International Journal of Scientific Research and Engineering Development-– Volume 6 Issue 5, Sep- Oct 2023

Available at www.ijsred.com

RESEARCH ARTICLE OPEN ACCESS

Evaluating the Effects of Temperature and Pressure on Rheological and Fluid Loss Properties of Synthetic Based Drilling Fluids Formulated With Micronized Weighting Agents

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Abstract:

In adverse drilling environments such as High-Pressure High Temperature (HPHT) wells, high temperatures and pressures encountered downhole by drilling fluids may degrade their chemical constituents. This may undermine the drilling fluid's ability to carry out its functions effectively and result in problems while drilling. The main objective of this study was to evaluate the effects of temperature and pressure on fluid losses and rheological properties of novel, synthetic based drilling fluids (SBDFs) formulated with different sizes and types of weighting agents. Weighting additives such as 53µm barite, 25-30µm barite, 5-9µm barite, 7-9µm Ferox (Iron-Oxide) and 6-8µm Fero-Bar (blend of dual-weighted agents of Ferox and Barite) were used to formulate different mud samples (each 16.5ppg) to carry out rheology tests within temperature and pressure ranges of 120^{o}F to 400^{o}F and 14.7Psi to 12,000Psi and HPHT fluid loss tests in the laboratory. The mud sample weighted with 53µm barite (un-micronized) was used as the control sample to compare with the performance of other drilling fluid samples (i.e micronized mud samples). The outcome of the tests indicate that the mud samples formulated with weighting materials of ultra-fine particles sizes (5µm to 9µm) indicated a more resilient, near-flat rheological profile and lower HPHT fluid losses across elevated temperature and pressure ranges than the mud sample weighted with weighting materials from coarser particles sizes (53µm). Therefore, the use of micronized weighting agents of ultra-fine particles sizes to weigh up the advanced mud premix helped to bridge some of the already established challenges associated with traditional drilling fluids in HPHT drilling environments such as high temperature gelation of the drilling fluids, poor rheological control, and severe HPHT fluid losses.

Keywords —High pressure high temperature (HPHT), Barite, Ferox, Fero-Bar, weighting agents, particles sizes.

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I. INTRODUCTION

Drilling fluids perform certain critical functions during drilling operations such as control of formation pressures, maintaining wellbore stability, cuttings transport from the wellbore, cooling of drill bit etc. To achieve the goal of controlling the formation pore pressure drilling operations, weighting additives or agents are usually added to drilling fluids to build up the fluid density more than the anticipated downhole formation pore pressure. These weighting agents are usually critically selected and optimized so that their properties and quantities do not negatively affect the functions for which the drilling fluids were designed for in the first place. When deciding on the choice of weighting agents, some of the important properties usually considered include its chemical inactivity, effects on other properties of the drilling fluid, specific gravity, material availability, ease of crushing etc. Thus, they are usually high-density minerals which when suspended in the drilling fluid; provide high hydrostatic pressure to counterbalance the formation pore pressure downhole (Jafari, 2021). However, in adverse drilling environments such as High-Pressure, High-Temperature (HPHT) wells, the elevated temperatures and pressures encountered by the drilling fluids downhole may undermine their technical performance and result in problems during the drilling operations. Uncontrolled changes downhole in the drilling fluid's pressure and temperature could modify the rheological properties of drilling fluid that may negatively affect the fluid's ability to carry out vital functions, which are dependent on the drilling fluid's properties. Wells with a high bottom hole temperature and pressure more than 300^{o}F and 10,000Psi respectively are considered as high pressure, high temperature HPHT wells (Oriji, 2015). HPHT wells are considered critical because of the more severe well conditions like borehole instability, fractured formation, and excessive lost circulation, thus several design processes are needed to be considered to ensure that HPHT wells are drilled safely and economically to the desired depth (Oriji and Dosunmu; 2012). Some of the challenges faced by conventional drilling fluids in HPHT environment include high temperature gelation, high temperature fluid loss, loss of rheological control, thermal degradation of the drilling fluid constituents, sagging of the weighting materials, uncontrollable ECD in narrow drilling windows, high gas solubility etc (Davoodi et al, 2018, Zhong et al, 2019, Ali et al, 2020, Basfar et al, 2018, Bradley et al, 2002). If the rheological and fluid loss properties of drilling fluids are not well managed during drilling operations, it may result fall in hydrostatic coloumn of fluid due to excessive fluid losses to the formation, cuttings bed accumulation, poor fluid hydraulics and hole cleaning, pipe dticking, uncontrollable ECD in narrow drilling windows which may result to kick intake, formation fracture and fluid loss circulation. Hence, understanding the influence of pressure and temperature on rheological and fluid loss properties of drilling fluids is crucial to design drilling fluids that can function optimally in the anticipated operating conditions. This will enable the driller to have a better understanding and control for pressure control and other critical aspects that drilling fluids play during drilling operations(Rommetveit and Bjorkevoll, 1997, Ahmadi, 2018). Raj et.al (2016) reviewed past works related to shear rate estimation for non-Newtonian fluids with or without yield point or yield stress with the help of basic integral equation of coquette flow. It confined the equations that were developed for determination of shear rate along with the rheological properties for non-rheological properties for the non-Newtonian fluid with or without yield stress. Gautam et.al (2020) utilized top grade developed PAC□grafted copolymers to formulate water-based mud (WBM) with American Petroleum Institute (API) □grade bentonite and alpha□glycol functionalized nano fly ash. Steady shear viscosity and viscoelasticity tests were carried out to evaluate the rheological resilience of the WBM above 200°C. The outcome of the laboratory investigation under high-pressure high temperature (HPHT) conditions showed that the efficiency of the WBM might be significantly enhanced by improving the elastic properties of the drilling fluid by controlling the molecular weight of the intended PAC□grafted copolymer.

Gautam et.al (2021) predicted rheological properties that are temperature and pressure dependent (e.g shear viscosity, apparent viscosity (AV), and plastic viscosity (PV)) at HPHT conditions by means of the basic momentum transport mechanism (kinetic theory) of liquids. The model were tested with twenty-six different types of HPHT drilling fluids using water, formate, oil, and synthetic oil as base fluids. The developed model may be used for predicting (with high precision) the rheology many drilling fluids. Gautam and Guria (2022) appraised a more precise and comparatively novel shear rate equation that was centered on the empirical model for high yield stress drilling fluids to evaluate the frictional pressure drop in laminar and turbulent flow regimes under surface and downhole conditions. A Fann viscometer was employed to measure the shear rates using the empirical model, which is different from the conventional shear rates. The newly developed shear rates can be used used to predict model parameters of Bingham plastic (BP), power-law (PL), Herschel–Bulkley (HB), and Robertson-Stiff (RS) models, and the equivalent frictional pressure drops. Bageri et al (2021) studied the changes in drilling fluid's rheological and fluid loss properties created by adding different weighting agents. Some water-based mud samples were formulated and weighted up with similar concentration of weighting agents such as ilmenite, barite, hematite and Micromax. The properties of the used weighting agents' were estimated. Afterwards, the rheology of the mud samples were measured at 80 °F. The fluid loss test was measured at 200 °F and 300 psi differential pressure to form a filter cake over the sandstone core samples. The outcome of the laboratory investigations established that the plastic viscosity (PV), yield point (YP), and filter cake sealing properties were all considerably impacted by the ratio of the large to fine particle size (D90/D10) of the weighting agents irrespective of the weighting material type.

