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Meeting deepwater drilling challenges in Niger-Delta with high performance water-based mud

Os desafios de perfuração em águas profundas no Delta do Níger com lama à base de água de alto desempenho

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Resumo

A lama à base de água de alto desempenho, um tipo de fluido usado para perfuração em águas profundas, apresenta desafios semelhantes enfrentados pela lama aquosa à base de água usada para operação onshore. Esses desafios emanam devido à condição de alta temperatura encontrada em formações de águas profundas. Os desafios incluem a diminuição da densidade, viscosidade e outras propriedades reológicas da lama de perfuração, sob condições de alta temperatura que podem levar ao não cumprimento dos objetivos de perfuração. Uma investigação experimental foi realizada com a lama à base de água de alto desempenho projetada para perfuração na região do delta do Níger, onde a caulinita do tipo argila é predominante. Quatro amostras de lama foram formuladas com concentração de Cloreto de Sódio (NaCl) variando de 3%, 5%, 7% e 9% e aumentando a temperatura da condição da superfície para 140°F. As propriedades da lama à base de água de alto desempenho foram observadas em diferentes concentrações de salinidade. O estudo mostra que a densidade e a viscosidade tendem a aumentar com o aumento da temperature, onde a lama tem alta concentração de salinidade de 7% a 9%. Outras propriedades reológicas da lama à base de água de alto desempenho aumentam com o aumento da temperatura, mas diminuem acima de 118°F, exceto para a amostra de 9% de NaCl, que aumenta com o aumento da temperatura. A conclusão deste estudo experimental é que o aumento na concentração de NaCl aumenta a densidade, a viscosidade e outras propriedades reológicas da lama à base de água de alto desempenho em perfurações de formações em águas profundas, sob condições de alta temperatura. Estes resultados possibilitaram a realização de mudanças de perfuração em águas profundas na região do Delta do Rio Niger.

Palavras-chave: Delta do Níger. Argila. Temperatura. Cloreto de Sódio. Densidade. Viscosidade. Propriedades reológicas.

Abstract

High performance water-based mud, a drilling fluid type used for deepwater drilling is posed with similar challenges faced by the aqueous water-based mud used for onshore drilling. These challenges emanate due to high temperature condition encountered in deepwater formations. The challenges include decrease in density, viscosity and other rheological properties of the drilling mud under high temperature condition which can lead to failure to meet drilling objectives. An experimental investigation was carried out on the high-performance water-based mud designed for drilling in the Niger delta region where clay type kaolinite is predominant. Four mud samples were formulated by varying the concentration of Sodium Chloride (NaCl) ranging from 3%, 5%, 7%, and 9% and increasing the temperature from surface condition to 140 °F. The properties of the high-performance water-based mud was observed at different salinity concentration. The study shows that the density and viscosity tend to increase with increasing temperature where the mud has high salinity concentration of 7% to 9%. Other rheological properties of the high-performance water-based mud increases at increasing temperature but decreases above 118 °F except for the 9% NaCl sample which increases with an increasing temperature. The conclusion drawn from this experimental study is that the increase in NaCl concentration increases the density, viscosity and other rheological properties of the high-performance water-based mud when drilling through deep-water formations under high temperature condition. This has provided solution to the deep-water drilling changes.

Keywords: Niger Delta. Clay. Temperature. Sodium Chloride. Density. Viscosity. Rheological properties.

Nomenclature

Symbol	Description	Unit
γ	Shear rate	sec^{-1}
θ	Dial reading	
τ	Shear Stress	$lbs/100ft^2$
μ_a	Apparent Viscosity	cp

Abbreviation

AV	Apparent Viscosity
HPWBM	High Performance Water-Based Mud
NaCl	Sodium Chloride
NaOH	Sodium Hydroxide
OBM	Oil-Based Mud
PAR-C	Poly Anionic Cellulose – Regular
PV	Plastic Viscosity
ROP	Rate of Penetration
RPM	Revolution Per Minute
WBM	Water-Based Mud
YP	Yield Point

1. Introduction

The drilling fluid is one of the major components of any drilling operation. Its importance is amplified by the severity of losses that can result from its improper selection and control. This is doubly true in deepwater operations where it is arguably the most important factor in deciding whether a project is successfully and efficiently completed. A drilling fluid, or mud, is any fluid that is used in a drilling operation in which that fluid is circulated or pumped from the surface, down the drill string, through the bit, and back to the surface via the annulus (ASME, 2005; Gardner, 2003). According to (Baker, 1995; Chukwu, 2008; Darley H. C, 1988) drilling fluid must fulfil many functions in order for a well to be drilled successfully, safely, and economically. Drilling fluid could be classified as oil-based and water-based.

