On the application of nanosilica in water based mud drilling practices: an approach to improve filtration control

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Abstract

Rheological and filtration properties of water based muds play vital roles in having a good drilling efficiency through hostile and harsh environments. However, there are many occasions in which controlling the variation of mud properties due to disintegration of additives is barely possible resulting in stuck pipe, kick incident or even loss of wells. The aim of this study is to propose an approach to enhance filtration characteristics of water based muds using nanoparticle additives. The results obtained from zeta potential measurements indicated that bentonite and nanosilica particles are both negatively charged with the values of -28 mV and -27 mV at the pH of 8 respectively. Evaluating rheological parameters of different mud samples revealed that the unmodified nanosilica causes reduction in the yield point of the samples rising concerns in the cuttings carrying capacity of drilling fluids. This issue was resolved by modifying the surface charge of nanosilica using a cationic surfactant. Filtration tests conducted under LPLT and HPHT conditions indicated that adding modified nanosilica into the mud samples results in formation of a thin and low permeability filter cake which can be a great asset in drilling through high permeable and small pore throat formations.

1. Introduction

Bentonite is the major solid phase composition of drilling fluids, added mainly to achieve a desired rheological behaviour. However, bentonite is sensitive to temperature and in a high temperature environment, its degradation results in increasing the filtration loss and ineffective upward transportation of cuttings (Bourgoyne et al., 1986; Kelessidis et al., 2006). To improve the rheological properties of bentonite, polymer additives were introduced but found to be thermal insulators with limited applications under extreme downhole conditions (Mahto and Sharma, 2004; Mao et al., 2015). Besides, the micro-particle size of polymers makes them inefficient for controlling fluid loss in high permeable formations (Abdo and Haneef, 2013). An alternative method to improve the bentonite based drilling mud temperature limitations is to modify the surface charge of bentonite particles (Barry et al., 2015). This modification may improve the interaction of bentonite with additives and enhance the rheology and filtration control of drilling muds (Barry et al., 2015).

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Nanoparticles have found their applications in the oil and gas industry and been successfully used in enhanced oil recovery (Zargartalebi et al., 2014), reservoir deliverability (Hoelscher et al., 2012) and drilling fluid design (Srivatsa and Ziaja, 2012; Sadeghalvaad and Sabbaghi, 2014; Barry et al., 2015). In fact, there have been many studies reporting the integration of nanoparticles with drilling mud formulations in recent years. Although improvements of rheology and filtration loss have been indicated by many (Amanullah and Al-Tahini, 2009; Amanullah et al., 2011; Srivatsa and Ziaja, 2012; Zakaria et al., 2012; Sadeghalvaad and Sabbaghi, 2014; Barry et al., 2015; Ismail et al., 2016), there are studies rising concerns about the reduction of cutting carrying capacities of water based muds (Vryzas et al., 2015; Mahmoud et al., 2016) when nanosilica was added to drilling muds. This indicates the fact that the nature and interaction of bentonite with nanosilica have not been fully understood.

Bentonite clay has a negative surface charge which is mainly because of the substitution of low valence atoms in its lattice (Luckham and Rossi, 1999; Missana and Adell, 2000). The stability of colloidal suspensions of bentonite is, therefore, a function of the surface charge of bentonite and the pH of the aqueous system. Barry et al. (2015) and Hafshejani et al. (2016) illustrated the negative surface charge face and positive charge edge of bentonite clay platelet. Bourgoyne et al (1986) explained the mode of the interaction of hydrated bentonite which is due to the edge-to-edge (E-E) and edge-to-face (E-F) associations caused by unbalanced net charges on the edge and surface of bentonite platelets. As a result, in a high pH and high temperature environment with presence of cations, the bentonite solution aggregates and flocculates resulting in increasing the yield point of drilling mud and decreasing the capacity to control the filtration loss. This situation may become far worse when nanosilica with a negative surface charge is added to the water based mud having an interaction with bentonite in the aqueous environment which would be dominated by a strong electrostatic repulsive force (Missana and Adell, 2000; Yalcin et al., 2002; Ma et al., 2010). Vryzas et al., (2015) and Mahmoud et al., (2016) showed that as a result of this repulsive force, deflocculation occurs causing an increase in viscosity and reduction of the yield point which is a crucial parameter to have a good cutting carrying capacity during drilling. The filtration loss of the aqueous system also increases by this integration. To resolve this issue, either the surface of bentonite (Sibel et al., 2012; Barry et al., 2015) or that of nanosilica (Ma et al., 2010; Ahualli et al., 2011; Ghanbari and Naderifar, 2016) must be modified. However, most of the studies carried out in recent years are providing discussions on changes observed in rheological properties and there are very limited number of studies concerning filtration loss of water based muds having nanosilica included.

The aim of this study is to have a deeper look into the interactions posed by nanosilica when it is added to a water based mud. Rheology and filtration loss of mud samples having different concentrations of modified and unmodified nanosilica were investigated under Low Pressure Low Temperature (LPLT) and High Pressure High Temperature (HPHT) conditions, and the nature of the filter cake was examined to evaluate its applications.

2. Silicate Based Muds

Sodium or potassium silicate based drilling fluids are known as effective and successful approaches for drilling through reactive and low/high preamble formations because of their inhibitive and filtration control characteristics (McDonald et al,., 2007). The mechanisms by which silicates are able to prevent mud filtration and water hydration are as follows:

- **Pore plugging:** This is perhaps the most important characteristics of a silicate based mud. Soluble silicate solutions start out as mono-silicate, that partially polymerises to form negatively charged silicate oligomers. The process is halted at pH 11-12 due to mutual repulsion, leaving oligomers which can partially penetrate micro-pore structures. Filtrate containing these oligomers is given by hydraulic flow or diffusion into pore fabrics where:

  I.   Pore fluid (pH +/- 7) dilutes the filtrate whereby the oligomers overcome their mutual repulsion and coagulate to form silicate gels.