In this work, the use of microparticles or micronized weighting agents that employ ultra□fine particles of a weighting agent was exploredto engineer drilling fluids with physical and chemical properties that is significantly different from their coarse particles counterparts with the possibilities to overcome some of the limitations of conventional drilling fluids in HPHT environment. Samples of synthetic based drilling fluids (SBDFs) formulated with micronized weighting agents comprise 53µm barite, 25-30µm barite, 5-9µm barite, 7-9µm Ferox (Iron-Oxide) and 6-8µm Fero-Bar (blend of dual-weighted agents of Ferox and Barite). The developed mud samples were subjected to HPHT rheology and HPHT fluid loss tests to evaluate the impact of temperature and pressure on their rheological properties and fluid losses respectively. Standard laboratory procedures were followed to carry out the rheology tests and HPHT fluid loss tests. Comparisons of the results were made based on the same premix formulation so that the effects of using different particles sizes and weighting agents can be clearly seen from the tests outcomes. The mud sample weighted by 53µm barite was used as the control for comparison or reference to other mud samples weighted up with barite.

2.0 MATERIALS AND METHODS: LABORATORY INVESTIGATION

2.1 SELECTION OF WEIGHTING AGENTS

Weighting agents from MI Swaco's advanced weightingagents research project, (WARP) were used to carry out these laboratory investigations. The particles of barite and haematite (Iron III Oxide) weighting agents were milled to ultra-fine particle sizes with particles size distribution (PSD) of different sizes. The Particle sizes was determined by laser diffraction method using the Malvern Mastersizer 2000. An 8-speed Ofite rotational viscometer was used in this study to measure the rheological properties of drilling fluids samples at standard pressure and temperature conditions. A Fann-75 viscometer was used for taking rheology measurements of the drilling fluids samples at selected, elevated pressures and temperatures conditions. See table 2.1 below for details of major equipment that was used to conduct the laboratory tests.

Table 2.1: List of Major Laboratory Equipment used for rheology tests.

S/N	Names of Major	Function	Model
1	OFITE 8-Speed	Rheology	800,
2	OFITE Pressurized Drilling fluid	Provide accurate density readings	800, #100-

S/N	Names of Major	Function	Model
3	HAMILTON Beach Triple Spindle	Stirring/Mixing of drilling fluid	HMD 400-CE
4	Stirring Hot Plate	Precise liquid temperatures	Corning PC-
5	S.METTLER Precision/Electronic	Precision Weighting	PB602-S
6	FANN Model 75 Automatic	Allows rheology measurements	Model 75
7	OFITE Model MB HTHP Filter Press	For high pressure and high	#171-51-C: 230V
8	Malvern	For	Model-
9	Hot Roller Oven (Ofite 5-Roller	For Heating and hot rolling	173-00-1-RC

Table 2.2: *Particles size distribution and properties of 53µm Barite (weighting agent) Used*

Test Item	Limit
Particle Size Distribution D-10	25µm
Particle Size Distribution D-50	**53 µm**
Particle Size Distribution D-90	75 µm
Typical Properties	
Physical appearance	Dry: Tan to Grey powder
Bulk density	1,920 – 2,400 kg/m^3 [120-150 lb/ft^3]
Density	4.20 g/cm^3
Melting Point	1580^{o}C
Odour	Odourless or no characteristic odour
Barium Sulphate	4.0 mg/m^3 (60-100%)
Quartz	0.3 mg/m^3, max. (<4%)
Crystalline Silica	0.3 mg/m^3, max. (<2%)
Mercury	1.0 mg/kg, max. (<1%)

Table 2.3: *Particles size distribution and properties of 5-9µm Barite (weighting agent) Used*

Test Item	Limit
Particle Size Distribution D-10	2 - 4 µm
Particle Size Distribution D-50	**5 - 9 µm**
Particle Size Distribution D-90	11 – 21 µm
Typical Properties	
Physical appearance	Dry: gray to white powder
	Muds: light to dark brown
Bulk density	1,920 – 2,400 kg/m^3 [120-150 lb/ft^3]
Density	4.10 g/cm^3
Barium Sulphate	4.0 mg/m^3 (60-100%)
Arsenic	40 mg/kg, max. (1%)
Lead	1000 mg/kg, max. (<1%)
Cadmium	3.0 mg/kg, max. (<1%)
SiO_2	6 wt%, max. (<2%)
Moisture	0.5 wt%, max. (<2%)
Mercury	1.0 mg/kg, max. (<1%)

Table 2.4: *Particles size distribution and properties of 7-9µm Ferox (weighting agent) Used*

Test Item	Limit
Particle Size Distribution D-10	4 - 6 µm
Particle Size Distribution D-50	**7 - 9 µm**
Particle Size Distribution D-90	10 – 12 µm
Hematite	95-100%
Quartz or Crystalline SiO_2	0-5%
Typical Properties	
Physical appearance	Powder, dust
Colour	Red to black
Odour/Taste	Odourless or no characteristic odour
Solubility	Insoluble in water

Bulk density	2,178 kg/m^3 [136 lb/ft^3]
Particle hardness	5–6 Mohs hardness scale (1 – 10)
Minimum Specific gravity	4.8
Density	4.8 g/cm^3

Table 2.5: *Particles size distribution and properties of 25-30µm Barite (weighting agent) Used*

Test Item	Limit
Particle Size Distribution D-10	15 - 18 µm
Particle Size Distribution D-50	**25 - 30 µm**
Particle Size Distribution D-90	75 µm
Typical Physical Properties	
Physical appearance	Dry: tan powder
	Muds: dark tan
Bulk density	1,714 - 2,162 kg/m^3 [107-135 lb/ft^3]
Minimum Specific gravity	4.2
Density	4.2 g/cm^3
Soluble hardness (as calcium)	250 mg/kg, max
Barium Sulphate	4.0 mg/m^3 (70-95%)
Quartz	0.3 mg/m^3, max. (<3%)
Crystalline Silica	0.3 mg/m^3, max. (<3%)
Mercury	1.0 mg/kg, max. (<1%)

Note: *Particle sizes was determined by laser diffraction method using the Malvern Mastersizer2000. Density was measured by a helium gas pycnometer.*

2.2 DRILLING FLUID SAMPLES PREPARATION

Different samples of synthetic based drilling fluids were formulated from novel based drilling fluid constituents to prepare the mud premix which is uniform for the five samples of drilling fluids that were used for the tests.

The mud premix was formulated in the following procedure:

1. 160.21 ppb of Paradril BN base oil used to prepare the continuous phase of the drilling fluid.
2. 5.0ppb of Versagel was mixed with the continuous phase (Paradril BN base oil) to act as high temperature viscosifier.
3. 10ppb of alkaline was added to the mixture to increase the alkalinity of the mixture.
4. 9ppb of Suremul chemical was added to the mixture to lower the interfacial tension between oil and water and form stable or strong emulsions with small droplets.
5. 5ppb of Surewet was blended with the mixture to preferentially oil-wet the weighting agents and drill solids and in that way prevent these solids from becoming water-wet.
6. 7.81ppb of Calcium Chloride was added to the mixture and stirred to increase the chloride content in the mud or control the water phase salinity
7. 1ppb of Ecotrol RD was then blended with the mixture for filtration control or limit excessive fluid loss (of the continuous phase of the drilling fluid) to the formation.

8. 2ppb of Suremod was then added to the mixture to act as the rheology modifier for high viscosity at low shear rates.