A new water-based mud system was successfully introduced as a high-performance, environmentally compliant alternative to oil and synthetic emulsion-based muds. The new high-performance, water-based mud (HPWBM) is designed to close the significant drilling performance gap between conventional WBM and emulsion-based mud systems. The system has undergone extensive field testing on very challenging deepwater wells that would otherwise have been drilled with oil or synthetic-based muds and it has met the primary drilling objectives of drillers, hence becoming the default drilling fluid in deepwater operations.

The compositions, environmental fates, and toxicological and ecological effects in the marine environment of WBFs have been studied in detail, particularly in the U.S. (Boehm et al., 2001) of typical WBM materials based on their functional category with their respective functions in WBM formulations and the typical chemical additive used to achieve the desired effects. (Mullen, Tanche-Larsen, Clark, & Giles, 2005) states that solid removal efficiency is not a prevalent problem when drilling with OBM. Owing to the high levels of mechanical and chemical inhibition afforded by OBM, cuttings which have sat in an annulus for a considerable length of time can often be circulated up at a later date still in an apparently “fresh” condition.

According to (van Oort, Lee, Friedheim, & Toups, 2004) drill bits, bottom hole assemblies and drill-strings run in an OBM are oil wet, and as there is little or no tendency for water wet shale or clay cuttings to adhere to oil wet steel, the occurrence of bit balling or drill string accretion is uncommon with OBM. Understandably this leads to higher ROP. (Bland, Mullen, Gonzalez, Harvey, & Pless, 2006) discussed that changes to mud chemistry alone do not alleviate bit balling and products which seek to reduce agglomeration by altering the wet state of the metal surfaces and surface of the cuttings are much more likely to produce results.

(Alderman, Gavignet, Guillot, & Maitland, 1988) discussed the complex rheology of water-based muds. They stated that, given the complex structure of these fluids resulting from the electrostatic interaction of clay particles, the fluid behavior is heavily determined by the shear history it has been subjected to. This is independent of the temperature and pressure effects on rheology. The authors have sought to separate these two effects and provide a simple constitutive equation describing the change in rheological parameters with pressure and temperature. (Carney & Guven, 1982) investigated the effect of polymer addition on drilling fluids containing clay based viscosifiers. The observations they have made on water-based muds containing Bentonite clay resonate with the central theme of the project. Since their investigation concentrated on water-based drilling fluids used in geothermal drilling operations, where the temperatures are quite extreme, it provides a rare insight into WBM behavior in Ultra HPHT conditions. (Davison et al., 1999) described the hysteresis effect in yield stress values in water- based fluids containing bentonite. The fluid was heated to 195°F (90 ^{o}C) and then cooled down to 30 ^{o}F (-1^{o}C) which is representative of offshore drilling conditions where subzero temperatures may be experienced in the riser section. The yield stress seemed to increase during the heating cycle but does not reduce on the cooling cycle but continued to increase instead. This is a strong indicator of the fact that the mud had flocculated at higher temperatures and this state was maintained on the cooling down cycle. (Sinha 1970) conducted rheological measurements to quantify the effect of pressure and temperature on various water based and oil-based drilling fluid formulations. (Piber, Prohaska, Hublik, & Thonhauser,

2006) recognized this and performed several cyclic loading tests on polymer and clay-based water muds. They concluded that in contrast to Xanthan based fluids, which show an irreversible viscosity decrease over cycles, bentonite suspensions have a different, more complex, and stronger time and temperature dependent viscosity behavior when cyclic loads are applied.

