Impact of Nano-Bentonite in Water-Based Mud (WBM) on Reservoir Formation Damage

by

Hing Chai Shing

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

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Approved by,

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UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

MAY 2013

CERTIFICATION OF ORIGINALITY

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

HING CHAI SHING

ABSTRACT

Drilling operations often cause formation damage around the wellbore which leads to productivity impairment and high skin factor. The main factors of formation damage are mud filtrate loss and spurt loss due to poor quality mud cake. Interaction between mud filtrate and formation results in severe damage such as clay swelling which causes wellbore instability. Conventional macro and micro based drilling fluids are unable to fulfill certain functional tasks in the increasingly challenging drilling and production environment. Nanotechnology has come to the forefront of research in the past decade with numerous applications in various tindustries. Nano-particles are expected to offer better solutions in preventing formation damage and drilling related issues due to their enhanced physical, mechanical, chemical, thermal and environmental characteristics. Therefore, this project investigates the applicability of nano-bentonite as drilling mud additive in water based mud (WBM) and its impact on formation damage and overall drilling operation.

This paper describes the formulation and preliminary test results of several nano-based drilling fluids starting with the production of nano-particle size bentonite through mechanical grinding using planetary ball mill. The nano-based drilling fluids were formulated using a blend of nano-bentonite and several mud additives to study the rheological and filtration properties and evaluate its suitability for oil and gas field application. Initial mud formulation without the use any mud additives showed lower performance in term of mud rheology. Different combinations of nano-bentonite and mud additives were then tested to obtain the desirable rheological and filtration properties along with the gelling behavior and mud cake quality. The experiments showed that nano-based drilling fluids are able to reduce the mud spurt and filtrate loss with the deposition of thin, well dispersed and effective mud cake. Therefore, these muds could be adopted and used in drilling operations in normal formations to reduce formation damage and drilling related problems.

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Honorably thanking Universiti Teknologi PETRONAS (UTP) for giving me this opportunity to complete my Final Year Project (FYP). Special thanks to all Petroleum Engineering Department staff for their kind support and help. My utmost appreciation and gratitude towards my FYP supervisor, Mr. Ali F. Mangi Alta'ee who provided me guidance and support throughout the process. Many thanks also to Petroleum Engineering Drilling Lab technicians, UTP Nanotechnology Research Centre and Civil Engineering Department for their kind assistance. Not to be forgotten, all the people directly or indirectly involved in completing this project.

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CHAPTER 1:

INTRODUCTION

1.1 Project Background

1.1.1 Drilling Fluid

Schlumberger Oilfield Glossary (2013) defines drilling fluid as "any of a number of liquid and gaseous fluids and mixtures of fluids and solids (as solid suspensions, mixtures and emulsions of liquids, gases and solids) used in operations to drill boreholes into the earth." The main constituents of drilling fluids include water, oil/gas, and chemical additives. The drilling fluids are classified according to the component that dictates the functions and performance of the mud: (1) water-base, (2) non-water-base and (3) gaseous (pneumatic). Water based mud (WBM) which will be focused in this project consists of water or saltwater as main liquid phase and the wetting (external) phase. WBM can be categorized into fresh water, seawater, salt water, lime, potassium, and silicate mud. Other than the main fluid phase, drilling fluid contains suspension of solids and additives as well to fulfill the drilling requirements. The functions of a drilling fluid are: (1) transport cuttings from wellbore to the surface; (2) cool and lubricate drilling bit; (3) minimize friction between the drilling string and borehole wall; (4) maintain wellbore stability; (5) prevent sudden fluid influx; (6) form a thin, low-permeability filter cake to seal pores in surrounding formation, and (7) gather information available from drilling cuttings, cores, and electrical logs (Hossain and Al-Majeed, 2012).

1.1.2 Bentonite

Bentonite is a clay mineral used as drilling fluid additives. Its main functions are to increase the mud viscosity and control fluid loss to the formation. Bentonite also adds suspension characteristics to the drilling fluid, often referred as gel strength or the ability to suspend and carry solid out of the wellbore. A high quality bentonite should consist mainly of montmorillonite (Brindley and Brown, 1980). However, other clay minerals can often be found in bentonite such as elites, kaolinites, chlorites and non-clay components such as quartz and feldspar. Montmorillonitic clays possess the swelling ability to act as viscosifier and assist the formation of low permeability filter cake. Therefore, the bentonite quality will be affected by the presence of other minerals. The swelling capacity of montmorrilonite is determined by the type of exchangeable ions, with sodium montmorillonite performing the best. Bentonite extender such as sodium carbonate can be added to further enhance the mud viscosity by slightly flocculating the bentonite in suspension. It was shown that sodium is essential to obtain a well dispersed bentonite suspension.

1.1.3 Nano-based drilling fluid

Nanotechnology enables the manipulation of matters on the nanometer scale, making it possible to create a new generation of materials with enhanced mechanical, optical and magnetic properties. Through nanotechnology, nano-materials which range from 1 nm to 100 nm, can be synthesized. The dimension of nanomaterials lies between the atomic and macroscopic materials, hence they will demonstrate their own unique properties instead of atomic and macroscopic properties. This includes surface effect, small size effect, quanta size effect and macroscopical quantum tunnel effect (Nabhani *et al*., 2011). The fact that nano-materials possess specific characteristics in comparison with traditional materials greatly expands the application range of nano-materials in various fields. Nanotechnology may provide better solutions to problems related to drilling operations, and improve the comprehensive benefit of petroleum production and development (Kong *et al*., 2010).

Nano-based drilling fluid contains at least one additive with particle size in the range of 1-100 nanometers. Physically, a nano sized particle has a dimension that is thousand millionths of a meter. 100 nanometer particles have diameters that are about 800 to 1000 times smaller than the diameter of a human hair (Saeid *et al*., 2006). Nano-based drilling fluid can be classified into simple nano-fluid and advanced nano-fluid based on the number of nano-sized additives in the fluid Simple nano-fluids contain only one nano particle additive whereas advanced nano-fluids contain more than one nano-sized additives. Nano-materials can be categorized as single functional or multifunctional based on the functions they perform. A multifunctional nano-material can carry out several functional tasks of the fluid, hence reduces the solid/chemical content of the fluid and substantially decreases the overall cost.

1.2 Problem Statement

During drilling operation, drilling fluid is the first foreign fluid that contacts the formation zone. The solid additives used in mud formulation can cause severe formation damage due to poor quality filter cake. Drilling will generate cutting debris containing micro-sized and colloidal particles which can damage the reservoir. Hence, drilling muds must be able to form a well dispersed, tight and thin plaster like external mud cake on the borehole wall to protect the reservoir zone beyond the wall. Interaction between the invading solids and liquids with the formation may lead to precipitation, clay swelling, pore throat blockage which will create barrier to hydrocarbon flow. Therefore, prevention of formation damage is more cost effective than cleaning the damage after production starts.

Fluid penetration into shale formation will cause serious wellbore stability issue because interaction between water and shale formations will result in clay swelling. Conventional drilling fluids are too large in size, therefore they are unable to form effective mud cake to seal off the shale surface and prevent fluid invasion. The resulting clay swelling will block existing flow path and affect the reservoir productivity. Problems associated with clay swelling such as sloughing shale, hole closure and cave-ins pose setback to drilling operations. It can reduce hole cleaning efficiency, rate of penetration, and even result in the loss of the drilling assembly or total abandonment of the well. These issues will significantly increase exploration and production costs.

Oil based mud (OBM) can prevent shale instability issue as there is no interaction between oil and shale. However, the use of OBM is uneconomical and not environmental friendly. Hence, water-based mud would be preferred if it could prevent fluid penetration into the formation. Sealing the exposed clayey surfaces is the most effective way to prevent contact between argillaceous rock and water. Therefore, there is a need to develop a nano-based WBM that can seal off the formation zone effectively by forming high quality mud without compromising the rheological properties requirements of the mud.

1.2.1 Problems Identification

The problems identified are:

i. Conventional WBM are unable to form effective mud cake to prevent filtrate loss into formation, leading to formation damage.
ii. OBM can prevent wellbore stability issues related to shale but is not cost effective and may cause environmental problems.

1.3 Objectives

This project aims to investigate the applicability of nano-bentonite in water based mud (WBM) for controlling formation damage and drilling-related issues. The objectives of this project are stated below:

i. To formulate a stabilized nano-based WBM using nano-bentonite as the mud additive.
ii. To study the impact of nano-bentonite on the drilling fluid's rheological properties and formation damage (reservoir skin factor).
iii. To compare the performance of nano-based WBM against the conventional WBM.

1.4 Scope of study

This project will revolve around drilling fluids (WBM to be exact) used for normal drilling operations. It is highly relevant to the program of study and has future applications in the oil and gas industry. It will require execution of laboratory experiments for drilling fluid formulation and evaluation. The laboratory testing could be conducted at UTP Block 15 Core Analysis Lab which provides all the necessary equipments. In addition, it might require UTP Nanotechnology Research Centre facilities for nano-material preparation and characterization. The proposed topic is related to the university curriculum structure and the project is feasible to be completed within the proposed time.

CHAPTER 2:

LITERATURE REVIEW

2.1 Water-Based Mud (WBM)

Water based mud is a type of drilling fluid whereby water is the continuous phase (Rigsmarts, 2013). Mud additives are added in order to alter the rheological properties of the mud to fulfill its functional tasks. WBM possesses advantage over oil based mud (OBM) and synthetic based mud (SBM) that it has higher fracture gradient and is relatively cost effective compared to its counterparts. The rheological properties of WBM are also not so strongly affected by changes in pressure and temperature. However, WBM has less lubricating power and may cause wellbore stability issues especially in shale formation. The efficiency of hole cleaning using WBM is relatively lower. Despite its disadvantages, environmentally-friendly WBM will be preferred over OBM and OBM if its properties could be enhanced.

2.2 Formation Damage Mechanisms

Jilani *et al.* (2001) defined formation damage as the process that results in reduction of the flow capacity of hydrocarbon bearing zone. The zone of altered permeability is referred as skin and the resulting effect as skin effect. Skin factor can be defined using the following equation: $S=(k/k_s–1).ln(r_s/r_w)$, where k is the reservoir permeability; k_s is the damaged zone permeability; r_s is the damaged zone radius; and r_w is the well radius. Formation damage during drilling is commonly caused by spurt loss and mud filtrate loss (Amanullah and Al-Tahini, 2009). Spurt loss refers to the instantaneous flux of fluid into the formation in contact before the formation of filter cake. These early spurt loss contributes to a great extent of formation damage due to solid and fluid invasion into the virgin reservoir. Solid particles invasion during spurt loss causes pore bridging which impedes fluid flow into the well. Filtrate from the drilling fluid may cause chemical reactions including clay swelling and dispersion and salt precipitation which lead to formation of internal mud cake. This results in severe formation damage as the mud cake is difficult to remove by the conventional production back flow.

Wellbore instability is a serious concern especially in shale formation. Water-based mud will cause wellbore instability when fluid penetration into shale formations results in clay swelling (Cai *et al*., 2012). The particles in conventional drilling fluids are unable to seal the nano-sized pore throats of shales due to their large size. This prevents the formation of effective mud cake on the shale surface to prevent fluid invasion. Shales account for 75% of the all footage drilled (Steiger, 1992) and are responsible for 90% of wellbore-stability problems.

Shale might contain up to 80 percent of water-sensitive clays - montmorillonites, illites, and interlayered varieties (O'Brien and Chenevert, 1973). These clays will easily hydrate and swell when come into contact with filtrate from water-based mud, eventually blocking the pore throats. Dispersion of shale cuttings poses another drilling problem. Dispersion refers to a continuous and often rapid disintegration of the shale surface as the material is contacted by a water-based fluid and swells. The degree of shale dispersion depends on the amount of expandable clay present in the shale. Clay dispersion causes sloughing and uncontrolled buildups of finely divided, low-gravity solids in the mud system. If the dispersion of shale cuttings persists, it may result in damage of the surface handling equipment and halt the operation.

Al-Bazali *et al*. (2005) found that the average pore-throat sizes of shales range from 10 to 30 nm. In contrast, drilling-fluid additives such as bentonite and barite have average particle diameters in the range of 100 to 10,000 nm, which is much larger than the pore size. Conventional filtration additives also fail to form mud cakes due to the extremely low permeability and small pore-throat size observed in shales. Nano-sized particles have the ability to plug pore throats in shales, thus preventing fluid loss. Abrams (1977) proposed that the median particle size of a bridging additive should be equal to or slightly greater than one-third of the median pore size of the formation and that the concentration of bridging- sized solids must be at least 5% by volume of the solids in the final mud mix. Therefore, nano particles can come into play to prevent spurt and mud filtrate loss.