  II.   Oligomers react with free polyvalent cations associated with clay surfaces (or edges) to form insoluble precipitates.

  III.   The gelled and/or precipitated silicates provide a physical barrier which prevent further filtrate invasion and pore penetration. The wellbore and formations are, thus, pressure isolated and filtration stops.

- **Osmotic dehydration:** The barrier of gelled/precipitated silicates also acts as a highly selective osmotic membrane through which the drilling fluid's water activity can be reduced. This generates an osmotic pressure driving osmotic flow of waters across the silicates membrane from formations to the drilling fluid. Although the amount of water involved is minimal, this process will dehydrate the near-wellbores shale effectively: dehydration leads to larger near wellbore effective stresses and an increase in shale strength, both of which are beneficial to stability (Alford et al., 2005).

- **Ion Exchange:** An additional advantageous of monovalent ions such as K^+ included in a silicate based mud is that they can be exchanged by Ca^{+2} and Mg^{+2} at the clay surface, making these ions available to precipitate. The high salinity will also lower silicate gelation times and increases the deposition of silicate gels (Fritz and Jarrett, 2007).

Silicate based muds are cheaper than synthetics, which are widely used for drilling through HPHT conditions, and can provide excellent wellbore stability, together with a good metal/shale and metal/sandstone lubricity (McDonald et al., 2007). They are also environmental friendly and less prone to bit balling which is required to have a high rate of penetration (ROP). However, they require attentions on good hole cleaning practices because of reduction in the yield point of muds (Soric et al., 2004). The WBM having silicates has also a temperature limitation of 225°F.

Nanosilica has been used for stabilizing invert emulsion drilling mud in HPHT operations with potential of inhibitive even in low concentrations (Amanullah and Al-Tahini, 2009). Nano scale size and high surface area of nanosilica makes it a strong and reactive additive for a drilling mud formulation (Alias et al., 2014). These nanoparticles also have a high thermal stability (higher

than that of a conventional silicate), and are affinitive to acidic gases such as H_2S and CO_2. In other words, nanosilica based muds can overcome on many of the limitation of a conventional silicate based mud while marinating all of its advantageous. However, there are few issues regarding the rheology and dispersion of nanosilica based muds which need to be addressed and resolved before considering its possible applications. These issues are raised in this paper and solutions are provided.

3. Materials and Methods

3.1. Materials

For the purpose of this study, nanosilica was purchased from the US Research Nanomaterial, Inc., having a BET specific surface area of 170-200 m^2/g and spherical particle size of 15-20 nm with a purity of 99.5%. Hydrochloric acid (HCl), sodium hydroxide (NaOH) together with cationic surfactant alkylbenzyldimethylammonium chloride with a molecular weight of 284 $gmol^{-1}$ were purchased from the Merck Schuchardt OHG, Germany. Bentonite, fresh and deionized water with the pH of 6.9-7.2 were used as part of this study to prepare mud samples required to perform the tests.

3.2. Zeta potential measurement

To measure the surface charge of bentonite and nanosilica, the Malvern Zetasizer Nano-ZS of Malvern instrument was used. In this experiment, 5 mg/L of nanosilica solution was prepared, stirred with Silverson homogenizer for 10 minutes, having 0.1M HCl and 0.1M NaOH to vary the pH from 1.0 to 10.0. A similar methodology was applied when zeta potential measurements were done to determine the surface charge of bentonite.

3.3. Nanosilica surface charge modification

For modifications, 2.5 wt% cationic surfactant alkylbenzyldimethylammonium chloride was dissolved into deionized water. Different concentrations of nanosilica (0.5 wt%, 1 wt% and 2 wt%) were then prepared and added to the solution while pH was adjusted in the range of 8.0-8.5 using 0.1M NaOH. The solution was then completely mixed by the Silverson homogenizer for 15 minutes, followed by ultrasonification for 1 hour in the temperature of 60°C.

3.4. Mud Samples

Seven configurations of mud samples were prepared, each having a five weight-percent (5.0wt%) bentonite mixed with 350cc of fresh water. The mixture was stirred with a constant speed mixer at 11,000 rpm for 20 minutes. The nanosilica dispersed in alkylbenyldimethylammonium chloride surfactant solution, prepared earlier, was added to the samples. The mixture was then stirred at 11,000 rpm for 15 minutes. The pH of the solutions was adjusted and maintained at 8.5-9.0. Samples were hydrated for 24 hours to ensure that the clay swelling is counted. Rheological and filtration loss measurements were then conducted. Table 1 gives a summary of the mud samples prepared for the purpose of this study.

Table 1: Mud samples with their abbreviated names

Sample concentration	Abbreviation
5 wt% Bentonite	Base Fluid
5 wt% Bentonite+0.5 wt% Nanosilica	A-0.5wt%
5 wt% Bentonite+1.0 wt% Nanosilica	A-1.0wt%
5 wt% Bentonite+2.0 wt% Nanosilica	A-2.0wt%
5 wt% Bentonite+0.5 wt% Nanosilica+2.5 wt% ABDACl	B-0.5wt%
5 wt% Bentonite+1.0 wt% Nanosilica+2.5 wt% ABDACl	B-1.0wt%
5 wt% Bentonite+2.0 wt% Nanosilica+2.5 wt% ABDACl	B-2.0wt%

3.5. Rheological Measurements

Rheological measurements were done with the aid of the Fann VG viscometer model 35 following the API standard procedures recommended for the water based mud (API recommended practice 13B-1, 1997). Readings were carried out three times to ascertain consistency in the results. Rheological parameters of Bingham and Power law models including the plastic viscosity, yield point, consistency and behaviour index together with the gel strength were then determined.