Despite the success attained, drilling fluids are still posed with challenges and this study tends to investigate the technical challenges (density, viscosity and rheology variation with temperature) faced by deepwater drilling fluid (HPWBM) during drilling operation with the variation of the sodium chloride concentration (a shale inhibitor) due to the significant degree of clay dispersion it cause not regarding it percentage composition and to determine which concentration will retain the significant property of HPWBM at elevated temperature which is paramount to the driller. High demand on oil and gas and increased depletion rate of near surface reservoirs around the world require the industry to look for oil in deeper and more challenging reservoirs.

The incidence of high temperature and pressure at deep formations tend to affect the performance of the drilling fluid and ideally, to study the effect of pressure and temperature on a given sample, a full factorial design would be applied. However, this tends to be impractical and proves difficult for limited resources and choosing the conditions which represent the wells environment and what the drilling fluid will experience is critical. Due to temperature increase from the surface ongoing down the formation, the properties of drilling fluid tend to vary, and these technical challenges include the variation of plastic viscosity, yield point, viscosity and density with temperature which affect the integrity of the mud composition, well design, regulatory compliance, and drilling efficiency. Furthermore, at deep formation the level of salinity tends to increase which is believed to influence the behaviour and property of the mud thereby affecting the performance of the mud.

Efficiency in drilling operations require the use of improved mechanisms of evaluating rheological properties and density of a high-performance water-based mud. The practice of extrapolation of fluid properties from surface to some moderate downhole conditions is not reliable and could result in significant inaccuracies in wellbore hydraulic calculations. From this experiment, new laboratory results can be added as supporting information to existing literature. This is seen when varying concentration of sodium chloride is utilized as an inhibitor to demonstrate the effect of salinity on the properties of HPWBM at downhole condition since these varying concentrations provide same effect of shale inhibition at a significant degree. The study was limited to the design of high-performance water-based mud. Due to some limitations in terms of equipment availability, the experimental investigation is designed under ambient pressure condition and a maximum temperature of 140°F. Only Bingham plastic model was considered in this study.

2. Methodology

2.1 Materials and Equipment

The mud type used for this study is the high-performance water-based mud which is used for deep-water drilling and this mud type was designed for drilling in the Niger delta region where the clay type kaolinite is predominant or for drilling a section of the hole with this clay type. The materials (sample additives) and equipment used are shown in Table 1.

Table 1- List of Materials and Equipment

MATERIALS	EQUIPMENT/APPARATUS
Water	Water Bath
Bentonite	Weigh Balance
PAC-R	Rotational Viscometer
Sodium Chloride	Mud Balance
Caustic Soda	Electric Mixer (Hamilton Beach)
Partially hydrolyzed poly acrylamide (PHPA)	Measuring Cylinder (500ml)
Barite	Thermometer
	Stirring Rod
	Sieve (0.8mm)
	Spatula
	Mud Cup

Properties of Additives used

The design of high-performance water-based mud for use in deepwater drilling depends on the X-Ray diffraction (XRD) analysis use to determine the clay mineralogical composition of the formation and thus determines the suitability of the mud type for the particular formation. Therefore, the aforementioned additive is used for this well type and their various application is shown in Table 2.

Table 2- Additives and their Application

ADDITIVES' NAME	APPLICATION
Water	Aqueous Phase
PHPA	Encapsulation, Shale inhibition
NaOH	PH Control
NaCl	Shale Inhibition, Decrease water activity, initial weighing agent, ROP improvement
Barite	Weighting agent
Bentonite	Primary Viscosifier, Wall Building property
PAC-R	Fluid Loss Control

Formulations for HPWBM

Varying concentrations of NaCl ranging from 3%, 5%, 7%, and 9% was used for the formulation of the mud type. The concentration of other additives and the temperature schedule at which the mud sample was subjected on the course of the experiment is shown in Table 3.