2.3 Formation Damage Testing

Pressure leak off or pressure penetration test can be used to simulate drilling fluid circulation process in the wellbore under in situ conditions (Riley *et al.*, 2012). It can examine the effect of filter cake on filtrate loss prevention through physical plugging.

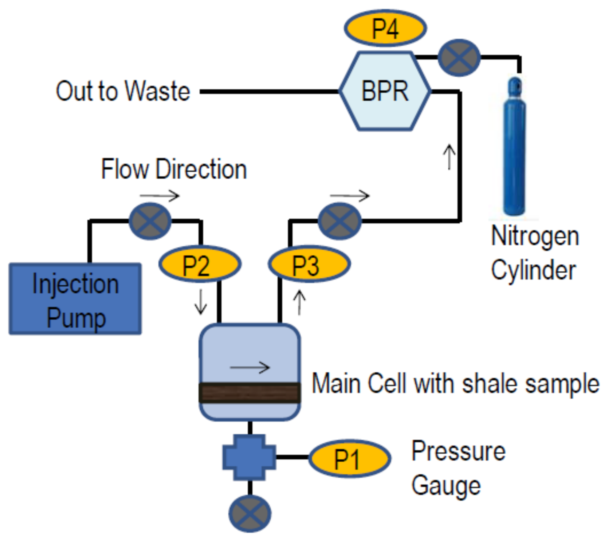


Figure 1: Pressure leak off test experimental setup

A core holder is used to mount the core used in the experiment. A test fluid is circulated across the surface of the core from the injection end at a constant pressure while the pressure build up in the bottom of the core is measured. The permeability across the core is determined from the pressure build up at the bottom of core. The test is repeated using water-based mud to indicate its filter loss control property. The more significant the permeability reduction between the water-based mud and test fluid, the better is the physical plugging through filter cake formation.

2.4 Bentonite as Fluid Loss Control Agent

Bentonite can be classified into sodium bentonite or calcium bentonite according to the dominant exchangeable cation (Trauger, 1994). However, the main constituent of bentonite is montmorillonite. Montmorillonite are three-layered minerals which consist of two tetrahedral layers sandwiched around a central octahedral layer as shown in Figure 2.

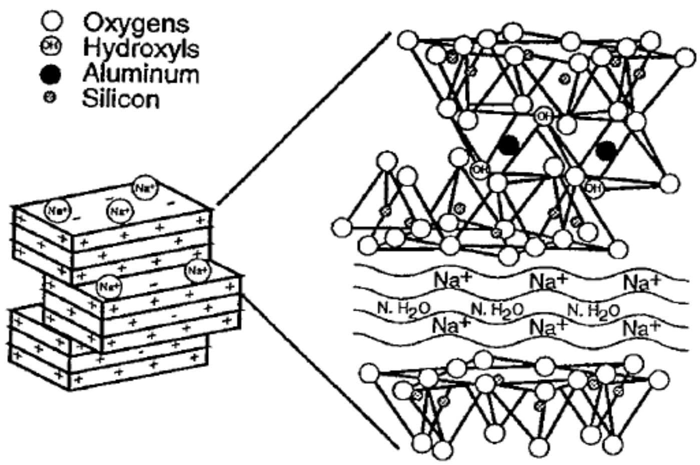


Figure 2: Schematic molecular structure of sodium montmorillonite

The platelets of montmorillonite are mostly grouped together in a face-to-face arrangement with exchangeable cations (sodium or calcium) in the interlayer region between the platelet. The presence of exchangeable cations allows water to be absorbed in the interlayer region, causing remarkable increase in the interlayer space. This is referred as the swelling properties of bentonite.

Other than being the drilling fluid's viscosifier, bentonite also acts as the fluid loss control agent by forming mud cake to prevent solid and filtrate loss. The formation of effective external mud cake depends on several factors such as the average pore size in formation, median size of bridging particles and their concentration as well as drilling operation conditions like overbalance drilling which affect the mud deposition (Jilani *et al.*, 2001).

2.5 Nanotechnology in Drilling Fluid

The laws governing nano-materials are drastically different than that of macro and micro scale materials due to beyond colloidal sizes of nano-particles with their close proximity to the atomic scale compared to macros and micros (Islam, 2004). Nano-materials exhibit superior properties compared to their parent materials due to factors like nano-particle grain boundary, surface area per unit/mass or volume, size of the particles, purity and perfection of the particles, etc. This creates unique properties to the nanos that are non-existent in the mother source. Increased surface area to volume ratio of nano-materials enables dramatically increased interaction potentials with a significantly lower concentration of the materials. This property plays an important role in the development of a smart fluid to eliminate shale-mud interactions and the consequent borehole instability.

To avoid mud induced formation damage, it is important to use drilling fluids with no/negligible spurt and filtrate loss potential (*Jilani et al.*, 2001). The best way to minimize formation damage caused by solid and filtrate invasion is by building uniform, low-permeability and high strength filter cake around the wellbore. Nano-based fluids are expected to minimize the scope of reservoir damage with their ability to form thin, non-erodible and impermeable mud cake and improve well productivity. The formation of thin and uniform mud cake enables efficient cleaning by back flow after drilling and completion operations.

Howard *et al*. (1951) stated that the control and prevention of lost circulation of drilling mud is essential during drilling operations. The severity of the loss of circulation depends on the location, nature, formations, and in-situ stresses in the vicinity of the thief zones. Loss of circulation occurs in poorly consolidated formations due to high poro-perm characteristics of the formation. The presence of fractures in formation also results in partial to total loss of circulation. Micro and macro material-based lost circulation material (LCM) showed limited effectiveness in preventing loss of circulation. Nano-particles with sealing and strengthening potential can be used to provide effective sealing of the porous and permeable zones, fractured and cavernous formations due to their smaller size compared to the conventional LCM.

Formations which are poorly consolidated are mechanically weak and often load to borehole instability problem because of little cementation and inter-particle cohesion (Amanullah and Richard, 2006). Conventional macro or micro-material-based drilling mud is unable to prevent sanding, hole collapse, washout, fracturing etc. due to their inability to strengthen near wellbore formation and widen the mud weight window. In contrast, nano-particles are able to access to the pores and inter-granular contact surfaces of the unconsolidated sand particles easily due to their ultrafine size. Nano-materials with gluing and cementing properties can strengthen the formation by forming bonded networks of particles within the formation matrix, therefore avoiding collapse and other unconsolidated formation related borehole instability.

Drilling operations of deviated, horizontal and extended reach wells can be severely affected by solids sagging and cuttings bed formation (Amanullah and Tan, 2001). The settlement of rock cuttings in wellbore will reduce the hole cleaning efficiency of drilling mud. Nano-particles with quick gelling and fragile gel characters can effectively transport the cuttings from wellbore and reduce the hole cleaning problems. The fragile characteristic of nano-based drilling mud can reduce required pump pressure to initiate of circulation after the mud remains static for a period. Directional drilling and extended reach drilling often encounter problems due to increase in torque and drag while drilling as reported by Amanullah and Al-Tahini (2009). Friction between the drill string and borehole wall contributes to the torque and drag issues. The ability of nano-based fluid to form continuous and thin lubricating mud cake effectively reduces the frictional resistance between the pipe and borehole wall.

The wear and tear of down hole tools and equipments is another major problem encountered while drilling, especially in deviated, horizontal and extended reach wells (Amanullah *et al*., 2011). The macro and micro sized additives added in conventional drilling mud to fulfill certain functional tasks increase the kinetic energy impact and accelerate the wear and tear of the equipments. By using nano-sized particles, the wear and tear of down hole equipments is dramatically reduced, thus reducing the non-producing time (NPT) for replacing damaged equipments. Amanullah and Al-Tahini (2009) also identified high solids content of drilling mud as the factor that increases formation damage, reduces well productivity and decreases the rate of penetration (ROP). The ROP can be improved significantly by the reduction of the amounts of desirable and non-desirable solid content of drilling mud. Nano-based fluid only requires small volume of nano-particles due to their high surface area to volume ratio; therefore it can dramatically reduce the solids content of mud with a significant increase in the ROP.

2.6 Planetary Ball Milling

Ball milling represents one of the mechanical attrition methods of producing nanoparticles from the “top-down” process (De Castro and Mitchell, 2002). Planetary ball mill can be used to reduce the particle size down to nano scale. The fundamental principle of size reduction in ball milling devices depends on energy imparted to the sample during impacts between the milling media. The collision between the grinding balls crushes the sample between them, hence reducing their size as shown in Figure 3.

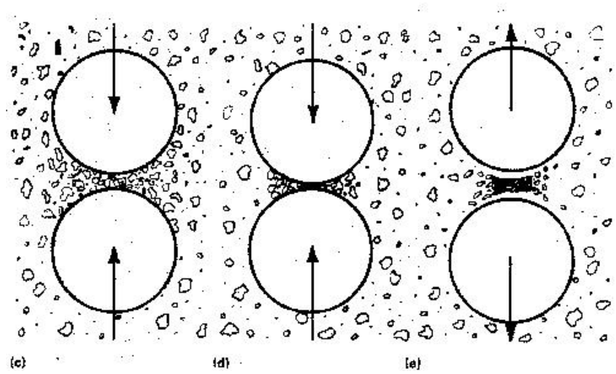


Figure 3: Fundamental principle behind ball milling

Planetary ball mill operates on planet-like movement of its vials which are arranged on a rotating disk and rotated around their own axes. The rotation produces centrifugal force to crush the material and reduce its particle sizes though the friction effect. Several factors affect the size of ball milling product, which include grinding speed, time and the amount of grinding balls used.

2.7 Formulation of Nano-based Drilling Fluid

Stabilization of nano-particles in drilling mud is essential during the fluid formulation in order to prepare a homogenous and stable nano-based drilling fluid (Amanullah *et al*., 2011). High surface forces of the nano-particles trigger quick flocculation of mechanically dispersed particles when mechanical agitation ceases, leading to the agglomeration of the particles. Gravitational force will cause the sedimentation of the particles once the flocs and aggregates of nano-particles become physically significant. Therefore, there is a need to enhance the viscous characteristics of the fluid in order to create shielding around the nano-particles and prevent agglomeration. Chemicals, polymer and surfactants with high shielding or neutralizing capabilities are able to provide long term stability of nano-based fluid, but is uneconomical. Therefore, identification of an economically attractive, technically suitable and environment friendly additive was an important part of the fluid formulation. Long term stability of the formulated nano-based fluid is important so that it can maintain its rheological properties to fulfill its functional tasks while drilling.

2.8 Literature Review Summary

Conventional water based mud is unable to form effective mud cake and prevent reservoir formation damage. The main formation damage mechanisms include spurt and filtrate loss as a result of poor mud cake formation which cannot seal the borehole wall effectively. Interaction between the invading fluids and the formation leads to wellbore stability issues, especially in shale formations. Nanotechnology is expected to provide solution to a better WBM which can reduce formation damage and drilling related problems. Due to their ultra fine particle size, nano-particles exhibit superior properties compared to their parent materials such as increased surface area to volume ratio. The enhanced properties of nano-particles make the development of smart fluid for drilling applications possible. Nano-based drilling fluids have the ability to form thin and impermeable mud cake to prevent fluid invasion into formation. It is also able to prevent loss of circulation and borehole stability issues due to unconsolidated formation. The use of nano-particles enhances wellbore cleaning efficiency and reduces wear and tear of downhole equipments. This could significantly increase drilling rates and minimizes drilling and completion risks. However, the synthesis of nano-based fluids will require stabilizing agents in order to prevent nano-particles from agglomerating and ensure long term performance of the fluid.

