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# Changes in Drilling Fluid Rheology with Emulsifier Type

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## Abstract

Occurrence of pressure surges following circulation stops, due to the high structuration in the drilling mud, increases risk of formation fracturing. Structuration displayed by the mud depends on its rheological properties. Suspension of cuttings under low shear rate flowing conditions is also correlated to the mud's rheology. Rheology of viscoelastic mixtures such as drilling muds are highly temperature dependent, leading to variations in their hydrodynamic properties and particle suspension capabilities.

The use of oil-based muds (OBM) translates to higher rates of penetration, better hole cleaning and lubrication of the drill string. However, excessive increase in their viscosities at low temperatures leads to substantial technical challenges. Water-based muds (WBM) in comparison are less prone to compressibility (expansibility) effects resulting from surrounding conditions and are environmentally friendly. The chemistry of surfactants used in stabilizing the base emulsion of both WBMs (oil-in-water) and OBMs (water-in-oil) is critical in the rheology they display.

In this study, temperature-induced phase inversion of WBMs to OBMs resulting from the chemistry of nonionic surfactants was assessed. Samples were prepared using different surfactant types (nonionic, ionic) to determine the transition of the base emulsion from oil-in-water to water-in-oil. The constituents of the samples were deionized water, synthetic paraffin oil and Wyoming bentonite. Their rheological properties were measured using a scientific rheometer at temperatures ranging from 0 – 90 ℃ (32 - 194 °F).

For constant oil-water ratios, results showed OBM samples to have higher shear stresses at high shear rates at lowest and highest measurement temperatures in comparison to WBM. Hydrophile-lipophile balance of surfactants was also observed to have a major effect on the viscoelastic properties of the samples through varied degrees of emulsification of the dispersed phase.

## Introduction

It is essential for muds used during operations to display optimum and reliable hydraulics in order to minimize well control problems resulting from low or excessive pressure on the wellbore. This is essential in successful completion of the well, safety of rig personnel and equipment as well as preservation of the environment. In the current economic stance of oil prices, lowering breakeven price is paramount. In the case of offshore operations, improvement and development of new technology and practices to minimize costs is critical. This can be achieved, among other measures, by reducing the level of maintenance requirements of drilling muds and optimization of their performance.

The selection of OBMs for drilling has long been a regular choice by operators. Their superior technical performance to aqueous muds has been proven consistently in domains such as rates of penetration, borehole stability, ionic inhibition, sticking avoidance and cuttings conditioning[1]. To continue, their greater tolerance to solid contaminants further explains their widespread use over WBMs. These aforementioned advantages over WBMs stem from the intrinsic properties of their continuous organic phase[1].

However, in offshore operations the substantial changes in their rheological behavior as a function of temperature and pressure result in various drilling problems[2]. When cooled down in the riser to temperatures close to 5 ℃ (41 °F), high surge/swab pressures following a trip or connection are observed as well as high gel strengths and fluid viscosity[2]. Further downhole, with elevated temperatures, significant shear thinning may lead to barite sagging, poor hole cleaning and lost circulation due to cutting bed formation[2].

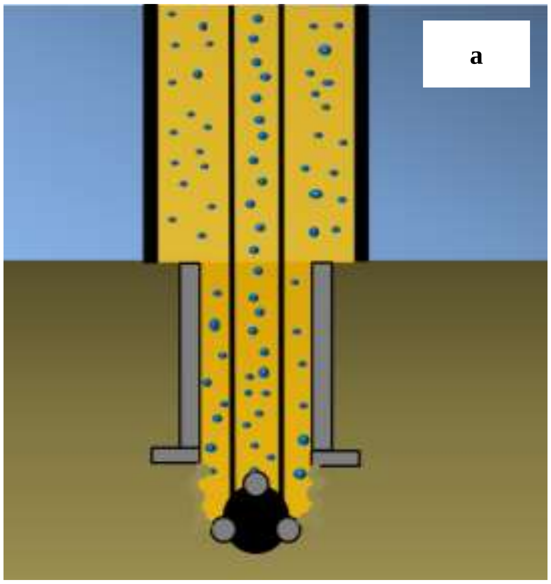
These drawbacks observed during drilling with OBMs are explained by the compressibility, gas solubility and change in intrinsic viscosity of the base oil with temperature and pressure[3]. The aforementioned challenges led to the development of Flat Rheology Invert Drilling Fluids (FRIDF) which are basically defined as drilling fluids having consistent 3 and 6 rpm readings, yield point and 10 minutes gel strength over wide ranges of temperature. Their development basis is a structured matrix of polymer, organoclay and emulsifier interactions which help in the effective prevention of fluid loss to induced fractures[4]. In comparison to conventional OBMs, FRIDFs have been successful in delivering consistent desired mud rheology when used in offshore operations, explaining its use in the drilling of hundreds of deepwater wells.

As consistent as their rheology behavior is over wide ranges of temperature and pressure, the 'uniform' hydraulics (ECD) observed with FRIDFs does not always translate to 'uniformly low'[1]. To continue, multiple reports from field operations using FRIDF have highlighted its difficult maintenance and engineering, excessive 10 min gel strength following its contamination with low-gravity solids and the ineffectiveness of certain rheology modifiers above certain elevated temperatures[2]. The reliable prediction of hydrostatic pressure is challenged when using FRIDFs just as it is with OBMs. This is due to the compressibility (expansivity) of the continuous organic phase that leads to mud density variation with temperature and pressure. The high solubility of natural gas in oil-based drilling muds adds further complexity to kick detection and may cause well control complications[1,5].

WBMs, despite being overlooked in deepwater drilling operations have noteworthy advantages to their use. In addition to being more environmentally friendly, the aqueous continuous medium addresses many drilling hydraulic problems associated to the continuous organic medium of FRIDFs. WBMs are significantly less compressible than their non-aqueous counterparts, allowing more reliable estimation of the hydrostatic pressure applied to the formation[1]. The low solubility of formation hydrocarbon gases in WBMs, 10 – 100 times lower than in oil-based fluids[5], allows better corrective actions through early kick detection. The lower compressibility of aqueous muds provides an additional advantage to the use of their non-aqueous counterparts where lower incremental ECDs are observed with WBM in comparison to OBMs[1].

## Surfactant Types in Drilling Muds

FRIDFs (OBMs) and WBMs both have advantages and drawbacks associated to their use in the extreme temperatures and pressures encountered in deepwater drilling. The ideal offshore drilling fluid would be a 'hybrid mud', a dual WBM-OBM (Figure 1b), one that self-displays the properties of either under conditions (temperature) in which disadvantages of one mud are prevailed by the advantages of the other. The critical component in the composition of such a hybrid mud is one that is well known to play a major role in the rheological behavior displayed by drilling muds in general, surfactants.