Table 3- List of Additives, their corresponding concentration, and the temperature schedule

ADDITIVES	CONCENTRATION	TEMPERATURE SCHEDULE (ºF)	
Water	350ml	CASE 1	Ambient condition
Bentonite	10.5g	CASE 2	104
PAC-R	1.5g	CASE 3	111
NaOH	2.0g	CASE 4	118
PHPA	5.0g	CASE 5	127
Barite	20g	CASE 6	133
NaCl	3%, 5%, 7%, 9%	CASE 7	140

2.2 Methods/Procedures

(1) The additives used for the preparation of the mud sample was sieved and weighed.
(2) 350ml of water and the concentrations of other additives was agitated until a complete mixture was formed.
(3) The temperature of the mud sample at ambient condition was measured and recorded.
(4) The mud sample was then poured on a mud cup until completely filled and the lid firmly placed on top making sure that some mud is squeezed out of the vent hole.
(5) The excess mud was wiped from the exterior of the balance; the balance was seated with its knife edge on the stand (fulcrum) and was levelled by adjusting the rider.
(6) The mud density was read from the edge of the rider as indicated by the marker on the rider.
(7) The mud sample was then transferred to a test cup where it is filled to the scribed line, the upper housing of the rotational viscometer was tilted back, the cup was located under the sleeve (the pins on the bottom of the cup were fitted to the holes in the base plate) and the upper housing lowered to its normal position.
(8) The knurled knob between the rear support posts was turned to raise or lower the rotor sleeve until it is immersed in the sample to the scribed line.
(9) The rotational viscometer turned the rotor sleeve at either of the two speeds, 300 or 600 rpm in a cup of mud. The dial reading was allowed to stabilize (the time depends on the sample's characteristics) and the resulting torque on the mud was measured by a concentric bob and read through the window.
(10) The procedures 2-10 was repeated for the following temperatures 104 ºF, 111 ºF, 118 ºF, 127 ºF, 133 ºF, 140 ºF.
(11) The procedures 2-10 was repeated for each concentration of NaCl.

Formula employed

The Fann V-G meter speed, rpm is converted to shear rate γ, sec^{-1} thus

$$1\ sec^{-1} = 1.703\ rpm \quad (1)$$

The dial readings to shear stress (in $lbs/100ft^2$) by multiplying by the conversion factor, 1.0678

Plastic Viscosity

$$PV = \theta 600 - \theta 300, \text{ in cp} \quad (2)$$

Yield Point

$$YP = \theta 300 - PV, \text{ in } lbs/100ft^2 \quad (3)$$

Apparent Viscosity

$$\mu_a = \frac{\theta 600}{2}, \text{ in cp} \quad (4)$$

Shear stress

$$\tau = pv\left(\frac{\gamma}{300}\right) + yp, \text{ lb/100 sq ft} \quad (5)$$

Safety Precautions

- To avoid flocculation, bentonite was added to water before caustic soda to allow a high degree of hydration of the individual clay platelet.
- Additives used were passed through 840micron sieve to ensure consistent sample surface area.
- A preset temperature of 187 ºF was set for the water bath.
- The concentration of NaOH was reduced due to excessive foaming of the mud sample and considerable increase in the temperature of the sample at ambient condition.

3. Results and Discussion

3.1 Rheological properties

As seen from Figure 1(a) (3% NaCl concentration) dial reading for both 600 and 300 rpm showed inclined increase (25.5-53 and 20-35) from 86 °F -118 °F and a decline after 118 °F (48-40 and 32-27) from 127 °F- 140 °F. The reading at 86°F was below API standard (30) and the 3% NaCl was stable up to 127 °F. A similar trend was seen in Figure 1(b) for 5% NaCl concentration for both 600 and 300 rpm but an increase was seen at 140°F where the maximum dial reading was obtained, and this means that the 5% NaCl can be used for stability up to 140°F. As can be seen from Figure 1(c), 7% NaCl concentration the dial reading followed a similar trend as in the case of 3% NaCl but here, a minimal decline is noticed at 600 rpm and uniform dial reading at 118-127 °F and 133-140 °F for 300 rpm. This means that the 7% NaCl began to be active at 127 °F. As shown in Figure 1(d), for 9% NaCl concentration, a similar trend occurs but, in this case, the dial reading at 133-140 °F are uniform for 600 rpm and from 118-140 °F for 300 rpm uniform dial reading was maintained and it was observed that the dial reading for this concentration was increasing with an increase in temperature which means that the 9% NaCl was stable beyond 140 °F. From the plots of dial reading against temperature for all mud samples, dial reading decreases as NaCl concentration increases with the exception of the 9% NaCl where the value appreciated and also, dial reading increases at increasing shear for each sample.