CHAPTER 3:

METHODOLOGY

3.1 Research Methodology

The general workflow of this project is as shown below:

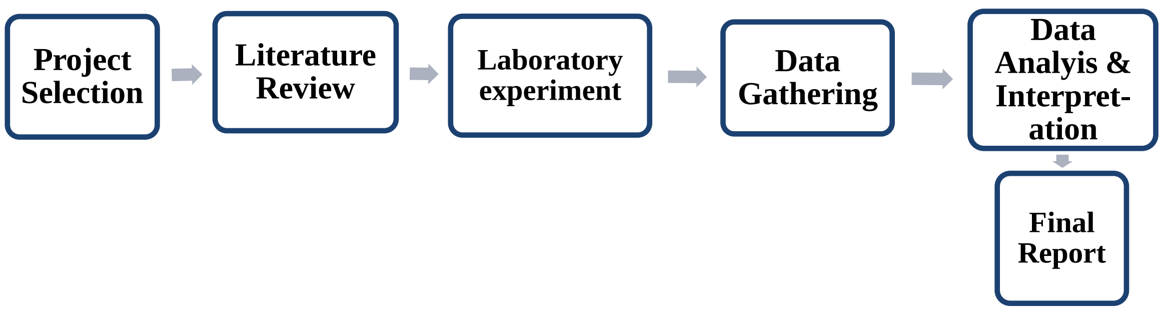
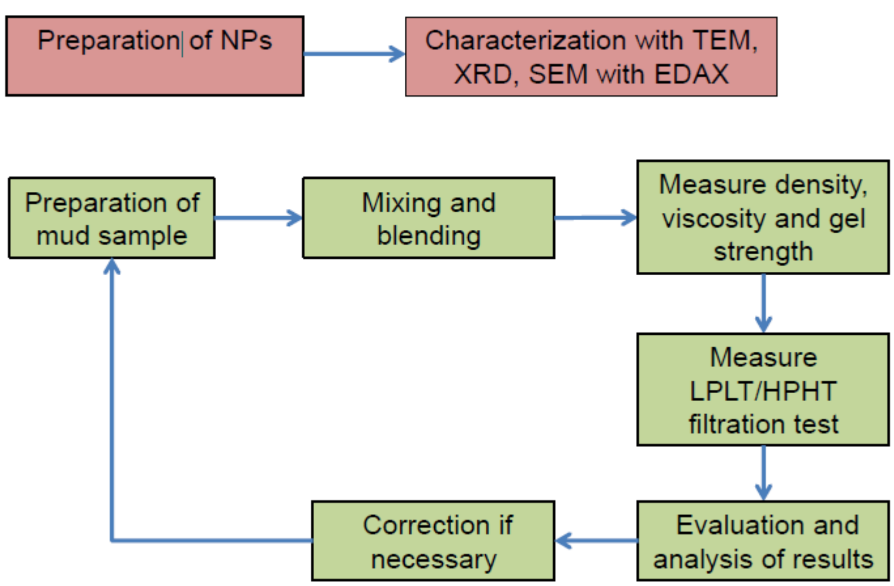


Figure 4: Project Workflow

The suggested experimental protocol is as shown below:



Abbreviations

NP : Nano-particle

TEM : Transmission Electron Microscopy

XRD : X-Ray Diffraction

SEM : Scanning Electron Microscopy

EDAX : Nano-particle characterization equipment

Figure 5: Experimental protocol

3.2 Project Activities

The project involves mainly laboratory experiments on drilling fluid as categorized below:

i. **Nano-particle preparation and characterization**

Nano-material preparation equipment will be used to prepare nano-bentonite with particle dimension of 1-100 nm. The nano-bentonite will then be characterized using equipments such as TEM, XRD and SEM (subject to availability).

ii. **Drilling fluid characterization**

The rheological properties of the drilling fluid formulated will be measured using a FANN (Model 35A) Viscometer at room temperature. The viscometer is operated at different RPM readings in order to calculate the plastic viscosity (PV), yield point (YP) and gel strength.

Plastic Viscosity (centipoises) = 600 RPM reading - 300 RPM Reading

Yield Point (lb/ft^2) = 300 RPM Reading - Plastic Viscosity

Filtration test is conducted to measure filtrate loss and mud cake building ability.

iii. **Formation Damage Testing**

Non-destructive formation damage testing, which is leak-off test will be conducted in this project. The leak-off experiment is used to simulate the drilling fluid circulation process in the wellbore at bottomhole conditions. The equipment involved is TEMCO FDS-800-10000 HTHP Formation Damage Test System designed for formation damage testing of core samples under reservoir conditions. This equipment is able to perform testing such as initial oil saturation, secondary water flooding, formation damage with leak-off through the core and before-and-after permeability measurement, in both forward and reverse directions. Fluids such as brine, oil, drilling mud etc. can be injected into and through the core sample.

3.3 Tools / Equipment

i. Nano-particle preparation and characterization

Fritsch Planetary Mill PULVERISETTE 5 classic line

- To mechanically grind the bentonite powder up to nano scale.

Field-Emission Scanning Electron Microscope (FESEM)

- To image and characterize the size of nano-bentonite.

ii. Drilling fluid characterization

FANN (Model 35A) Viscometer

- To measure drilling fluid's yield point, plastic viscosity and gel strength.

Standard API Filter Press

- To measure drilling fluid's filtration properties.

iii. Formation Damage Testing

TEMCO FDS-800-10000 HTHP Formation Damage Test System

- To perform pressure leak off test to measure drilling fluid's damage prevention properties.

Figure 6: FANN (Model 35A) Viscometer

Figure 7: TEMCO FDS-800-10000 HTHP Formation Damage Test System

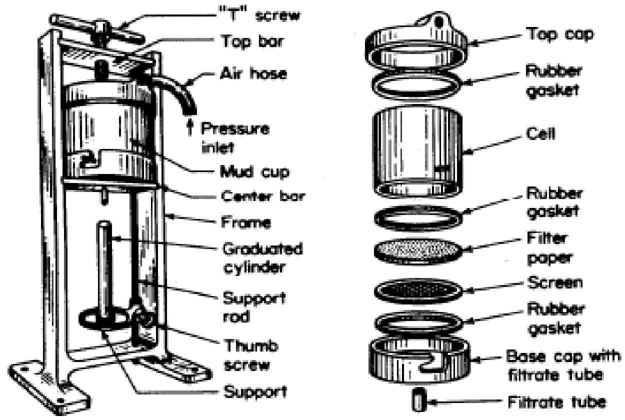


Figure 8: Standard API Filter Press

Figure 9: Fritsch Planetary Mill PULVERISETTE 5(left) and 10 mm Zirconia grinding balls (right)

3.4 Key Milestone

No	Activities	Date
1	Submission of Extended Proposal	27 Feb 2013
2	Proposal Defence (Oral Presentation)	13 Mar 2013
3	Submission of Interim Draft Report	8 – 12 Apr 2013
4	Submission of Interim Report	17 Apr 2013
5	Submission of Progress Report	11 July 2013
6	Submission of Draft Report	1 August 2013
7	Submission of Dissertation (soft bound)	August 2013
8	Submission of Technical Report	1 August 2013
9	Oral Presentation	14 August 2013
10	Submission of Project Dissertation (hard bound)	August 2013

3.5 Gantt Chart

Final Year Project I

No	Detail/Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14
1	Topic Selection	■	■	■												
2	Preliminary Research Work			■	■	■	■	■								
3	Submission of Extended Proposal							■								
4	Proposal Defence									■	■					
5	Project Work Continues											■	■	■	■	■
6	Submission of Interim Draft Report														■	
7	Submission of Interim Report															■

Final Year Project II

No	Detail/Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14	15
1	Project Work Continues																
2	Submission of Progress Report																
3	Project Work Continues																
4	Pre-SEDEX																
5	Submission of Draft Report																
6	Submission of Dissertation																
7	Submission of Technical Report																
8	Oral Presentation																
9	Submission of Project Dissertation																

3.6 Experimental Procedure

3.6.1 Nano-particle preparation and characterization

1. The bentonite sample is grinded using Fritsch Planetary Mill PULVERISETTE 5 under different settings as shown in the tables below to determine the milling effect on the final particle size of bentonite.

Table 1: Milling settings for sample 1

Sample amount (Bentonite)	10 g
Grinding balls	10 mm Zirconia balls (300 g)
Ball to sample weight ratio	30:1
Grinding jar	500 ml Zirconia jar
Time	24 hours (pause 15 minutes after every one hour)
Speed	400 rpm
Grinding medium (Isopropanol)	100 ml

Table 2: Milling settings for sample 2

Settings	Step 1	Step 2
Sample amount (Bentonite)	30 g	30 g
Grinding balls	10 mm Zirconia balls (300 g)	1 mm Zirconia balls (1200 g)
Ball to sample weight ratio	10:1	40:1
Grinding jar	500 ml Zirconia jars	500 ml Zirconia jars
Time	10 hours	6 hours
Speed	400 rpm	400 rpm
Grinding medium (Isopropanol)	250 ml	250 ml

Table 3: Milling settings for sample 3

Sample amount (Bentonite)	30 g
Grinding balls	10 mm Zirconia balls (300 g)
Ball to sample weight ratio	10:1
Grinding jar	500 ml Zirconia jar
Time	6 hours (pause 15 minutes after every 5 minutes)
Speed	400 rpm
Grinding medium (Isopropanol)	100 ml

2. The grinded sample is recovered from the grinding jars and the grinding balls are separated from the sample.
3. The sample is heated in oven at 100 degree Celsius for 18 hours to remove the remaining isopropanol.
4. The grinding jars and balls are cleaned after each operation by milling them using sand and water for a few hours.
5. The sample is imaged using FESEM to determine the final particle size of the product.
6. The optimum milling setting is used to produce more nano-bentonite samples for drilling fluid formulation and evaluation.

Figure 10: Field Emission Scanning Electron Microscopy machine

3.6.2 Drilling fluid preparation and rheology measurement

1. 22.5g of the sample (bentonite) is added into 350 ml of distilled water and mixed thoroughly using the mud mixer for 20 minutes.
2. The mud weight in ppg is measured using mud balance.
3. To measure the mud rheological properties, the recently agitated mud is placed into a cup. The upper housing of the viscometer is tilted back and the cup is located under the sleeve (the pins on the bottom of the cup fitted into the holes in the base plate). The upper housing is then lowered into its normal position.
4. The knurled knob between the rear support posts is turned to raise or lower the rotor sleeve until it is immersed in the sample to the scribed line.
5. The sample is stirred for about 5 seconds at 600 rpm and then the desired rpm is selected for the testing.
6. The dial reading and rpm are taken when it is stabilized (time varies according to the sample).
7. The rheological properties are calculated using the equations below:

   Plastic Viscosity (in centipoise-up) = 600 RPM reading - 300 RPM Reading

   Apparent Viscosity (in centipoise-cp) = $\dfrac{600 RPM\ reading}{2}$

   Yield Point (in lb/100 ft2) = 300 RPM Reading - Plastic Viscosity

8. To measure the gel strength, the sample is stirred at 600 rpm for 15 seconds.
9. The RPM knob is turned to STOP position.
10. The RPM knob is switched to the GEL position after the desired time (10 seconds or 10 minutes).
11. The maximum deflection of the dial before the gel breaks is recorded as gel strength in lb/100 ft^2 (lb/100 ft^2 x 5.077 = Gel strength in dynes/cm^2), either 10 s gel strength or 10 min gel strength.
12. Step 1 to 11 are repeated for nano-based mud of different formulations until the desired properties are achieved.

3.6.3 Low Pressure Low Temperature (LPLT) filter test

1. The mud cell is detached from the filter press frame.
2. The bottom of filter cell is removed and the filter paper is placed at the bottom of the cell.
3. The mud is poured into the cup assembly with the filter paper and screen on top of the mud and the screw clamp is tightened.
4. The mud assembly is clamped to the frame with the air pressure valve closed while holding the filtrate outlet end finger tight.
5. A graduated cylinder is placed underneath to collect the filtrate.
6. The air pressure valve (100 psi) is opened and the timing is started at the same time.
7. The amount of filtrate collected is recorded for specified intervals up to 30 minutes.
8. The air pressure valve is closed once the experiment ends and the remaining air is released.
9. The mud is removed and the mud cake formed on the filter paper is measured using the Vernier caliper.

3.6.4 High Pressure High Temperature (HPHT) filter test

1. The joints of the mud cell are lubricated and the cell is filled with mud.
2. The filter paper is placed on top of the mud and the mud cell is locked.
3. The mud cell is reversed so that the filter paper is at the bottom of mud.
4. The heating jacket is turned on and the mud cell is placed into the jacket.
5. The air pressure valve (500 psi) is opened once the temperature of the cell reaches the desired temperature (150 °F) and the timing is started.
6. The bottom valve of the cell is opened partially to allow filtrate to flow out.
7. The amount of filtrate collected is recorded for specified intervals up to 30 minutes.
8. The air pressure valve is closed once the experiment ends and the remaining air is released.
9. The mud is removed and the mud cake formed on the filter paper is measured using the Vernier caliper.

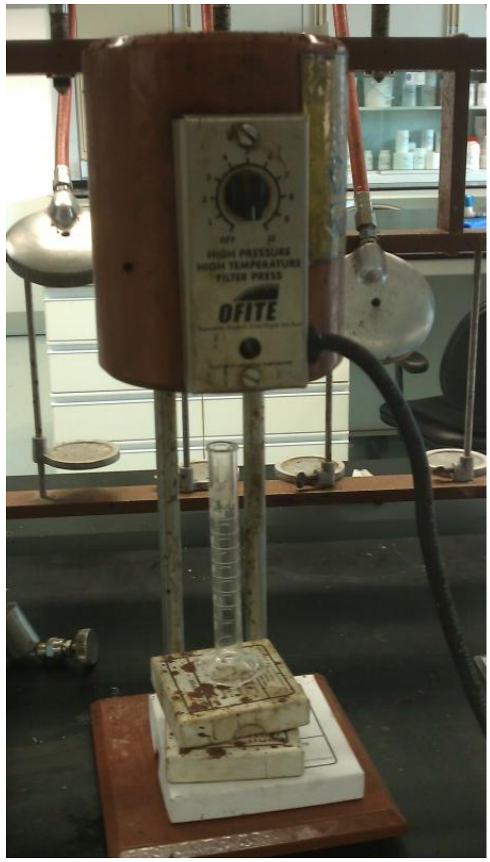


Figure 11: HPHT filter press

CHAPTER 4:

RESULTS AND DISCUSSIONS

4.1 Nano-particle Preparation and Characterization

The products of ball milling under different configurations are characterized using FESEM to determine the size of the bentonite particles after grinding. The required size of final particles should be in the range of 1 to 100 nm. From the FESEM images which show the particle size of sample, the optimum milling settings are then selected to produce more samples for further testing. The FESEM images of sample produced from different settings are shown below.

