonite and America bentonite, respectively. America bentonite is the high cost but the cost of bentonite from the local in Thailand is less than foreign countries. When comparing the cost of bentonite with transport cost is found the cost of transport in the country is cheaper than foreign country. Therefore, the comparison cost of bentonite from Thailand could be reduce the imported cost, however the qualitative and performance is less than America bentonite. Finally, the bentonite from Thailand (Saraburi, Lopburi and Kanchanaburi) sources could be used instead of foreign bentonite in the condition of experimental well, the well do not control the penetration rate too much or shallow well.

5.3 Recommendations

The uncertainties and adequacies of the research investigation and experiments lead to the recommendations for further study as follows.

- The dynamic filtration test should be performed to test under high temperature and pressure that represents the real circulated borehole condition.
- The effect of salinity or electrolyte on drilling mud should be measured due to this effect could occur from sodium chloride and potassium chloride.
- The bentonite source, it should be tested bentonite from Thailand compare to other bentonite source such as China, Indonesia, India, and others.
- The efficiency testing of drilling mud with bentonite from Lopburi, Saraburi and Kanchanaburi should be adding other additives such as Xantan gum, Guar gum, CMC, polymer and other to comparing the bentonite from United State of America.

REFERENCES

AI-Homadhi, E.S. (2013). **Improving Local Bentonite Performance for Drilling Fluids Applications** [On-line]. Available: http://faculty.ksu.edu.sa/alhomadhi/Documents/Local%20Bentonite.pdf.

API Recommended Practice 13B-1. (1997). **Recommended Practice for Field Testing Water-based Drilling Fluids** (2^{nd} ed.). American petroleum institute. Washington D.C.

API Specification 13A. (2010). **Oil-Well Drilling-Fluid Materials** (18^{th} ed.). American petroleum institute. Washington D.C.

Apugo-Nwosu, T.U., Mohammed-Dabo, Ahmed, A.S., Abubakar, G., Alkali, A.S., and Ayilara, S.I., (2011). Studies on the suitability of ubakala bentonitic clay for oil well drilling mud formulation. **British Journal of Applied Science & Technology.** 1(4): 152-171.

Baker Hughes. (2006). Fundamentals of Drilling Fluids. **In Drilling Fluids Reference Manual.** Baker Hughes. 1-30.

Bourgoyne Jr, A.T., Millheim, K.K., Chenevert, M.E., and Young Jr, F.S. (1986). **Drilling Fluids**. In: **Applied Drilling Engineering.** SPE Vol. 2. 41-84.

Chilingarian, G.V. and Vorabutr, P. (1983). **Drilling and Drilling Fluids.** (2^{nd} ed). Elsevier. Amsterdam. 767p.

Department of Mineral Resources. (2013). **Bentonite** [On-line]. Available: http://www.dmr.go.th/main.php?filename=Bentonite.

Department of Primary Industries and Mines. (2007). **Specification of bentonite** [On-line]. Available: http://www.dpim.go.th/bdp/pdf/Industrial_Minerals-HandBook.pdf.

Department of Primary Industries and Mines. (2014). **Mineral Prices** [On-line]. Available: http://www.dpim.go.th/minerals-minerals/index.php.

Dewu, B.B., Arabi, S.A., Oladipo, M.O.A., Funtua, I.I., Mohammed-Dabo, I.A., and Muhammad, A.M. (2011). Improvement of rheological properties of bentonite clays using sodium carbonate and a synthetic viscosifier. **International Archive of Applied Sciences and Technology.** 2 (2): 43-52.

Gatlin, C. (1960). **Petroleum Engineering Drilling and Well Completions.** Prentice Hall, Texas. 7-93.

Guichard, B., Wood, B., and Vongphouthone, P. (2008). Fluid loss reducer for high temperature high pressure water based-mud application. **Eliokem SAS**. 1-14.

Hensen, E.J.M., and Smit, B. (2002). Why Clays Swell. **Journal Phys. Chem.** 106: 12664-12667.

Horpibulsuk, S. (2011). Sealing Performance of Cement-Bentonite Mixtures in Salt Fractures. In **Industrial Wastes Storage in Rock Salt.** (pp. 22-23).

Lloyd, L. (2011). **Handbook of Industrial Catalysts.** New York: Springer. ISBN 978-0387246826: 181-182.

Lyons, W. (2009). **Working Guide to Drilling Equipment and Operations.** Elsevier Science Technology. London.

MI-Swaco. (1998). Polymer Chemistry and Applications. In **Fluids Engineering Manual.** Revision No: A-0

Mutturee, Y., Tengjaroenkul, B., Pimpukdee, K., Sukon, P. and Tengjaroenkul, U. (2012). Effect of temperature on efficiency of bentonite to adsorb aflatoxin B1. **KKU Vet. J.** 22 (2): 234-241.

Oliveira, L., Rios, R., Fabris, J., Sapag, K., Garg, V., and Lago, R. (2003). **Applied Clay Science.** 22 (4): 169–177.

Petroleum Support (2013). Water Base Drilling Additive (online): http://petroleumsupport.com/water-based-mud-additives/

Penn, C. and Zhang, H. (2013). An introduction to the land application of drilling mud in Oklahoma. **OSU Fact Sheet**, **WREC-102.** Oklahoma Cooperative Extension Service. Stillwater, OK.

SIEP (2003). **Well Engineers Notebook**, Edition 4, May 2003, (I-1 to I-18).

