



An Experimental Analysis of the Factors Affecting Barite Segregation in Water Based Drilling Fluids

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Abstract: Barite segregations is a phenomenon that can lead to dire problems when not controlled properly. Many methods have been discovered and tested to reduce the effect of barite sagging. This research looks into two different drilling fluids, freshwater and seawater based. The experimentation looks at varying concentrations of Flowzan and Prehydrated Bentonite and seeing how that effects the sag factor of the fluids. For the freshwater samples, we found a critical Flowzan concentration that shows the highest sag factor. For the seawater though, we found a general decrease of sagging with the increase of PHB concentration. The findings would be more conclusive if we tested for a wider range of concentrations for both Flowzan and PHB.

1. INTRODUCTION

Drilling phase is one of the most important parts of developing a field. The durability of the well and its performance is greatly related to the quality of the drilling. A good drilling will also have an effect on how fast the project can start make profits as the drilling phase become shorter and more efficient. There are number of different factors that can hinder the quality of the drilling job and in some cases stop it or damage the wellbore and cause catastrophic disasters. Barite sagging is a one of the main causes of damage in the wellbore during the drilling stage.

Any drilling job needs a drilling fluid that can provide the engineers with:

- enough hydrostatic pressure to prevent the well from collapsing in,
- removing the drilling cuts to the surface,
- cools down and lubricates the drill bit during the drilling job,
- suspend the drilling cuts within itself during the drilling and when drilling is stopped,
- seal the permeable zones in the wellbore to prevent lost circulation,
- control the corrosion caused by corrosive gasses such as H₂S,
- Provide hydraulic energy to the bit to fasten and improve the drilling and finally help the engineer to the cementing and completion after the drilling was done.

Barite Sag is a common phenomenon that occurs while drilling for oil and gas. Barite, BaSO₄ is a weighing agent used to increase the density of drilling fluids to a desired level. It has a high density of 4.2 g/cm³. The problem that occurs in this phenomenon is that as the mud is circulated through the borehole, the barite that was dissolved in the mud starts separating from the liquid phase and settles down. This separation of barite from the aqueous phase creates an undesired density gradient and causes a lot of further problems.

Barite sag can occur in both conventional and deviated wells. In vertical wells, higher density drilling fluids or barite-rich phase settles on the bottom of the well bore while the lower density fluid form layers on the upper part of the column. This usually occurs during static conditions i.e. when drilling is stopped or very low shear rate (rpm). Additionally, a very low shear-rate viscosity can also result in barite sag.

However, deviated wells are more susceptible to barite sag as in deviated wells, gravity induces an additional settling effect which results in sediment beds of barite at the bottom of the borehole. In deviated wells, Boycott effect is the reason for barite sagging. In an inclined tubing, the vertical distance of the settling particles is greatly reduced as compared to that in vertical columns. Hence the process of sedimentation is accelerated.

Barite sagging can cause some serious problems during drilling operations. These problems are:

- loss of mud circulation,
- well bore instability, and
- Uneven mechanical friction which can cause pipes and tools to get stuck downhole.

Barite sagging, if not controlled properly, can lead to a complete shutdown and well abandonment. Hence, this study is being conducted to look in detail at the various chemical and physical factors, that affect barite sag, so that more viable and optimal solutions can be derived to control the extent of barite sag.

Barite sagging is just a general term used to describe the phenomenon of which the weighting material detaches itself from its own liquid phase and slowly settles down the wellbore. But many more specific examples of barite sagging have been looked into and researched to further expand our understanding of this phenomenon. From dynamic to static sagging, in wells that are vertical, horizontal or deviated, all of these scenarios have been heavily examined and studied.

The extent of the research that has been done in regards to barite sagging is surely well deserved as barite sagging can cause major problems while drilling in the field such as loss circulation, sudden changes of density in the drilling fluid which could further escalate into a blowout. Problems with cementation, well control issues and stuck pipe, all have been encountered mainly due to barite sagging.

The research papers available look into a wide range of aspects related to barite sagging, but I will mainly look at the research conducted that studies adding different substances into the drilling fluids and comparing the effects that the new substances can cause to the sagging affect. Another major topic that I will try to cover is the different methods that have been used through the years to measure barite sagging in the laboratory environments.

2. WHAT IS BARITE SAGGING?

“Barite sag results if the rheological properties of the drilling fluid are inadequate to keep the weighing agent suspended” (Saasen et al, 1991). It is important to know under what conditions the sagging happens. “The phenomenon is likely to occur under dynamic conditions, elevated temperature and inadequate annular flow velocity” (Parviznia et al, 2011). The damages that the barite sagging can cause are severe and are varied. The problems range from stock pipe, lost circulation in which the drilling fluid penetrates the formation and can cause further problems, it can cause the wellbore to be unstable during the drilling job and increase the risk of having kicks and it will also result in a bad and inadequate cementing after finishing the drilling operation.

Segregation of barite is a slow process. “In directional drilling operations the settling process is accelerated.” (Skalle 1999). It mainly forms in the lower sides of the borehole during the drilling process and can cause difference in density above and below that cross-sectional area. (Skalle 1999, Parviznia et al 2011). The segregation of the barite sediments can also happen when the drilling process is stopped during different operations such as pipe trappings to change the bit in which the drilling will be stopped for long periods of time and the mud starts to thicken due to its gel strength.

Early studies have shown that the fluid’s particles settlement is a function of the tubing inclination. (Boycott 1920). Other experiment following the Boycott’s experiment have indicated that barite sagging is also a similar case to the Boycott’s experiment. (Hanson et al 1990, Saasen et al 1995, Bern 1996, Bern 1998, Omland 2004).

The above statements will draw a conclusion that a barite segregation is more likely to happen in horizontal or inclined wells. Although in vertical wells the situation is different. “In vertical wells the settling of weighting material is generally not a problem due to the long settling distance. In horizontal wells the distance to the lower side of the wall is only about 0.2 m, which leads to rapid generation of solids beds.” (Skalle 1999).

Furthermore, it is also vital to know what fluids are more potential to have barite sagging or what property of the fluid will make it more potential to have barite segregation. “Sag potential is directly related to the weight-loss of the circulating fluid” (Bern et al 1998).

Bern et al. 1998 found out that the sag beds which form in the low side of the borehole are more responsive to removal by velocity and pipe rotation than most cuttings beds, tend to flow rather than slide when placed at angle and can still “slump” downwards angles Up to 75°, about 10-15° greater than cuttings beds.

3. FACTORS AFFECTING BARITE SAG

There are two major types of factors that affect barite sag in drilling process: Drilling fluid related and Drilling process related. Factors concerned with drilling fluids are rheology, density and particle size etc. These factors are related to the composition of the drilling mud. Whereas, drilling operation related factors are annular velocity and drill-pipe rotation etc.