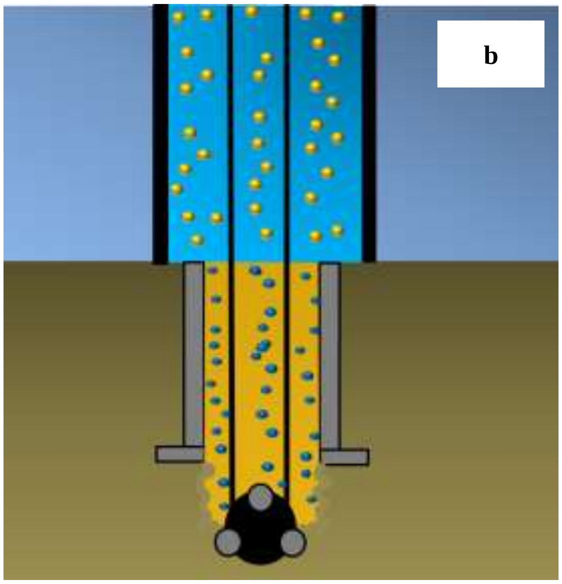


**Figure 1: Base Emulsion variation with Temperature: FRIDF & OBM (a) vs 'Hybrid' Mud (b).**

Apparent viscosity, plastic viscosity, yield stress and gel strength are all rheological parameters determined by the nature of the resultant viscoelastic mixture of the prepared drilling mud. Base emulsions in addition to different additives such as clay, polymers and weighting agents form the skeleton of the viscoelasticity displayed by muds. Viscoelastic substances or mixtures show mechanical properties that are characteristic of solids or liquids depending on the rate at which they are deformed[6].

WBMs and FRIDFs (OBMs) have oil-in-water (O/W) and water-in-oil (W/O) base emulsions respectively. Both types of emulsions are stabilized using surfactants. Most surfactants used in the preparation of W/O base emulsions in OBMs are alkanolamides and imidazolines[7]. For WBMs, nonionic, anionic and nonionic-anionic blends are used in the stabilization of the O/W base emulsion[8,9]. Surfactant selection used in the stabilization of either emulsion is based on Griffin's empirical quantitative hydrophile-lipophile balance (HLB)[10]. Surfactants with HLB values between 8-18 tend to stabilize O/W emulsions while W/O are stabilized by those having values between 3-6[11].

## Phase Inversion of Drilling Fluids' Base Emulsion

Phase inversion is defined as the process by which an O/W emulsion inverts to a W/O emulsion and vice versa[12]. There exists two types of phase inversions; catastrophic phase inversion (CPI) and transitional phase inversion (TPI). In CPI, phase inversion is brought about by increment of the dispersed phase volume fraction or by continuous agitation of the emulsion mixture. Surfactants having lower affinity for the continuous phase are used in this process[13]. TPI on the other hand is obtained by altering the phase affinity of surfactant(s) through temperature or by changing the composition of the surfactant mixture at a given temperature[12]. CPI has seen high levels of application in the downstream sector of the oil and gas industry, where it is commonly used to lower the viscosity of W/O emulsion mixtures formed by water and crude oil.

Application of TPI for the improvement of offshore drilling and completion operations was part of the study performed by Arvind Patel[14]. His study highlighted the benefits of using OBMs for the drilling stage due to the advantages inherent to their use, and WBMs for the completion stage for better filtercake clean ups, improved cementing, and enhanced production in openhole completions. The designed drilling mud did not require any peculiar changes in operation or additives other than those typically used in OBMs. TPI was achieved by the protonation and deprotonation of the nonionic surfactants using water-soluble acid and water-soluble base respectively.

Temperature-induced phase inversion is a form of TPI that causes inversion of base emulsions at the Phase Inversion Temperature (PIT) of nonionic surfactants. Transition from O/W to W/O base emulsions are observed to be more distinct for emulsion mixtures using non-polar oils such as paraffin over polar oils such as isopropyl myristate[15]. The HLB of nonionic surfactant mixtures used in preparing emulsions has been assessed as being a key factor in the temperature transitional behavior displayed. The HLB value at which temperature-induced phase inversion occurs varies depending on the chemistry of the surfactant used but typically ranges between 7 – 10[15]. Changes in the curvature of the geometry of the surfactant monolayer and solubility with temperature explains the stabilization of different emulsion types at low and high temperatures[16].

## Materials and Experimental Method

Deionized water, synthetic paraffin oil and Wyoming bentonite were used in preparing the oil and water-based mud samples. A magnetic bar mixing device was used in dispersing and homogenizing the surfactant (or surfactant mixture) at 900 rpm for 20 minutes in the oil phase. The final step in the sample preparation was the mixing of bentonite and the dispersed phase into the continuous emulsion phase using a Hamilton beach mixer at maximum speed for 3 minutes. The continuous matrix phase varied with respect to the mud type prepared; paraffin oil in OBM and deionized water in WBM. The dispersion of the surfactant mixture in the oil phase for WBM samples was part of the chemical procedure to investigate phase inversion.

Tables 1 to 3 show the variables that are; surfactant type, surfactant mixture and individual surfactants used in the experimental analysis. Effect of HLB on the rheological properties of the samples was investigated as well; 4.0, 4.3, 7.5 and 11.5. All samples were studied under temperatures spanning 0 – 90 ℃ (32 – 194 °F). Equilibration time of 5 minutes was observed at all temperatures to ensure samples reached thermal steady-state before initiating the subsequent test.

**Table 1: Surfactant Type and Hydrophile-Lipophile Balance.**

| Surfactant | Type | HLB |
|---|---|---|
| Sorbitan Monooleate | Nonionic | 4.3 |
| Polysorbate 80 | Nonionic | 15 |
| Polyoxyethylene (10) Oleyl Ether | Nonionic | 12.4 |
| Polyoxyethylene (2) Oleyl Ether | Nonionic | 4.0 |
| Sodium Dodecyl Sulfate | Anionic | 40 |
| Cetrimonium Bromide | Cationic | 10 |

**Table 2: WBM Surfactant Mixtures and Hydrophile-Lipophile Balance.**

| Surfactant | Mixture | HLB |
|---|---|---|
| Polyoxyethylene (10) Oleyl Ether | Mixture 1 (Nonionic) : M1 Nonionic | 7.5, 11.5 |
| Polyoxyethylene (2) Oleyl Ether | | |
| Sorbitan Monooleate | Mixture 2 (Nonionic): M2 Nonionic | 7.5, 11.5 |
| Polysorbate 80 | | |
| Sodium Dodecyl Sulfate | Mixture 3 (Ionic): M3 Ionic | 11.5 |
| Cetrimonium Bromide | | |

**Table 3: OBM Surfactants and Hydrophile-Lipophile Balance.**

| Surfactant | | HLB |
|---|---|---|
| Sorbitan Monooleate | S1 | 4.3 |
| Polyoxyethylene (2) Oleyl Ether | S2 | 4.0 |

All measurements were performed 24 hours after sample preparation to ensure the base emulsion was stable and the bentonite fully hydrated. Measurements were repeated with fresh samples at each run to ascertain reproducibility. An Anton Paar scientific rheometer was used in characterizing the behavior of the sample under flow and at rest through flow curve and stress sweep tests. Microscopic analysis of the samples was achieved through the use of a Leica microscope to evaluate the variation in the mud sample's microstructure as a function of temperature.