APPENDIX A

EXPERIMENTAL DATA

APPENDIX A

Chemical properties

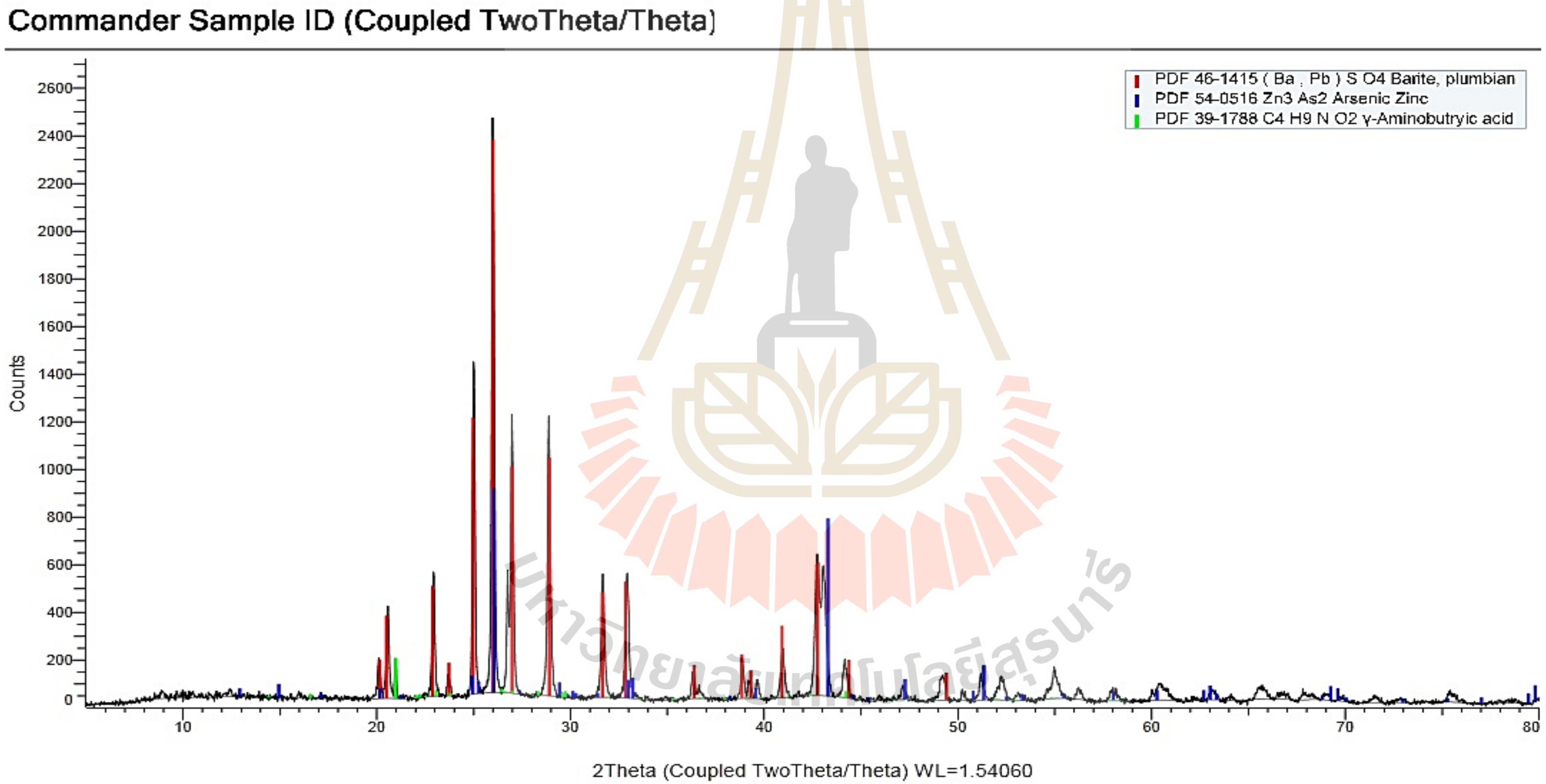

Figure A1 XRD of barite.