To develop a specific drilling fluid sample, the mud premix is then weighted up to 16.5ppg using weighting agents of different types and particles size distributions.The weighting additives used include 53µm barite, 25-30µm barite, 5-9µm barite, 7-9µm Ferox (Iron III Oxide) and 6-8µm Fero-Bar (blend of dual-weighted agents of Ferox and Barite). The 53µm barite mud sample is used as the control sample to compare the behaviour of other mud samples weighted with micronized or ultra-fine microparticles size weighting agents.

Table 2.6 below shows the details of the weighting agent's type and particles size distribution for each sample of the formulated drilling fluids.

Table 2.6: Particles size distribution (PSD) of weighting agents that were used.

S/N	Weighting agents	Particles Size Distribution	
1	Barite-Sample 1	D-10	25 µm
		D-50	53 µm
		D-90	75 µm
2	Barite-Sample 2	D-10	15 - 18 µm
		D-50	25 - 30 µm
		D-90	75 µm
3	Barite-Sample 3	D-10	2 - 4 µm
		D-50	5 - 9 µm
		D-90	11 – 21 µm
4	Ferox (Iron III Oxide)	D-10	4 - 6 µm
		D-50	7 - 9 µm
		D-90	10 – 12 µm
5	FeroBar (blend of 20% 7-9 µmFerox& 80% 5-9 µm Barite)	D-10	5 - 9 µm
		D-50	6 - 8 µm
		D-90	7 - 9 µm

Table 2.7 indicates the compositional details of the drilling fluids samples and quantities of weighting agents that were used to prepare the different samples of drilling fluids. Five different samples were prepared from the same drilling fluid premix and barite or Ferox (Haematite) or a blend of both as the weighting agent. The five samples of drilling fluids used for the investigations have been listed below;

1. Sample #1: 53 µm barite weighted SBDF
2. Sample #2: 25 - 30 µm barite weighted SBDF
3. Sample #: 5 - 9 µm barite weighted SBDF
4. Sample #4: 7 - 9 µm Iron III Oxide/ferox weighted SBDF
5. Sample #5: Ferobar (blend of 20% 7-9 µmferox and 80% 5-9 µm barite) weighted SBDF

Table 2.7: Drilling fluid samples and their compositions

Sample #1: 53µm barite weighted SBDF **MW = 16.5ppg**	**Sample #2:** 25-30µm barite weighted SBDF **MW = 16.5ppg**	**Sample #3:** 5-9µm barite weighted SBDF **MW = 16.5ppg**	**Sample #4:** 7-9µm ferox weighted SBDF	**Sample #5:** 6-8µm fero-bar (20%: 7-9µm ferox& 80%: 5-9µm barite) **MW = 16.5ppg**
Premix 160.21ppb Paradrill BN 7.81ppb Calcium Chloride 5ppb Versagel HT 10ppb Lime 9ppb Suremul 5ppb Surewet 2ppb Suremud 6ppb Versatrol HT 1ppb Ecotrol RD 21.86ppb Water	***Premix*** 160.21ppb Paradrill BN 7.81ppb Calcium Chloride 5ppb Versagel HT 10ppb Lime 9ppb Suremul 5ppb Surewet 2ppb Suremud 6ppb Versatrol HT 1ppb Ecotrol RD 21.86ppb Water	***Premix*** 160.21ppb Paradrill BN 7.81ppb Calcium Chloride 5ppb Versagel HT 10ppb Lime 9ppb Suremul 5ppb Surewet 2ppb Suremud 6ppb Versatrol HT 1ppb Ecotrol RD 21.86ppb Water	***Premix*** 160.21ppb Paradrill BN 7.81ppb Calcium Chloride 5ppb Versagel HT 10ppb Lime 9ppb Suremul 5ppb Surewet 2ppb Suremud 6ppb Versatrol HT 1ppb Ecotrol RD 21.86ppb Water	***Premix*** 160.21ppb Paradrill BN 7.81ppb Calcium Chloride 5ppb Versagel HT 10ppb Lime 9ppb Suremul 5ppb Surewet 2ppb Suremud 6ppb Versatrol HT 1ppb Ecotrol RD 21.86ppb Water
Weighting Material 505.46 ppb Barite	***Weighting Material*** 498.56 ppb Barite	***Weighting Material*** 530.36 ppb Barite	***Weighting Material*** 458.31 ppb Ferox	***Weighting Material*** 485.82 ppb Fero-Bar

Note: The Premix was uniform for all mud samples and produced the starting drilling fluid for all samples prior to addition of weighting material to increase the densities of the drilling fluid samples to 16.5ppg. The mud sample weighted by 53µm barite was used as the control for comparison or reference to other mud samples.

Table 2.8 below describes the functions of different drilling fluids additives that were used in the preparation of the drilling fluids samples.

Table 2.8: Drilling fluid additives used and their functions.

S/N	Name of Additive	Function
1	Paradrill BN	Base Fluid/Oil
2	Calcium Chloride	Salinity/Shale

S/N	Name of Additive	Function
3	Versagel HT	High Temperature
4	Lime	Alkalinity/ PH
5	Suremul	Emulsifier
6	Surewet	Wetting Agent
7	Suremud	Rheology Modifier
8	Versatrol HT	Filtration
9	Ecotrol RD	Filtration
10	Water	Internal Water
11	Barite-Sample 1 (d-50:	Weighting agent
12	Barite-Sample 2 (d-50: 25-	Weighting agent
13	Barite-Sample 3 (d-50: 5-	Weighting agent
14	Iron III Oxide or Ferox (d-	Weighting agent
15	FeroBar(blend of 20% 7-9	Weighting agent

2.3 LABORATORY TESTS

Standard laboratory procedures were followed to carry out rheology tests and HPHT fluid loss tests. Comparisons of the results were made based on the same premix formulation so that the effects of using different particles sizes for weighting agents can be clearly seen from the tests outcomes. The mud sample weighted by 53µm barite was used as the control for comparison or reference to other mud samples.

a. Rheology test results at standard temperature and ambient pressure prior to aging

The five drilling fluids samples (each of 16.5ppg) developed for this experiment were used to carry out standard rheology tests to examine the effects of temperatures and pressure (within the ranges of standard conditions) on the rheological properties of the drilling fluids. The test was carried out in the laboratory using an 8-Speed OFITE Viscometer at standard conditions (temperature of 120^{o}F and ambient pressure conditions, 14.7psi).

b. Rheology tests at elevated temperatures and high pressures

For this research, the FANN Model 75 Automatic viscometer was used to measure the rheology of the drilling fluid samples within temperature and pressure ranges of 120^{o}F to 400^{o}F and 14.7Psi to 12,000Psi respectively to examine the influence of temperature and pressure on synthetic based drilling fluids formulated with weighting agents of different particles sizes and types.

c. Rheology test results at standard temperature and ambient pressure after aging

Samples of the five drilling fluids (16.5ppg each) were collected in different aging cells and heated to 320^{o}F using the Ofite 5-Roller Oven. The temperature in the roller oven was maintained at 320^{o}F for a minimum period of 16hrs. After the expiration of the time, the samples were retrieved and allowed to cool. The rheological properties of the drilling fluid were then re-measured using the 8-Speed Ofite viscometer.

d. HPHT fluid loss test

For filtration measurements at high pressure and high temperature i.e HPHT Fluid loss test, samples of the five drilling fluids were subjected to a fluid loss test in the laboratory using a OFITE Model MB HTHP Filter Press. Samples of the drilling fluids are in turn heated in a controlled environment to a temperature of 350°F which is the downhole anticipated temperature in the wellbore. After the test temperature has been attained, the volume of the filtrate was determined at a pressure differential of 500psi to simulate downhole pressure condition.