3.6. LPLT and HPHT Filtration Measurements

Low Pressure Low Temperature (LPLT) fluid loss measurements were carried out according to the recommended API standard procedure using the LPLT filter press, at the operating pressure of 100 psi and ambient temperature. The filtrate volumes were collected every 5 minutes for each sample and the thickness of the filter cake was measured using the Fann supplied ruler.

The HPHT fluid loss tests were conducted using the HPHT filter press at the differential pressure of 500 psi (i.e., 600 psi regulated pressure and 100 psi backpressure) and the temperature of 250°F. The filtrate volume was collected at a regular time interval and the test was stopped after 30 minutes. The filter cake deposit on the filter paper was then carefully rinsed and measured. Permeability of the filter cake was determined by the rate of filtration through the filter cake as described by the Darcy's law and expressed as:

$$\frac{dV}{dt} = \frac{KA\Delta P}{\mu h} \tag{1}$$

where dV/dt is the rate of filtration, A is the cross-sectional area, K is the permeability, ΔP is the differential pressure, μ is the viscosity and h is the filter cake thickness obtained from the following equation:

$$h = \frac{V_f}{A(\frac{f_{sc}}{f_{sm}} - 1)} \tag{2}$$

$$V_f = A\sqrt{\frac{2K\Delta P}{\mu}(\frac{f_{sc}}{f_{sm}} - 1)} \times \sqrt{t} \tag{3}$$

where f_{sc} is the volume fraction of solids in the filter cake, f_{sm} is the volume fraction of solids in the drilling fluid and t is the time of the filtration test in minutes. It worth mentioning that the

cross section of the filter cakes was constant at 31.2 cm^2 and the viscosity of the filtrate was measured at the room temperature for determination of permeability.

4. Results and Discussions

4.1. Zeta Potential and pH Relationships

The Zeta Potential (ZP) apparatus measures the electrostatic charge on the surface of particles and indicates the colloidal stability of dispersed particles in an aqueous system (Hunter, 1988). The results obtained from this measurement indicated that at the pH of 1, the surface of bentonite and nanosilica particles are both negatively charged and the ZP decreases with increasing the pH of the aqueous system. At the pH of 8 to 9, the ZP of nanosilica shows a maximum negative charge which indicates the fact that at this state there is a sufficient and adequate hydroxyl group on the surface of nanosilica. Likewise, for the aqueous bentonite solution, which is also pH dependent, negative charges were observed which are responsible for the electrostatic repulsion effect between nanosilica and bentonite. A similar finding was reported by Missana and Adell, (2000) and Ma et al., (2010). Figure. 1 shows the relationship between the ZP and pH ranges of the aqueous system for bentonite and nanosilica.
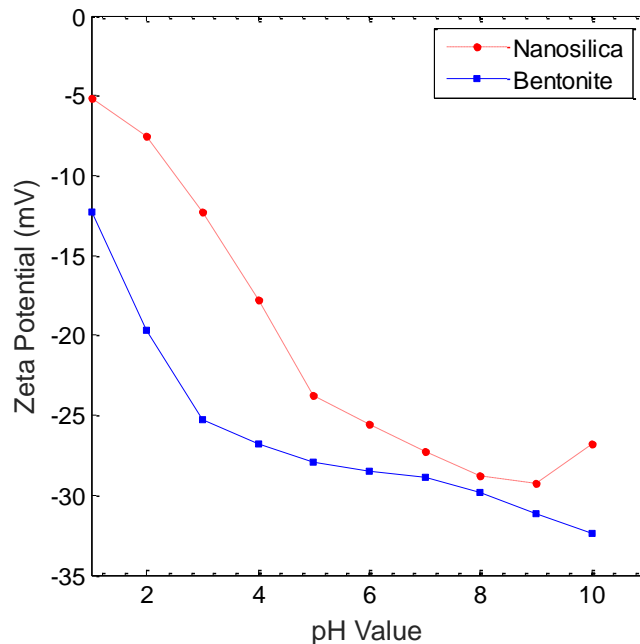

Figure 1: The relationship between the ZP and pH of the aqueous system for nanosilica and bentonite

4.2. Modification of Nanosilica

Figure 2 depicts the reaction mechanism taking place when nanosilica is modified by the alkylbenzyldimethylammonium chloride (ABDACl) cationic surfactant. The pH of the aqueous solution and large surfaces of nanosilica plays important roles in this modification process. The