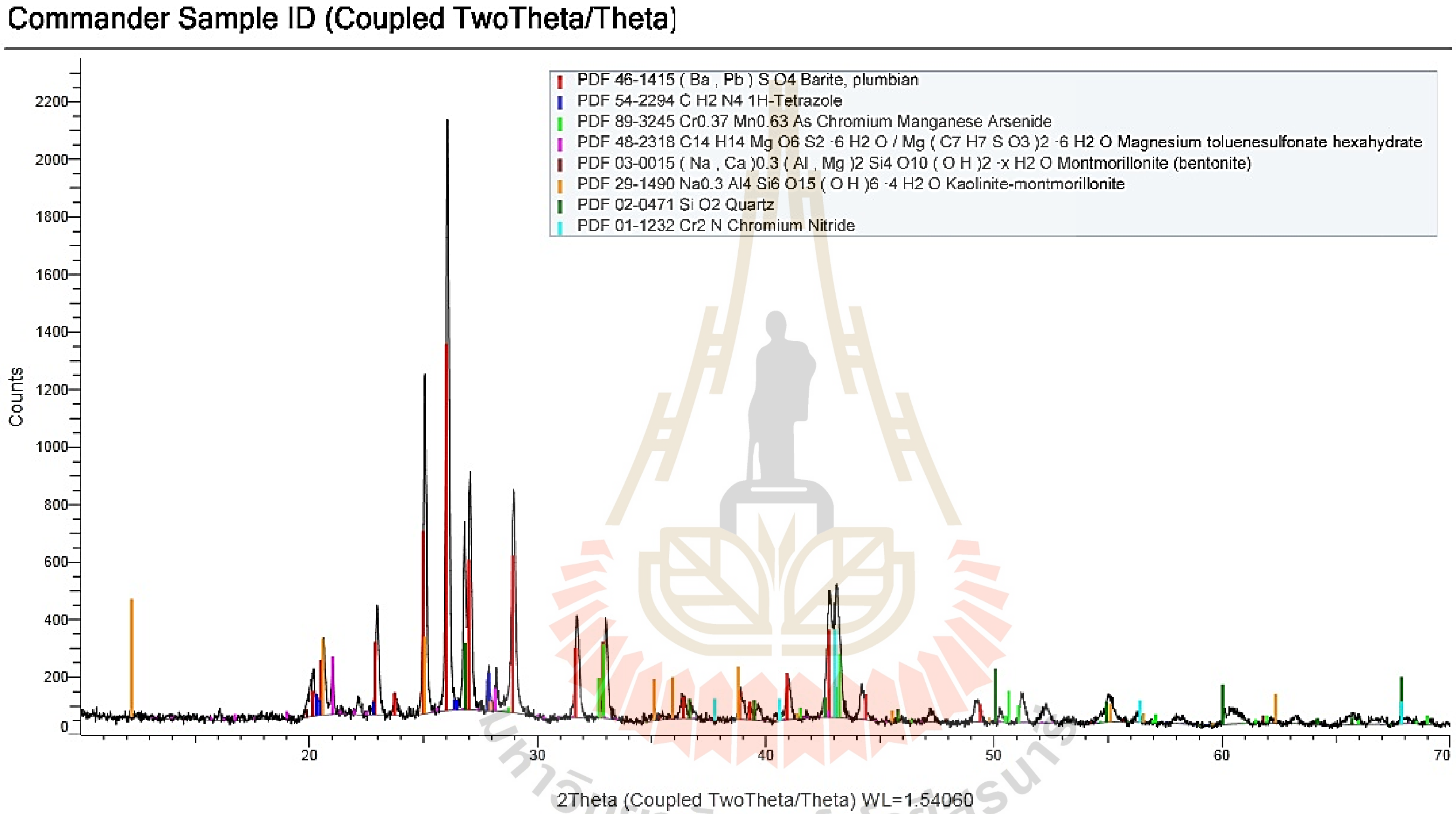

Figure A2 XRD of water-based drilling mud mixed with America bentonite at 30°C (No.1).

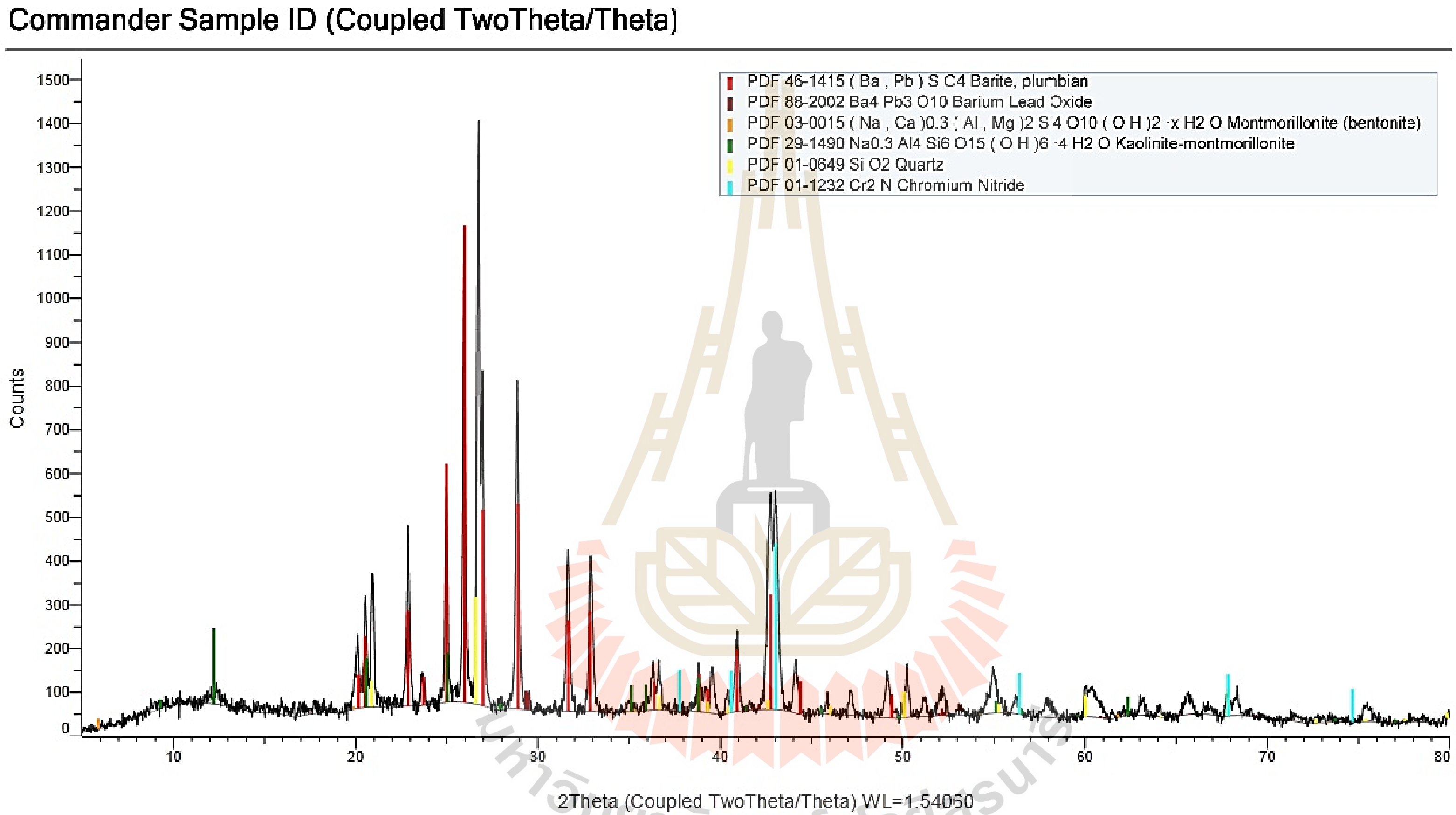

Figure A3 XRD of water-based drilling mud mixed with Saraburi bentonite at 30°C (No.4).