Flow curves were measured at shear rates spanning four order of magnitude (0.1 – 3,000 $s^{-1}$). All samples were pre-sheared at 50 $s^{-1}$ for 1 minute to confer them the same initial state. Flow curve data was obtained by subjecting the sample to ramping temperatures and obtaining flow curves data at each temperature. The level of structuration of the samples was studied through stress sweeps; 0 to 50 Pa (0 – 104 lbf/100ft$^2$) to determine their yield stress and their deformation (shear strain) profile thereafter. Filter press measurements were equally performed at room temperature and pressure to determine the level of fluid loss of the samples as a function of mud type, surfactant type and HLB. The bentonite concentration was kept constant at 9 wt.% for flow curve measurements and 6 wt.% for fluid loss tests and microscopic analysis. The lower concentration selection for the latter was to allow better visual characterization of the samples.

## Results and Discussions

Cuttings transport, frictional pressure losses and formation fracture risk are among the functions and hydrodynamic (static) properties of muds that are highly dependent on their rheology. Rheology of viscoelastic mixtures such as emulsions and suspensions are highly temperature dependent. Thus, in offshore operations, the type of surfactant used in stabilizing the base emulsion of drilling muds is a determining factor on the successful completion of the well. Data for flow curve and structuration characterization were obtained at an O:W=70:30 and surfactant concentration of 3 wt.%.

### *Frictional Pressure Losses*

Figures 2 to 8 show the change in the flow behavior of the mud samples with temperature. This behavior varies with temperature, surfactant type and HLB. For WBM stabilized with Mixture 1 (M1) of nonionic surfactants (Figures 2 and 4), sample flow behavior oscillates between shear thinning and thickening with a pronounced level of 'wall slip' at shear rates less than 10$^2$ s$^{-1}$. One major observation was the higher shear stress level with increasing temperature of WBM M1 at HLB of 7.5 in comparison to 11.5.

For WBM stabilized with Mixture 2 (M1) of nonionic surfactants (Figures 3 and 5), the flow behavior at an HLB of 7.5 was close to that of a Bingham plastic model fluid while it showed greater similarity to a Power Law model fluid at an HLB of 11.5. The level of 'wall slip' observed in these samples was close to nil. Holistically, just as for WBM M1, shear stresses of WBM M2 sample decreased with temperature increase.

High levels of 'wall slip' behavior was observed for WBM stabilized with Mixture 3 (M3) of ionic surfactants (Figure 6). The phenomenon showed to be more pronounced as temperatures increased. The implications of the latter are less reliable flow curve data for use in drilling hydraulics parameter estimation at elevated downhole temperatures. The decrease in shear stress with temperature increase was less distinct then than that of WBM samples stabilized with nonionic mixtures M1 and M2.

The flow behavior of OBM samples (Figures 7 and 8) at 0 ℃ was significantly different from its flow curve profiles at higher temperatures. In Figure 7, for OBM stabilized with Surfactant 1 (S1), the mud sample had shear stress levels one order of magnitude greater at 0 ℃ than those at higher temperatures for shear rates less than 10 s$^{-1}$. For OBM stabilized with Surfactant 2 (S2), a similar difference is observed as shown in Figure 8 for shear rates greater than 10$^2$ s$^{-1}$. For OBM S1, the pattern of decreasing shear stress with increasing temperature is observed; this is not the case for OBM S2 for shear rates less 10 s$^{-1}$. 'Wall slip' occurrence was observed to be more pronounced in OBM stabilized with S2.

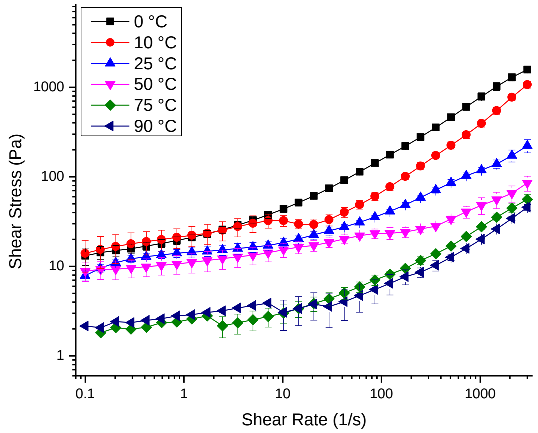


**Figure 2: Flow Curve. WBM M1 Nonionic - HLB: 7.5.**

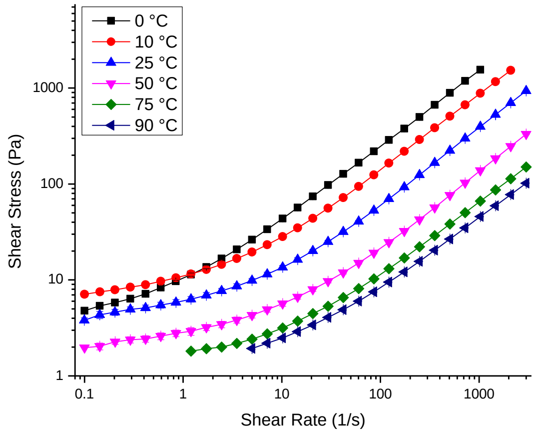


**Figure 3: Flow Curve. WBM M2 Nonionic - HLB: 7.5.**

During mud circulation, the parasitic pressure loss ($\Delta P_d$) is accounted for by frictional pressure loss in surface equipment, drill pipe, drill collar, drill bit and drill string annulus as given by Equation 1[17].

$$\Delta P_d = \Delta P_S + \Delta P_{dp} + \Delta P_{dc} + \Delta P_{dca} + \Delta P_{dpa} \qquad (1)$$

$\Delta P_S$: Surface equipment frictional pressure
$\Delta P_{dp}$: Drill pipe frictional pressure loss
$\Delta P_{dc}$: Drill collar frictional pressure loss
$\Delta P_{dca}$: Drill collar-annulus frictional pressure loss
$\Delta P_{dpa}$: Drill pipe-annulus frictional pressure loss

In offshore drilling, the additional parameter to be accounted for is the riser-annulus frictional pressure loss ($\Delta P_{ra}$). The typical shear rates experienced by drilling muds when flowing through the different conduits that make up the circulating system are $10^3$, $10^5$ and $10^2$ $s^{-1}$ in drill string, drill bit, and annulus respectively[18]. For the wider cross-sectional areas such as that between the drill pipe and riser, shear rates can be ≤10 $s^{-1}$.

When comparing the flow curves (Figures 2 to 8) of WBM vs OBM samples, although not highly substantial it is observed that at the lowest (0 ℃) and highest (90 ℃) temperatures OBM show higher shear stresses at shear rates prevalent in the drill string ($10^3$ $s^{-1}$). This implies higher frictional pressure losses are expected when using OBM and thus less pump pressure will be available at the bit to achieve maximum nozzle velocity. No significant difference was observed when comparing the effect of HLB (7.5 vs 11.5) on WBM samples at the lowest and highest measurement temperature.

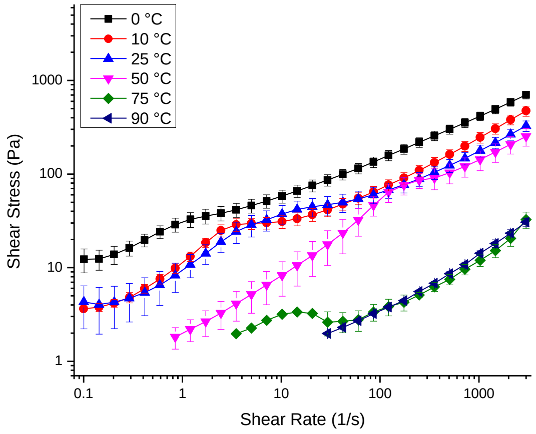


Figure 4: Flow Curve. WBM M1 Nonionic - HLB: 11.5.