pH of 8 to 9 is appropriate for the modification of nanosilica to take place because at this pH, the negative hydroxyl group located on the surface of nanosilica is readily available. Nanosilica used for this modification was within the range of 15 to 20 nm which has a large surface area by which the cationic surfactant can interact. By adding the positive cationic ABDACl surfactant, an ionic attraction between the positive surface of ABDACl surfactant and the negative surface of nanosilica occurs, resulting in having a positive charge surfactant grafted on the nanosilica through the negative hydroxyl group as shown in Figure 2. At this state, the steric repulsion between nanosilica and bentonite increases, leading to a stable mono-dispersed system. This stability was further evaluated by the ZP measurement. Figure 3 shows the size distribution of the modified nanosilica dispersed in the aqueous system in the range of 20 − 40 nm, where particles within the size of 30 nm have the highest intensity of 90%. Polydispersity index (PDI) value of 0.28 obtained from the size distribution analysis further confirmed the monodisperse nature of the modified nanosilica which prevents the agglomeration of nanosilica in the aqueous system.
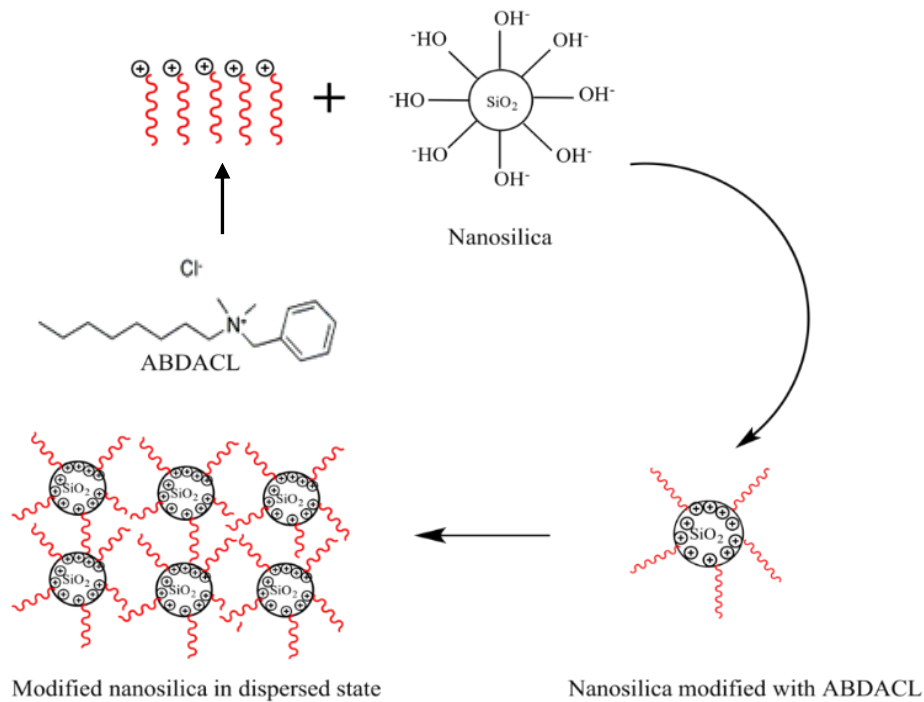

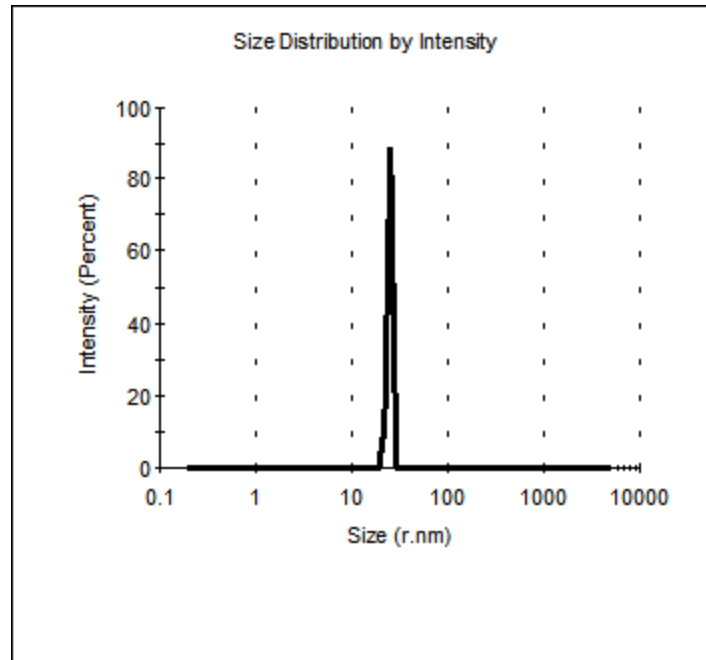Figure 2: Surface modification of nanosilica when ABDACl cationic surfactant is added

Figure 3: The modified nanosilica size distribution in an aqueous medium

Zeta Potential (ZP) is defined as the potential difference between the static layer of a fluid attached to solid particles and the dispersion system measured in mV (Hunter, 1988). The value of ZP obtained from the samples having the modified nanosilica indicated the stability of the colloidal suspension. It should be noticed that having the ZP in the range of +30 mV and -30 mV indicates the instability of nanosilica with tendency to aggregate and flocculate. Surfaces with the ZP of greater than +30 mV or less than -30 mV are generally stable. Figure 3 shows the zeta potential measurements for the unmodified and modified nanosilica surfaces with the same concentration.

As shown in Figure 4, the ZP values of the unmodified nanosilica is -23.1mV to -21.2 at 78°F and -20.3 mV to -18.7 mV at 140°F. The ZP ranges is in the unstable region indicating the likelihood of aggregation in the aqueous medium. At this state, the interaction between the unmodified nanosilica and bentonite particles causes the viscosity of the drilling mud to increase and the yield point to decrease (Mahmoud et al., 2016). The ZP of the modified nanosilica, on the other hand, shows values of 53.3 mV to +54.6 mV at 78°F and +50.1 mV to 51.4 mV at 140°F, which are in the stable region. As a result, one may conclude that the modified nanosilica is completely dispersed in the aqueous medium and its interaction with bentonite particles increases the viscosity and the yield point of water based muds (Barry et al., 2015).
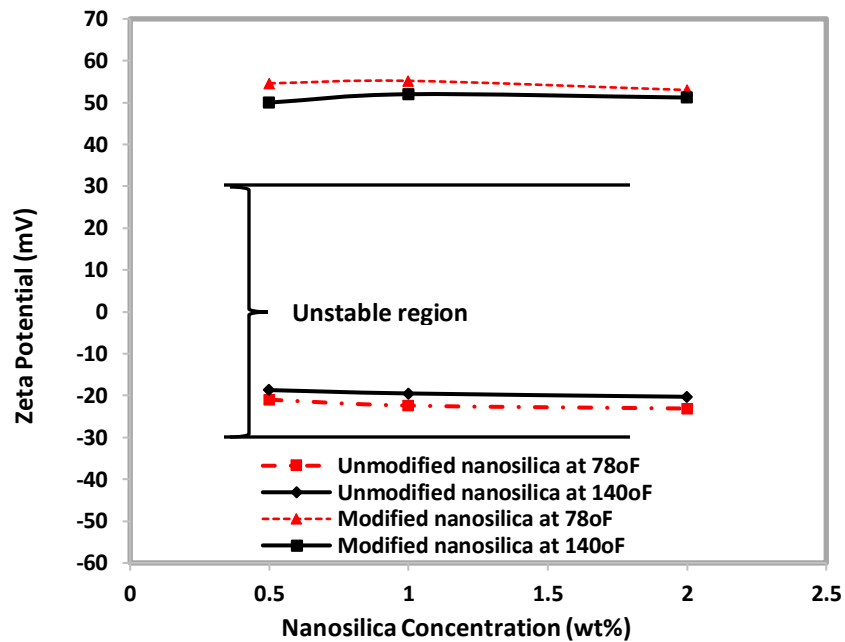
Figure 4: Zeta potentials of unmodified and modified nanosilica dispersed in the mud samples with a same concentration