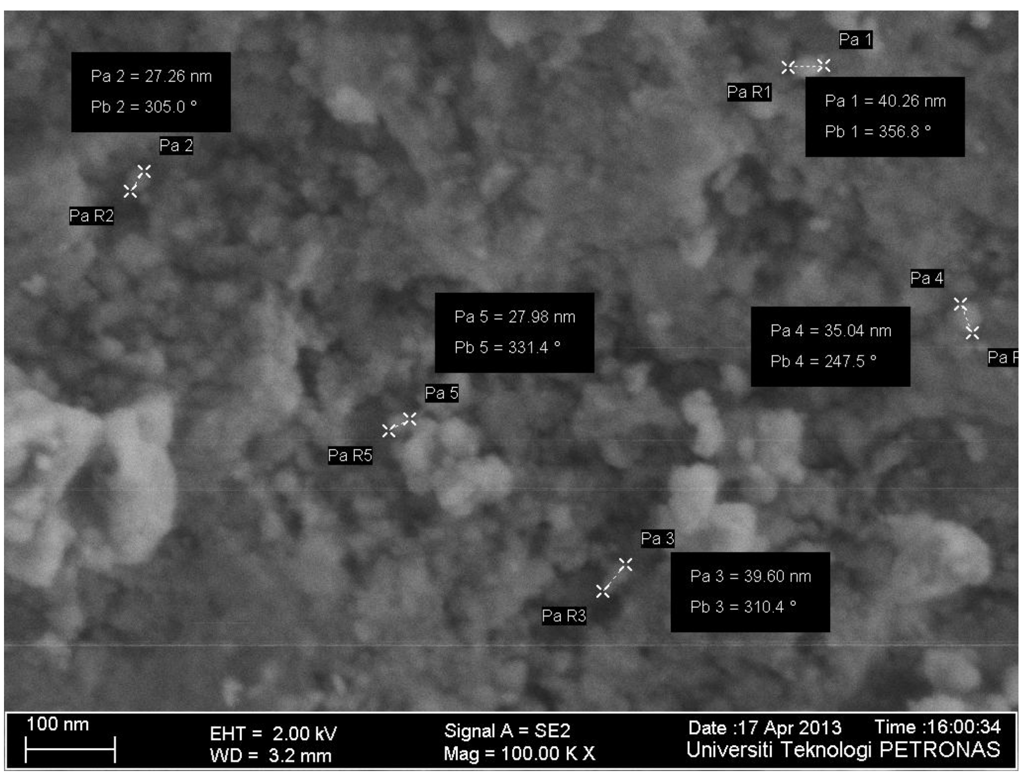


Figure 12: FESEM image for sample 1

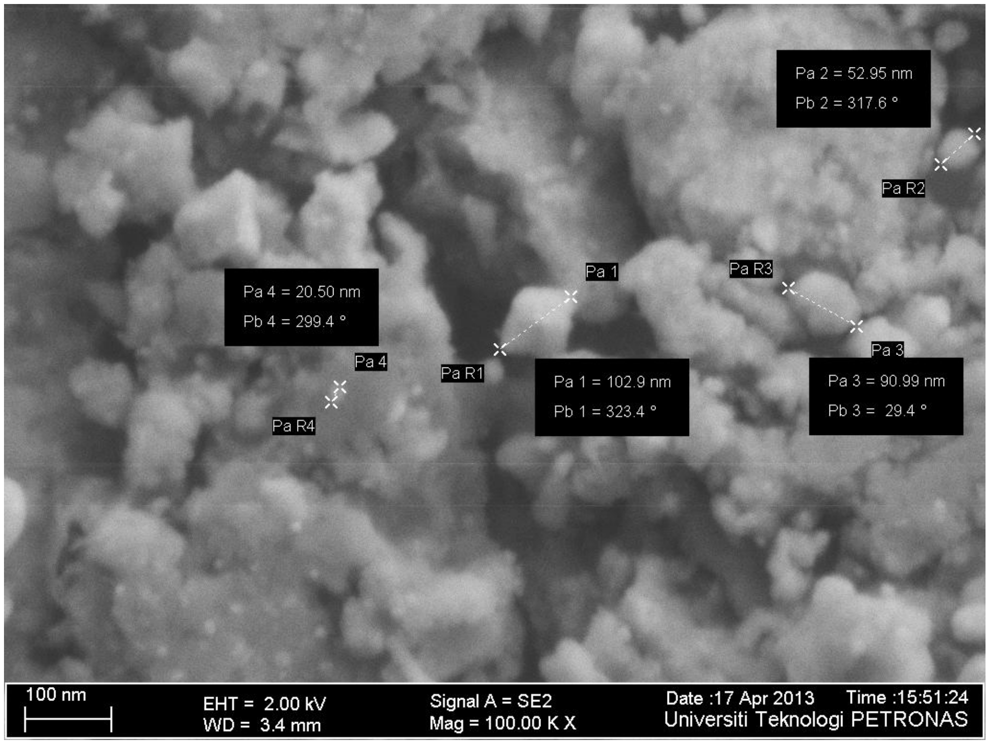


Figure 13: FESEM image for sample 2

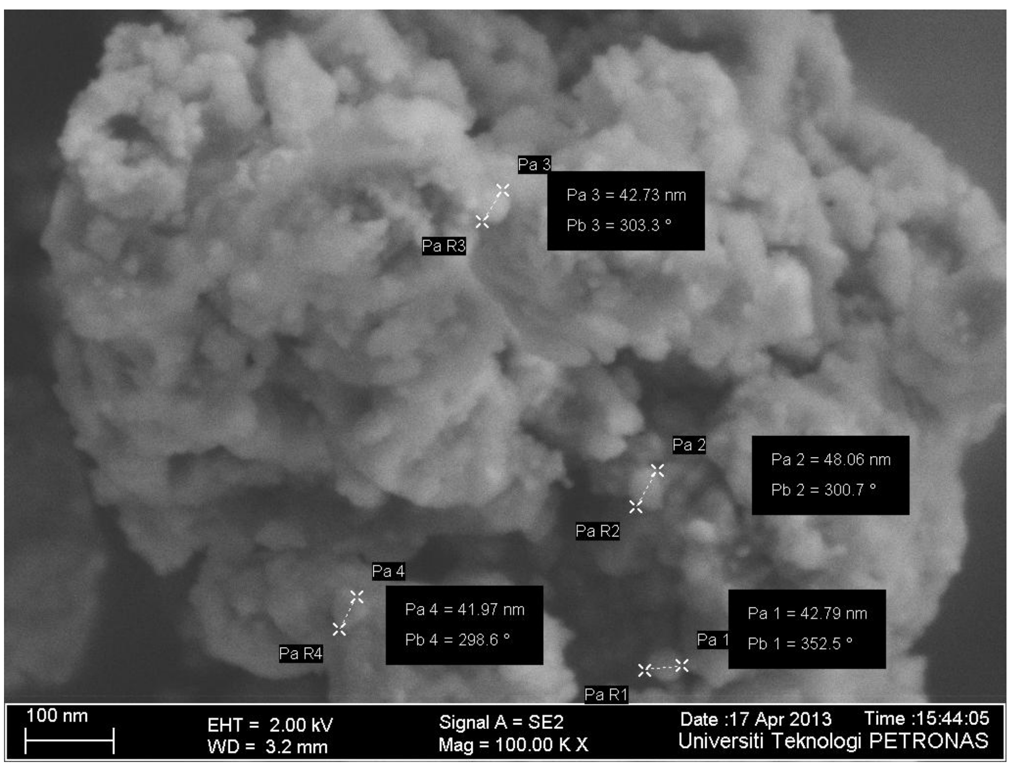


Figure 14: FESEM image for sample 3

As observed, the milling of bentonite under settings 1 and 3 are able to achieve the desired particle size, which is below 100 nm. Configuration 3 is selected since it is able to produce more nano-bentonite samples after each cycle to shorten the milling time.

Figure 15: Nano-bentonite produced from ball milling (left) and the macro-sized bentonite (right).

4.2 Nano-based drilling fluid formulation

Initial mud formulation using nano-bentonite alone without any additives showed much lower rheological properties as shown in table below. The table compares the rheological properties including plastic viscosity, yield point and gel strength of the nano-based drilling fluid against the conventional drilling fluid using bentonite.

Table 4: Rheological properties of mud using bentonite and nano-bentonite

Rheology	Bentonite	Nano Bentonite (NB)
600 rpm	36	6
300 rpm	27	3
200 rpm	22	3
100 rpm	18	1
6 rpm	8	0
3 rpm	4	0
Plastic Viscosity (PV)	9	3
Yield Point (YP)	18	0
Gel Strength 10 s	12	0
Gel Strength 10 min	16	0

This phenomenon occurs due to the structural changes of montmorillonite present in the bentonite caused by mechanical deformation via high energy ball milling. The mechanical milling process caused a reduction of the particle size and change in morphology of the bentonite particles as well. Initial submicron-sized flaky and plate-like particles with pseudo-hexagonal morphology of montmorillonite turned into aggregates of almost rounded particles with sizes in the nanometer range as shown in Figure 12, 13 and 14. This resulted in a change in the swelling properties of bentonite, hence the lower performance in rheology.

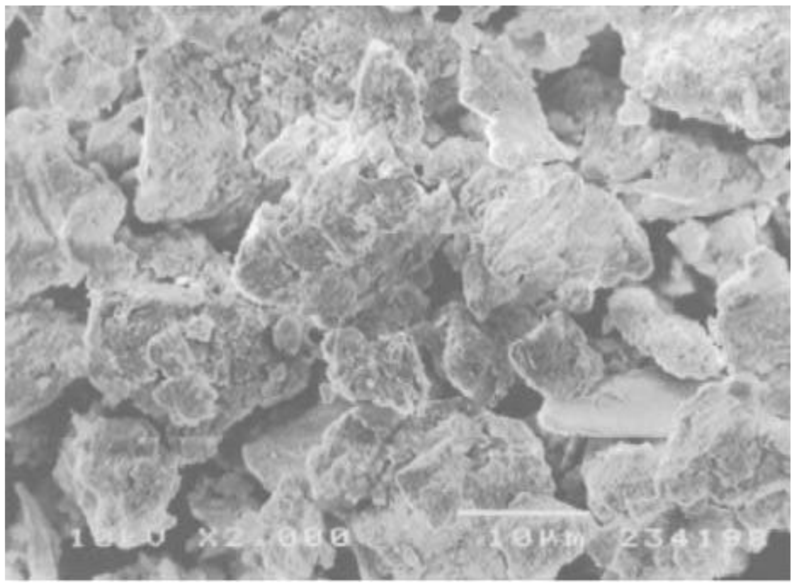


Figure 16: FESEM image of conventional bentonite before milling which shows flaky and plate-like structure.

After leaving the mud for 24 hours, flocculation took place and the mud agglomerate deposited at the bottom. This is due to easy agglomeration of nano-particles as the surface forces trigger quick flocculation of mechanically dispersed particles once the agitation is stopped. The surface forces create flocs and agglomerates, followed by the action of gravitational force which leads to the sedimentation of the mud. This is shown in the following figure.

Figure 17: Initial formulated nano-based mud (left) which flocculates 24 hours after mixing (right).

Mud additives were added in order to enhance the rheological properties of the nano-based drilling fluid so that it complies with the API Specification 13A, section 9 requirement for bentonite.

Table 5: API specifications for bentonite

Properties	**API 13A, section 9 Specifications**
Viscometer 600 rpm	30 minimum
Viscometer 300 rpm	23 minimum
Plastic Viscosity (PV)	7 minimum
Yield Point (YP)	50 maximum
YP/PV Ratio	3 maximum
Filtrate Volume	15 cm^3 maximum

Different mud additives were added in increasing concentration until the nano-based drilling fluid met the minimum API specifications. Among the additives used were polyanionic cellulose (PAC), Xanthan gum, and starch.