3.1. Factors Related to Drilling Fluids

3.1.1. Rheology

Rheology is the study of deformation and flow of matter. It deals especially with non-Newtonian flow of liquids and plastic flow of solids at different dynamical conditions. The most important parameters that affect the rheology of a fluid are temperature and pressure. Mud rheology is measured continuously to ensure that desired effects are being attained by the oilfield fluids being used. There are three parameters which better define the fluid behavior. These parameters or “Rheological properties” are derived from the Bingham plastic fluid model and are Plastic Viscosity (PV), and Yield Point (YP). Along with this, the Thixotropy or time-dependent shear thinning property, is another important factor affecting barite sag.

In oil-based fluids, an increase in shear rate increases the viscosity of the fluid and it behaves like a shear-thickening fluid or a dilatant. However, as the shear rate is increased further, after a particular critical shear rate, the viscosity reduces drastically. This produces a thixotropic effect which promotes the sagging of barite particles. This is because there is not enough viscous drag to hold the barite particles in suspension.

It is found out that low-shear-rate (LSR) rheology of the fluid affects the barite sag. It consists of low share rate viscosity or LSRV, and low gel strength. The share rate of a particle settling in a LSR environment can be estimated by Stokes’ Law:

$$V_s = 430.2 \frac{(SG_{solid} - SG_{liquid})gd^2}{\mu} \dots\dots\dots(1)$$

Where measurements are in Imperial units.

Yield stress or gel strength is another viscoelastic property of the drilling fluid. It is required to keep the barite particles in suspension. Gel strength varies as conditions are altered from static to dynamic or vice versa. It is found out that at very low shear rates an internal solid-like structure is formed which holds particles in suspension but it breaks down rapidly as shear rate is increased. The yield stress τ_s necessary to prevent barite sag in static conditions can be estimated from Buoyancy forces and viscous drag:

$$\tau_s = 2.70(SG_{solid} - SG_{liquid})gd \dots\dots\dots(2)$$

Where measurements are in Imperial units.

3.1.2. Temperature

Temperature is another key factor that affects the barite sag. Changes in temperature produce a change in viscosity and density of the drilling fluid, which in terms affects sag. A high temperature promotes barite sag as the internal structure of the fluid breaks and the viscosity decreases.

3.1.3. Density

How density can affect sagging can be best explained by an alternate form of the Stokes law:

$$V_s = \frac{2(\rho_p - \rho_f)gd^2}{9\mu} \dots\dots\dots(3)$$

From this equation, it can be seen that V_s , the velocity of the settling particle is directly proportional to the difference in mass densities of particles and fluid. Therefore, the denser the liquid is the lesser will be the mass density differential and consequently the sedimentation rate of the particles will be slower. Hence, an increase in fluid density reduces barite sag.

3.1.4. Solid Contents

Addition of solid contents in the drilling fluid increases the resistance to the settling motion. This is because a concentrated suspension of solid particles will prevent barite from settling too quickly because they will collide with each other and decrease the velocity with which the barite particles were settling.

3.1.5. Particle Size and Shape

The effect of particle size on barite sag can be understood by the Stokes' law. Considering the following equation:

$$V_s = \frac{2(\rho_p - \rho_f)gd^2}{9\mu} \dots\dots\dots(3)$$

It can be seen that for a constant viscosity, and mass densities, square of particle size d^2 , is directly proportional to the settling velocity V_s . Also this is supported by the research conducted by Massam et al. Barite samples with greater mean diameters had higher dynamic sag as compared to samples with lower average diameters.

Particle shape also affects the settling of particles in a fluid. For example, there may be particles with same volume and mass but different shapes, and their rate of sedimentation will be entirely different from one another. This is because drag force is a function of the projected area of the particle in the direction in which it is falling. Therefore, spherical particles will have a smaller drag coefficient and will settle faster than particles with less rounded surfaces but same mass and volume.

3.1.6. Other Correlations Used in this Study Include the Following

VSST (Viscometer Sag Shoe Test) calculation:

$$VSST \left[\frac{lbm}{gal} \right] = 0.833 \times (WT2 - WT1) \dots\dots\dots(4)$$

BPU (Bed Pick-Up) calculation:

$$BPU(\%) = 83.3 \times \frac{(WT2 - WT3)}{VSST} \dots\dots\dots(5)$$

Dynamic Sag Factor:

$$Sag\ factor = \frac{\rho_{bottom}}{\rho_{bottom} + \rho_{top}} \dots\dots\dots(6)$$

Density calculation:

$$\rho = \frac{(Total\ Mass - Mass\ of\ syringe)}{10\ mL} \dots\dots\dots(7)$$

3.1.7. Interfacial Chemistry of the Dispersed Solid and Aqueous Phases

Interfacial chemistry of the dispersed phases i.e. solid and aqueous phases can also influence barite sag in drilling fluids. The type and concentration of the emulsifying agent and wetting agent can have an effect on sag. Studies have shown that it is much more difficult to maintain barite in suspension in oil-based muds as compared to forming suspension in water-based muds. This is because barite is an inorganic salt and will form intermolecular interactions in a hydrophilic medium i.e. water.

3.2. Factors Related to Drilling Process

3.2.1. Annular Velocity

The mud weight remains fairly consistent when the annular velocity is high. However, at low annular velocities, barite sag starts occurring and the difference in top and bottom mud density increases. This is further shown from the experimental data obtained from the study conducted by Nguyen et al.

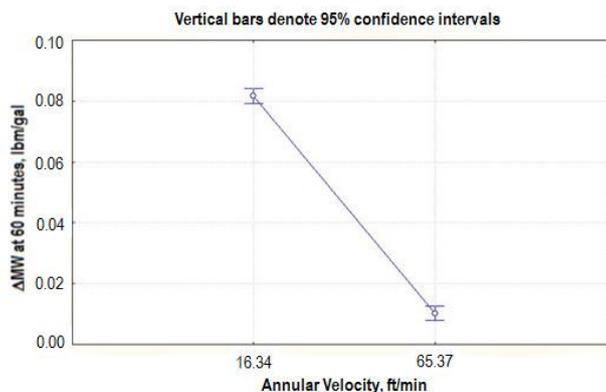


Figure1. Overall Effect of Annular Velocity

3.2.2. Drill-Pipe Rotation Speed

The rotation speed of the drill pipe also affects the barite sag rate. Generally, a very low or zero rotational speed of drill string increases barite sag and the difference in top and bottom mud densities increases. This can be seen in Figure 2. that as the rpm is increased the change in density, ΔMW decreases considerably.

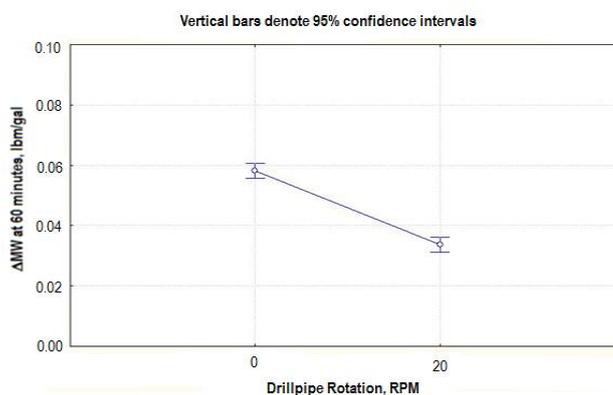


Figure2. Overall Effect of Drill-Pipe Rotation

However, the rotation of drill pipe introduces a shear-rate in the fluid column of the annulus. If this shear-rate is greater than the critical shear rate discussed in Section 3.1.1., it would produce a thixotropic effect and the viscosity will decrease, thus increasing the rate of settling of barite particles.