4.3. Rheological Properties

The results obtained from the rheological measurements indicated that the interaction of bentonite and unmodified nanosilica in the mud samples reduces the yield point, as shown in Figure 5. In fact, the yield point of samples having 0.5 wt% and 1 wt% unmodified nanosilica is lower than the base fluid while the yield point of the sample containing 2% of unmodified nanosilica was slightly higher than that of the base fluid. This can be attributed to the electrostatic repulsion between bentonite particle and the unmodified nanosilica which has resulted in a deflocculated particle structure. A similar rheological behaviour was observed by Vryzas et al., (2015) and Mahmoud et al., (2016) even at a higher temperature. Figure 5 shows the rheogram of the modified nanosilica where the yield point consistently increases as the concentration of nanosilica increases. This could be as a result of flocculation of bentonite particles in the presence of active positive charged nanosilica particles. Table 2 summarises the rheological parameters of the mud samples having unmodified and modified nanosilica additives.

It is evident from Table 2 that the plastic viscosity of mud samples having unmodified and modified nanosilica increases as the concentration of nanosilica increases. It is known that a relatively low plastic viscosity is often required for having a high efficiency during drilling as the viscosity of the mud increases automatically when it is exposed to cuttings. Therefore, a high viscous mud may not be really in demand when nanosilica is added. According to the studies conducted by Jain et al. (2015) and Ismael et al. (2016), the plastic viscosity of muds having nanoparticles should not exceed 18 to 29 cP at 78°F to ensure that it can still be properly

circulated without inducing too much frictional pressure loss. Interestingly, plastic viscosity of the mud sample containing modified nanosilica obtained is within the required range.
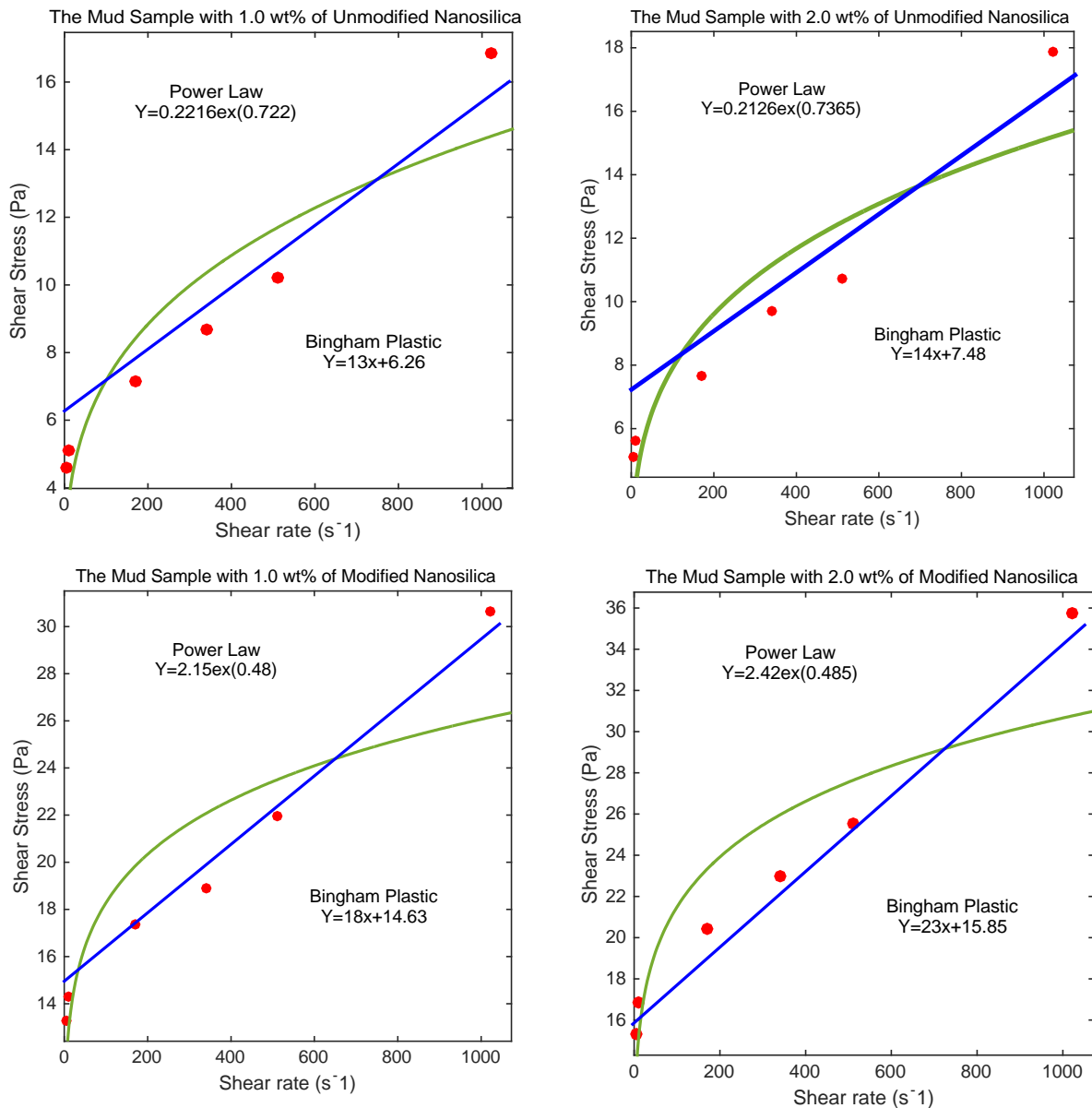