4.2.1 Nano-bentonite (NB) with Polyanionic Cellulose (PAC)

Table 6: Rheological properties of different nano-based mud using PAC

Rheology	NB + 0.1% PAC	NB + 0.2% PAC	NB + 0.3% PAC	NB + 0.4% PAC	NB + 0.5% PAC
600 rpm	17	31	44	62	82
300 rpm	10	20	29	41	56
200 rpm	8	15	22	31	44
100 rpm	5	10	14	21	29
6 rpm	0.5	2	2	3	4
3 rpm	1	1	1	2	2
Plastic Viscosity (PV)	7	11	15	21	26
Yield Point (YP)	3	9	14	20	30
Gel Strength 10-s	0.5	1	2	4	6
Gel Strength 10- min	1	3	6	12	18

Table 6 shows the rheological properties of nano-based drilling mud formulated using nano-bentonite and different concentrations of PAC. It is observed that PAC was able to tailor the properties of the nano-based mud in order to meet the API specifications. 0.4% is the maximum amount of PAC that can be added to the nano-based mud as the mud started to agglomerate once the concentration of PAC exceeded 0.5%. Below 0.5% addition of PAC, the mud formulated remained stable and no flocculation was observed after leaving the mud for several days as shown in the figure below. PAC acts as a viscosity modifier and fluid loss control agent and prevents the flocculation of the nano-particles. The addition of PAC alone is insufficient as the gel strength is too low, therefore other mud additives were then added to alter the mud properties.

Figure 18: Nano-based drilling fluid after mixing (left) and several days after mixing (right). The mud remained stable with no flocculation.

4.2.2 Nano-bentonite (NB) with Starch

Table 7: Rheological properties of different nano-based mud using starch

Rheology	NB + 0.1% Starch	NB + 0.2% Starch	NB + 0.3% Starch
600 rpm	18	23	26
300 rpm	12	16	18
200 rpm	10	13	15
100 rpm	7	9	12
6 rpm	2	3	4
3 rpm	1	2	3
Plastic Viscosity (PV)	6	7	8
Yield Point (YP)	6	9	10
Gel Strength 10-s	2	3	5
Gel Strength 10-min	19	26	28

From the table above, it is observed that starch has a smaller impact on the drilling fluid’s rheological properties as compared to PAC. However, it improves the gel strength of mud more effectively. The mud formulated also remained stable after mixing and no flocculation was observed. Similar to PAC, other mud additives were required in addition to starch to enhance the mud properties.

4.2.3 Nano-bentonite (NB) with Xanthan Gum

Table 8: Rheological properties of different nano-based mud using Xanthan gum

Rheology	NB + 0.1% Xanthan	NB + 0.2% Xanthan
600 rpm	20	36
300 rpm	15	26
200 rpm	12	21
100 rpm	9	16
6 rpm	4	7
3 rpm	2	4
Plastic Viscosity (PV)	5	10
Yield Point (YP)	10	16
Gel Strength 10-s	4	10
Gel Strength 10-min	25	42

Xanthan gum acts as a viscosifier for the drilling fluid which enhances its rheological properties and gel strength effectively. However, the nano-based mud started to agglomerate when its concentration of Xanthan gum reached 0.2%. Therefore, it is recommended to add Xanthan gum along with other additives (PAC or starch) to enhance the mud properties.

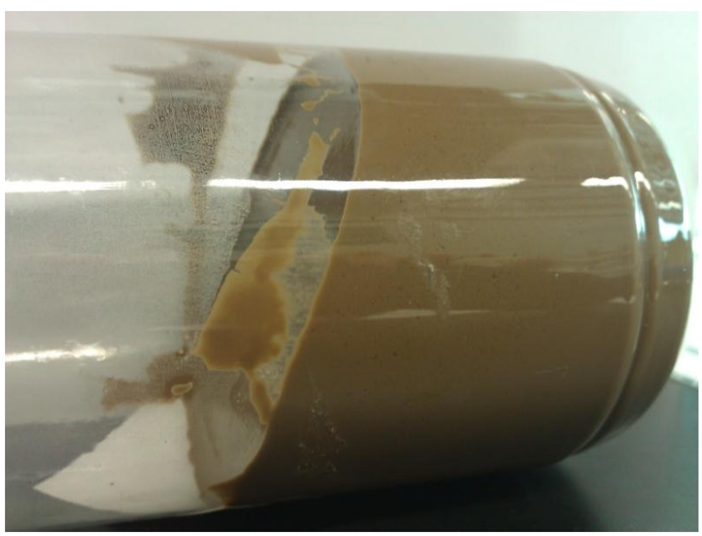


Figure 19: Nano-based mud with 0.2% Xanthan gum which is too viscous to flow.

4.2.4 Nano-bentonite (NB) with different mixture of additives

Table 9: Rheological properties of different formulations of nano-based mud

Rheology	NB + 0.1% Xanthan + 0.1% PAC	NB + 0.1% Xanthan + 0.2% PAC	NB + 0.1% Xanthan + 0.1% Starch	NB + 0.1% Xanthan + 0.2% Starch	NB + 0.1% Xanthan + 0.3% Starch	NB + 0.1% Xanthan + 0.5% Starch
600 rpm	40	73	26	28	32	43
300 rpm	27	52	17	19	22	31
200 rpm	22	44	14	15	18	26
100 rpm	15	31	10	10	13	19
6 rpm	4	12	2	3	4	6
3 rpm	3	10	1	1	3	4
Plastic Viscosity (PV)	13	21	9	9	10	12
Yield Point (YP)	14	31	8	10	12	19
Gel Strength 10-s	6	12	2	4	5	9
Gel Strength 10-min	30	34	19	23	26	30

From the table above, the formulations which met the API specifications were then selected to proceed with the filtration test in order to evaluate the ability of the nano-based mud to prevent spurt loss and filtrate loss. The mud selected were NB + 0.1% Xanthan + 0.1% PAC; NB + 0.1% Xanthan + 0.2% PAC; NB + 0.1% Xanthan + 0.3% Starch; and NB + 0.1% Xanthan + 0.5% Starch. These muds fulfilled the API requirements and were closest to the conventional bentonite rheological properties. These nano-based muds were tested for LPLT filtration test.

4.2.5 Nano-bentonite (NB) as additive to Conventional WBM

Nano-bentonite was added in different concentrations as mud additives to the conventional WBM to evaluate their impacts on the mud properties as shown in the following table.

Table 10: Rheological properties of conventional WBM with addition of NB and additives

Rheology	50% Bentonite 50 % NB	75% Bentonite 25 % NB	75% Bentonite 25 % NB + 0.1% PAC	75% Bentonite 25 % NB + 0.1% Xanthan + 0.1% Starch
600 rpm	21	28	55	35
300 rpm	12	19	38	26
200 rpm	10	16	31	21
100 rpm	7	11	21	17
6 rpm	2	4	5	7
3 rpm	1	3	4	5
Plastic Viscosity (PV)	9	9	17	9
Yield Point (YP)	3	10	21	15
Gel Strength 10-s	1	6	8	11
Gel Strength 10-min	6	21	31	29

It is observed that the combinations of bentonite and nano-bentonite alone in the WBM (either 50% bentonite 50% NB or 75% bentonite 25% NB) is insufficient to meet the minimum API requirements. Therefore, mud additives were added to alter the properties. These muds would then be tested for their filtration properties.

Table 11: Rheological properties of conventional WBM with addition of NB and additives

Rheology	Bentonite + 10 ppg NB	Bentonite + 5 ppg NB	Bentonite + 5 ppg NB + 0.1% Starch	Bentonite + 5 ppg NB + 0.1% PAC
600 rpm	75	46	47	70
300 rpm	60	35	37	56
200 rpm	54	33	33	46
100 rpm	45	27	28	40
6 rpm	36	16	17	30
3 rpm	33	13	13	26
Plastic Viscosity (PV)	15	11	10	14
Yield Point (YP)	45	24	27	42
Gel Strength 10 s	33	15	16	28
Gel Strength 10 min	75	39	45	68

The addition of 10 ppg of NB into conventional WBM was unsuitable as it resulted in instant agglomeration due to high content of bentonite additives in the mud. As for the addition of 5 ppg of NB, other additives were required to tailor the mud properties. It is observed that combination of bentonite + 5 ppg NB + 0.1% PAC also resulted in agglomeration. Therefore, the mixture of bentonite + 5 ppg NB + 0.1% starch was the only mud to be tested for filtration properties.

4.3 Low Pressure Low Temperature (LPLT) Filtration Test

The nano-based drilling fluids which met the API requirements for rheological properties were tested for filtration properties. The results are summarized as below. The detailed results were tabulated in the Appendices section.

Table 12: Summary of LPLT tests of nano-based drilling fluids

Nano-based Drilling Fluid	Spurt Loss (ml)	Filtrate Loss (ml)	Reduction in Filtrate Loss	Mudcake Thickness (mm)
Bentonite	2	12.5	-	2.4
Bentonite + 0.1% PAC	2	11	12%	2.2
NB + 0.1% Xanthan + 0.3% Starch	2	11	12%	1.4
NB + 0.1% Xanthan + 0.5% Starch	1.5	9.75	22%	1.3
NB + 0.1% Xanthan + 0.1% PAC	4	13.5	-8%	1.9
NB + 0.1% Xanthan + 0.2% PAC	2	11	12%	1.7
75% Bentonite 25% NB + 0.1% PAC	2	11	12%	1.5
75% Bentonite 25% NB + 0.1% Xanthan + 0.1% Starch	1.5	11.25	10%	1.6
Bentonite + 5 ppg NB	2.5	14	-12%	2.1
Bentonite + 5 ppg NB + 0.1% Starch	1.5	12	4%	1.8

The conventional WBM using bentonite and treated bentonite served as the benchmark for the comparison of mud filtration properties. The spurt loss and filtrate loss for conventional WBM are 2 ml and 12.5 ml respectively with a mud cake of 2.4 mm. The conventional WBM treated with 0.1% PAC showed slightly improved filtration properties with spurt loss and filtrate loss of 2 ml and 11 ml respectively. The mud cake thickness was reduced slightly to 2.2 mm.

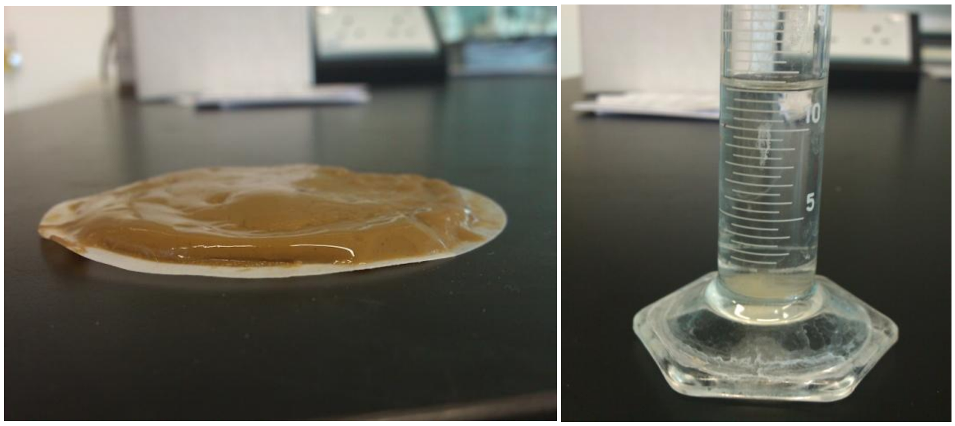


Figure 20: Mud cake and filtrate loss of conventional WBM during LPLT test.

From the LPLT tests conducted, it showed that some nano-based drilling fluids were able to reduce the filtrate loss and spurt loss up to 22% and 25% respectively. The mud cakes deposited by the nano-based mud were also relatively thinner compared to the conventional WBM. The results are plotted in the following graphs.