3.2.3. Eccentricity

Eccentricity is the measure of how-off center a pipe is within another pipe, circular column or the open-hole. It is expressed in percentage. If there is a high eccentricity or the pipe lies on the lower side of an inclined wellbore, the fluid flow will be much slower on the lower side. This reduced fluid velocity will increase the rate of sedimentation. The overall effect of eccentricity on ΔMW is displayed in Figure 3.

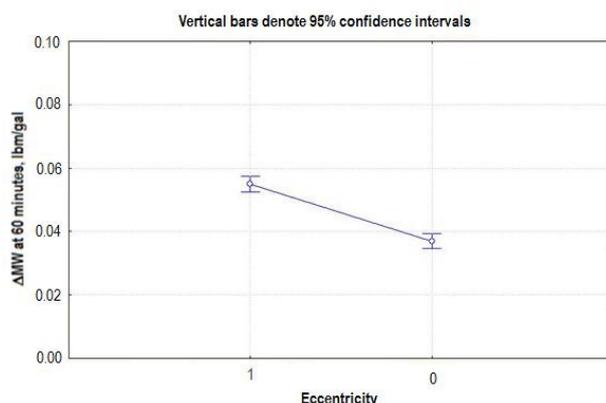


Figure3. Overall Effect of Eccentricity on Difference in Mud Weight

3.2.4. Inclination Angle

Angle of inclination also effects barite sag. In an inclined well, the distance that particle has to cover for settling is reduced and the particles settle more quickly on the lower sides of the inclined columns. This results in sedimentation beds of barite. After a certain time period, the sedimentation reaches a critical thickness, after which it slides down to the bottom of the whole. This also increases the rate of barite sag. A study conducted by Nguyen et al. shows that as the well inclination angle is changed from 60° to 45°, the barite sag is actually reduced. This is further evident in Figure 4.

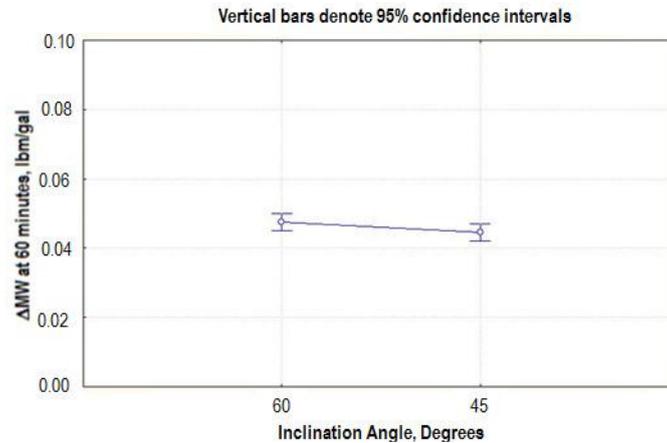


Figure 4. Effect of Inclination Angle

3.2.5. Time

Time is also an underlying factor in the process of barite sag. This form of sedimentation is time-dependent and with time, the barite sag increases as more and more barite settles on the bottom of the well bore. This would further cause fluctuation in densities and wellbore pressure.

4. METHODS OF MEASUREMENT

In early times, barite sagging was looked at only in static situations, as it was believed that sagging does not occur in a dynamic system, basically the thought of having barite sag in the well with a rotating drill was never inspected and was almost unheard of. When more and more research was pushed through, many started to look upon dynamic sagging. To further look at the subject, different apparatuses were created to test dynamic sagging.

In 1991 the Viscometer Sag Test, or VST in short, was created by D.T Jefferson to easily measure the change in density in the weighting fluids used. “The original VST measures the density increase at the bottom of an API mud thermocup after mixing the mud sample at 100 rpm with a standard field viscometer” (Zamora and Bell, 2004). With the fluid in the mud thermocup, samples can be taken from the bottom of the cup using a syringe at any time needed. Since samples can be taken at ease and at any time, it could be used to measure the rate at which the sagging occurs depending on the chosen mud mixture.

To measure the density of the samples, you can simply measure the volumes from the syringe or place it in a graduated cylinder, and find the mass of the fluid using a digital scale for accurate readings. With the two values in hand you can use the simple density equation to calculate the density of the sample. Or a more direct approach to measure the density of the mud is to simply use a retort cup or a mud balance.

The original Viscometer Sag Test apparatus has been the benchmark of laboratory dynamic testing, but there have been many methods of trying to improve it for a more accurate and realistic results. This is where Zamora and Bell created the sag shoe to advance the original apparatus for testing. This upgrade was simply the addition of a round thermoplastic piece that has two inward slanted sides that lead to a small semicircular cutout called the collection well. The same general procedure used in the VST can be used with the Viscometer Sag Shoe Test, VSST.

This simple upgrade the original VST procedure helps speed up the process of sagging as the slopes on the top of the sag shoe help the weighting material to gather in a single and concentrated point

called the collection well. From the collection well, samples can be easily taken via a syringe and tested for its density. According to Zamora and Bell's results, the VSST has shown an improvement in the "consistency, sensitivity, and accuracy of measuring barite-sag tendencies". And since most of the sagged material accumulates in the collection well it "ensures that bed samples are extracted from and replaced in the same location, thereby allowing multiple sampling and measurement of the relative ability of the test mud to pick up the sag bed."

5. ROLE OF ADDITIVES

There are various additives used during the mud formulation. These additives include: Soda Ash, Caustic Soda, NaCl, Flowzan, Polysal HT and Barite. Each of these additives have a unique role in the functioning and behavior of mud and affect its properties differently. The additives restore the mud properties even in HPHT conditions.

Water is the main medium in which mud is formulated. It acts as a solvent and vehicle for the various additives. Water used can be fresh water, drill water or seawater. Each of these are different in terms of salinity, solubility and density.

Caustic soda and soda ash is primarily used for controlling the pH of the mud. It also controls the calcium ion contamination in mud which occurs due to influx of formation water in borehole.

NaCl (Sodium Chloride) acts as an initial weighing agent, increasing the mud weight. It also affects the viscosity of the mud. Adding NaCl to mud also improves the Rate of Penetration while drilling.

Flowzan is a widely known mud viscosifier, and was used in this experiment to alter the viscosity of the muds. Polysal HT (HT denoting high temperature) is used in water based muds to decrease the fluid loss. Also, it maintains the rheological properties of mud at high temperatures and prevent the mud from thinning at higher temperatures. Another viscosifier and fluid loss control agent is PHB (Prehydrated Bentonite), also known as Sodium Montmorillonite.