2.4 ASSUMPTIONS MADE FOR RHEOLOGY TESTS.

1. There is minimum or no entrance of formation solids into the active mud solids in the wellbore during the tests.
2. There is minimum or no increase of mud density in the wellbore during the dynamic aging tests.
3. There is uniformity of temperature throughout the roller oven during the dynamic aging tests.
4. There is adequate headspace of air (10% to 15% of the volume of the aging cell) left in the aging cells to prevent piston even during the dynamic aging tests.
5. There are no leaks from the aging cells during the dynamic aging tests.
6. The inner linings of the metallic material of the aging cells do not react with the drilling mud at elevated temperatures during the dynamic aging tests.
7. The oven aging temperature is the anticipated wellbore temperature.
8. There is uniformity of temperature throughout the drilling mud in the wellbore. i.e while heating up the drilling mud in the thermocup.

3.0 RESULTS AND DISCUSSIONS

3.1 RHEOLOGY TEST RESULTS PRIOR TO AGING

i. Plastic viscosities results for drilling fluid samples

Plastic viscosity is the mechanical friction between solid particles in drilling fluids and fluid layers in the drilling mud. Essentially, plastic viscosity is a function of the liquid phase viscosity, the size of particles in the fluid, the shape of solid particles and the number of particles (Bridges, 2020). It is preferrable that the plastic viscosity of the drilling mud be as low as reasonably possible (ALARP). From Fig 3.1 below, the 53 µm Barite weighted mud displayed the highest plastic viscosity value among the all other mud samples while the 25-30µm barite weighted mud indicated the least value. Since the mud sample weighted with 5-9µm barite has more solid particles (530.36ppb) than other samples, it would have thought that this particular mud sample will most likely produce the highest plastic viscosity value (considering that the pre-mix is uniform for all mud samples). The result from Fig 3.1 shows that this is not the case. The mud sample weighted with 5-9µm barite produced a plastic viscosity value of 23cP which is the second lowest value among other mud samples. Besides, this value is within the desirable benchmark (15-25cP) at the standard temperature (120^{o}F) and ambient pressure (14.7psi). This would mean higher hydraulic energy at the drilling bit, improved rate of penetration, better hole cleaning and lesser wear on mud pump and drilling equipment. The ultra-size particles sizes of the weighting agents which have been treated or coated with polymers is partially responsible for producing different, expected physical and chemical properties compared to the mud samples weighted with coarse particles size (mud sample weighted with 53µm barite). The slurry produced is low-viscous, high-density fluid which will lead to improved drilling efficiency. Comparing the PV profiles for the mud samples weighted with 7-9µm Ferox (458.31ppb) and 6-8µm Fero-Bar (485.82ppb) are compared, the mud sample weighted with Ferox indicated a slightly higher and more consistent PV profile across pressure and temperature conditions. Again, the PV result obtained is contrary to traditional concept or belief about plastic viscosity (related to the solid particles concentration) and can be linked to the modified physical and chemical properties of the mud sample formulated with smaller particles and the slight difference in the types of weighting agent used. Hence, the mud samples with the least PV values are more desirable since it implies that for these samples, the resistance caused by the mechanical friction within the drilling fluids between solids and liquids, and the deformation of liquid under shear stress/pressure is the lowest and these fluid samples will drill more rapidly due to the low viscosity of mud that is exiting the drill bit.

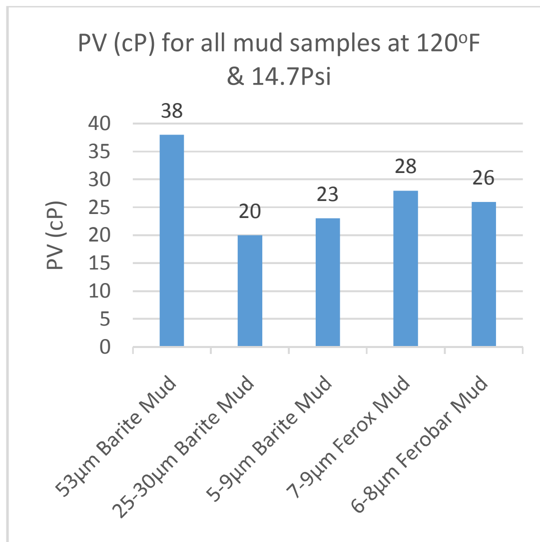

Fig 3.1:PV for all drilling fluids samples @ standard conditions of 120^{o}F and ambient pressure

ii. Yield Points of the drilling fluids samples

From Fig 3.2, the higher YP values obtained with mud samples with smaller particles sizes may be ascribed to the newer particles' sizes formed by milling the weighting materials to ultra-fine particles sizes which creates more sites for interactions in the fluid and more solid concentrations or forces of attraction among the colloidal particles in drilling fluid. When the YP plots from the mud samples formulated with Ferox is compared with Fero-bar particles, both plots are some differences between them. This may be because of the slight modification in the components of the weighting agents in the mud samples. Excessive YP also implies a high gel strength, high surge and swab pressures, high ECD, high mud pump pressure requirement, high tendency to fracture formation and loss circulation, etc. Hence the optimal YP values (not necessarily the highest YP values) is preferred as this will mean that for these samples, the drilling fluid will be able to carry cuttings out of the wellbore annulus with little propensity that may lead to drilling problems during drilling operations. The ultra-size particles proportions of the weighting agents treated or coated with polymers is partly liable for producing mud samples with different physical and chemical properties compared to mud samples weighted with coarse particles size (mud sample weighted with 53µm barite).

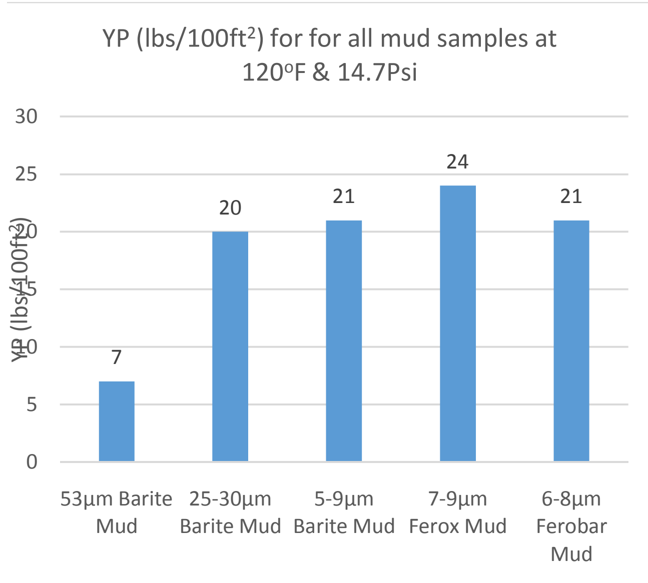

Fig 3.2: Yield Point test results for all drilling fluids samples @ Standard Conditions of 120°F and Ambient Pressure.

iii. Gel Strength of the drilling fluids samples

From the 10-min Gel strength test result shown in Fig 3.3 below, it is obvious that other mud samples formulated with smaller particles sizes indicated better gel strength characteristics (within desirable benchmarks) when compared to the mud sample that was formed with coarser particles sizes (i.e mud sample weighted with 53µm barite) which does not fall within the acceptable range of measurements for gel strengths. In Fig 3.3, when the gel strength plots from the mud samples weighted with Ferox and the Fero-bar particles, it is observed that the mud sample with Ferox produced a slightly higher gel strength characteristic. Since gel strength is a measure of inter particles forces in a drilling fluid and the amount of gel structure that will occur when circulation is stalled, excessive gel strength implies that the mud is highly viscous and has a high yield point which is not usually desirable while drilling. Hence, the mud profiles with the highest gel strength profiles are not necessarily the samples with the highest gel strength quality. Instead, the mud profiles whose values falls within the acceptable benchmark is preferred. This implies that the colloidal particles in the mud sample can develop and retain an acceptable gel structure under non-flowing or static conditions. The good thixotropic properties and gel strength characteristics of these mud samples formulated from micronized weighting agents can be traceable to additional inter particles forces or bonds in a drilling fluid formed by the extra particles present.