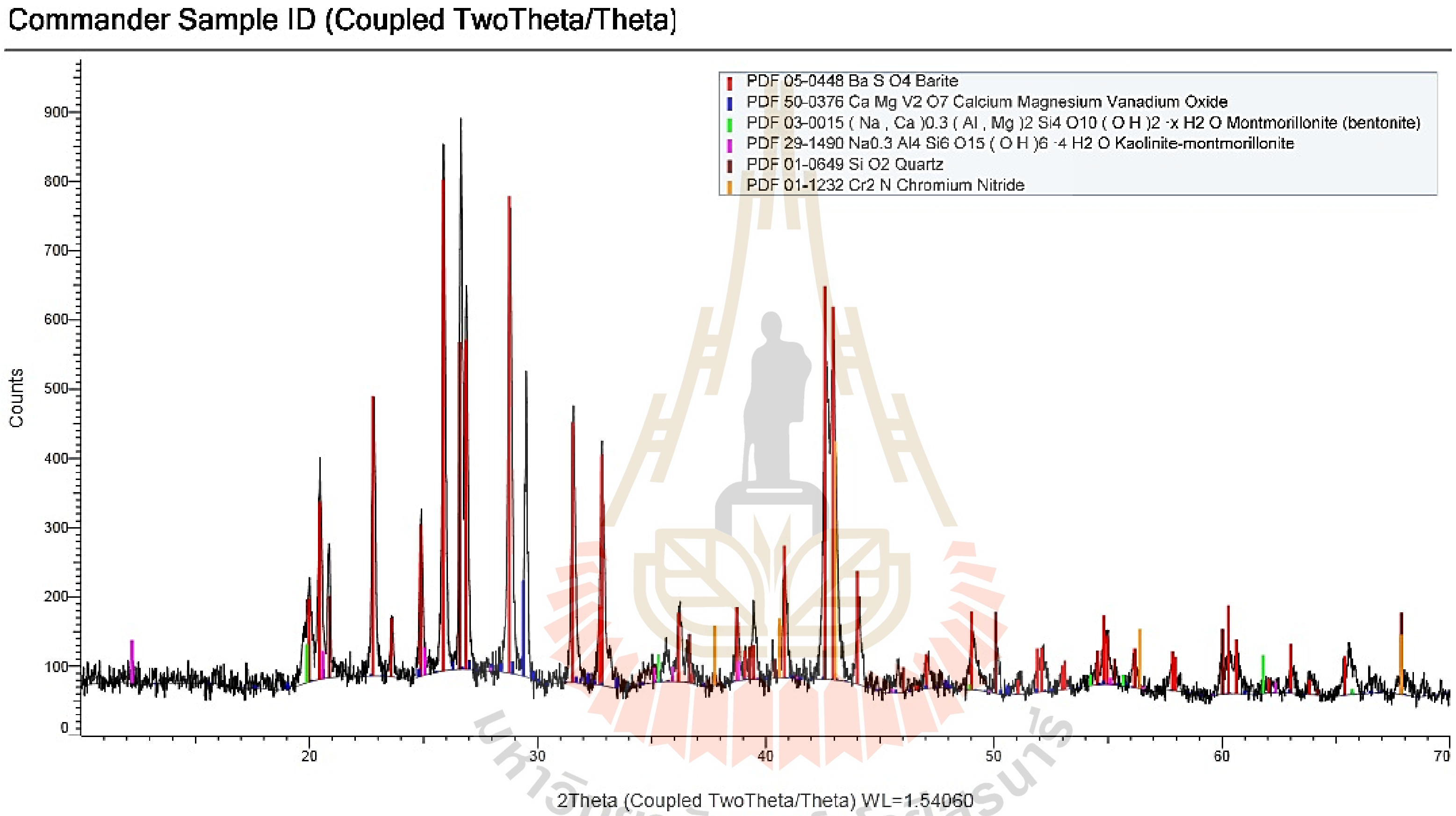

Figure A4 XRD of water-based drilling mud mixed with Lopburi bentonite at 30^{o}C (No.7).