Barite is the main weighing agent used in the mud. With density measured at 4.2 g/mL, it is the densest additive and even small amounts significantly increase the mud weight.

6. SAG MINIMIZATION

(Bern, et al. 1998) According to Bern et al., factors that affect barite sagging are the following:

- Well planning and operational practices
- Mud properties
- Pipe's annular velocity
- Pressure and temperature
- Particle size of solids

As stated before, the focus will be on the additives that could be mixed with the drilling fluid that could in turn increase or decrease the sagging effect. The additive in question here is calcium chloride and its effect on sagging has been investigated extensively by Dare Ayoade. The fluid used to test the different concentration of salt firstly had a fixed density of 12ppg for all samples. The samples also have to have an 80/20 ratio of oil to water, having a fixed ratio and a fixed density is a key element during this experiment since the only factor that is looked upon is the salt concentration and nothing else. A set amount of viscosifiers, emulsifiers, lime, filtration control additives and barite make up the fluid's components as a whole. The sample amount chosen was 350ml per sample and all the components were mixed for 42 minutes at speed of 6000rpm. Five samples have been created with different amount of salt added to the mix, 15, 20, 25, 30 and 35% salt concentration has been used in each batch.

To ensure testing that's relevant to the industry, the mix created needs to have similar properties as the mud used on the field. To ensure that it does, it needs to meet the American Petroleum Institute standards. It has been tested for density, viscosity, gel strength, weighting material concentration and electric stability.

The method of sag testing in their experiment was using The Viscometer Sag Shoe Test, as stated before, the slanted surfaces helped accelerate the deposition of weighting material and concentrated it in the collection well, all samples were taken directly from the collection well using a syringe, 10ml mud samples were taken each run. The samples with different salt concentrations were firstly tested

for gel strength, both 10-second and 10-minute gel strength seemed to have higher values as the concentration of salts increased. And since gel strength helps with keeping solids from settling down a fluid, this test itself could be an indication of the salt’s ability to effect barite sagging.

The final VSST test for the sample yielded results that were almost predictable due to the gel strength tests. The mix with 15% concentration of CaCl₂ was shown to have the most sag tendencies. The sagging effect decreases with the increase of salt concentration, but the results of 35% showed a slight increase from the general trend. The difference of sag levels between 15% and 35% was seen to be of 96% difference. Avoade concludes saying “The 15% CaCl₂ oil-base fluid sample is not recommended” and “Typical salt concentrations used in the industry today range from 25% to 30%. Salt concentrations of 30% to 35% are highly recommended” (Avoade, 2013).

Tehrani and Popplestone researched a very similar topic as Avoade, they used the exact same setup and method testing but instead of looking into salt concentration, they looked at the use of different polymers and viscosifiers. The additives are the following:

- Polyethylene Glycol
- Scleroglucan
- Two different grades of Sepiolite
- Two different grades of liquid brine viscosifier (ionic polymer)

Similar to Avoade’s experiment, Tehrani and Popplestone also looked at the 10-second and 10-minute gel strength of the samples. The gel strength seemed to have very varying results depending on which polymer used compared to the base mud, some had a slight increase while others had a slight increase in both 10-seconds and 10-minute strength. Unlike Avoade’s experiment, there was no obvious correlation with gel strength and sag reduction, as the results show both the reduction and increase of sagging when the polymers were added. The polyethylene glycol had an increase of sagging of 0.059%, but the most effective polymer to reduce sagging was the ionic polymer, showing a 28.7% reduction of barite sag.

7. METHODOLOGY

- Set up the viscometer with a thermocup (sag shoe included)
- Place mud sample of 140 mL into the thermocup and heat to 120 Fahrenheit
- Set viscometer to 100 RPM for 30 minutes
- Draw a 10 mL mud sample from the bottom of the sag shoe
- Clear the syringe from any air bubble and weigh the sample (WT1)
- Slowly pour back the sample into the thermocup
- Set viscometer at 600 RPM for 20 minutes
- Draw a 10 mL mud sample from the bottom of the sag shoe
- Clear the syringe from any air bubble and weigh the sample (WT2)

8. RESULTS

In order to proceed with the freshwater systems, the trend below shows the different mud formulation with varying Flowzan concentrations (concentration in ppb, pounds per barrel) used.

Table1. Mud Formulation

Components	Density, g/mL	Formulation				
		1.1	1.2	1.3	1.4	1.5
		Mass, g	Mass, g	Mass, g	Mass, g	Mass, g
Drill Water	1.00	266.93	266.76	266.59	266.43	266.26
Soda Ash	2.54	0.25	0.25	0.25	0.25	0.25
Caustic Soda	2.13	0.30	0.30	0.30	0.30	0.30
NaCl	2.16	108.00	108.00	108.00	108.00	108.00
Flowzan	1.50	0.50	0.75	1.00	1.25	1.50
Polysal HT	1.50	5.00	5.00	5.00	5.00	5.00
Barite	4.20	122.50	122.50	122.50	122.50	122.50
Total Mass		503.48	503.56	503.64	503.73	503.81
Mud Weight, ppg		11.99	11.99	11.99	11.99	12.00

Viscometer Sag Shoe Test (VSST) was conducted on the formulations above. The test was done with three trials each. The results are presented below. In addition to VSST, rheology has been conducted.

9. ANALYSIS

The first batch of samples to test was the freshwater. Five samples were tested, all having the same main constituents, but each sample will have a different concentration of Flowzan. Table 2 shows the exact component amounts for all five freshwater samples. It also shows the variation of Flowzan that will be added to test. Before testing, a particle size distribution test was made for the seawater samples and most of the particles lay between 1.3 to 1.7 μg.

Table2. The mass and volumes of mud components for each freshwater sample along with resultant mud weight.

Components	ρ	1.1		1.2		1.3		1.4		1.5	
		Mass	Volume								
	[g/mL]	[g]	[mL]								
Drill Water	1	266.9	266.9	266.8	266.8	266.6	266.6	266.4	266.4	266.3	266.3
Soda Ash	2.54	0.3	0.1	0.3	0.1	0.3	0.1	0.3	0.1	0.3	0.1
Caustic Soda	2.13	0.3	0.1	0.3	0.1	0.3	0.1	0.3	0.1	0.3	0.1
NaCl	2.16	108.0	50.0	108.0	50.0	108.0	50.0	108.0	50.0	108.0	50.0
Flowzan	1.5	0.5	0.3	0.8	0.5	1.0	0.7	1.3	0.8	1.5	1.0
Polysal HT	1.5	5.0	3.3	5.0	3.3	5.0	3.3	5.0	3.3	5.0	3.3
Barite	4.2	122.5	29.2	122.5	29.2	122.5	29.2	122.5	29.2	122.5	29.2
Total Mass		503.5	350.0	503.6	350.0	503.6	350.0	503.7	350.0	503.8	350.0
Mud Weight [ppg]		11.99		11.99		11.99		11.99		12.00	

Table 3 shows all the calculations done to find the sagging factor of freshwater sample 2. A density measurement was taken from two different places to measure the difference in density after testing. Sample were taken from both the top and bottom of the thermocup, and the density difference was calculated using Eq. 7., taking into account the mass of the syringe when doing the calculations and ignoring the value anomalies. The calculation of density allows us to clearly see the sagging effect for each of the samples, which allows us to easily compare each sample.