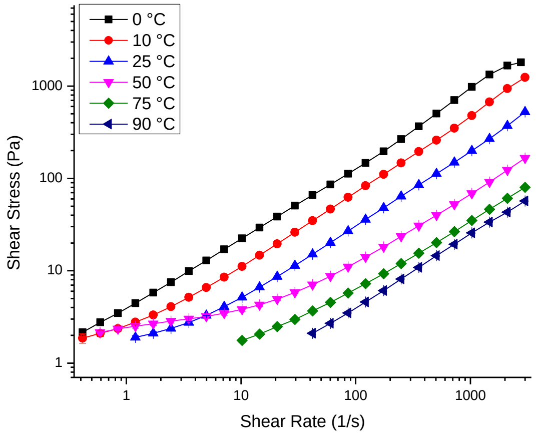


Figure 5: Flow Curve. WBM M2 Nonionic - HLB: 11.5.

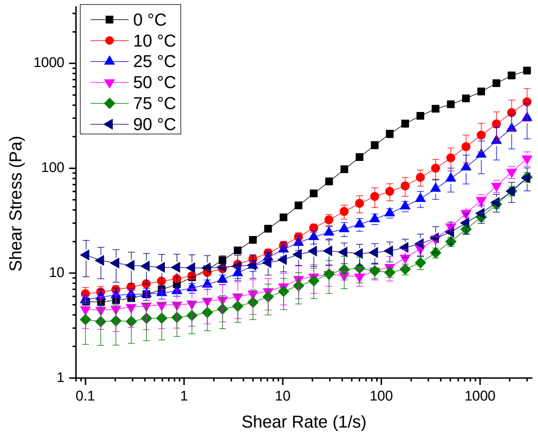


Figure 6: Flow Curve. WBM M3 Ionic - HLB: 11.5.

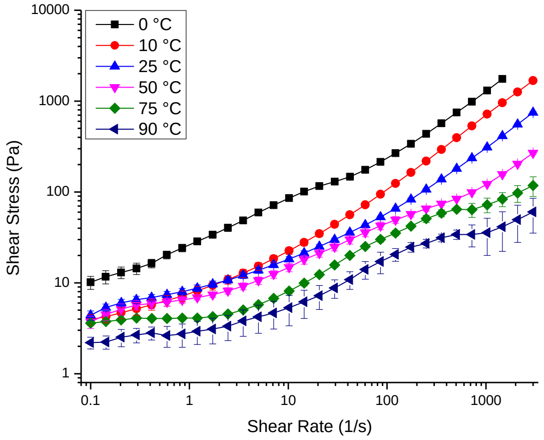


Figure 7: Flow Curve. OBM S1 Nonionic - HLB: 4.3.

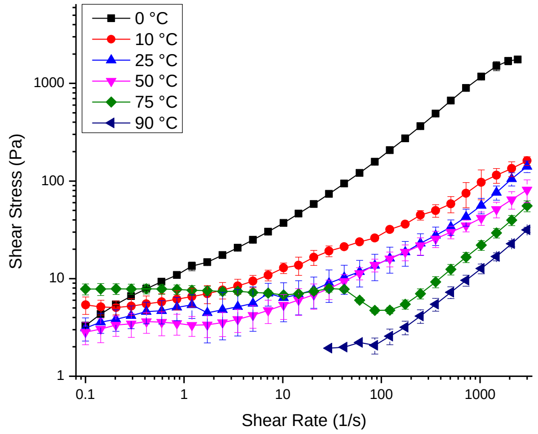


Figure 8: Flow Curve. OBM S2 Nonionic - HLB: 4.0.

### *Cuttings Suspension and Formation Fracture*

Under static conditions, it is essential for the drilling mud to display optimum structuration properties to prevent particle (drill cuttings, solid additives) sedimentation. The rheological parameter of relevance to assess the mud's capability in performing that function is its yield stress. The yield stress of the mud provides a drag force in a direction opposite to the resultant net force exerted on the particle by gravity and buoyancy (Equation 2)[18].

$$\tau_y \pi d_p^2 = \frac{\pi}{6} d^3 \Delta\rho g \qquad (2)$$

$\tau_y$: Yield stress
$d_p$: Particle diameter
$\Delta\rho$: Mud-particle density difference
$g$: Gravity

The consistency of the magnitude of rheological properties such as yield stress displayed by drilling muds is a function of, amongst other factors, its shear history dependency. Figures 9 to 16 show the hysteresis loop of WBM and OBM samples at temperatures of 10, 50 and 90 ℃. For WBM stabilized by nonionic surfactant Mixture 1 (M1), a very high shear history dependency of the sample at an HLB of 7.5 (Figure 9) in comparison to an HLB of 11.5 (Figure 11) is observed at temperatures of 10 and 50 ℃. A rheopectic behavior was detected for the sample at a temperature of 50 ℃ and HLB of 11.5.

Figures 10 and 12 show the absence of virtually any shear history dependency in WBM sample stabilized by nonionic Mixture 2 (M2), as is indicated by the close to nil area of the hysteresis loop. The latter underscores the importance of the chemical structure and nature of surfactants used. For WBM stabilized by ionic surfactant Mixture 3 (M3), shear history dependency is observed to vary with temperature as is seen in Figure 13. The hysteresis loop area of WBM M3 sample is observed to increase in size to the temperature of 50 ℃ before decreasing again.

OBM samples showed different variations in their hysteresis loop area based on their surfactant chemistry (Figures 14 and 15). The mud sample stabilized by Surfactant 1 (S1) showed relative independence from its shear history till the temperature of 90 ℃, while the sample stabilized by Surfactant 2 (S2) showed an opposite trend. Its shear history dependency was observed to be very high at low temperature (10 ℃) before gradually decreasing with increasing temperatures.