Figure 5: The shear stress-strain rate plot of water based mud having (a) unmodified nanosilica (b) modified nanosilica in its composition

The gel strength of a drilling fluid describes the behaviour of the drilling fluid when the drilling operation is stopped by shutting down the pump (Kelessidis et al., 2006). Gel properties of the drilling mud prevent cuttings and solid particles of mud from settling down to the bottom of the hole, increasing the chance of stuck pipe. A high gel strength, however, requires a high pump pressure to re-start the circulation and may cause difficulty during drilling. Guo et al. (2006) indicated that the gel strength for water based mud without nanoparticles should be within the range of 6 to 8 lb/100 ft^2 which is in agreement with the values reported for the base fluid of this

study. This range for the nanoparticle application of water based mud is within 6-10 lb/100 ft^2 (Ismail et al., 2016) which is close to the values obtained from the samples having unmodified nanosilica. For the samples containing modified nanosilica, however, a higher value was observed which could be due to well dispersed solid content in the samples and the interaction of the surfactant with bentonite particles in the aqueous system. This difference between the gel strength of modified and unmodified nanosilica bearing mud samples does not seem to be large enough to cause any re-circulation difficulties.

4.4. Rheological Models

Bingham plastic and Power law models were used to explain the rheological behaviour of the mud samples (see table 2 and Figure 5). The results obtained indicated that the flow behaviour index (n) of all samples is less than unity which is an indication of the shear thinning behaviour. Consistency index (k) for the samples having unmodified nanosilica was far less than that of the base fluid while samples with the modified nanosilica had the consistency index of bigger than that of the base fluid. This is important to know because as the parameter k increases, the hole cleaning capacity of the drilling fluid increases due to having a higher annular viscosity (Sadeghalvaad and Sabbaghi, 2014).

Table 2: Rheological properties of Bentonite-WBF with unmodified and modified nanosilica additives

| Sample | Bingham plastic model | | | Power law model | | | 10mins Gel Strength (lb/100ft^2) |
	YP (Pa)	PV (cP)	R^2	K (Pa.S^n)	n	R^2	
Base Fluid	7.12	10.00	0.9961	0.9708	0.4851	0.9938	7.00
A-0.5wt%	5.74	11.00	0.9968	0.2471	0.6877	0.9953	8.00
A-1.0wt%	6.26	13.00	0.9986	0.2216	0.7220	0.9941	10.00
A-2.0wt%	7.48	14.00	0.9982	0.2126	0.7365	0.9963	10.00
B-0.5wt%	12.86	15.00	0.9975	2.2831	0.4592	0.9976	12.00
B-1.0wt%	14.63	18.00	0.9984	2.1507	0.4805	0.9951	13.00
B-2.0wt%	15.85	23.00	0.9981	2.4270	0.4851	0.9934	13.00

It is known that water based muds are non-Newtonian fluids with shear thinning characteristics where viscosity decreases as the shear rate increases (Ismail et al., 2016). Figure 6 shows the relationship between the viscosity and shear rate of the mud samples prepared in his study.

As shown in Figure 6, the mud samples exhibit a shear thinning characteristics and samples with the modified nanosilica promote the attraction between the positively charged nanosilica and negatively charged bentonite particles via face-to-face and edge-to-face interaction. This attraction results in formation of a rigid bentonite structure which increases the plastic viscosity and yield point of the mud (Jung et al., 2011).
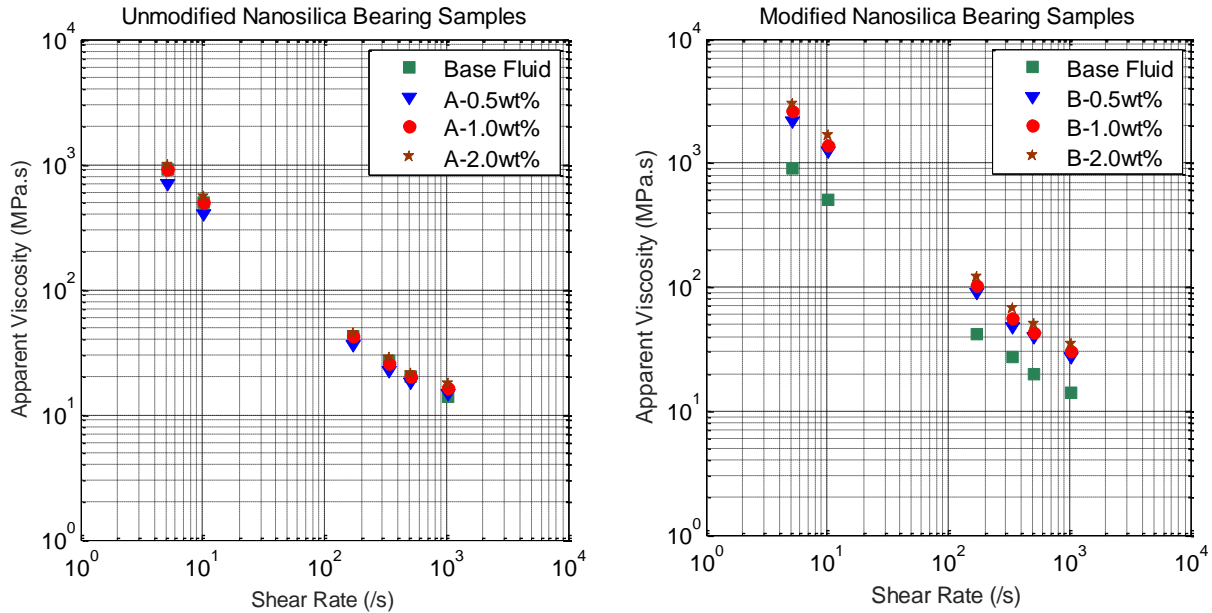
Figure 6: Viscosity-Shear rate relationships of mud samples having (a) unmodified nanosilica (b) modified nanosilica