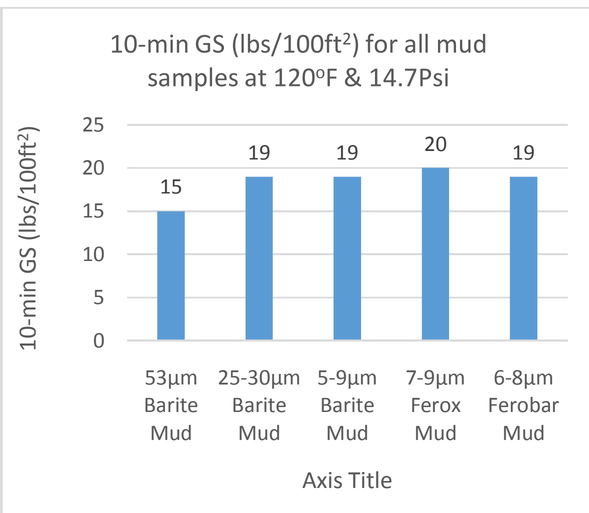

Fig 3.3: 10-min Gel Strength test results for all mud samples at Standard Conditions of 120^{o}F and 14.7Psi

3.2 RHEOLOGY TESTS AT ELEVATED TEMPERATURES AND PRESSURES

To conduct rheology tests across high pressure and temperatures values, each of the drilling fluid samples (mud density of 16.5ppg) were subjected to elevated temperature and pressure values from 120^{o}F to 400^{o}F and 14.7Psi to 12,000Psi respectively in incremental stages with the use of a Fann-75 Viscometer in the laboratory.

i. Yield Point, YP

Fig 3.4 indicates the yield point (YP) values of the different mud samples that were obtained when plotted across elevated temperatures and pressures. The YP-plots slightly decreased with increasing temperature and pressure above 200°F/4000psi as the organophilic clays (which acts as a viscosifier and gelling agent) component of the drilling fluid system become broken down at higher temperatures. When the mud samples developed with barite weighting agents are analysed, the YP plots obtained from mud samples with smaller particles sizes (25-30µm barite, 5-9µm barite) indicate a better, near-flat rheological profile. This indicates that these samples have a more robust yield point characteristics or better cuttings carrying index compared to mud sample weighted with coarser particles sizes of the same material under increasing temperature and pressure conditions. When plots for the mud samples formulated with barite of different particles sizes are contrasted, the sample weighted with 5-9µm barite displayed the highest YP values for the range of temperatures and pressure conditions that the fluids were subjected to during the test. Since YP is an indication of the ability of the mud to lift or carry drilled cuttings out of the wellbore annulus, the mud sample with higher and more resilient YP values is more desirable or better than that with lower YP values. The higher YP values obtained with mud samples with smaller particles sizes is attributable to the larger surface are to volume ratio which creates more sites for interactions in the fluid and leads to a greater force of attraction among the colloidal particles in drilling fluid sample. Hence, mud samples with smaller particles sizes modifies their physical and chemical properties when contrasted with larger particles weighting agents. In Fig 3.4, when the YP plots from the mud samples weighted with Ferox is compared with Fero-bar particles, the mud samples with almost similar particles sizes, the mud sample with 7-9µm Ferox is slightly 6-8µm Fero-Bar. This may be due to the difference in the make-up or constituents of the weighting agents in the drilling fluid mixture. Hence, mud samples with optimal YP (not necessarily the highest YP values) and consistent values across increasing temperature and pressure values is more desirable. This will mean that for these mud samples, the drilling fluid will be able to carry cuttings out of the wellbore annulus without necessarily, increasing the equivalent circulating density (ECD) nor require high pump pressure to circulate the mud during drilling or break circulation after the mud had been left static in the hole. The high pressures that would have been generated in this process with exceedingly high YP could have easily fractured the formation and lead to circulation losses, kick possibilities etc or even lead to other drilling problems. The observed near flat or resilient yield point profiles of the mud samples with smaller particles across elevated temperatures and pressures are more pronounced than with the sample with coarser particles sizes. This can partly be attributed to the enhanced or enlarged surface area (to volume ratio) of the micronized particles that allows heat to effectively diffuse into or out of the particles at very large rates due to the large surface area of a material in microparticles or micronized form. The film on the newly exposed surfaces area is coated with other substances that are quite different from the material of the microparticles and the surrounding medium thereby producing a fluid which constituent is thermally stable.

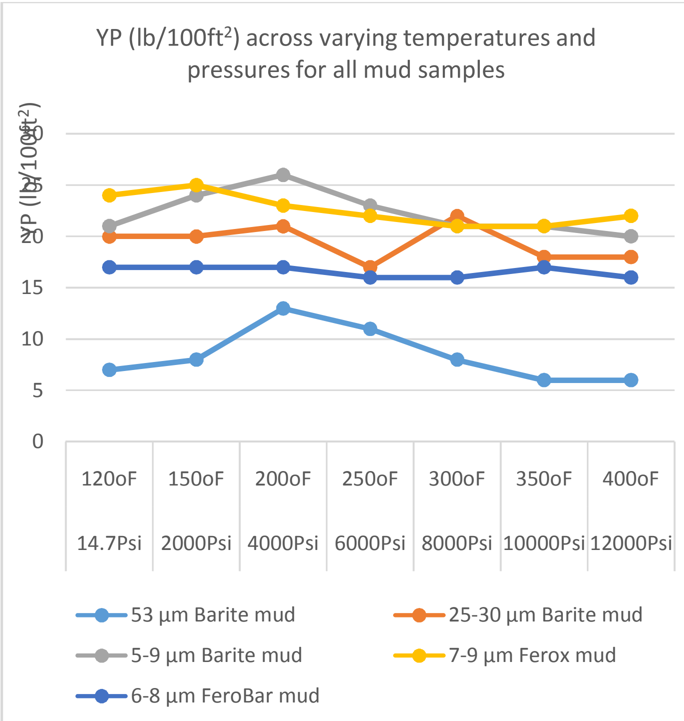

Fig 3.4: YP across varying temperature and pressure for all mud samples.