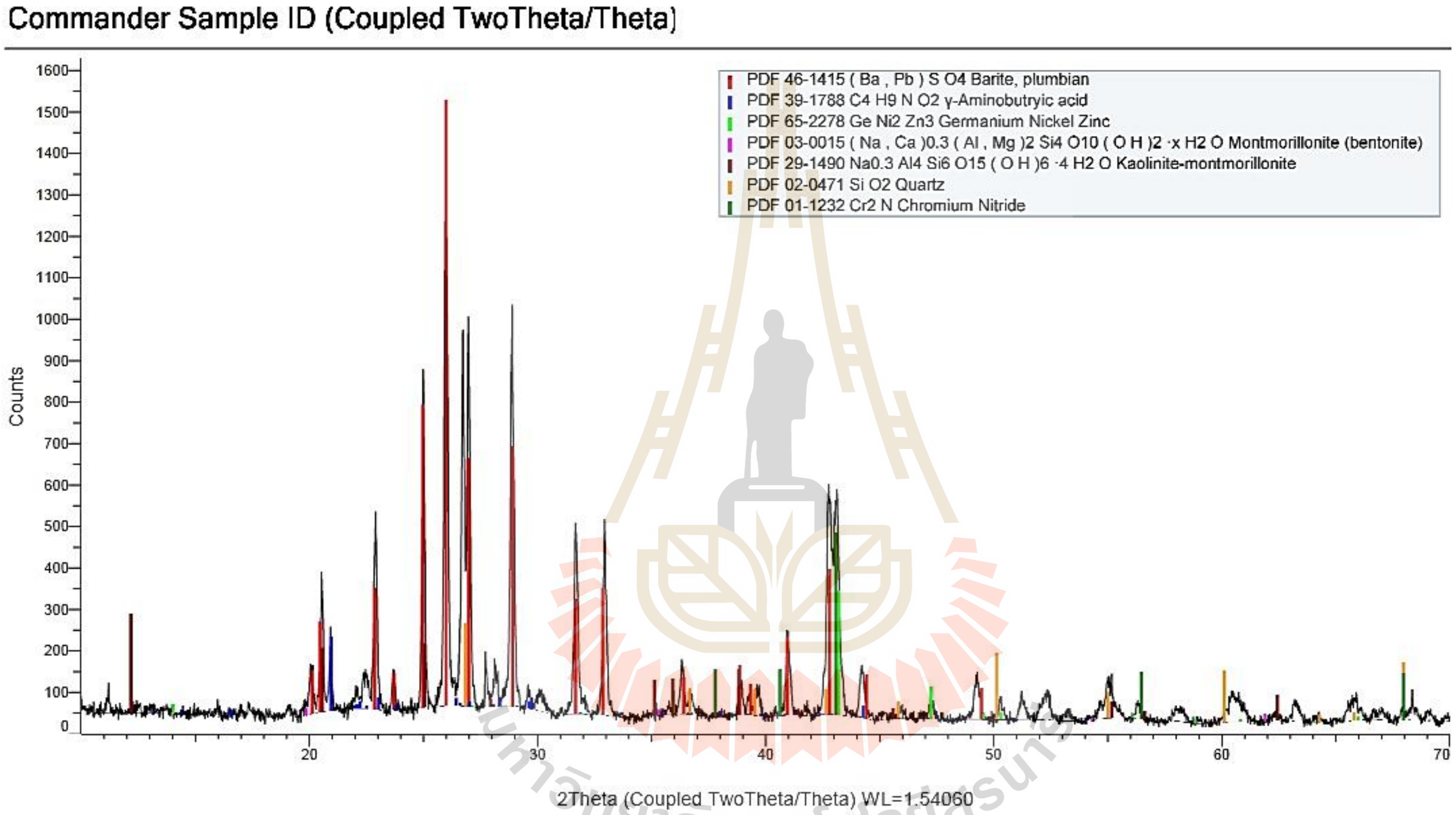

Figure A5 XRD of water-based drilling mud mixed with Kanchanaburi bentonite at 30^{o}C (No.10).

APPENDIX A

Physical properties

Fann viscometer data and parameters for all tested

Table A1 Water-based drilling mud mixed with America bentonite (Base) at temperature 30°C (No.1).

RPM	Reading #1	Reading #2	Reading #3	Reading #4	Average reading	γ (sec^{-1})	τ (lb$_f$/ft^2)
600	41.0	41.0	41.0	42.0	41.3	1021.8	43.780
300	29.0	29.0	30.0	30.0	29.5	510.9	30.966
200	26.0	26.0	26.0	26.0	26.0	340.6	27.763
100	21.0	21.0	22.0	21.0	21.3	170.3	22.424
6	18.0	19.0	18.0	19.0	18.5	10.2	19.220
3	17.0	17.0	19.0	18.0	17.8	5.1	18.153
PV	12.0	12.0	11.0	12.0	11.8		
AV	20.5	20.5	20.5	21.0	20.6		
YP	17.0	17.0	19.0	18.0	17.8		
Gel$_{in}$	17.0						
Gel$_{10}$	19.0						

Table A42 Water-based drilling mud mixed with America bentonite (Base) at temperature 60°C (No.2).

RPM	Reading #1	Reading #2	Reading #3	Reading #4	Average reading	γ (sec^{-1})	τ (lb$_f$/ft^2)
600	55.0	54.0	55.0	55.0	54.8	1021.8	57.661
300	43.0	43.0	44.0	44.0	43.5	510.9	46.983
200	39.0	40.0	40.0	39.0	39.5	340.6	41.644
100	34.0	36.0	34.0	34.0	34.5	170.3	36.305
6	31.0	30.0	32.0	30.0	30.8	10.2	32.034
3	26.0	29.0	28.0	28.0	27.8	5.1	28.831
PV	12.0	11.0	11.0	11.0	11.3		
AV	27.5	27.0	27.5	27.5	27.4		
YP	31.0	32.0	33.0	33.0	32.3		
Gel$_{in}$	26.0						
Gel$_{10}$	28.0						

Table A3 Water-based drilling mud mixed with America bentonite (Base) at temperature 90°C (No.3).

RPM	Reading #1	Reading #2	Reading #3	Reading #4	Average reading	γ (sec^{-1})	τ (lb_f/ft^2)
600	60.0	60.0	59.0	58.0	59.3	1021.8	63.000
300	49.0	49.0	48.0	47.0	48.3	510.9	51.254
200	44.0	43.0	43.0	44.0	43.5	340.6	45.915
100	39.0	38.0	39.0	38.0	38.5	170.3	40.576
6	31.0	30.0	31.0	31.0	30.8	10.2	33.102
3	29.0	29.0	32.0	33.0	30.8	5.1	32.034
PV	11.0	11.0	11.0	11.0	11.0		
AV	30.0	30.0	29.5	29.0	29.6		
YP	38.0	38.0	37.0	36.0	37.3		
Gel_{in}	29.0						
Gel_{10}	32.0						

Table A4 Water-based drilling mud mixed with Saraburi bentonite at temperature 30°C (No.4).

RPM	Reading #1	Reading #2	Reading #3	Reading #4	Average reading	γ (sec^{-1})	τ (lb_f/ft^2)
600	9.0	10.0	9.0	10.0	9.5	1021.8	9.610
300	7.0	7.0	7.0	7.0	7.0	510.9	7.475
200	5.0	5.0	5.0	5.0	5.0	340.6	5.339
100	3.0	3.0	3.0	4.0	3.3	170.3	3.203
6	2.0	2.0	2.0	2.0	2.0	10.2	2.136
3	1.0	1.0	1.0	1.0	1.0	5.1	1.068
PV	2.0	3.0	2.0	3.0	2.5		
AV	4.5	5.0	4.5	5.0	4.8		
YP	5.0	4.0	5.0	4.0	4.5		
Gel_{in}	1.0						
Gel_{10}	2.0						

Table A5 Water-based drilling mud mixed with Saraburi bentonite at temperature 60^oC (No.5).

RPM	**Reading #1**	**Reading #2**	**Reading #3**	**Reading #4**	**Average reading**	**γ (sec^{-1})**	**τ (lb$_f$/ft^2)**
600	11.0	11.0	11.0	10.0	10.8	1021.8	10.678
300	9.0	9.0	9.0	8.0	8.8	510.9	8.542
200	7.0	7.0	6.0	6.0	6.5	340.6	6.407
100	5.0	4.0	4.0	4.0	4.3	170.3	4.271
6	3.0	3.0	3.0	3.0	3.0	10.2	3.203
3	2.0	1.0	1.0	1.0	1.3	5.1	1.068
PV	2.0	2.0	2.0	2.0	2.0		
AV	5.5	5.5	5.5	5.0	5.4		
YP	7.0	7.0	7.0	6.0	6.8		
Gel$_{in}$	2.0						
Gel$_{10}$	3.0						

Table A6 Water-based drilling mud mixed with Saraburi bentonite at temperature 90^oC (No. 6).