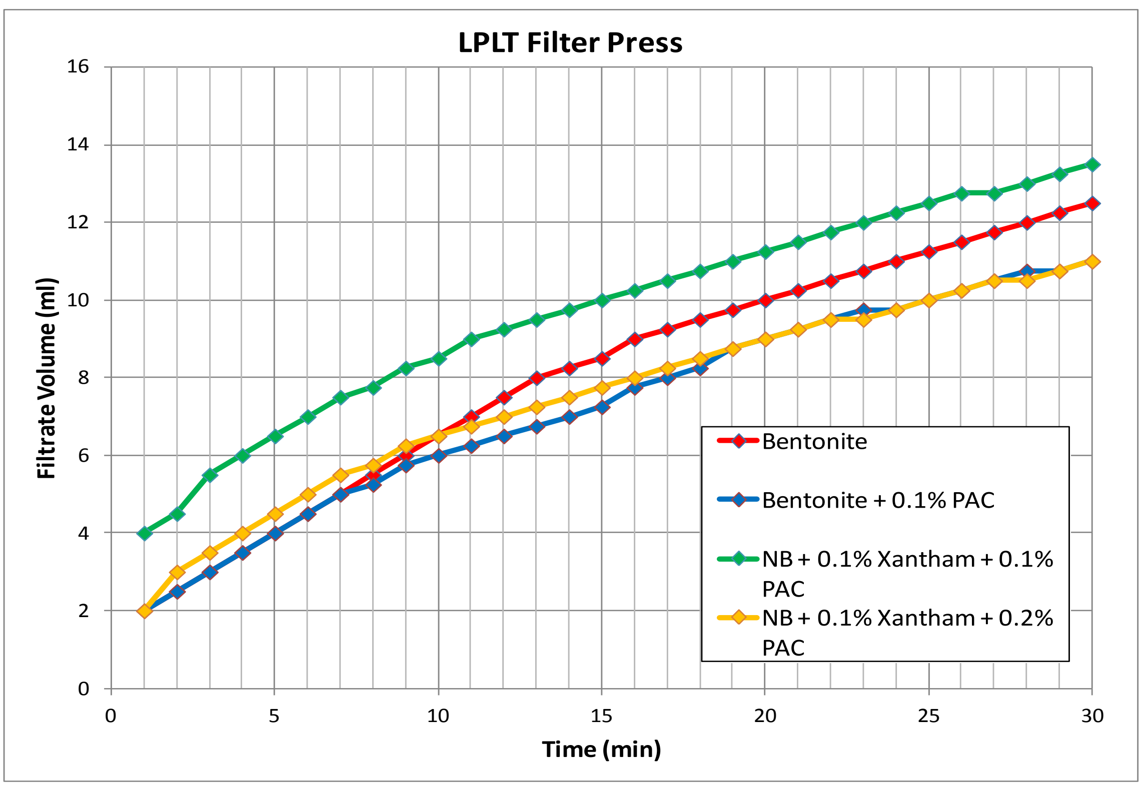


Figure 21: LPLT filtrate volume versus time plot 1

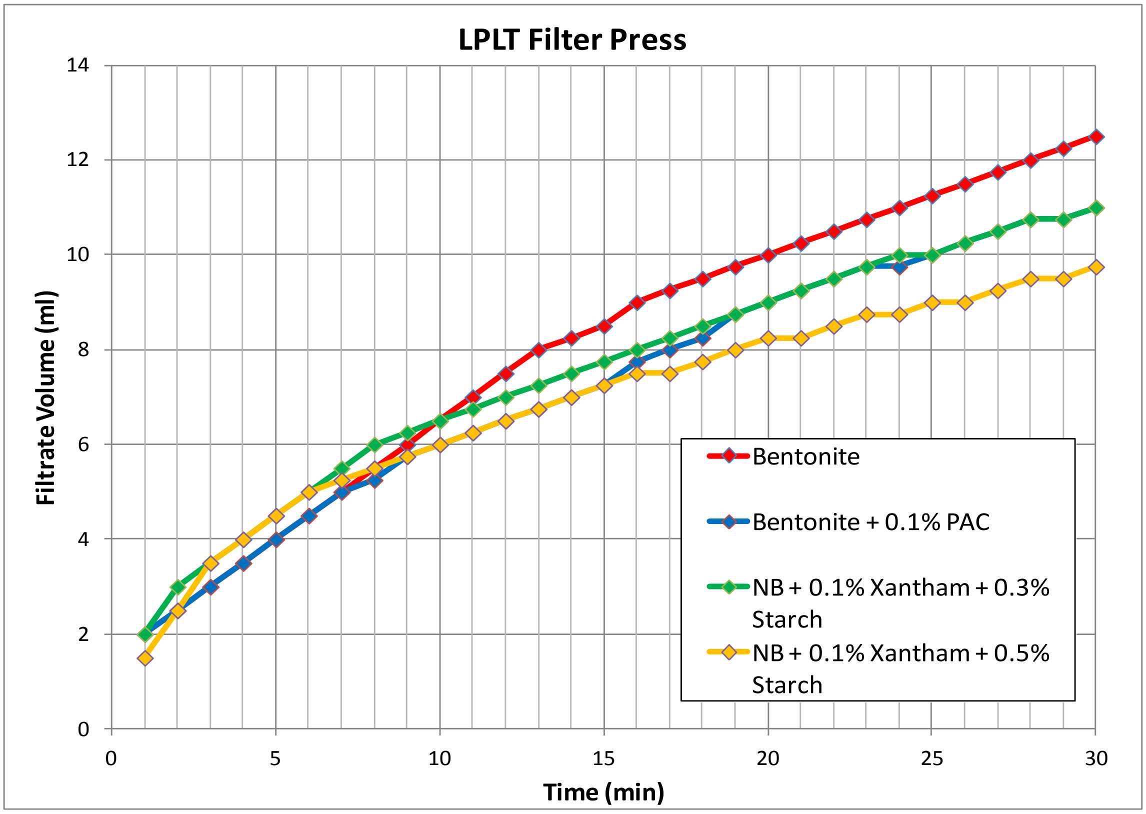


Figure 22: LPLT filtrate volume versus time plot 2

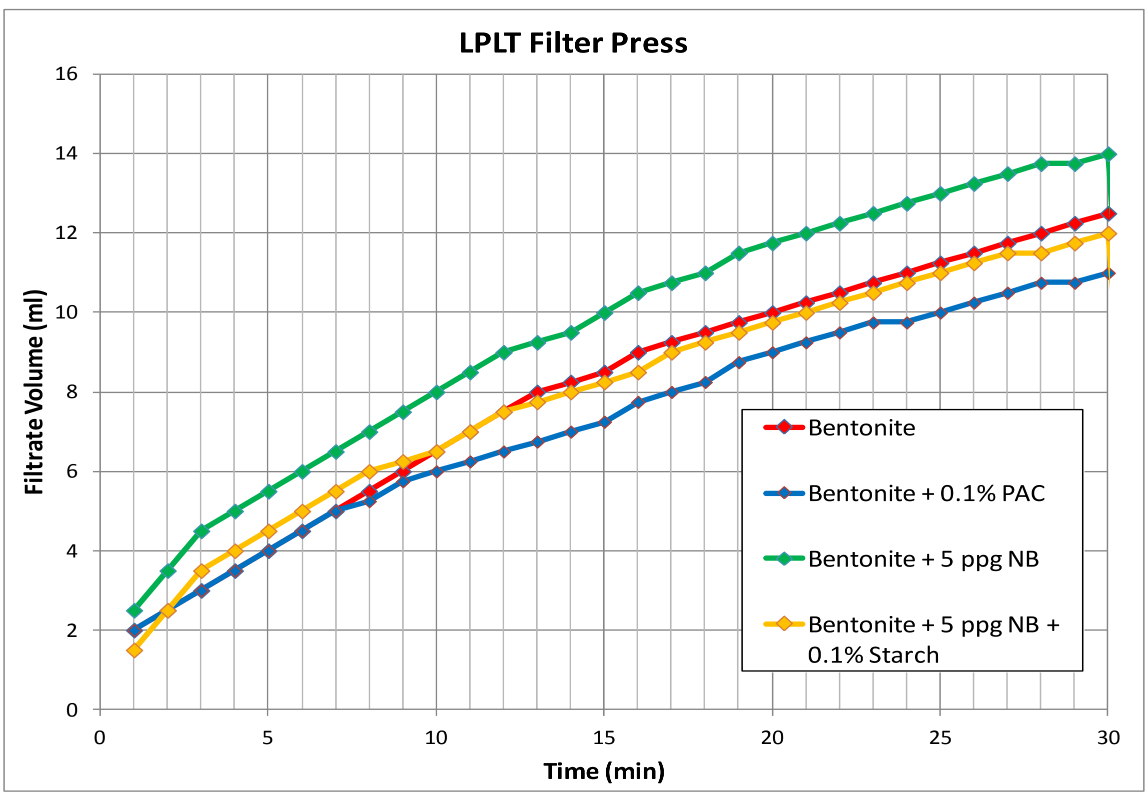


Figure 23: LPLT filtrate volume versus time plot 3

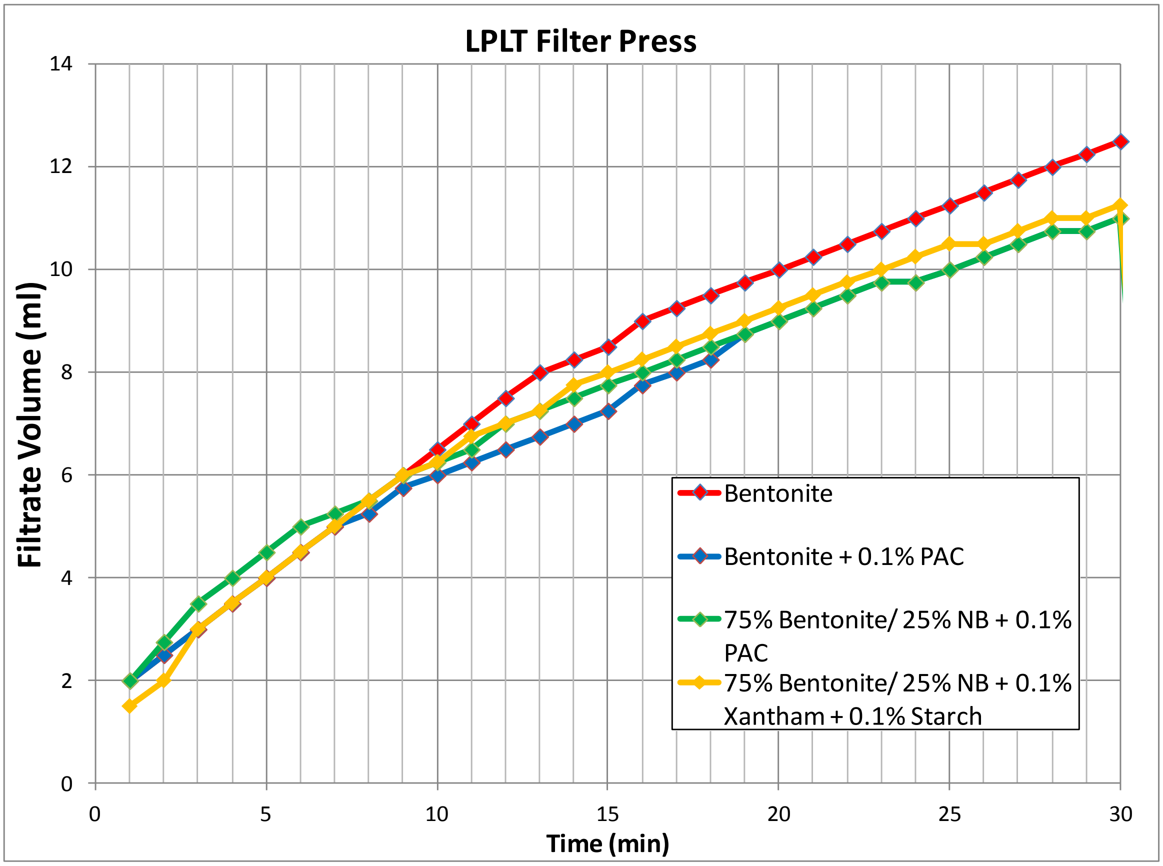


Figure 24: LPLT filtrate volume versus time plot 4

From the plots above, we can infer that nano-based drilling fluids formulated using nano-bentonite only with other mud additives (Figure 21 and 22) are able to reduce the filtrate loss to the same extent or even lower than the treated bentonite which acts as the benchmark. In a particular formulation, which is NB + 0.1% Xanthan + 0.5% Starch, the initial spurt loss was reduced to 1.5 mm compared to the usual 2 mm in other cases. As observed in the graphs, there is a decline in the rate of filtrate loss for the nano-based drilling fluids starting from the 10^{th} minute onwards. This could be explained by the deposition of effective and less permeable mud cake which minimize the filtrate loss through the filter paper. Generally, the mud cakes deposited by these nano-based muds were also thinner compared to the treated WBM which deposited a 2.2 mm mud cake. The reduction in mud cake thickness was in the range of 0.3 mm to 0.9mm.

However, it is observed that for nano-based drilling fluid formulated using nano-bentonite only with other additives, the filtrate were not clear as the nano-particles were too small that they were able to pass through the openings in the filter paper during initial spurt loss. This caused the filtrate to be contaminated as shown in the following figure.