ii. Plastic Viscosity, PV

Fig 3.5 indicates the PV across varying temperature and pressure for all mud samples that were investigated. It is a given that since the premix is uniform for all the mud samples with the only difference being the type weighting agent or particles sizes and quantity of these particles in the mixture. Hence, one would have naturally expected that the sample with the most quantity of weighting agent will indicate the highest values of PV for the temperature and pressure conditions considered. From Fig 3.5 result, when all the mud samples weighted up with barite are analysed, it is anticipated that that the sample with barite of 5-9µm sizes (530ppb) being the sample with the most quantity of weighting materials should indicate the highest PV values. Contrary to this traditional logic, the result shows that the although the mud sample with 5-9µm barite has the most solids (530ppb) compared to the mud samples weighted with 25-30µm barite (498.56ppb) and 53µm barite (505.46ppb), nevertheless, it indicated the least and most consistent PV values across increasing temperature and pressure conditions. The smaller particles sizes in the mud sample allow heat and pressure to rapidly diffuse across the fluid mixture and the particles surfaces that have been treated or coated with polymers is responsible for producing different, expected physical and chemical properties compared to mud samples weighted with coarser particles sizes. The films on the newly exposed microparticles surfaces of the weighting agent are coated with other substances that are quite different from the material of the microparticles and the surrounding medium. Thus, the developed mud sample is thermally stable or robust to high temperature. This is what is responsible for the smaller PV value and more consistent near-flat PV profile across increasing temperature and pressure conditions as seen in Fig 3.5. When the PV profiles for the mud samples weighted with 7-9µm Ferox (458.31ppb) and 6-8µm Fero-Bar (485.82ppb) were compared, It can be seen that the mud sample weighted with Ferox indicated a slightly higher and more consistent PV profile across pressure and temperature conditions. Again, the PV result obtained is contrary to the traditional concept or belief about plastic viscosity (which base PV to amount of solids concentration in the fluid). Rather, It may be linked to the modified physical and chemical properties of the mud sample formulated with smaller particles and also the slight difference in the types of weighting agent used. Hence, the mud samples with the least and consistent PV values are more desirable since it implies that for these samples, the resistance caused by the mechanical friction within the drilling fluids between solids and liquids, and the deformation of liquid under shear stress/pressure is the lowest and these fluid samples will drill more rapidly due to the low viscosity of mud that is exiting the bit.

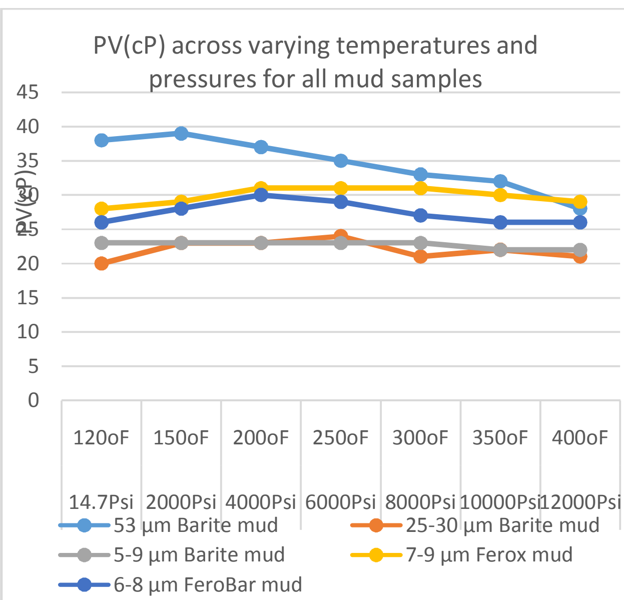

Fig 3.5: PV across varying temperature and pressure for all mud samples

iii. Low stress yield point, LSYP

Fig 3.6 below indicates the low stress yield point (LSYP) measurements plots for different mud samples across elevated temperatures and pressures. The LSYP-plots slightly decreased with increasing temperature and pressure above 200°F/4000psi as the organophilic clays (that acts as a viscosifier and gelling agent) component of the drilling fluid system become broken down at higher temperatures. When the mud samples developed with barite weighting agents were examined, one can observe that the LSYP profiles for mud samples with smaller particles sizes (25-30µm barite and 5-9µm barite) were of higher values and indicate a flat rheological profile across elevated temperatures and pressures compared to the mud sample with coarse weighting particles. Compared to mud sample weighted with coarser particles sizes of the same material under increasing temperature and pressure conditions, the mud samples with smaller particles sizes possess a more vigorous LSYP characteristics or better cuttings carrying capacity in the wellbore area where the flow rate is low. From Fig 3.6, LSYP plots for the mud samples formulated with barite of different particles sizes, the sample weighted with 5-9µm barite displayed the maximum LSYP values for the range of temperatures and pressure conditions that the fluid samples were subjected. Hence, given that LSYP is an index of the capacity of the mud sample to carry drilled cuttings out of the wellbore annulus in the wellbore area where the flowrate or shear stress is relatively lesser, these mud samples with higher and more resilient LSYP measurements are more advantageous than those with lower LSYP values. The greater LSYP values from mud samples with smaller particles sizes is ascribed to the larger surface are to volume ratio which creates more sites for interactions in the fluid and leads to a greater force of attraction among the colloidal particles in drilling fluid sample. Therefore, the mud samples with smaller particles sizes modifies their physical and chemical properties when juxtaposed with mud sample made from larger particles weighting agents. When we compare the LSYP plots from the mud samples weighted with Ferox and the Fero-bar particles in Fig 3.6, we observe that these mud samples with almost similar particles sizes (7-9µm Ferox weighted mud and 6-8µm Fero-Bar weighted mud) have very similar LSYP signatures despite the difference in the make-up of the weighting materials. This may be due to the slight difference in the make-up or constituents of the weighting agents in the drilling fluid mixture. The mud samples with smaller particles recorded flat low stress yield point profiles across elevated temperatures and pressures compared to the sample formulated with coarser particles sizes. This may be due to the enlarged surface area (to volume ratio) of the micronized particles which creates further reactivity and allows heat to effectively diffuse into or out of the particles at very large rates due to the large surface area of a material in microparticles or micronized form. Furthermore, the coatings on the newly exposed surfaces area of the microparticles are quite different from the material of the microparticles and the surrounding medium as a result, produces a fluid whose constituents are thermally stable.

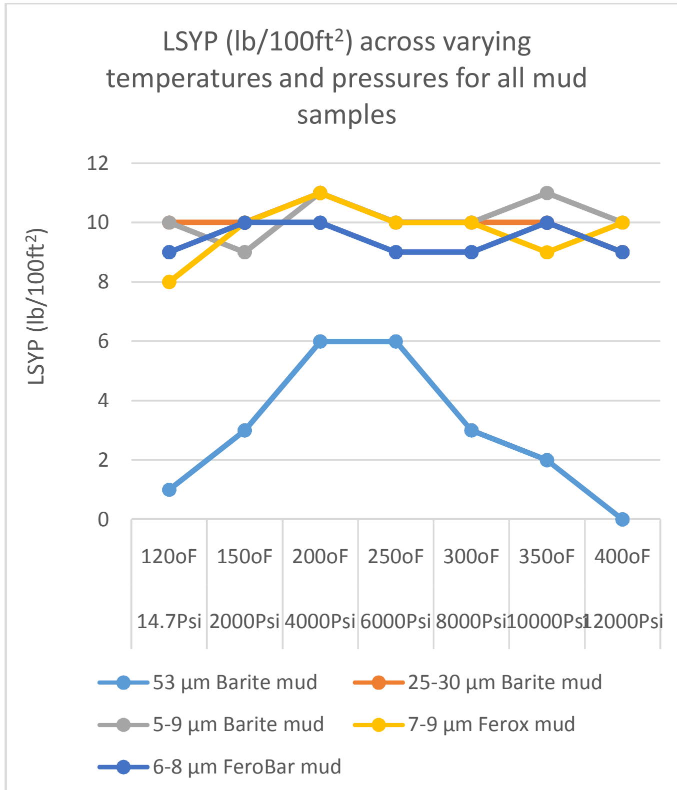

Fig 3.6: LSYP across varying temperature and pressure for all mud samples

From figures 3.4, 3.5, 3.6, 3.7, and 3.8, the rheological properties of the mud samples decreased slightly with increasing temperature and pressure above 200°F/4000psi as the organophilic clays (which as as a viscosifier and gelling agent) component of the drilling fluid system begins to break down at higher temperatures however in a more resilient manner. Compared to the mud sample weighted with 53m barite, the rheological profiles of drilling fluids samples weighted with smaller particles sized weighting additives generally reveal a near flat rheological profile across elevated temperatures and pressure values.