RPM	**Reading #1**	**Reading #2**	**Reading #3**	**Reading #4**	**Average reading**	**γ (sec^{-1})**	**τ (lb$_f$/ft^2)**
600	12.0	12.0	12.0	12.0	12.0	1021.8	12.814
300	10.0	10.0	10.0	10.0	10.0	510.9	10.678
200	8.0	8.0	8.0	8.0	8.0	340.6	8.542
100	6.0	6.0	6.0	6.0	6.0	170.3	6.407
6	4.0	4.0	4.0	4.0	4.0	10.2	4.271
3	2.0	2.0	2.0	2.0	2.0	5.1	2.136
PV	2.0	2.0	2.0	2.0	2.0		
AV	6.0	6.0	6.0	6.0	6.0		
YP	8.0	8.0	8.0	8.0	8.0		
Gel$_{in}$	4.0						
Gel$_{10}$	5.0						

Table A7 Water-based drilling mud mixed with Lopburi bentonite at temperature 30°C (No.7).

RPM	Reading #1	Reading #2	Reading #3	Reading #4	Average reading	γ (sec⁻¹)	τ (lbf/ft²)
600	30.0	31.0	30.0	31.0	30.5	1021.8	32.034
300	22.0	20.0	21.0	21.0	21.0	510.9	22.424
200	17.0	18.0	18.0	18.0	17.8	340.6	18.153
100	14.0	14.0	14.0	13.0	13.8	170.3	13.881
6	10.0	10.0	10.0	9.0	9.8	10.2	9.610
3	8.0	8.0	8.0	8.0	8.0	5.1	8.542
PV	8.0	11.0	9.0	10.0	9.5		
AV	15.0	15.5	15.0	15.5	15.3		
YP	14.0	9.0	12.0	11.0	11.5		
Gel_{in}	8.0						
Gel_{10}	10.0						

Table A8 Water-based drilling mud mixed with Lopburi bentonite at temperature 60°C (No.8).

RPM	Reading #1	Reading #2	Reading #3	Reading #4	Average reading	γ (sec⁻¹)	τ (lbf/ft²)
600	44.0	44.0	44.0	44.0	44.0	1021.8	46.983
300	35.0	36.0	36.0	36.0	35.8	510.9	37.373
200	29.0	29.0	30.0	29.0	29.3	340.6	30.966
100	23.0	23.0	23.0	23.0	23.0	170.3	24.559
6	18.0	19.0	18.0	17.0	18.0	10.2	19.220
3	13.0	14.0	14.0	14.0	13.8	5.1	13.881
PV	9.0	8.0	8.0	8.0	8.3		
AV	22.0	22.0	22.0	22.0	22.0		
YP	26.0	28.0	28.0	28.0	27.5		
Gel_{in}	13.0						
Gel_{10}	14.0						

Table A9 Water-based drilling mud mixed with Lopburi bentonite at temperature 90°C (No.9).

RPM	Reading #1	Reading #2	Reading #3	Reading #4	Average reading	γ (sec^{-1})	τ (lb_f/ft^2)
600	63.0	62.0	63.0	63.0	62.8	1021.8	66.204
300	55.0	55.0	55.0	54.0	54.8	510.9	57.661
200	44.0	44.0	45.0	44.0	44.3	340.6	46.983
100	36.0	36.0	36.0	36.0	36.0	170.3	38.441
6	24.0	23.0	23.0	23.0	23.3	10.2	24.559
3	14.0	13.0	14.0	14.0	13.8	5.1	13.881
PV	8.0	7.0	8.0	9.0	8.0		
AV	31.5	31.0	31.5	31.5	31.4		
YP	47.0	48.0	47.0	45.0	46.8		
Gel_{in}	14.0						
Gel_{10}	15.0						

Table A10 Water-based drilling mud mixed with Kanchanaburi bentonite at temperature 30°C (No.10).

RPM	Reading #1	Reading #2	Reading #3	Reading #4	Average reading	γ (sec^{-1})	τ (lb_f/ft^2)
600	11.0	11.0	11.0	10.0	10.8	1021.8	10.678
300	6.0	6.0	6.0	6.0	6.0	510.9	6.407
200	4.0	4.0	4.0	4.0	4.0	340.6	4.271
100	4.0	3.0	3.0	3.0	3.3	170.3	3.203
6	3.0	2.0	2.0	2.0	2.3	10.2	2.136
3	1.0	1.0	1.0	1.0	1.0	5.1	1.068
PV	5.0	5.0	5.0	4.0	4.8		
AV	5.5	5.5	5.5	5.0	5.4		
YP	1.0	1.0	1.0	2.0	1.3		
Gel_{in}	1.0						
Gel_{10}	2.0						

Table A11 Water-based drilling mud mixed with Kanchanaburi bentonite at temperature 60^oC (No.11).

RPM	Reading #1	Reading #2	Reading #3	Reading #4	Average reading	γ (sec^{-1})	τ (lb_f/ft^2)
600	13.0	13.0	13.0	12.0	12.8	1021.8	12.814
300	9.0	9.0	9.0	8.0	8.8	510.9	8.542
200	7.0	7.0	7.0	6.0	6.8	340.6	6.407
100	5.0	4.0	4.0	4.0	4.3	170.3	4.271
6	4.0	3.0	3.0	3.0	3.3	10.2	3.203
3	2.0	2.0	2.0	2.0	2.0	5.1	2.136
PV	4.0	4.0	4.0	4.0	4.0		
AV	6.5	6.5	6.5	6.0	6.4		
YP	5.0	5.0	5.0	4.0	4.8		
Gel_{in}	2.0						
Gel_{10}	3.0						

Table A12 Water-based drilling mud mixed with Kanchanaburi bentonite at temperature 90^oC (No.12).