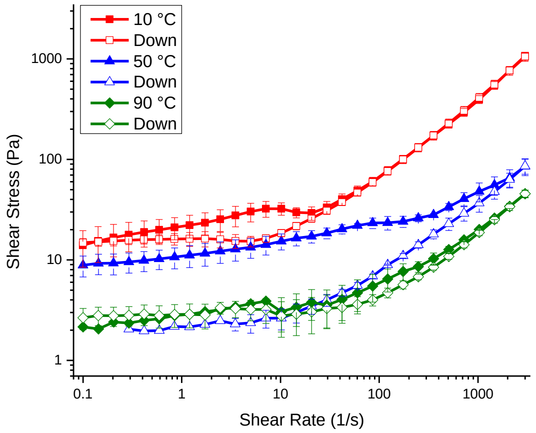


**Figure 9: Hysteresis Loop. WBM M1 Nonionic - HLB: 7.5.**

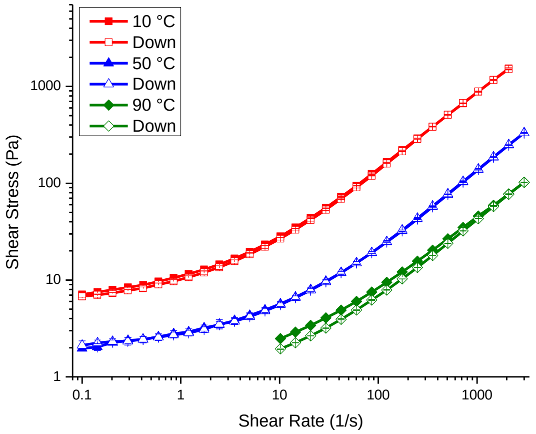


**Figure 10: Hysteresis Loop. WBM M2 Nonionic - HLB: 7.5.**

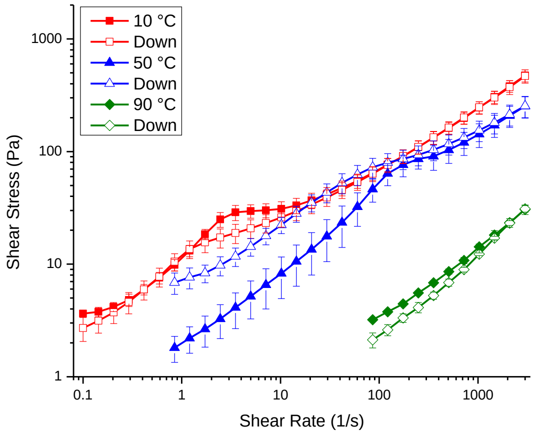


**Figure 11: Hysteresis Loop. WBM M1 Nonionic - HLB: 11.5.**

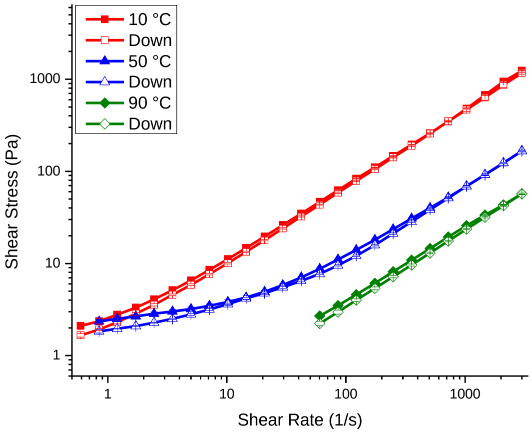


**Figure 12: Hysteresis Loop. WBM M2 Nonionic - HLB: 11.5.**

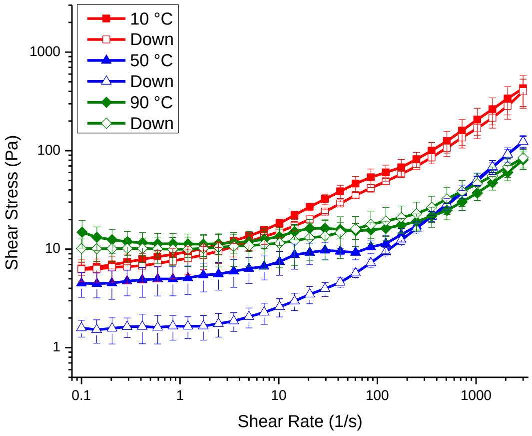


**Figure 13: Hysteresis Loop. WBM M3 Ionic - HLB: 11.5.**

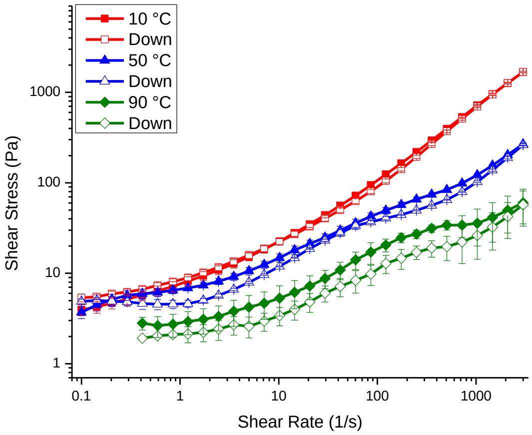


**Figure 14: Hysteresis Loop. OBM S1 Nonionic - HLB: 4.3.**

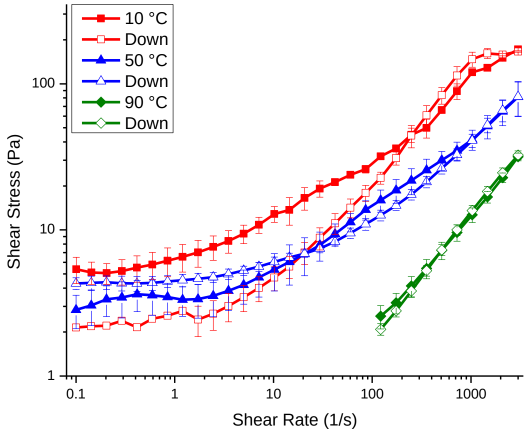
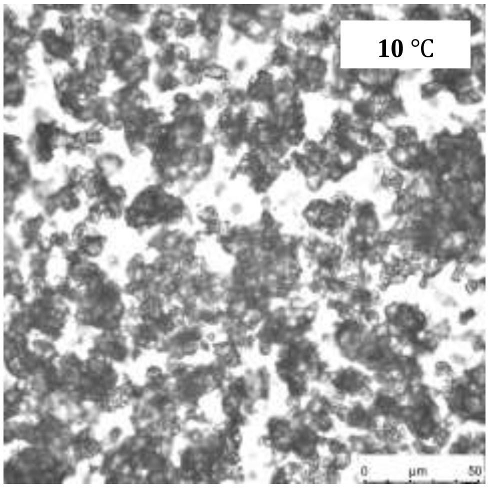


**Figure 15: Hysteresis Loop. OBM S2 Nonionic - HLB: 4.0.**

The comparison in the significance of shear history dependency between WBM and OBM samples shows no clear-cut trend. In other words, depending on the type of surfactant used in stabilizing the base emulsion of the WBM samples, shear history dependency can be less or greater than that of the OBM samples. WBM M2 samples show significantly less dependence on shear history than both OBM samples. On the other hand, WBM M1 and M3 samples show larger or comparable dependence on shear history.

Figure 16 shows the variation with increasing temperatures (10 to 90 ℃) of the microstructure of a 3 wt.% WBM M1 sample at an HLB of 7.5. At 10 ℃ (32 °F), the dispersed paraffin oil and bentonite particles can be seen in the continuous aqueous medium. As temperature was increased to 90 ℃ (194 °F), the formation of nano-sized water droplets in the continuous oil medium was observed indicative of the occurrence of temperature-induced phase inversion.