iv. Gel strength

From Fig 3.7, when the plots obtained from samples of mud weighted up by barite were compared, it could be seen the gel strength profile obtained from the 53µm barite mud produced the steepest bend when heated beyond 200^{o}F and 4000psi while the mud sample weighted with 25-30µm barite indicated the most stable gel strength characteristics across elevated temperatures and pressures. The gel strength plots slightly decreased with increasing temperature and pressure above 200°F/4000psi as the organophilic clays (which acts as a viscosifier and gelling agent) component of the drilling fluid system become broken down at higher temperatures.

When we compare the gel strength plots from the mud samples weighted with Ferox is and the Fero-bar particles in Fig 3.7, we observe that these mud samples with Ferox gave a higher gel strength characteristic, although less stable across elevated temperatures and pressures. Since gel strength is a measure of inter particles forces in a drilling fluid and the amount of gel structure that will occur when circulation is stalled, excessive gel strength implies that the mud is highly viscous and has a high yield point which is not usually desirable while drilling. Hence the mud profile with the highest gel strength profile is not necessarily the sample with the best gel strength quality. Instead, the best gel strength quality is the mud sample whose gel strength value falls within the acceptable standard/benchmark and remain stable or robust under increasing temperatures and pressure ranges. From Fig 3.7, It is seen that the mud weighted with 5-9µm produced a gel strength value of 14-25µm across the temperature and pressure range that it was subjected. This range of gel strength value is quite suitable and within the acceptable benchmark. This implies that the colloidal particles from smaller particles sizes in the mud sample can develop and retain an acceptable gel structure under non-flowing conditions even at the elevated temperatures and temperatures ranges as indicated.

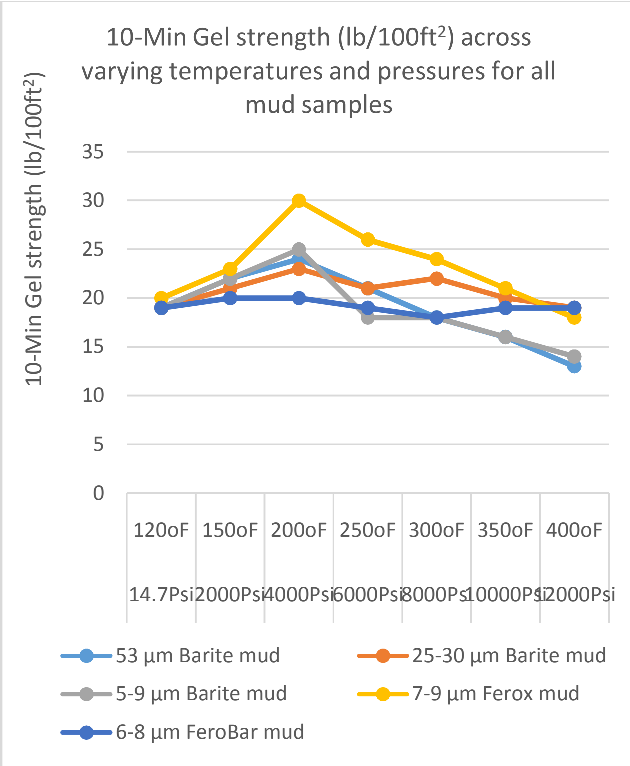

Fig 3.7: 10-Min Gel strength (lb/100ft2) across varying temperatures and pressures for all mud samples.

3.3 RHEOLOGY TEST RESULTS AFTER AGING

The five different mud samples were separately placed in aging cells and then subjected to a high temperature of 320°F in a roller oven for 16hrs to undergo dynamic aging. After the expiration of 16hrs, the aging cells were retrieved from the roller oven and allowed to cool before conducting rheology tests to examine the effects of dynamic aging on rheological properties of the drilling fluid samples. When the initial rheological properties (apparent viscosities, plastic viscosities, yield points and gel strengths) of the mud samples before aging were compared to their corresponding values after dynamic aging tests, the effects of an elevated temperature of 320°F after 16hours of hot rolling (dynamic aging) modified their rheological properties although in a limited or smaller extent. The changes in rheological properties after aging were within the acceptable or set rheological limits (benchmarks) for the mud samples except for the mud sample weighted with 53µm barite mud which did not meet the required benchmarks for the 3-6RPM readings, LSYP, PV and YP.

3.4 Effects of Aging on HPHT Fluid Loss

One of the desirable technical performances of drilling fluids is a fluid with minimal losses to the formation as possible within the desirable limits or benchmark while preventing excessive or thick filter cake formation on the wall during drilling operations. Poor filter cake formation characteristics on permeable zones in the wellbore may lead to stuck pipe and other drilling problems. Reduced oil and gas production may also result from reservoir damage (or formation damage) when a poor filter cake allows deep filtrate invasion. For nearly all mud samples tested, the observed fluid losses to the wellbore formation at HPHT conditions were within the acceptable limits for fluid losses that is required for a good filter cake formation with minimal formation damage. As seen from Fig 3.8, the 53µm barite weighted mud sample indicated the highest HPHT fluid loss measures before and after aging while the 5-9µm barite weighted mud showed the least values for HPHT fluid loss. This implies that smaller particles sizes will form the best quality of filter cake on the formation that will limit filtrate invasion and thus, fluid loss to the formation and formation damage during HPHT drilling operations. The HPHT fluid loss of all mud samples (except the mud samples weighted with 53µm barite) before and after aging indicated fluid losses values that is within the acceptable standard, before and after being heated to 320°F for 16hrs. The HPHT fluid loss for mud samples weighted with 53µm barite before and after aging (4.1 mls and 4.4 mls respectively) exceeded the desired benchmark (< 4mls).

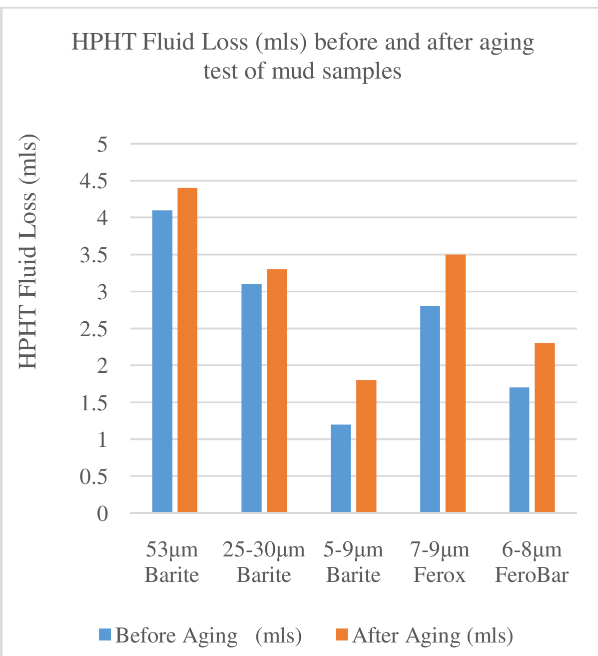

Fig 3.8 HPHT Fluid Loss before and after aging test of mud samples

Table 3.1 demonstrates the improvement in rheological properties and filtration loss with mud samples of different sizes and types of weighting agents at standard temperature and pressure (120°F & 14.7Psi).