Table3. Measurement and calculation results for freshwater mud sample 2.

Mud 1.2			
	Trial 1	Trial 2	Trial 3
Total Weight Top [g]	23.335	23.275	15.975
WT 1 [g]	14.770	14.710	7.410
Density Top [g/mL]	1.477	1.471	0.741
Total Weight Bottom @ 100 RPM [g]	24.665	25.755	18.160
WT 2 [g]	16.100	17.190	9.595
Density Bottom [g/mL], 100 RPM	1.610	1.719	0.960
Total Weight Bottom @ 600 RPM [g]	24.670	24.985	18.055
WT 3	16.105	16.420	9.490
Bed Pickup [g/mL], 600 RPM	1.611	1.642	0.949
Delta Density [g/mL]	0.133	0.248	0.219
Dynamic Sag Factor	0.522	0.539	0.564
VSST [lb. /gal.]	1.108	2.066	1.820
BPU [%]	-0.376	31.048	4.805

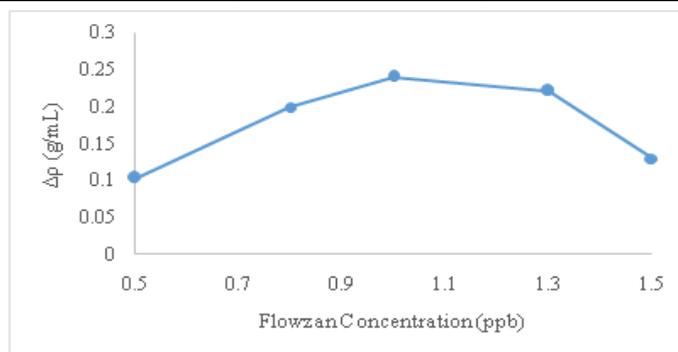


Figure5. Change in bed pickup with the corresponding addition of Flowzan.

Upon calculating all the Bed Pickup values for all sample, we can plot them and create a possible trend. Figure 5 shows a clear critical Flowzan concentration. At a Flowzan concentration of 1.0 ppb, we have a peak value of Bed Pickup of 1.86 g/mL. Decreasing or increasing the Flowzan concentration would decrease the Bed Pickup as shown. The sample with 0.5 ppb concentration has a value of 1.51 g/mL. The highest Flowzan concentration yields a Bed Pickup value of 1.6 g/mL

To compare sagging factor of each sample, an important observation is needed, we need to compare each sample's change in density, since this could be easily translated to sag factor. In Figure 6 we can see a trend that follows the same general trend as Figure 5. We have a peak density difference at the sample of 1.0 ppb Flowzan concentration with a value of 0.24 g/mL.

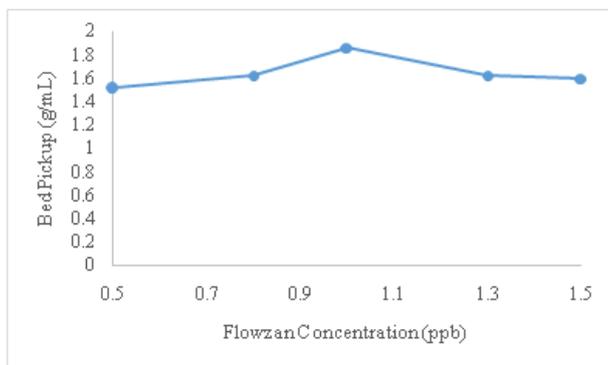


Figure6. Difference in density measured at top and bottom mud samples.

Change in density can be translated to sag factor, which can clearly and finally show the direct effect of Flowzan on barite segregation. Naturally, the plot follows the same trend as before since it was derived from Figure 6. Again, we see a critical Flowzan concentration of 1.0 ppb that shows the highest value of sag factor of 0.53. The sag factor decreases to 0.513 for the 0.5 ppb concentration sample. The highest Flowzan concentration shows a sag factor of 0.52.

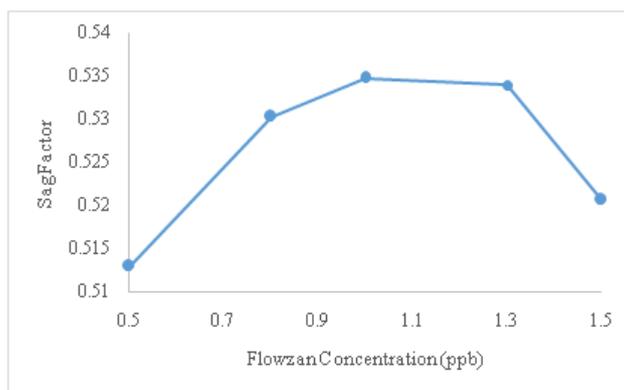


Figure7. Sag factor of each freshwater mud samples with varying Flowzan concentrations.

Table 4 shows the constituents of the seawater mud samples with varying amount PHB. Table 5 includes the results for the calculations and measurements for the second seawater sample.

Table4. The mass and volumes of mud components for each seawater sample along with resultant mud weight.

Components	ρ	2.1		2.2		2.3		2.4		2.5	
		Mass	Volume	Mass	Volume	Mass	Volume	Mass	Volume	Mass	Volume
		[g/mL]	[g]	[mL]	[g]	[mL]	[g]	[mL]	[g]	[mL]	[g]
Seawater	1.029	272.2	264.5	269.3	261.7	266.4	258.9	263.6	256.1	260.7	253.4
Soda Ash	2.54	0.3	0.1	0.3	0.1	0.3	0.1	0.3	0.1	0.3	0.1
Caustic Soda	2.13	0.3	0.1	0.3	0.1	0.3	0.1	0.3	0.1	0.3	0.1
NaCl	2.16	108.0	50.0	108.0	50.0	108.0	50.0	108.0	50.0	108.0	50.0
PHB	3.6	10.0	2.8	20.0	5.6	30.0	8.3	40.0	11.1	50.0	13.9
Polysal HT	1.5	5.0	3.3	5.0	3.3	5.0	3.3	5.0	3.3	5.0	3.3
Barite	4.2	122.5	29.2	122.5	29.2	122.5	29.2	122.5	29.2	122.5	29.2
Total Mass		518.2	350.0	525.3	350.0	532.5	350.0	539.6	350.0	546.8	350.0
Mud Weight [ppg]		12.3		12.5		12.7		12.8		13.0	

Table 5. Measurement and calculation results for seawater mud sample 2.