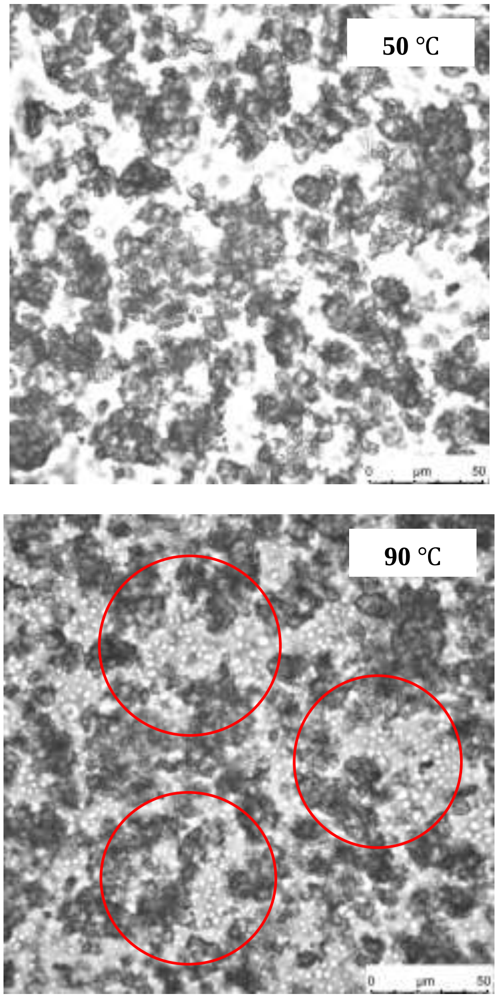


**Figure 16: Temperature-Induced Phase Inversion. O/W → W/O Base Emulsion. WBM M1 Nonionic - HLB: 7.5, O:W=60:40.**

The yield stress required for proper cuttings suspension under hydrostatic conditions, and the risk of formation fracture by excessive pump pressures required to re-initiate flow were evaluated through stress sweeps; 0 – 50 Pa (0 – 104 lbf/100ft$^2$). Figures 17 to 23 show shear strain variation as a function of shear stress and temperature (0, 25 and 90 ℃) for all mud samples at 2 wt.% surfactant (mixture) concentration and O:W=70:30. The WBM sample stabilized by nonionic surfactant Mixture 1 (M1) at an HLB of 7.5 had yield stresses greater than 50 Pa at all temperatures (Figure 17). This is shown by the low and linear increase in strain deformation with shear stress. At an HLB of 11.5 (Figure 19), the sample showed similar behavior with yield stresses exceeding 50 Pa at all temperatures, thus indicating good temperature-independent cutting suspension capabilities.

Figures 18 and 20 show the shear strain variation of the WBM samples stabilized by nonionic surfactant Mixture 2 (M2). As opposed to WBM M1, WBM M2 has a lower structuration level as is shown by the significant deformation it displays when shear stress is applied. However, the degree of deformation is observed to level out with increasing shear stresses.

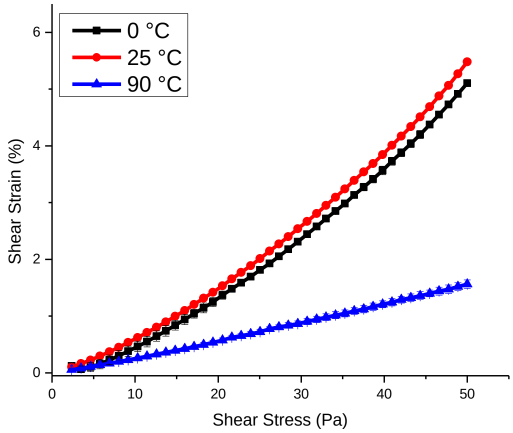


**Figure 17: Stress Sweep. WBM M1 Nonionic - 2 wt.% HLB: 7.5.**

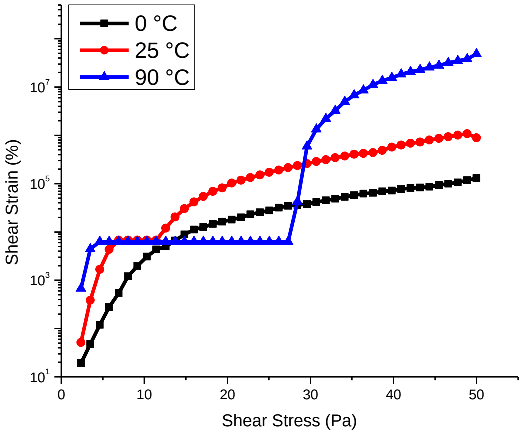


**Figure 18: Stress Sweep. WBM M2 Nonionic - 2 wt.% HLB: 7.5.**

This can be explained by the very high volume fraction of dispersed particles (liquid droplets, bentonite particles) in the continuous medium of the sample. At such elevated fractions of dispersed particles, ‘jamming’ of the particles due to their proximity to each other leads to shear thickening. The implication of the latter will be the need to apply higher stresses to further re-initiate flow. At an HLB of 7.5 and temperature of 90 ℃ (Figure 18), this phenomenon is well illustrated. Shear stress applied to the sample exceeds its ‘initial’ yield stress leading to its structure breakdown and flow, as shear stress approaches a value of ~5 Pa, jamming and thus shear thickening of the sample occurs. Flow is re-initiated around ~27 Pa before deformation is leveled out again.