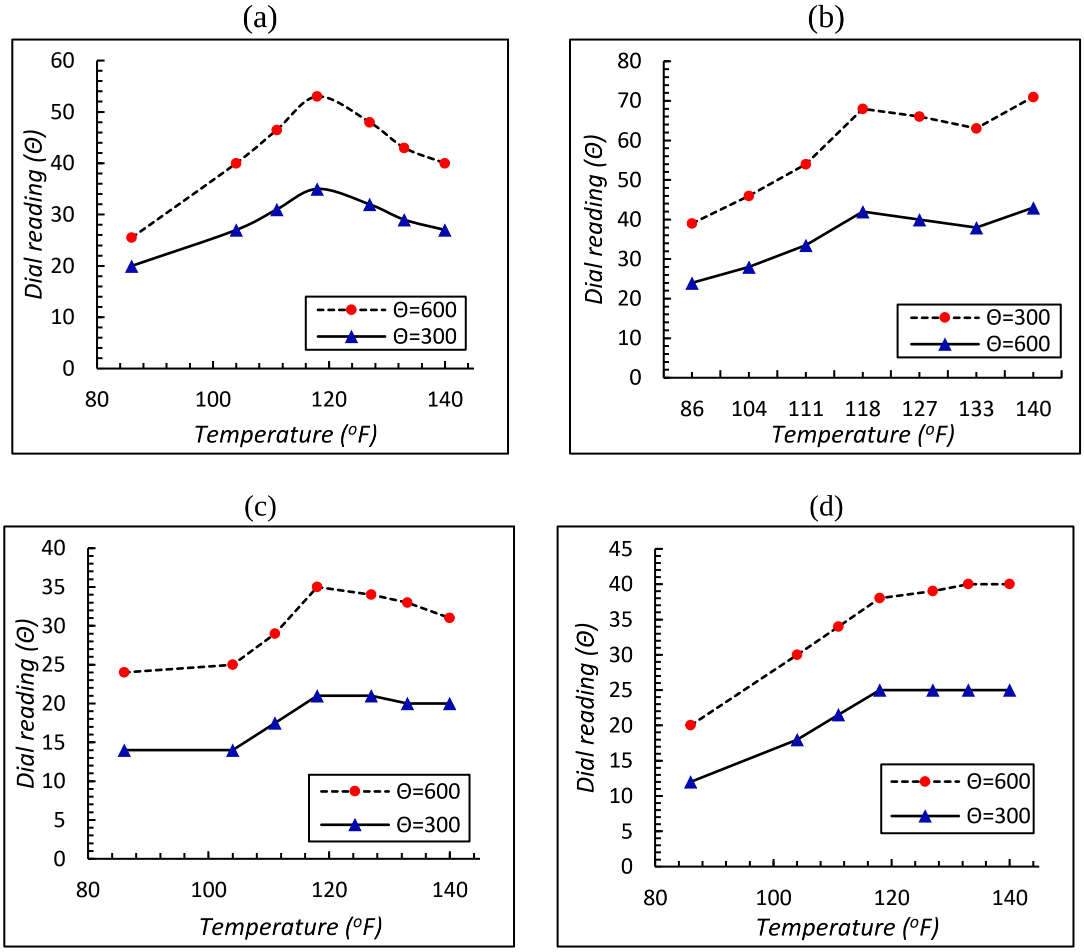
(a) (b) (c) (d)

Figure 1- Plot of Dial reading against Temperature at 600 rpm and 300 rpm for NaCl concentration (a) 3% (b) 5% (c) 7% (d) 9%