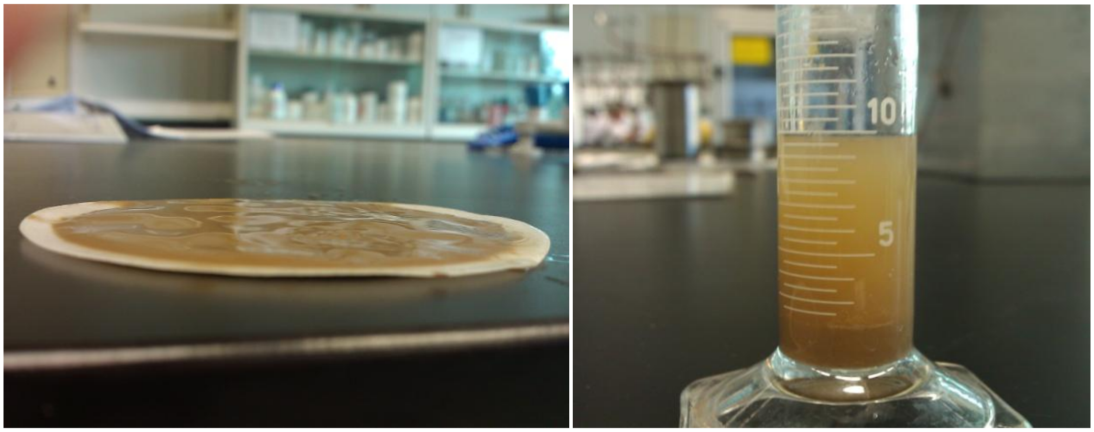


Figure 25: Ultra thin mud cake deposited (left) and mud-contaminated filtrate (right) of nano-based mud formulated using nano-bentonite and additives only.

This situation can be avoided if the nano-based drilling fluid is used in shale formations where the pore throat openings are usually in nano scale. According to the bridging theory's rule of thumb, the particle size of a bridging additive should be equal to or slightly greater than one-third of the median pore size of the formation for the bridging to form effectively. It will enable more effective deposition of mud cake to minimize spurt loss and filtrate loss. This can be further tested by using filter paper of smaller openings compared to the ones used in standard API filter loss test, Whatman Grade 50 filter paper with openings of 2.7 µm, which is much larger compared to the pore throats openings of shale formations.

For the nano-based mud formulated using a mixture of bentonite and nano-bentonite along with other additives, the filtrate was relatively clearer and free from solid additives. However, the reduction in filtrate loss and mud cake thickness was not as good as the nano-based mud which comprised of only nano-bentonite and mud additives. The reduction in mud cake thickness can be up to 0.5 mm in certain formulation. These nano-based muds were also found to be better in reducing the spurt loss to 1.5 ml compared to 2.0 ml in treated bentonite. The mud with good filtration properties, which were NB + 0.1% Xanthan + 0.5% Starch, NB + 0.1% Xanthan + 0.2% PAC, 75% Bentonite 25% NB + 0.1% PAC will then be tested using HPHT filter test.

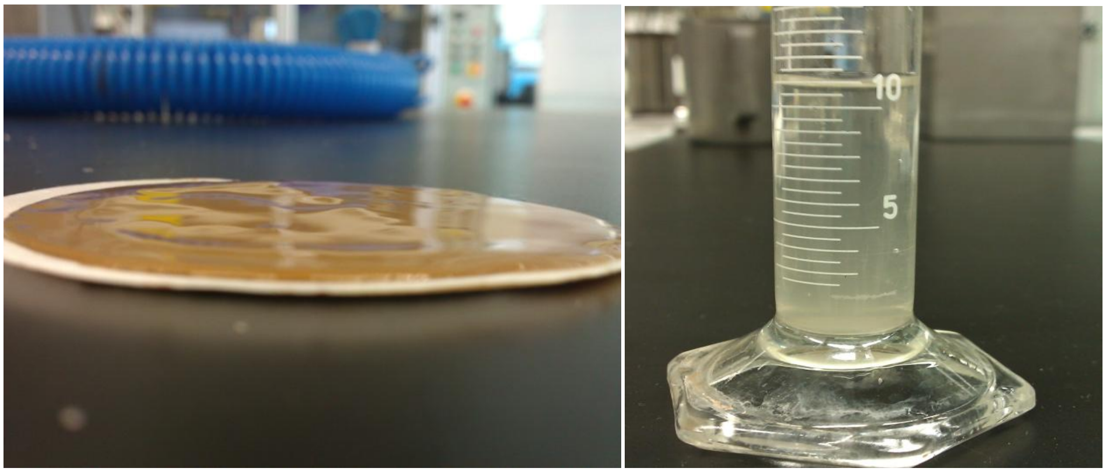


Figure 26: Thinner mud cake deposited (left) and clearer filtrate (right) of nano-based mud formulated using a mixture of bentonite and nano-bentonite.

4.4 High Pressure High Temperature (HPHT) Filtration Test

The selected muds with good filtration properties as determined from LPLT filtration test were tested in the HPHT filter press. The tests were conducted under high pressure of 500 psi and high temperature of 150 °F, which represents the reservoir conditions. HPHT filter press can evaluate the filtration properties of the mud in actual reservoir and is used to confirm the LPLT filter test results. The table below summarizes the results from the HPHT tests conducted.

Table 13: Summary of HPHT tests of nano-based drilling fluids

Nano-based Drilling Fluid	**Spurt Loss (ml)**	**Filtrate Loss (ml)**	**Reduction in Filtrate Loss**	**Mudcake Thickness (mm)**
Bentonite	3	18.5	-	5.4
Bentonite + 0.1% PAC	2.4	14.8	20 %	4.7
NB + 0.1% Xanthan + 0.5% Starch	2	11	40.5 %	4
NB + 0.1% Xanthan + 0.2% PAC	2	12.6	31.9 %	4.3

75% Bentonite 25% NB + 0.1% PAC	2	13.5	27 %	3.5

Similar to LPLT test, the conventional WBM using bentonite and treated bentonite served as the benchmark for the comparison of mud filtration properties. The spurt loss and filtrate loss for conventional WBM are 3 ml and 18.5 ml respectively with a mud cake of 5.4 mm. The conventional WBM treated with 0.1% PAC showed improved filtration properties with spurt loss and filtrate loss of 2.4 ml and 14.8 ml respectively. The mud cake thickness was reduced slightly to 4.7 mm.

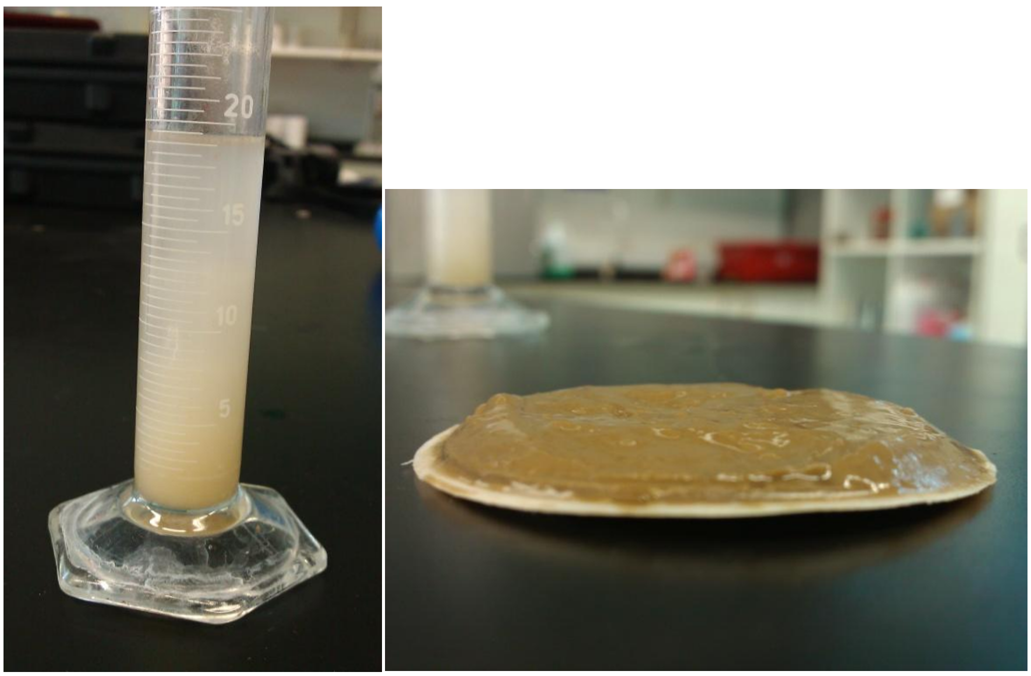


Figure 27: Mud cake and filtrate loss of conventional WBM during HPHT test.

From the tests conducted, it showed that the nano-based drilling fluids were able to reduce the filtrate loss and spurt loss up to 40.5% and 33% respectively. The mud cakes deposited by the nano-based mud were also much thinner compared to the conventional WBM. These nano-based drilling muds performed better compared to the bentonite mud and treated bentonite mud. The results are plotted in the following graph.

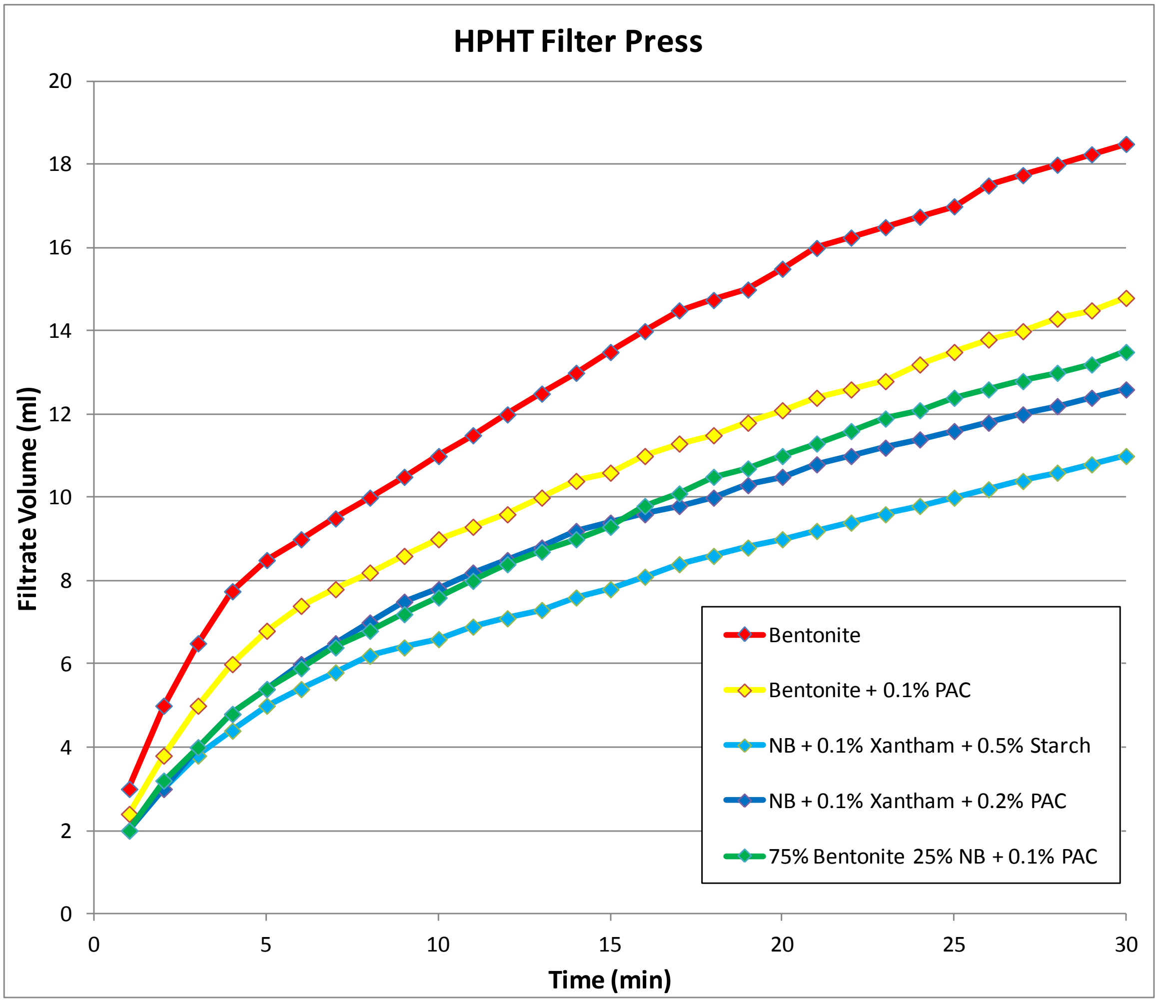


Figure 28: HPHT filter press plot

As shown in the plot above, the nano-based drilling fluids can greatly reduce the filtrate loss and spurt loss during the test duration of 30 minutes. The deposition of effective mud cake occurred quickly which helped reduce the filtrate loss. The formulation of nano-bentonite with Xanthan Gum and starch was able to reduce the filtrate loss up to 11 ml compared to 18.5 ml from the conventional bentonite mud. The mud cake formed was 4 mm which is 1.4 mm thinner than the bentonite mud.