RPM	Reading #1	Reading #2	Reading #3	Reading #4	Average reading	γ (sec^{-1})	τ (lb_f/ft^2)
600	14.0	14.0	15.0	15.0	14.5	1021.8	14.949
300	11.0	11.0	11.0	10.0	10.8	510.9	10.678
200	7.0	7.0	7.0	7.0	7.0	340.6	7.475
100	6.0	6.0	5.0	5.0	5.5	170.3	5.339
6	4.0	4.0	4.0	4.0	4.0	10.2	4.271
3	3.0	3.0	3.0	3.0	3.0	5.1	3.203
PV	3.0	3.0	4.0	5.0	3.8		
AV	7.0	7.0	7.5	7.5	7.3		
YP	8.0	8.0	7.0	5.0	7.0		
Gel_{in}	3.0						
Gel_{10}	4.0						

API static filtrate loss and mud filter cake thickness data for all tested

Table A13 Filtrate loss drilling mud mixed with bentonite in each country at temperature 30, 60 and 90°C.

Sample	**Temperature (°C)**	**No.**	**Filtrate loss (ml)**					
			1 min	**4 min**	**9 min**	**16 min**	**25 min**	**30 min**
America bentonite (Base)	30	1	2	4.5	7	10	12.5	13.5
	60	2	2	4.5	8	10.5	13	15
	90	3	2	5.5	9.5	12	15	17
Saraburi bentonite	30	4	39	78	110	138	171	180
	60	5	37	78	113	144	175	184
	90	6	36	81	120	153	181	195
Lopburi bentonite	30	7	2.5	6.5	10.5	14.5	18.5	20.5
	60	8	3	8	11	15	19	21
	90	9	4	7.5	11.5	15.75	19.75	21.5
Kanchanaburi bentonite	30	10	5.5	12	17.5	25	31	34
	60	11	7	18	27	35.5	43	47
	90	12	8	20	36	48	59	64

Table A14 Mud filter cake thickness drilling mud mixed with America bentonite (Base) at temperature 30, 60 and 90°C.

No.	Mud filter cake thickness (mm)			Average (mm)
	#1	#2	#3	
1	1.97	1.96	1.95	1.96
2	2.20	2.30	2.10	2.20
3	2.57	2.55	2.55	2.56

Table A15 Mud filter cake thickness drilling mud mixed with Saraburi bentonite at temperature 30, 60 and 90°C.

No.	Mud filter cake thickness (mm)			Average (mm)
	#1	#2	#3	
4	5.08	5.12	5.10	5.10
5	6.08	6.06	6.10	6.08
6	6.28	6.16	6.20	6.21

Table A16 Mud filter cake thickness drilling mud mixed with Lopburi bentonite at temperature 30, 60 and 90°C.

No.	Mud filter cake thickness (mm)			Average (mm)
	#1	#2	#3	
7	2.28	2.34	2.29	2.30
8	2.45	2.40	2.47	2.44
9	2.72	2.74	2.70	2.72

Table A17 Mud filter cake thickness drilling mud mixed with Kanchanaburi bentonite at temperature 30, 60 and 90^{o}C.

No.	**Mud filter cake thickness (mm)**			**Average (mm)**
	#1	**#2**	**#3**	
10	2.96	2.97	2.96	2.96
11	3.13	3.12	3.12	3.12
12	3.26	3.29	3.30	3.28

Fluid density data for all tested

Table A18 Fluid density all drilling mud.

Sample	No.	Average density				
		Temp. (°C)	Fluid density			Pressure gradient
			g/cm³	lb/gal	lb/ft³	lb/in²/1000ft
America bentonite (Base)	1	30	1.1	9.180	68.671	476.667
	2	60	1.098	9.163	68.546	475.800
	3	90	1.095	9.138	68.359	474.500
Saraburi bentonite	13	30	1.067	8.905	66.611	462.367
	14	60	1.063	8.871	66.361	460.633
	15	90	1.060	8.846	66.174	459.333
Lopburi bentonite	16	30	1.098	9.163	68.546	475.800
	17	60	1.095	9.138	68.359	474.500
	18	90	1.092	9.113	68.171	473.200
Kanchanaburi bentonite	19	30	1.075	8.971	67.110	465.833
	20	60	1.073	8.955	66.985	464.967
	21	90	1.070	8.930	66.798	463.667

Hydrogen ion concentration data for all tested

Table A19 Water based drilling mud in 30, 60, and 90 ˚C.

Sample	No.	Temp. (ºC)		pH reading			Average
				#1	#2	#3	
America bentonite (Base)	1	30	Mud	9.87	9.85	9.86	9.86
			Mud filtrate	9.51	9.53	9.53	9.52
	2	60	Mud	9.68	9.66	9.64	9.66
			Mud filtrate	8.81	8.81	8.82	8.81
	3	90	Mud	9.53	9.52	9.53	9.53
			Mud filtrate	8.55	8.53	8.53	8.54
Saraburi bentonite	4	30	Mud	7.88	7.88	7.85	7.87
			Mud filtrate	7.80	7.76	7.79	7.78
	5	60	Mud	7.58	7.6	7.58	7.59
			Mud filtrate	7.49	7.45	7.49	7.48
	6	90	Mud	7.47	7.48	7.49	7.48
			Mud filtrate	7.32	7.37	7.40	7.36
Lopburi bentonite	7	30	Mud	9.94	9.96	9.95	9.95
			Mud filtrate	9.73	9.71	9.71	9.72
	8	60	Mud	9.79	9.77	9.74	9.77
			Mud filtrate	9.64	9.63	9.63	9.63
	9	90	Mud	9.52	9.51	9.56	9.53
			Mud filtrate	9.37	9.38	9.38	9.38
Kanchanaburi bentonite	10	30	Mud	9.06	9.06	9.05	9.06
			Mud filtrate	8.97	8.94	8.92	8.94
	11	60	Mud	8.9	8.93	8.96	8.93
			Mud filtrate	8.82	8.81	8.81	8.81
	12	90	Mud	8.86	8.91	8.89	8.89
			Mud filtrate	8.72	8.72	8.70	8.71

Solid content and sand content data for all tested

Table A20 Solid content and sand content all drilling mud.