From Figure 2, the shear stress – temperature relationship shows a similar trend to that of the dial reading for all NaCl concentration at all shear rate or dial reading. For all the cases of shear rate, it was observed that the shear stress increases as temperature increasing from 86 ^{o}F to 118 ^{o}F for all NaCl concentration. However, shear stress decreases as temperature further increasing from 118oF to 140 ^{o}F for all NaCl concentration except for 5% NaCl concentration where slight increment was seen at temperature of 133 ^{o}F to 140 ^{o}F. Shear thinning occurs with increased shear rate, and this typifies that the mud sample is a drilling fluid. The noticeable difference between Figure 2(a) and Figure 2(b) is that shear stress increases with the shear rate. For instance, at 9% NaCl concentration and temperature of 118 ^{o}F, the shear stress obtained when the shear rate is 1022 sec^{-1} (660 rpm) was found to increase by 64% compared to the shear stress reported when the shear is 511sec^{-1} (300 rpm). More so, it is reported in Figure 2 that shear stress decreases as concentration of NaCl increases from 3% to 7%, except for the case of 9% concentration of NaCl.

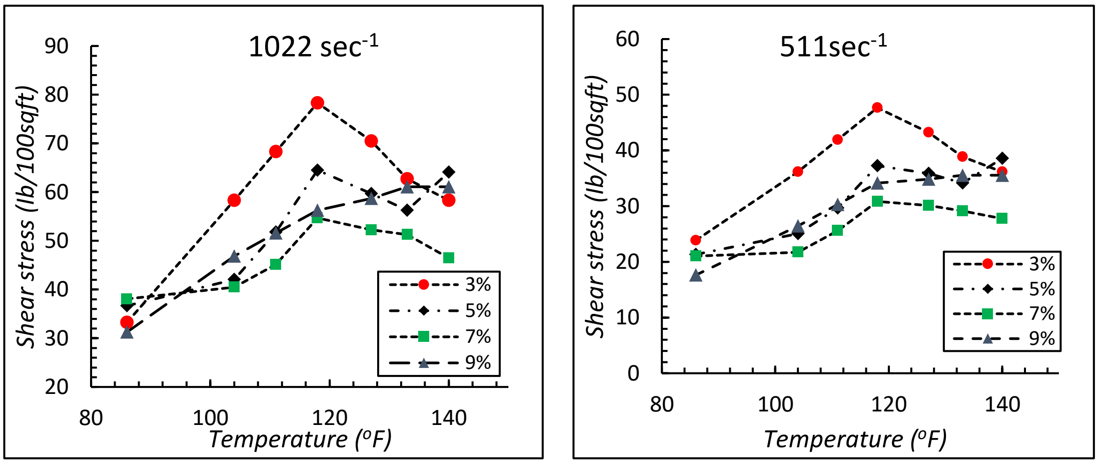
(a) (b)

Figure 2- Plot of shear stress against temperature at all NaCl concentration (a) 1022sec^{-1} (b) 511sec^{-1}

Figure 3(a) and Figure 3(b) show the plots of viscosity against temperature for all NaCl concentrations for 600 rpm and 300 rpm, respectively. A similar pattern of distribution was observed to that of the dial reading which shows an increase in viscosity with a corresponding increase in temperature up to 118°F where the viscosity decreases for all samples and as the NaCl concentration increases except for the 9% NaCl solution. This was as a result of the thermal degradation of the solids, polymers and other components of the mud samples and the expansion of the molecules which will lower the resistance of the fluid to flow. For the 9% NaCl solution, the montmorillonite platelet tends to flocculate which increases the viscosity at increasing temperature. Also, it can be seen from the plots that the viscosity of the mud sample tends to be high at low shear rate. Only noticeable difference between the Figure 3(a) and Figure 3(b) is that higher values of viscosities were obtained at dial speed of 300 rpm as compared to 600 rpm for a fixed concentration of NaCl.