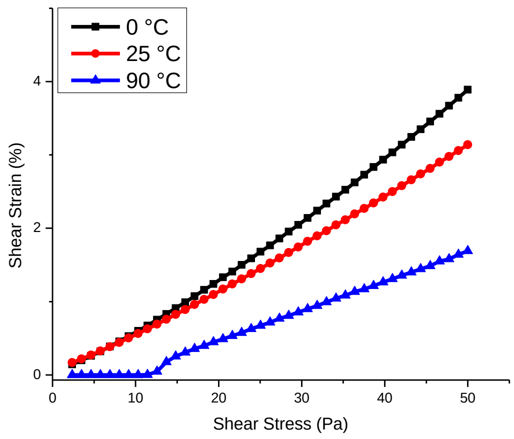


**Figure 19: Stress Sweep. WBM M1 Nonionic - 2 wt.% HLB: 11.5.**

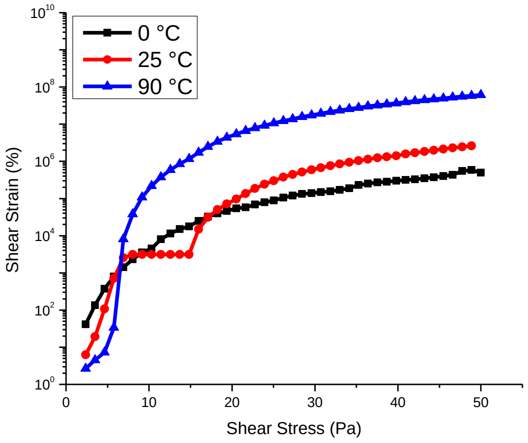


**Figure 20: Stress Sweep. WBM M2 Nonionic - 2 wt.% HLB: 11.5.**

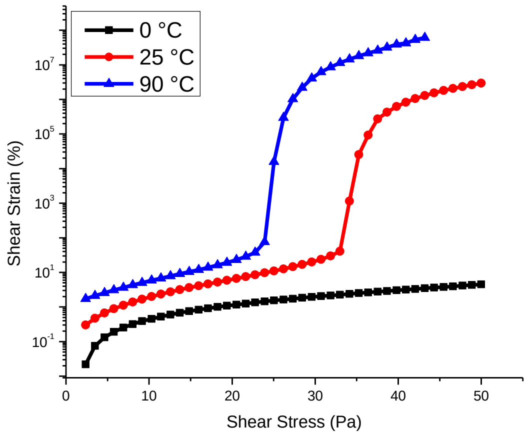


**Figure 21: Stress Sweep. WBM M3 Ionic - 2 wt.% HLB: 11.5.**

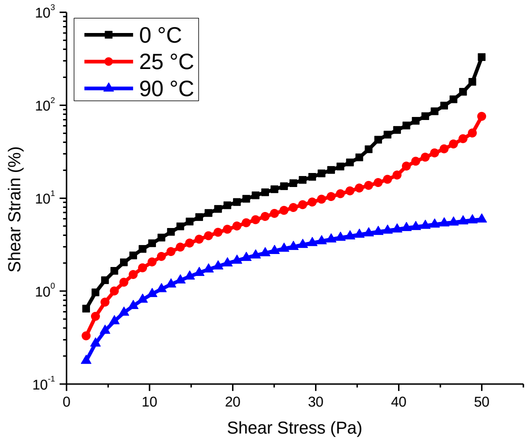


**Figure 22: Stress Sweep. OBM S1 Nonionic - 2 wt.% HLB: 4.3.**

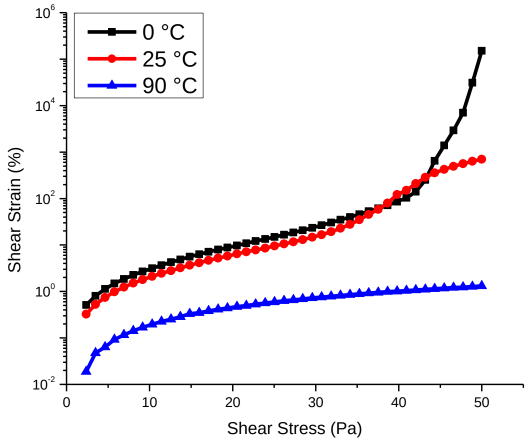


**Figure 23: Stress Sweep. OBM S2 Nonionic - 2 wt.% HLB: 4.0.**

The effect of using an ionic surfactant Mixture (M3) on the WBM's yield stress and deformation profile with temperature is shown in Figure 21. The sample did not yield at 0 ℃ but showed yield stresses of ~33 and ~24 Pa at temperatures of 25 and 90 ℃ respectively. As shear stress was increased, shear thickening due to jamming led to the leveling out of shear strain deformation. The results were indicative of its better cutting suspension capabilities at low temperatures. When compared, WBM M1 shows a higher capacity to prevent sedimentation of cuttings and solid additives than the WBM M2 and M3 samples. The latter also implies the need for higher pump pressures to re-initiate flow and thus greater risks of fracturing the exposed formation.

Figures 22 and 23 show the variation in yield stress and deformation profile of OBM samples with temperature and surfactant type (S1, S2). Both types of OBMs showed yield stresses greater than 50 Pa at 90 ℃. The major difference observed with WBM samples was in their strain deformation profile with increasing shear stress. As opposed to WBM samples, OBM samples showed exponential increase in their strain deformation with shear stress beyond a given stress value. This was observed at shear stresses greater than ~35 Pa in OBM S1 at 0 and 25 °C, and values greater than 40 Pa in OBM S2 at 0 °C. Complete breakdown of the microstructures in the OBM samples at those temperatures accounts for the exponential increase of strain deformation observed. The difference in the shear strain behavior observed stems from having a 70 vol.% dispersed oil phase in deionized water of the WBM as opposed to having 30 vol.% water phase dispersed in the paraffin oil of OBM. This highlights the more solid-like viscoelastic behavior of WBM samples over their OBM counterparts due to the greater volume fraction of dispersed phase at the same O:W ratio=70:30.

### *Fluid Loss to Formation*

Fluid loss measurements were conducted on each type of mud sample (WBM, OBM) at O:W=70:30 and 3 wt.% surfactant concentration. The measurements were carried to evaluate their formation damage potential at room temperature and pressure conditions. 150 mL volumes of the mud samples were prepared and fluid loss was recorded over 7.5 minutes.

Figures 24 – 26 show data output comparing the effect of mud type, HLB and surfactant chemistry. No difference trend was observed when comparing OBM with WBM at an HLB of 7.5 (Figure 24). The level of fluid loss between the samples were of the same order of magnitude, with fluid loss from OBM S1 (highest) being greater by a factor of ~4 than that of WBM M2 (lowest). At an HLB of 11.5, WBM samples showed different levels of fluid loss based on the nature of the surfactant mixture (Figure 25). All nonionic stabilized samples, WBM M1 and M2, showed the lowest level of fluid loss. The largest filtrate volume was recorded for WBM M3 (Ionic).