Mud 2.2			
	Trial 1	Trial 2	Trial 3
Total Weight Top [g]	22.96	23.19	23.60
WT 1 [g]	14.395	14.620	15.035
Density Top [g/mL]	1.440	1.462	1.504
Total Weight Bottom @ 100 RPM [g]	22.65	24.55	24.42
WT 2 [g]	14.085	15.985	15.855
Density Bottom [g/mL], 100 RPM	1.409	1.599	1.586
Total Weight Bottom @ 600 RPM [g]	23.31	23.66	22.61
WT 3	14.745	15.095	14.045
Bed Pickup [g/mL], 600 RPM	1.475	1.510	1.405
Delta Density [g/mL]	-0.031	0.137	0.082
Dynamic Sag Factor	0.495	0.522	0.513
VSST [lb. /gal.]	-0.258	1.137	0.683
BPU [%]	212.903	65.201	220.732

As it can be seen from **Figure 8**, as the amount of PHB increases in the mud, generally the Bed Pickup decreases. However, an anomaly can be seen in the data points at PHB concentration of 30 ppb which can be neglected. The anomaly can be associated with human error in measuring the value. The initial Bed Pickup was calculated to be 1.53 g/mL and dropped to 1.43 g/mL at the maximum PHB concentration.

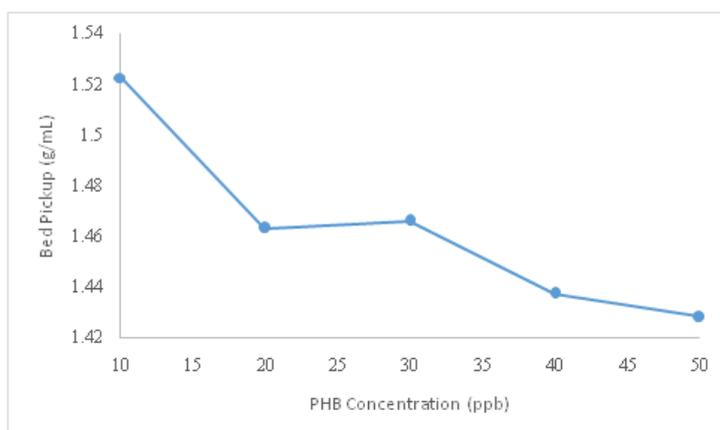


Figure 8. Change in bed pickup with the corresponding addition of PHB.

The trend for density follows the trend for the Bed Pickup. **Figure 9** shows as the concentration of PHB increases the density of the mud sample decreases. Here, an anomaly in data, similar to the anomaly in the Bed Pickup curve exists but it does not affect the total trend as it can be ignored. The density at the initial concentration of PHB

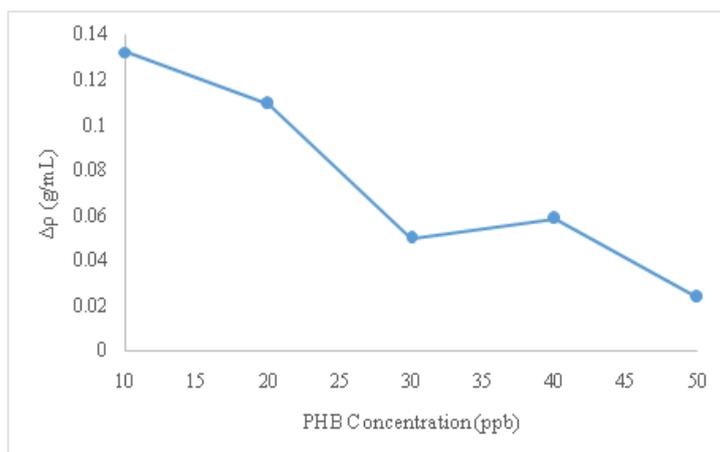


Figure 9. Difference in density measured at top and bottom mud samples.

The sag factor for seawater samples generally has a decreasing trend with increase of PHB, ignoring the anomaly at the PHB concentration of 40 ppb, it can be observed, from **Figure 10**, that the sag factor decreases from 0.52 to 0.5 as the PHB content increases in the mud.

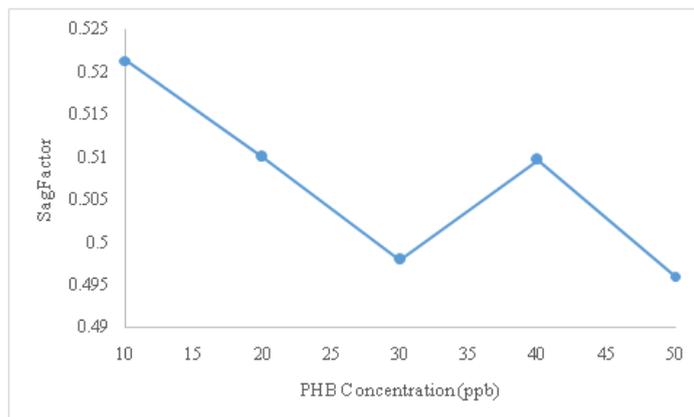


Figure10. Sag factor of each freshwater mud samples with varying PHB concentrations.

The results for rheology are presented in **Figure 11**, the freshwater mud follows the Herschel Buckley model while the seawater mud rheologically behaves as a Bingham plastic fluid. It can be seen that the seawater mud has less viscosity than the freshwater mud. The seawater based mud viscosity decreases as the amount of viscosifier (PHB) increases which is surprising as increase in PHB concentration must increase the viscosity of the mixture.

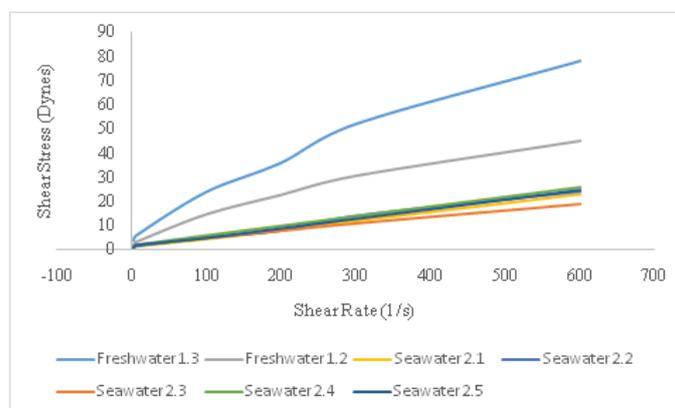


Figure11. Consistency Curves for Mud Samples

The sand content of the seawater mud as it was expected before decreases by the increase of PHB concentration. **Figure 12** shows that the sand content decreases from 1% to 0.25% and stays at that percentage to the maximum amount of PHB.