4.5. LPLT filtration

Filtrate characteristics of water based muds depend on the nature and quantity of colloidal materials included. Hence, an effective fluid loss control is achieved by adding substantial amount of certain colloidal materials (Kelessidis et al., 2006). In this study, the LPLT filtration test was conducted for all of the mud samples prepared using the modified and unmodified nanosilica. Figure 7 shows the cumulative filtrate volume plotted against the square-root of time derived from Equation (3). Table 3 summarizes the cumulative filtrate volume, the percentage of changes in the filtrate volume and the mud thickness measured.

Table 3: LPLT filtration volumes and mud thicknesses obtained from the samples having modified and unmodified nanosilica

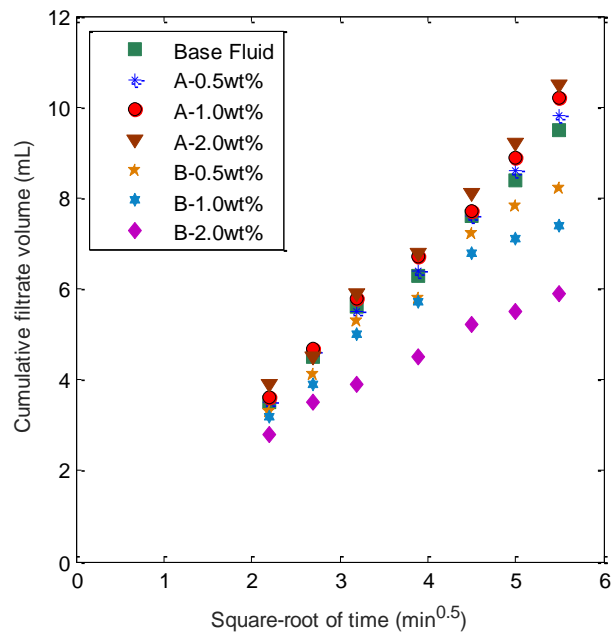| Samples	Cumulative Filtrate Volume (mL)	Filtration Change (%)	Filter cake thickness (/32 inch)
Base Fluid	9.5	-	4.0
A-0.5wt%	9.8	+3.2	4.0
A-1.0wt%	10.2	+7.4	4.5
A-2.0wt%	11.3	+18.9	4.5
B-0.5wt%	8.2	-13.7	3.5
B-1.0wt%	7.4	-22.1	3.5
B-2.0wt%	5.8	-38.9	3.0

Figure 7: Cumulative filtrate volumes of the mud samples containing modified and unmodified nanosilica obtained from LPLT tests

The results obtained indicated that the base fluid had a 9.5 mL filtrate volume while that of the samples with the unmodified nanosilica was higher by 11.3 mL. This increase in the filtrate volume is linked to the deflocculation of bentonite particles due to the electrostatic repulsion between the unmodified nanosilica and bentonite particles via face-to-face interaction which has resulted in failure to build a linked structure (see Fig. 8(a)). Samples with the modified nanosilica, on the other hand, gave a significant reduction in the cumulative filtrate volume by reaching to 5.8 mL in the sample having 2.0 wt% modified nanosilica. This reduction can be attributed to the electrostatic attraction via the interaction of face-to-face (modified nanosilica-bentonite) and edge-to-face (positive edge bentonite-negative face bentonite) as depicted in Fig. 8(b). The attraction traps the modified nanosilica between the bentonite particles and forms a linked structure retaining the fluid within the structure and resulting in reduction in the filtrate volume. From Table 3, it is also observed that the filter cake of the sample having 2.0 wt% modified nanosilica reduces by as much as 33.3% compared to the same sample having the unmodified nanosilica which indicates the application of the modified nanosilica in enhancing the filtration control properties of the water based mud.
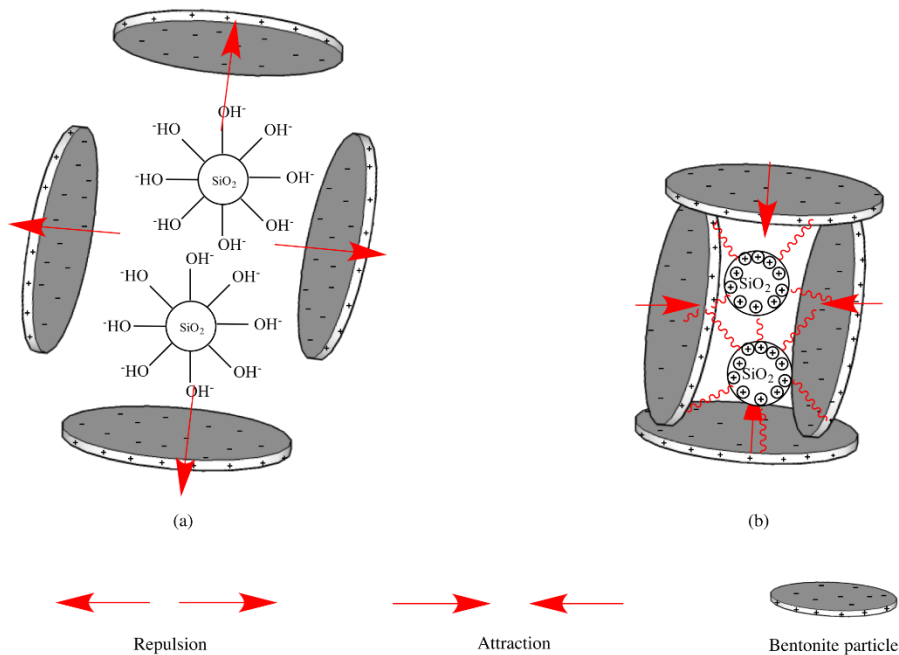
Figure 8: Repulsion and attraction between bentonite particles and (a) unmodified (b) modified nanosilica