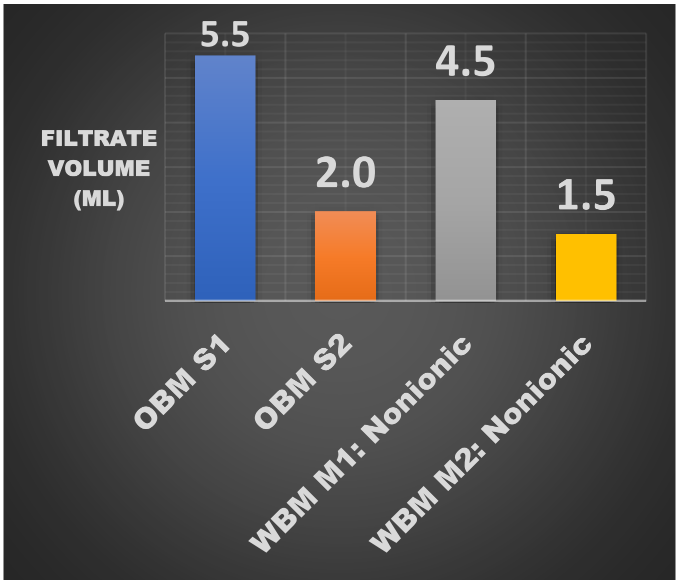


**Figure 24: Fluid Loss Test - OBM vs WBM (HLB: 7.5).**

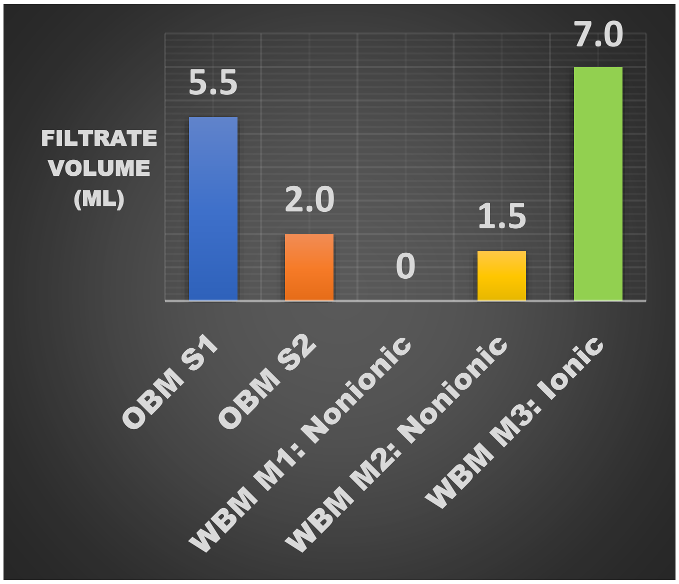


**Figure 25: Fluid Loss Test - OBM vs WBM (HLB: 11.5).**

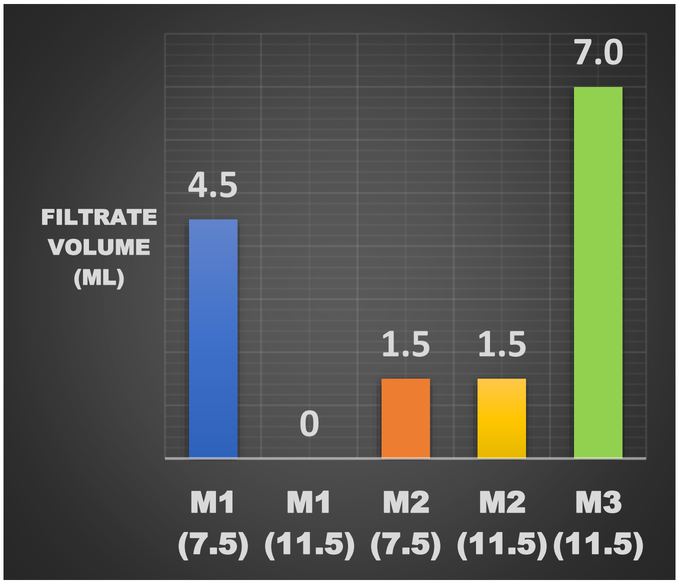


**Figure 26: Fluid Loss Test – WBM HLB Effect: 7.5 vs 11.5.**

Assessing whether the HLB of surfactant mixtures is a factor in the filtrate volume measured from each WBM sample is shown in Figure 26. The data was indicative of HLB effect on fluid loss for Mixture 1. On the other hand, Mixture 2 showed no variation in its filtrate volume with HLB.

Figures 27 and 28 illustrate the structure of the two surfactants used in Mixture 1. The length of the hydrophobic chain of surfactants promote emulsion stability by preventing droplet coalescence through steric repulsion[11]. The implication of the latter are higher concentrations of ‘small’ dispersed droplets in the continuous medium of the emulsion. Droplet size and size distribution are amongst the multiple factors that affect emulsion rheology. Figures 29 to 32 depict the chemical structures of the surfactants used in preparing Mixture 2 (Figures 29, 30) and Mixture 3 (Figures 31, 32).

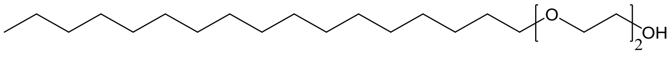


**Figure 27: Polyoxyethylene (2) Oleyl Ether.**

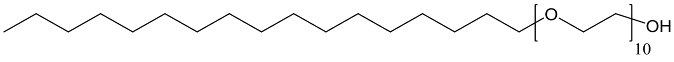


**Figure 28: Polyoxyethylene (10) Oleyl Ether.**

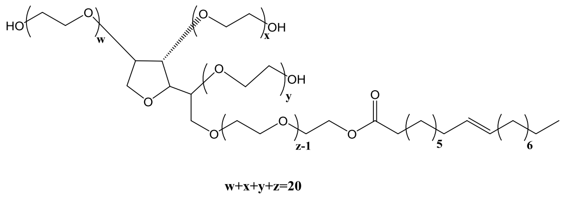


**Figure 29: Polysorbate 80.**

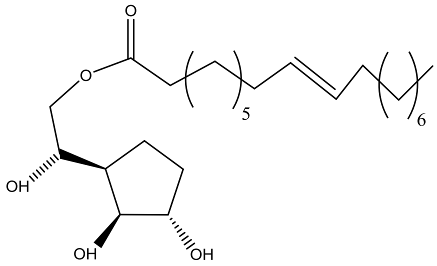


**Figure 30: Sorbitan Monooleate.**

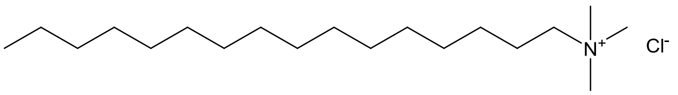


**Figure 31: Cetrimonium Bromide.**

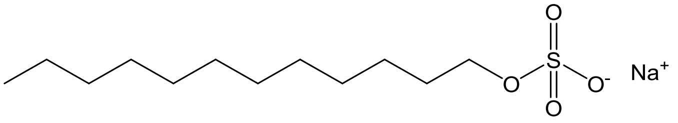


**Figure 32: Sodium Dodecyl Sulfate.**

## Conclusions

Challenges encountered with OBMs (FRIDFs) and WBMs pose different technical challenges as a result of the extreme temperature and pressure conditions that prevail in offshore drilling operations. Drilling fluids having an organic continuous medium, have temperature and pressure dependent static density and high gas solubility that adds complexity to kick detection during well control. WBMs however, do not dispose of most of the excellent properties that account for the widespread use of OBMs; higher rates of penetration, shale-swelling inhibition, drill string sticking prevention and conditioning of drill cuttings. The noteworthy advantages of WBMs that include; being more environmentally friendly and having lower compressibility effects with varying temperature and pressure cannot be overstated.

Measurements were performed to assess the difference in rheological behavior of WBM samples, prone to experience temperature-induced phase inversion of their base emulsion, and OBM samples. This was achieved by using different surfactant mixtures and HLB values. Results showed that frictional pressure losses at the elevated shear rates prevalent in the drill string were slightly greater for OBM samples than their WBM counterparts. This difference was observed at the lowest (0 ℃) and highest (90 ℃) measurement temperatures.

The level of shear history dependency was found to vary as a function of surfactant type and HLB. WBM samples stabilized by surfactant Mixture 2 (M2) showed high independence of their flow behavior from their shear history. OBM samples showed variation in their shear history dependency with temperature.

Highest structuration levels were displayed by the WBM sample stabilized by nonionic surfactant Mixture 1 (M1) at different temperatures. This was indicative of its good capacity of suspending drill cuttings and other solid additives following prolonged periods of static condition. OBM samples showed high structuration levels at 90 ℃ (194 ℉). At lower temperatures, OBM S1 showed exponential increase in its shear strain deformation with stresses above its yield stress indicating a complete breakdown of its microstructure.

Absence of significant differences was found in the filtrate volume measured for all samples at room temperature and pressure. All samples showed fluid loss of the same order of magnitude except for WBM M1 at an HLB of 11.5, for which no filtrate volume was recorded.

Holistically, results for all the experimental measurements performed highlighted the importance of different surfactant aspects; nature (nonionic vs ionic), structure and chemical group (Figures 27 to 32) and HLB of surfactant blends on the rheology of the final emulsion obtained. Depending on the type and combination of surfactants used in preparing drilling muds, their base emulsions will display differing rheological properties under varying temperature conditions.

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## Nomenclature

*CPI* = *Catastrophic Phase Inversion*
*FRIDF* = *Flat Rheology Invert Drilling Fluids*
*HLB* = *Hydrophile-Lipophile Balance*
*OBM* = *Oil-based Muds*
*O/W* = *Oil-in-Water emulsion*
*O:W* = *Oil-to-Water ratio*
*PIT* = *Phase Inversion Temperature*
*TPI* = *Transitional Phase Inversion*
*VOL.%* = *Volume Percent*
*WBM* = *Water-based Muds*
*W/O* = *Water-in-Oil emulsion*
*WT.%* = *Weight Percent*

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