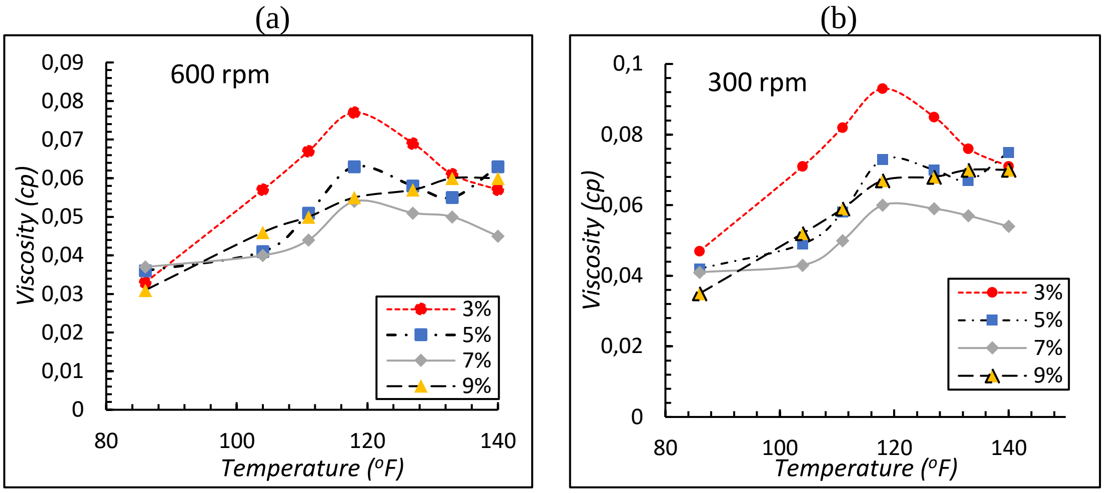

Figure 3- Plot of Viscosity against temperature for all NaCl concentration (a) 1022sec^{-1} (600rpm) (b) 511sec^{-1} (300rpm).

Figure 4 shows the plot of plastic viscosity against temperature for all concentration of NaCl at dial speed of 600 rpm. It can be seen that the slope of each NaCl sample became shallower from 118 °F with the exception of that of the 9% NaCl concentration which increases beyond 118°F. The point at which the curve of each sample intercept means that there was a change in the intrinsic property of the samples involved. A similar trend was observed in terms of the stability, activeness, and resistance of each mud sample as in the case of dial reading and only the plastic viscosity of 3% NaCl solution was below API standard.

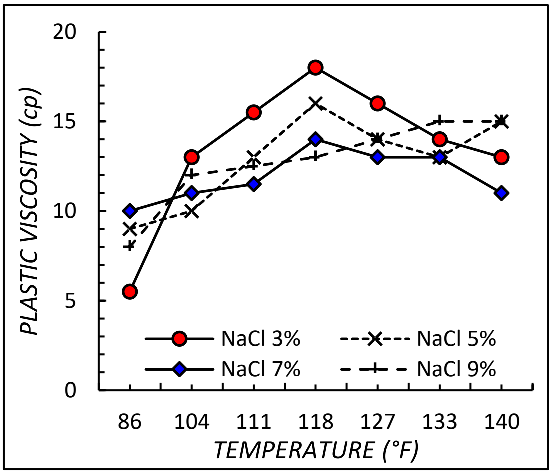

Figure 4- Plot of Plastic viscosity against temperature for all NaCl concentration at 600rpm.

Figure 5(a) and Figure 5(b) compare yield point and maximum yield point against temperature respectively at 600 rpm for all NaCl concentration. From Figure 5(a), the yield point of 3% NaCl was higher than that of other mud samples and the yield point for each mud sample was lower than their maximum value as seen in Figure 5(a) because they are not aggregation between individual plates. From here, the 3% sample has great ability to lift cuttings out of the annulus and provide better dynamic suspension of drilling cuttings and efficient cleaning of wellbore while drilling.