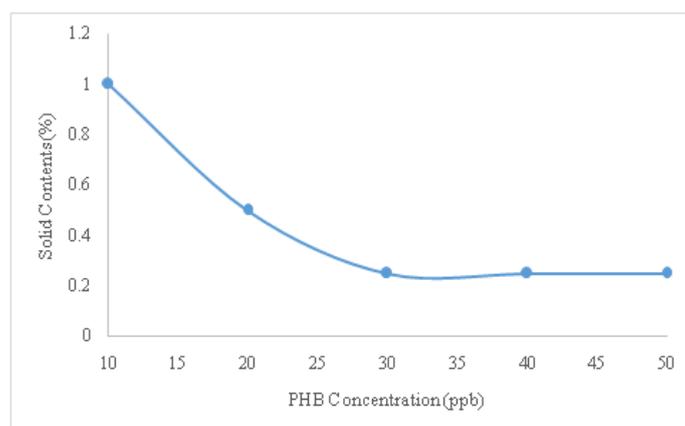


Figure12. Sand Content with Varying PHB

Figures 12 thru Figure 23 also show the graphical results of our experimental analysis of the Particle size, Surface area and Volume distributions for samples 2.1 thru 2.5.

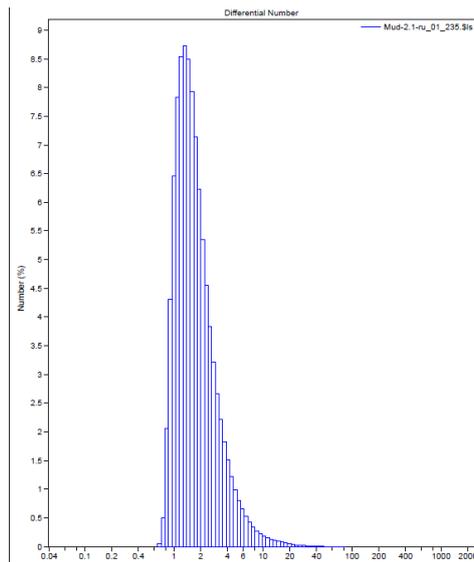


Figure12. Particle size distribution for sample 2.1

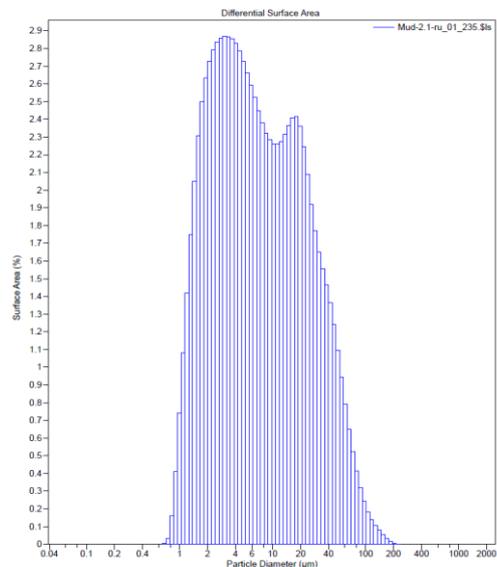


Figure13. Surface area distribution for sample 2.1

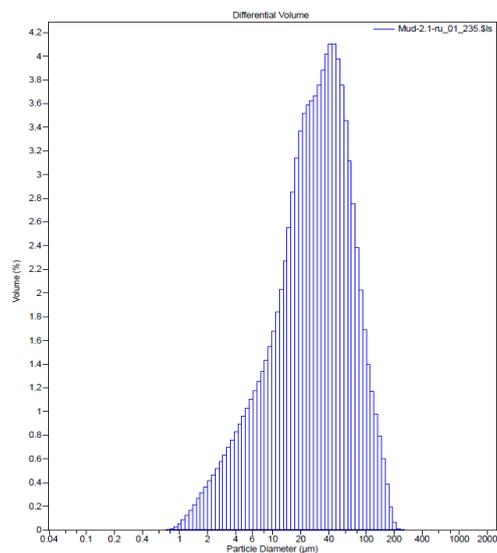


Figure14. Volume distribution for sample 2.1

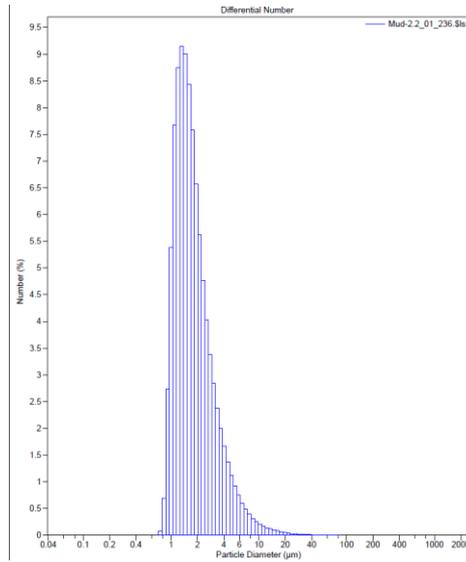


Figure15. Particle size distribution for sample 2.2

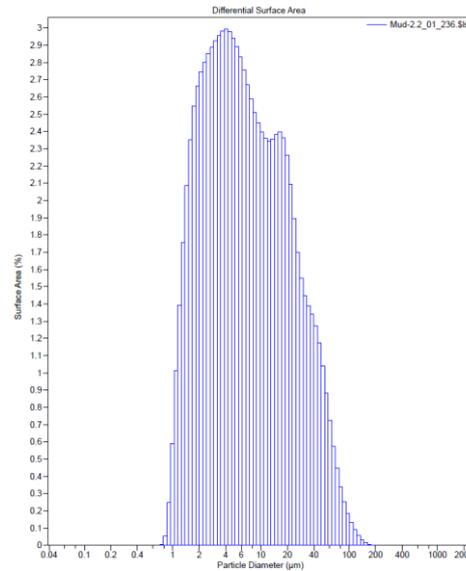


Figure16. Surface area distribution for sample 2.2

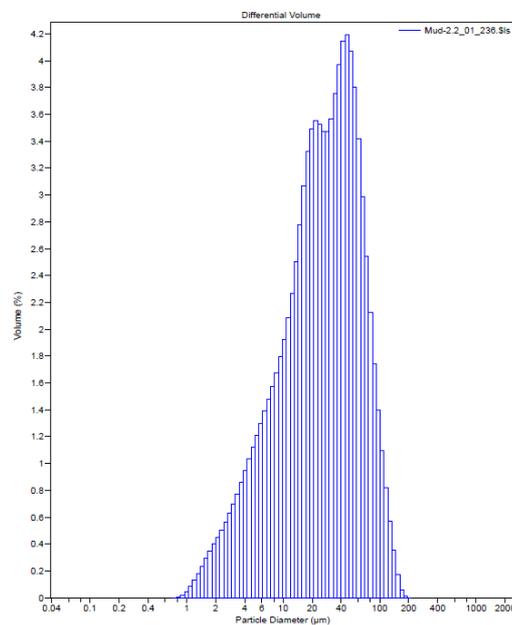


Figure17. Volume distribution for sample 2.2

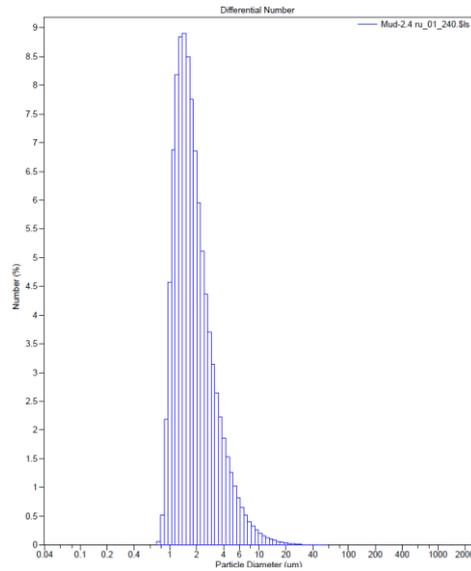


Figure18. Particle size distribution for sample 2.4

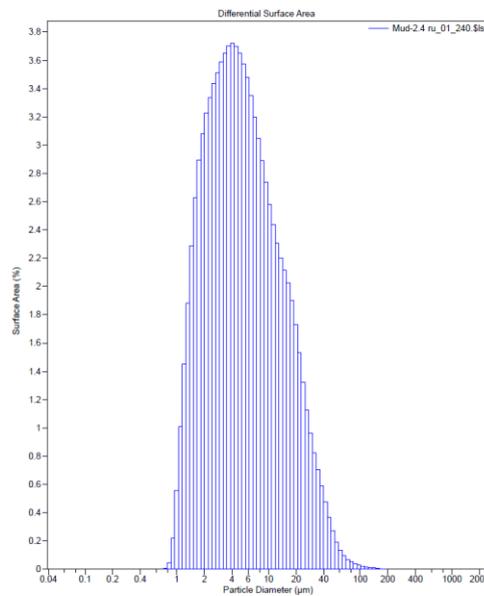


Figure19. Surface area for sample 2.4

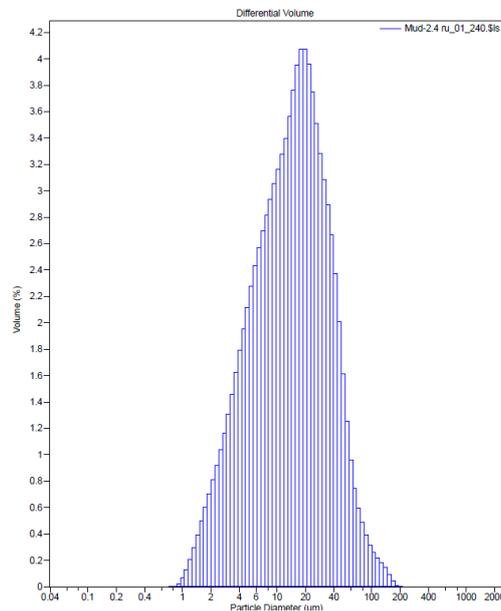


Figure20. Volume distribution for sample 2.2

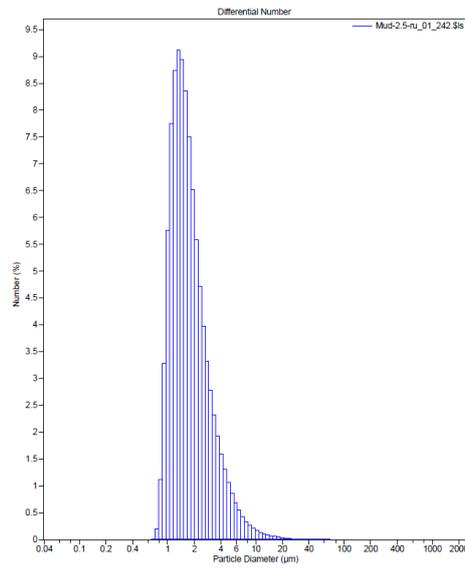


Figure21. Particle size distribution for sample 2.5

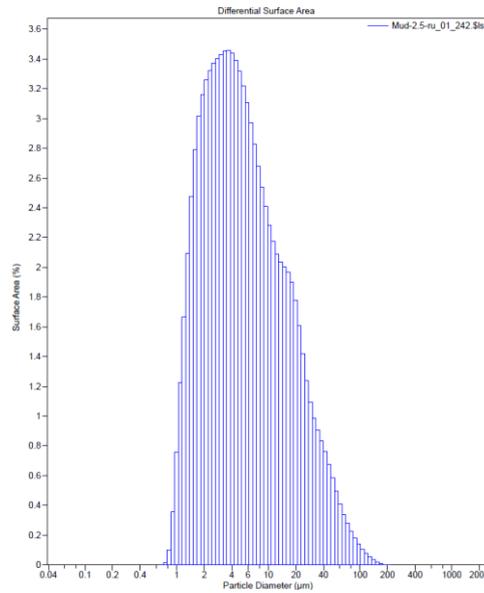


Figure22. Surface area distribution for sample 2.5

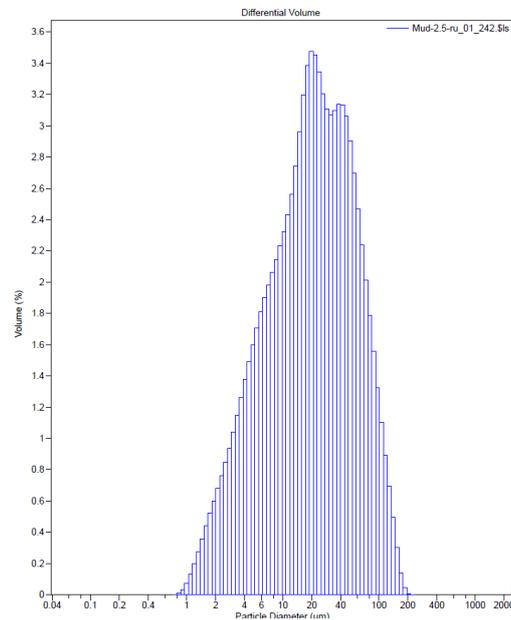


Figure23. Volume Distribution for sample 2.5

10. CONCLUSION

- It is evident that there is a correlation between the barite sagging and the concentration of Flowzan. A concentration of 1 ppb of Flowzan yielded in the highest sag factor.
- There is an inversely proportional relationship between the PHB and the barite sagging that occurs. In other words, the more PHB added, the lower the sag factor.
- The saltwater sample that yielded the smallest sag factor contained 50 ppb of PHB.
- In order to get more accurate and reliable data, it is recommended to test a wider range of Flowzan and PHB concentrations.
- A decrease of solid contents was observed with the increase of PHB in the seawater samples.

ACKNOWLEDGMENT

This publication was made possible by an UREP award [UREP 19-083-2-040] from the Qatar National Research Fund (a member of The Qatar Foundation). The statements made herein are solely the responsibility of the authors.

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Citation: Mahmood Amani, et.al. (2018). "An Experimental Analysis of the Factors Affecting Barite Segregation in Water Based Drilling Fluids", *International Journal of Petroleum and Petrochemical Engineering (IJPPE)*, 4(4), pp.14-31, DOI: <http://dx.doi.org/10.20431/2454-7980.0404003>

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