Sample	No.	Average solid content		Average sand content (%)
		Water (ml)	Solid (%)	
America bentonite (Base)	1	47	6	0.25
	2	46	8	0.26
	3	45.5	9	0.26
Saraburi bentonite	4	49	2	0.5
	5	48.5	3	0.55
	6	48	4	0.6
Lopburi bentonite	7	46.5	7	0.2
	8	46.5	7	0.25
	9	45.5	9	0.3
Kanchanaburi bentonite	10	46	8	0.5
	11	45.5	9	0.56
	12	45.5	9	0.58

Resistivity data for all tested

Table A21 Resistivity of drilling mud mixed with America bentonite (Base) at temperature 30°C (No.1).

Sample	Temperature (°F)	#1	#2	#3	Average (Ω.m)
		(Ω.m)			
Mud	79.7	5.76	5.80	5.77	5.78
Mud filtrate	75.0	6.6	6.55	6.53	6.56
Mud cake	75.9		4.67		4.67

Table A22 Resistivity of drilling mud mixed with America bentonite (Base) at temperature 60°C (No.2).

Sample	Temperature (°F)	#1	#2	#3	Average (Ω.m)
		(Ω.m)			
Mud	78.3	5.49	5.55	5.58	5.54
Mud filtrate	73.2	6.44	6.43	6.43	6.43
Mud cake	72.2		4.48		4.48

Table A23 Resistivity of drilling mud mixed with America bentonite (Base) at temperature 90°C (No.3).

Sample	Temperature (°F)	#1	#2	#3	Average (Ω.m)
		(Ω.m)			
Mud	79.9	5.32	5.36	5.39	5.36
Mud filtrate	73.7	6.08	6.07	6.14	6.10
Mud cake	72.7		4.18		4.18

Table A24 Resistivity of drilling mud mixed with Saraburi bentonite at temperature 30^{o}C (No.4).

Sample	Temperature (°F)	#1	#2	#3	Average (Ω.m)
		(Ω.m)			
Mud	78.5	18.24	18.36	18.28	18.29
Mud filtrate	74.7	19.14	19.19	19.2	19.18
Mud cake	75.6	16.17			16.17

Table A25 Resistivity of drilling mud mixed with Saraburi bentonite at temperature 60^{o}C (No.5).

Sample	Temperature (°F)	#1	#2	#3	Average (Ω.m)
		(Ω.m)			
Mud	78.2	17.75	17.52	17.55	17.61
Mud filtrate	73	19.02	18.98	18.94	18.98
Mud cake	72	15.73			15.73

Table A26 Resistivity of drilling mud mixed with Saraburi bentonite at temperature 90^{o}C (No.6).

Sample	Temperature (°F)	#1	#2	#3	Average (Ω.m)
		(Ω.m)			
Mud	77.4	16.38	16.54	16.49	16.47
Mud filtrate	73.3	18.44	18.53	18.49	18.49
Mud cake	71.4	14.87			14.87

Table A27 Resistivity of drilling mud mixed with Lopburi bentonite at temperature 30°C (No.7).

Sample	Temperature (°F)	#1	#2	#3	Average (Ω.m)
		(Ω.m)			
Mud	79.4	5.05	5.02	5.06	5.04
Mud filtrate	74.6	6.09	6.11	6.02	6.07
Mud cake	75.6	4.05			4.05

Table A28 Resistivity of drilling mud mixed with Lopburi bentonite at temperature 60°C (No.8).

Sample	Temperature (°F)	#1	#2	#3	Average (Ω.m)
		(Ω.m)			
Mud	78	4.84	4.77	4.79	4.80
Mud filtrate	72	5.55	5.43	5.50	5.49
Mud cake	71.4	3.51			3.51

Table A29 Resistivity of drilling mud mixed with Lopburi bentonite at temperature 90°C (No.9).

Sample	Temperature (°F)	#1	#2	#3	Average (Ω.m)
		(Ω.m)			
Mud	79.4	4.45	4.44	4.41	4.43
Mud filtrate	73	5.21	5.30	5.24	5.25
Mud cake	72	3.24			3.24

Table A30 Resistivity of drilling mud mixed with Kanchanaburi bentonite at temperature 30°C (No.10).

Sample	Temperature (°F)	#1	#2	#3	Average (Ω.m)
		(Ω.m)			
Mud	71.9	6.24	6.31	6.26	6.27
Mud filtrate	73.6	7.77	7.43	7.49	7.56
Mud cake	73.9	5.45			5.45

Table A31 Resistivity of drilling mud mixed with Kanchanaburi bentonite at temperature 60°C (No.11).

Sample	Temperature (°F)	#1	#2	#3	Average (Ω.m)
		(Ω.m)			
Mud	74	6.13	6.1	6.11	6.11
Mud filtrate	72.1	7.13	7.16	7.2	7.16
Mud cake	76.3	4.75			4.75

Table A32 Resistivity of drilling mud mixed with Kanchanaburi bentonite at temperature 90°C (No.12).

Sample	Temperature (°F)	#1	#2	#3	Average (Ω.m)
		(Ω.m)			
Mud	79	5.69	5.72	5.75	5.72
Mud filtrate	73.8	6.4	6.35	6.27	6.34
Mud cake	72.5	4.21			4.21

APPENDIX B

PUBLICATION

List of Publication

Phoovasawat, C. and Terakulsatit, B. (2016). **Comparison of the Rheological Property between Bentonite from Lopburi and Kanchanaburi Provinces and Others Commercial Bentonite in Drilling Mud.** The 5^{th} Suan Sunandha Academic National Conference on "Research for Sustainable Development", December 1^{st}–2^{nd}, 2016, 15PP.

BIOGRAPHY

Miss. Chalermluck Phoovasawat was born on December 5, 1991 in Nakhon Ratchasima province, Thailand. She received her Bachelor's Degree in Engineering (Geotechnology) from Suranaree University of Technology in 2013. For her post graduate, she continued to study with a Master's degree in the Geotechnology Program, Institute of Engineering, Suranaree university of Technology. During graduation, 2014-2016, she served in position of teacher and research assistant at SUT. Since 2014, she has been a part-time teacher laboratory at SUT.