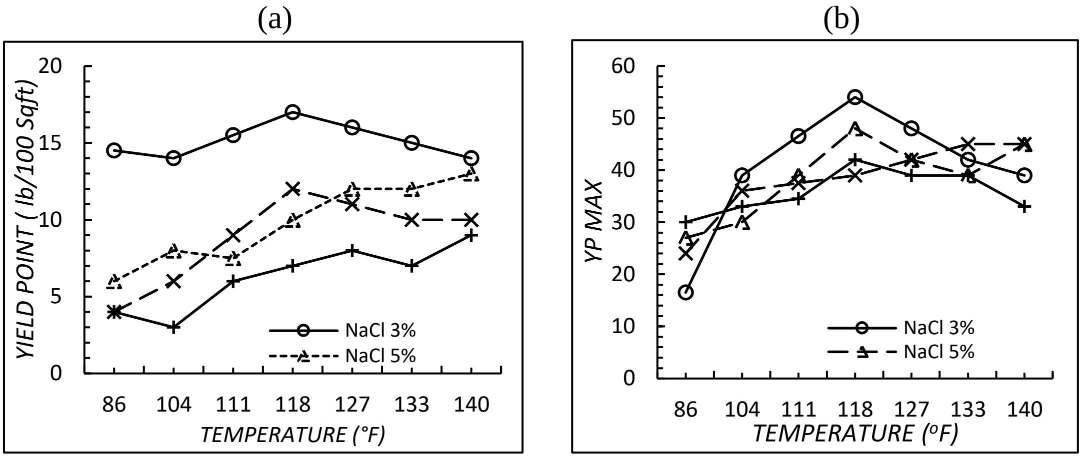

Figure 5(a)- Plot of yield point against temperature (b) Plot of maximum yield point against temperature for all NaCl concentration at 600rpm

3.2 Density

From Figure 6, the plot of density against temperature for 3% NaCl concentration shows that density was decreasing with an increase in temperature until it stabilizes at 133 °F. The density of the 5% NaCl solution was decreasing at a constant rate with an increase in temperature and stabilized at 133 °F. This trend changes as the concentration of the NaCl increases from 7% to 9%. The 9% concentration stabilizes at 104 °F with an increase in density value compared to the 7% concentration. The increase in density of the 9% NaCl was due to the corresponding increase in the plastic viscosity of the same mud sample as seen in Figure 4 since there was no increase of ultra-fine solid content in the mud system.

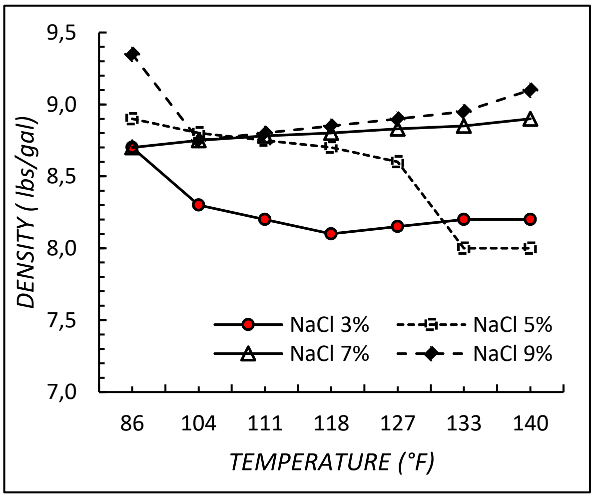

Figure 6- Plot of Density against Temperature For all NaCl concentration at 600 rpm

4. Conclusion

From the experimental analysis, it can be deduced that the compressibility of high-performance water-based mud followed the same trend with that of other aqueous based drilling fluid where density decrease with an increase in temperature. However, with an increase in sodium chloride concentration, the density tends to increase as the concentration increases but at a low margin from the surface. The problem of density variation which is exacerbated in deep-water can be annulled with an increase in the sodium chloride concentration as seen from the analysis. Therefore, the hydrostatic pressure of high-performance water-based mud can be managed with greater accuracy during the drilling operation and the desired bottomhole pressure can be accomplished and controlled with high performance water-based mud.

On the other hand, high-performance water-based mud viscosity increases with an increase in temperature which is contrary to other aqueous drilling fluid which decreases with an increase in temperature. This trend ceases at 118 °F where the viscosity began to reduce which means that 118 °F is the failure temperature (temperature at which viscosity undergo an abrupt change in behavior) of high-performance water-based mud where the viscosity declines to a lower value. This trend was annulled by the 9% NaCl sample where the viscosity increases with an increase in temperature. From here, it can be deduced that the viscosity of high-performance water-based mud increases with an increase in sodium chloride concentration. Also, other rheological properties follow the same relationship as viscosity for the high-performance water-based mud but for yield point, the value drops as temperature and sodium chloride concentration increase. This was noticed when 3% NaCl concentration has the greater ability to lift cuttings out of the annulus. It can be deduced from here that the high-performance water-based mud has a contrary property to other aqueous based mud which means that there is an increase in yield point upon increase in temperature and sodium chloride concentration.

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