4.6. HPHT filtration

Table 4 summarizes the filtration behaviour of the unmodified and modified nanosilica mud samples under the HPHT condition. The filtration volume change of the samples having 0.5 wt%, 1.0 wt% and 2.0 wt% unmodified nanosilica increased by 28.6%, 22.9% and 20.0% respectively compared to that of the base fluid sample while the thickness of the filter cake increases by as much as 12.5% for the same samples. The filter cake permeability measured as reported in Table 4 revealed a higher permeability for the unmodified nanosilica bearing samples compared to the base fluid. This indicates the formation of a poor rigid structure network of bentonite and unmodified nanosilica which results in deflocculation. It can then be concluded that, at elevated temperatures, bentonite particle tends to degrade and have to be supported by suitable additives, as otherwise high filtrate loss may take place. This effect explains the higher filtrate volume at HPHT condition compared to LPHT condition.

Table 4: HPHT filtration volumes and mud thicknesses of modified and unmodified samples

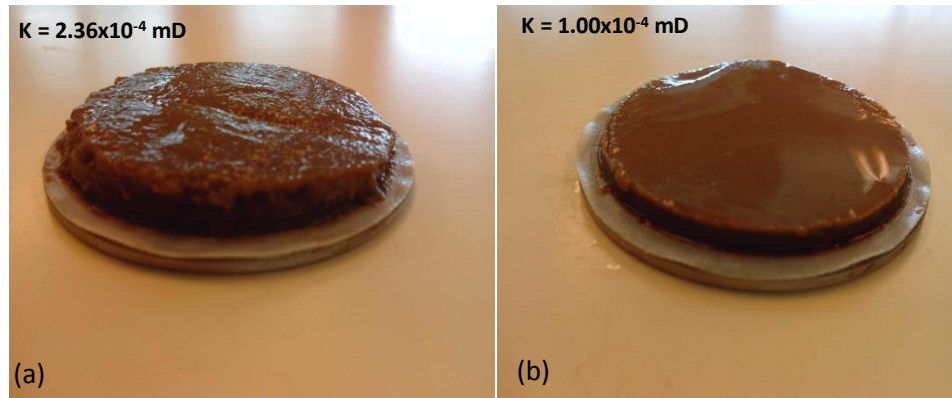| Sample	Cumulative Filtrate Volume (mL)	Filtration Change (%)	Filter cake thickness (/32 inch)	Filter cake permeability x10^{-4} (mD)
Base Fluid	35	-	4.0	1.75
A-0.5wt%	45	+28.6	4.0	2.53
A-1.0wt%	43	+22.9	4.5	2.41
A-2.0wt%	42	+20.0	4.5	2.36
B-0.5wt%	30	-14.3	3.5	1.31
B-1.0wt%	29	-17.1	3.5	1.27
B-2.0wt%	24	-31.4	3.5	1.00

Figure 9: Filter cake filtrations under the HPHT condition for (a) unmodified (b) modified nanosilica bearing samples

The results obtained for the modified nanosilica bearing samples, on the other hand, highlighted that there are as much as 31.4% reduction in the filtrate volume compared to that of the base fluid. It was also found that the sample having 2.0 wt% modified nanosilica gives a 45.2% reduction in the filtrate volume compared to that of the unmodified nanosilica under the HPHT condition. The other observation made and shown in Figure 9 indicated that the filter cake permeability for the sample with 2.0 wt% modified nanosilica was lower than that of the unmodified nanosilica. In fact, the filter cake of the modified sample was thin and non-erodible while that of the unmodified one was soft with a higher permeability. This supports the theoretical idea of the formation of the rigid structure network between bentonite and modified nanosilica as a result of electrostatic attraction. From this discussion, it can be concluded that 2.0 wt% modified nanosilica would be the best choice to control the fluid loss but a lower percentage might be selected if a lower viscosity and yield point is required for the water based mud to have a better efficiency during drilling.

5. Conclusion

In this study, an experimental investigation was done to evaluate rheological and filtration characteristics of water based muds formulated with nanosilica additives. The results obtained from zeta potential measurements confirmed that bentonite and nanosilica particles bears a negative charge and evidently repel each other in an aqueous environment. As a result, nanosilica was modified with a cationic surfactant alkylbenzyldimethylammonium chloride. The rheological study of the unmodified nanosilica bearing mud sample shows the reduction of yield point and increase of plastic viscosity. Conversely, the rheology of the mud sample having the modified nanosilica showed an increase in both yield point and plastic viscosity. It was also found that the

gel strength of both modified and unmodified samples increases when it was compared to that of the base fluid.

The filtration study under the LPLT condition indicates that the unmodified samples shows a high filtrate volume and filter cake thickness. This could be attributed to the fact that bentonite particle and unmodified nanosilica repel each other resulting in formation of a weak structure. Conversely, the results obtained from performing the LPLT filtration tests on the modified nanosilica bearing samples revealed a lower filtrate volume and filter cake thickness compared to the base fluid and unmodified samples. This could be due to that strong electrostatic attraction between bentonite particle and modified nanosilica. Under the HPHT condition, the modified mud samples showed a lower filtrate volume and filter cake thickness together with a lower permeability of filter cake compared to other samples. It can be concluded that adding the modified nanosilica to formulate water based mud improves filtration control properties significantly but caution should be taken in using it when a low viscous and gel strength mud is required.

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