Table 3.1: Improvement in rheological properties and fluid loss with different sizes and types of weighting agents at standard temperature and pressure (120°F & 14.7Psi)

Mud Sample	**Before Aging (cP)**	**% Change in AV compared with 53µm Barite**	**After Aging (cP)**	**% Change in AV compared with 53µm Barite**
53µm Barite	41.5		43.5	
25-30µm Barite	30	-27.71%	33.5	-0.229885057
5-9µm Barite	33.5	-19.28%	35	-0.195402299
7-9µm Ferox	40	-3.61%	42.5	-0.022988506
6-8µm FeroBar	34.5	-16.87%	37.5	-0.137931034
Plastic Viscosity				
Mud Sample	**Before Aging (cP)**	**% Change in PV compared with 53µm Barite**	**After Aging (cP)**	**% Change in PV compared with 53µm Barite**
53µm Barite	38		39	
25-30µm Barite	20	-47.37%	23	-41.03%
5-9µm Barite	23	-39.47%	24	-38.46%
7-9µm Ferox	28	-26.32%	30	-23.08%
6-8µm FeroBar	26	-31.58%	27	-30.77%
Yield Point				
Mud Sample	**Before Aging (lbs/100ft2)**	**% Change in YP compared with 53µm Barite**	**After Aging (lbs/100ft2)**	**% Change in YP compared with 53µm Barite**
53µm Barite	7		9	
25-30µm Barite	20	185.71%	21	133.33%
5-9µm Barite	21	200.00%	22	144.44%

7-9µm Ferox	24	242.86%	25	177.78%
6-8µm FeroBar	17	142.86%	21	133.33%
10' Gel strength				
Mud Sample	**Before Aging (lbs/100ft2)**	**% Change in GS compared with 53µm Barite**	**After Aging (lbs/100ft2)**	**% Change in GS compared with 53µm Barite**
53µm Barite	15		19	
25-30µm Barite	19	26.67%	22	15.79%
5-9µm Barite	19	26.67%	24	26.32%
7-9µm Ferox	20	33.33%	25	31.58%
6-8µm FeroBar	19	26.67%	25	31.58%
HTHP FLUID LOSS				
Mud Sample	**Before Aging (mls)**		**After Aging (mls)**	
53µm Barite	4.1		4.4	
25-30µm Barite	3.1	-24.39%	3.3	-25.00%
5-9µm Barite	1.2	-70.73%	1.8	-59.09%
7-9µm Ferox	2.8	-31.71%	3.5	-20.45%
6-8µm FeroBar	1.7	-58.54%	2.3	-47.73%
Low Stress Yield Point				
Mud Sample	**Before Aging (lbs/100ft2)**	**% Change in LSYP compared with 53µm Barite**	**After Aging (lbs/100ft2)**	**% Change in LSYP compared with 53µm Barite**
53µm Barite	1		2	
25-30µm Barite	10	900.00%	11	450.00%
5-9µm Barite	10	900.00%	10	400.00%
7-9µm Ferox	8	700.00%	9	350.00%
6-8µm FeroBar	7	600.00%	8	300.00%

4.0 CONCLUSION

It is usually preferred that drilling fluids systems possess physical and chemical properties that are resilient to high temperatures, high pressure and across time. This is required to ensure that the drilling fluids maintain near stable rheological properties even at such conditions instead of significantly varying such that these changes lead to undesirable consequences or problems during drilling operations. Laboratory investigations were carried out to evaluate the effects of temperature and pressure on rheological properties of synthetic based drilling fluids samples formulated with micronized weighting agents of different particles sizes; 53µm barite, 25-30µm barite, 5-9µm barite, 7-9µm Ferox (Iron-Oxide) and 6-8µm Fero-Bar (blend of dual-weighted agents of Ferox and Barite). Standard rheology tests were carried out in the laboratory using an 8-speed viscometer at standard conditions of temperature and pressure. HPHT rheology tests were undertaken in the laboratory using a FANN-75 viscometer within temperature and pressure ranges of 120°F to 400°F and 14.7Psi to 12,000Psi respectively. The rheological properties (PV, YP, LSYP and gel strength) values of the mud samples especially those weighted with particles sizes (25-30µm barite, 5-9µm barite, 7-9µm Ferox and 6-8µm Fero-Bar) decreased slightly with increasing temperature and pressure above 200°F/4000psi as the organophilic clays (which acts as a viscosifier and gelling agent) component of the drilling fluid system become broken down at higher temperatures although in quite an unyielding manner that still enables the drilling fluid to sustain critical functions longer during drilling operations. This resilient characteristic of the mud samples properties to high temperature and pressures conditions were most pronounced with the mud samples that were weighted with smaller particles size additives in the ranges of 5µm to 9µm than the mud sample formulated with weighting agent made of coarser particles sizes. The outcome of the HPHT fluid loss tests carried out on all the mud samples revealed that the mud sample weighted up with smaller particles sizes will form the best quality of filter cake on the formation that will limit filtrate invasion and thus, fluid loss to the formation and formation damage during HPHT drilling operations. Hence, the use of these advanced, micronized weighting agents of ultra-fine particles sizes to weigh up the advanced mud premix helped to bridge some of the already established limitations associated with conventional drilling fluids in HPHT drilling environments such as high temperature gelation of the drilling fluids, poor rheological control, and severe HPHT fluid losses to formation.

Further laboratory investigations should be carried out to investigate the effect of each factor (pressure and temperature) independently for clearer understanding of contribution of temperature and pressure on the fluid rheology and filtration loss. Additional laboratory experiments investigation should also be conducted using similar mud samples formulated with weighting agents of particles sizes (d-50) within ≤ 2µm to compare the effects of temperature and pressures on their rheological properties. Static and dynamic sagging tests should also be carried out on these different mud samples to examine the effects of different particles sizes of the weighting agents on the sagging potential of the muds.

5.0 CONTRIBUTIONS TO KNOWLEDGE

i. Compared with the mud sample weighted with coarser particles size (53µm barite), the rheological properties (PV, YP and LSYP) of mud samples weighted with smaller particles sizes weighting additives, generally demonstrated a near flat rheological profile across elevated temperatures and pressures.

ii. Mud samples weighted with weighting agents of ultra-fine particles sizes (of 5-25µm), indicated minimal fluid losses to the wellbore formation at HPHT conditions which were within the acceptable limits for fluid losses required for a good filter cake formation with minimal formation damage.

iii. The Gel strengths of all the mud samples formulated with micronized weighting agents of finer particles sizes indicated better gel strength characteristics (within the desirable benchmarks) when compared to that formulated with coarser particles sizes (mud sample weighted with 53μm barite).

iv. All mud samples investigated in the laboratory tests using the mud formulation did not demonstrate high temperature gelation characteristic with increasing temperature.

ACKNOWLEDGMENT

My profound gratitude goes to God Almighty for his strength, wisdom and all He gave me to put this paper together. A special thanks go to all who supported us one way or the other. God bless you all.

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