However, it is observed that for nano-based drilling fluid formulated using nano-bentonite and mud additives only, the filtrate were also not clear similar to the results from LPLT tests. As the nano-particles were too small, they were able to pass through the openings in the filter paper during initial spurt loss. This caused the filtrate to be contaminated as shown in the following figure. These muds could be further tested to be used in shale formations.

Figure 29: Unclear filtrate and mud cake of nano-based mud formulated using nano-bentonite and additives only.

As for the nano-based mud formulated using a mixture of bentonite and nano-bentonite along with other additives, the filtrate was clearer and free from solid additives similar to the conventional bentonite mud. The formulation of 75% bentonite and 25% NB + 0.1% PAC was able to reduce the filtrate loss to 13.5 ml which is a 27% reduction. In addition, the mud cake deposited was the thinnest among all the nano-based drilling fluids, which is 3.5 mm. Therefore, it proved to perform better in term of filtration properties compared to conventional WBM and could be used in drilling operations of conventional formations. The mud cake and filtrate are shown in the following figure.

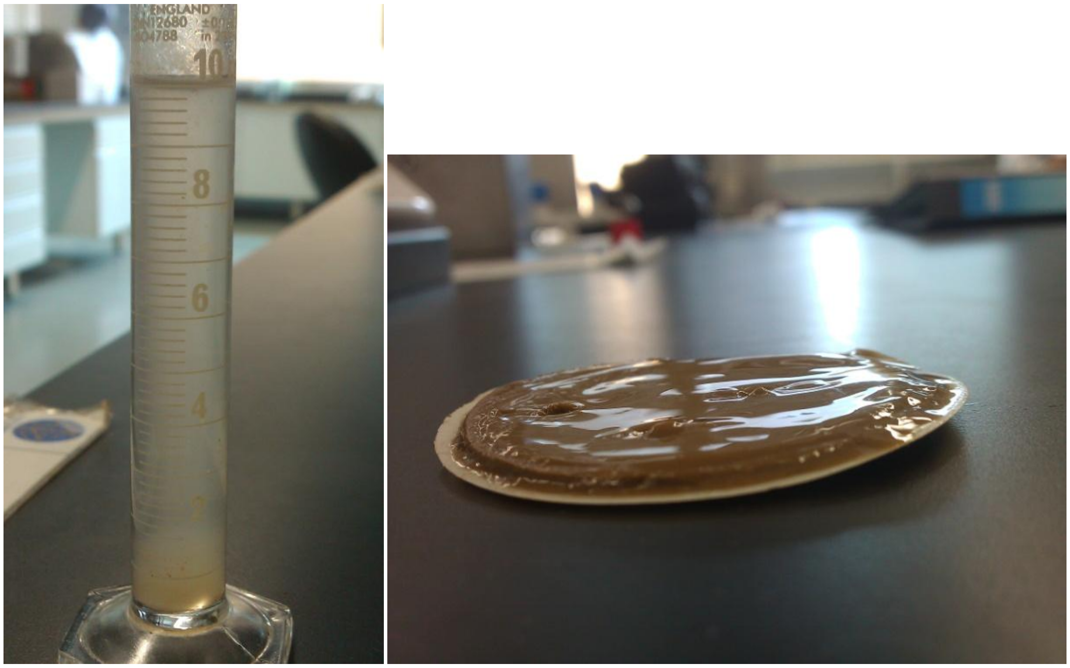


Figure 30: Clearer mud filtrate and thinner mud cake deposited by nano-based mud formulated using a mixture of bentonite and nano-bentonite.

4.5 Discussions

From the results shown, it is apparent that nano-based drilling fluids are able to reduce the filtrate loss and spurt loss during drilling operations. Due to ultrafine particle sizes of nano-particles that are much smaller than the pore throat sizes of the formations, nano-based drilling fluids are able to minimize fluid invasion and prevent wellbore stability issues especially in shale formations. The reduction of spurt loss in the nano-based drilling fluids is significant as mud spurt is one of the major factors that cause formation damage. Mud spurt carries particulate materials into the formation and causes blockage to the pores and pore throats, leading to the formation of an internal mud cake. The nano-particles are also expected to reduce shale-drilling mud interaction due to their easy access to shale matrix and eliminate formation damage due to clay hydration. However, this requires more testing using filter paper of smaller opening size.

The filtration tests conducted proved the deposition of thin, well dispersed and tight mud cake on the API filter paper by the nano-based drilling fluid compared to conventional WBM. Since the quality and thickness of mud cake deposited are important in any drilling operations, nano-based mud may play a significant role in reducing the mud cake related drilling and production problems. Firstly, the thin and well dispersed mud cake deposited by the nano-based fluids has the ability to reduce the differential pressure sticking problem and thus is highly desirable for geological formations that are prone to having differential pressure sticking problems while drilling.

Nowadays, due to an increasing shift from vertical and directional drilling to horizontal and extended reach drilling, there is a dramatic increase in torque and drag problems while drilling usually caused by the friction between the drill string and the borehole wall. Therefore, drilling fluid plays an important role in reducing the torque and drag problem. Nano-based drilling fluids can assist in reducing the frictional resistance between the pipe and the borehole wall by forming a continuous and thin lubricating film in the wall-pipe interface, therefore preventing stuck drilling pipe issues.

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CHAPTER 5:

CONCLUSION AND RECOMMENDATIONS

This project aimed at investigating the application of nano-bentonite in water based mud (WBM) for reducing formation damage and drilling-related issues. The objectives included producing nano-particle size bentonite from the conventional micro-sized bentonite and formulating a suitable nano-based WBM incorporating the nano-bentonite as the mud additive. This project also studied the impact of nano-bentonite on the nano-based drilling fluid's rheological properties and formation damage (reservoir skin factor) compared to the conventional WBM.

The objectives of this project are achieved through numerous experiments involving the production and characterization of nano-bentonite from planetary ball milling, nano-based drilling fluid formulation, and drilling fluid characterization which comprised of rheology and filtration tests. The results obtained proved that nanotechnology could play an important role in developing smart drilling fluids for drilling and completion operations. Due to their ultra fine particle size, nano-particles exhibit enhanced mechanical, optical, thermal and chemical properties. The use of nano-based WBM could reduce formation damage associated with mud spurt and filtrate loss as well as mud cake related drilling and production problems.

The LPLT and HPHT filter press showed that nano-based drilling muds can reduce the mud spurt and filtrate loss as well as deposit thinner and well dispersed mud cake. Different mud formulation gave different results. Mud formulation consisting of nano-bentonite and mud additives alone such as NB + 0.1% Xanthan + 0.5% Starch and NB + 0.1% Xanthan + 0.2% PAC can reduce the filtrate loss to a greater extent. However, the mud filtrate was not clear. The incorporation of nano-bentonite as additive into conventional WBM (75% Bentonite and 25% NB + 0.1% PAC) also resulted in lesser filtrate loss as well as thinner mud cake. Therefore, this nano-based drilling mud could be adopted and used in drilling operations in normal reservoir formations to reduce formation damage.

In the future, it is recommended that further testing should be conducted on the nano-based drilling fluid made up entirely of nano-bentonite and mud additives to investigate their application in problematic formations especially shale formations. The nano-based mud is expected to reduce filtrate loss significantly due to their ultra fine particle size and deposit much thinner, compact and effective mud cake. This could prevent wellbore instability when drilling shale formations. In addition, formation damage testing could be conducted on the nano-based drilling fluids to further examine their ability to reduce formation damage.

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APPENDICES

Table 14: Complete LPLT test results of nano-based drilling fluids 1

Time (min)	Bentonite	Bentonite + 0.1% PAC	NB + 0.1% Xanthan + 0.3% Starch	NB + 0.1% Xanthan + 0.5% Starch	NB + 0.1% Xanthan + 0.1% PAC	NB + 0.1% Xanthan + 0.2% PAC
1	2	2	2	1.5	4	2
2	2.5	2.5	3	2.5	4.5	3
3	3	3	3.5	3.5	5.5	3.5
4	3.5	3.5	4	4	6	4
5	4	4	4.5	4.5	6.5	4.5
6	4.5	4.5	5	5	7	5
7	5	5	5.5	5.25	7.5	5.5
8	5.5	5.25	6	5.5	7.75	5.75
9	6	5.75	6.25	5.75	8.25	6.25
10	6.5	6	6.5	6	8.5	6.5
11	7	6.25	6.75	6.25	9	6.75
12	7.5	6.5	7	6.5	9.25	7
13	8	6.75	7.25	6.75	9.5	7.25
14	8.25	7	7.5	7	9.75	7.5
15	8.5	7.25	7.75	7.25	10	7.75
16	9	7.75	8	7.5	10.25	8
17	9.25	8	8.25	7.5	10.5	8.25
18	9.5	8.25	8.5	7.75	10.75	8.5
19	9.75	8.75	8.75	8	11	8.75
20	10	9	9	8.25	11.25	9
21	10.25	9.25	9.25	8.25	11.5	9.25
22	10.5	9.5	9.5	8.5	11.75	9.5
23	10.75	9.75	9.75	8.75	12	9.5
24	11	9.75	10	8.75	12.25	9.75
25	11.25	10	10	9	12.5	10
26	11.5	10.25	10.25	9	12.75	10.25
27	11.75	10.5	10.5	9.25	12.75	10.5
28	12	10.75	10.75	9.5	13	10.5
29	12.25	10.75	10.75	9.5	13.25	10.75
30	12.5	11	11	9.75	13.5	11

Table 15: Complete LPLT test results of nano-based drilling fluids 2

Time (min)	75% Bentonite 25% NB + 0.1% PAC	75% Bentonite 25% NB + 0.1% Xanthan + 0.1% Starch	Bentonite + 5 ppg NB	Bentonite + 5 ppg NB + 0.1% Starch
1	2	1.5	2.5	1.5
2	2.75	2	3.5	2.5
3	3.5	3	4.5	3.5
4	4	3.5	5	4
5	4.5	4	5.5	4.5
6	5	4.5	6	5
7	5.25	5	6.5	5.5
8	5.5	5.5	7	6
9	6	6	7.5	6.25
10	6.25	6.25	8	6.5
11	6.5	6.75	8.5	7
12	7	7	9	7.5
13	7.25	7.25	9.25	7.75
14	7.5	7.75	9.5	8
15	7.75	8	10	8.25
16	8	8.25	10.5	8.5
17	8.25	8.5	10.75	9
18	8.5	8.75	11	9.25
19	8.75	9	11.5	9.5
20	9	9.25	11.75	9.75
21	9.25	9.5	12	10
22	9.5	9.75	12.25	10.25
23	9.75	10	12.5	10.5
24	9.75	10.25	12.75	10.75
25	10	10.5	13	11
26	10.25	10.5	13.25	11.25
27	10.5	10.75	13.5	11.5
28	10.75	11	13.75	11.5
29	10.75	11	13.75	11.75
30	11	11.25	14	12

Table 16: Complete HPHT test results of nano-based drilling fluids

Time (min)	**Bentonite**	**Bentonite + 0.1% PAC**	**NB + 0.1% Xanthan + 0.5% Starch**	**NB + 0.1% Xanthan + 0.2% PAC**	**75% Bentonite 25% NB + 0.1% PAC**
1	3	2.4	2	2	2
2	5	3.8	3	3	3.2
3	6.5	5	3.8	4	4
4	7.75	6	4.4	4.8	4.8
5	8.5	6.8	5	5.4	5.4
6	9	7.4	5.4	6	5.9
7	9.5	7.8	5.8	6.5	6.4
8	10	8.2	6.2	7	6.8
9	10.5	8.6	6.4	7.5	7.2
10	11	9	6.6	7.8	7.6
11	11.5	9.3	6.9	8.2	8
12	12	9.6	7.1	8.5	8.4
13	12.5	10	7.3	8.8	8.7
14	13	10.4	7.6	9.2	9
15	13.5	10.6	7.8	9.4	9.3
16	14	11	8.1	9.6	9.8
17	14.5	11.3	8.4	9.8	10.1
18	14.75	11.5	8.6	10	10.5
19	15	11.8	8.8	10.3	10.7
20	15.5	12.1	9	10.5	11
21	16	12.4	9.2	10.8	11.3
22	16.25	12.6	9.4	11	11.6
23	16.5	12.8	9.6	11.2	11.9
24	16.75	13.2	9.8	11.4	12.1
25	17	13.5	10	11.6	12.4
26	17.5	13.8	10.2	11.8	12.6
27	17.75	14	10.4	12	12.8
28	18	14.3	10.6	12.2	13
29	18.25	14.5	10.8	12.4	13.2
30	18.5	14.8	11	12.6	13.5