AADE-17-NTCE-129

Impact of Anionic Nanoparticles on the Rheological, Filtration and Hydraulic Properties of the Flocculated Water-Based Drilling Fluids

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Abstract

As "multi-function" additives, anionic nanoparticles can be used to enhance the properties of the water-based drilling muds (WBM) and simultaneously fulfill different drilling requirements. However, they may diminish the properties if they are poorly designed. Hence, the objective of this study is to experimentally investigate the potentiality of nanoparticles in the WBM. This is achieved by investigating and comparing the impact of very low concentrations of commercially affordable two types of nanoparticles on the rheological, hydraulic and filtration properties of flocculated water-based muds (WBMs). The optimum type and concentration that enhance these properties and optimize the hydraulics of the mud are targeted.

In this research, the samples were prepared as high pH (11.5-12) WBMs and with two different types and various concentrations of anionic nanosilica and nanotitanium particles. Series of laboratory tests were carried out for all samples using standard API Low Pressure Low Temperature (LPLT) filtration and rheological devices. For the hydraulic evaluation, a commercially available software was used to estimate the impact of the nanoparticles on the equivalent circulation density (ECD) and the drillpipe pressure (DPP) in a typical directional well.

Results show significant enhancements in the rheological and hydraulics properties of the flocculated WBMs treated by 0.1% wt. or less of nanosilica and 0.3% wt. or less of nanotitanium. The results show the ability of these concentrations to reduce the filtration, make the filter cake consistent, compacted, fragile, smooth, and thin and prevent the spurt water loss. However, the results reflect the poor impact of the concentrations above 0.3% by weight on the mud's properties.

As rheological modifiers and filtration inhibitors, nanoparticles used in this research play vital roles in reducing drilling problems and later costs if they are properly formulated. Hence, stuck pipe, formation damage, and shale swelling can be overcome. Thus, slim holes and horizontal wells can be drilled using water-based nanomuds instead of oil-based muds that are expensive and environmentally unacceptable.

Introduction

The failure to optimize or balance drilling fluid properties due to poor designs leads to many drilling problems and longer drilling times. This makes the drilling mud one of the major aspects that either increases or decreases the well cost and later the production capacity. Therefore, it has to be efficient enough to overcome the problems, thereby reducing the drilling costs. For instance, it has to overcome shale swelling, prevent stuck pipe, reduce bit balling, minimize generated torque and drag, prevent formation caving/sloughing, minimize surge and swab pressures, reduce reservoir damage, prevent mud circulation loss, and enhance insufficient hydraulics (Salih et al. 2016).

All these problems are directly related to the rheological, filtration and hydraulics properties of the drilling muds. In turn, these properties are directly related to the flocculation level of the mud. Flocculation is one of the detrimental phenomena in the WBMs. It results in poor mud properties (Salih et al. 2016).

The flocculated WBM is one of the causes of the above-mentioned problems. It results in high filtration, yield point, viscosity, gel strength, mudcake thickness, and low mud pumpability, and its rheological behavior and filtration property are not stable under complicated drilling conditions. Therefore, oil-based mud is a more suitable solution to minimize drilling problems. However, unlike the water-based muds, it is environmentally and economically unfavorable.

Exposing poorly designed WBMs to cationic bearing-environments, containments, lead to the flocculation. Hence, various soluble contaminants such as salts, cement, anhydrite or gypsum that are present in drilling operations result in flocculation (Salih et al. 2016). In addition, high temperature and high mud pH cause flocculation. Therefore, the WBM's properties must be enhanced to increase the resistance to contamination by various chemicals. This increases the stability under different conditions.

Conventional chemicals are used to treat the mud with poor performance under harsh conditions. For example, conventional filtration inhibitors do not function under high temperatures since they reduce the filtration by increasing the viscosity of the water-based mud's continuous phase. Therefore, researchers have recently incorporated the nanoparticles as new and smart additives to the water-based mud and have made it as a water-based nano mud.

The water-based nano mud contains one or more chemical additive particles sized in nanoscale, $1\text{m}=10^6\mu=10^9\text{nm}$. Unlike their parents, these nanoparticles are characterized by high surface area to volume ratio, by providing surplus charges to the mud, by having tiny sizes, by having super sensitivity, and by having perfect particles distribution (Amanulah et al. 2011).

Figure 1 illustrates the new particles after crashing a parent particle. As chemicals, they are strongly charged particles and they are classified into cationic and anionic nanoparticles according to the ion (atom) types on their surface. Therefore, few amounts of them can play significant roles and perform multi-functions in the drilling mud. The result is the water-based nano mud with the advantages of the oil-based mud, but it is cheaper and environmentally acceptable (Salih et al. 2016).

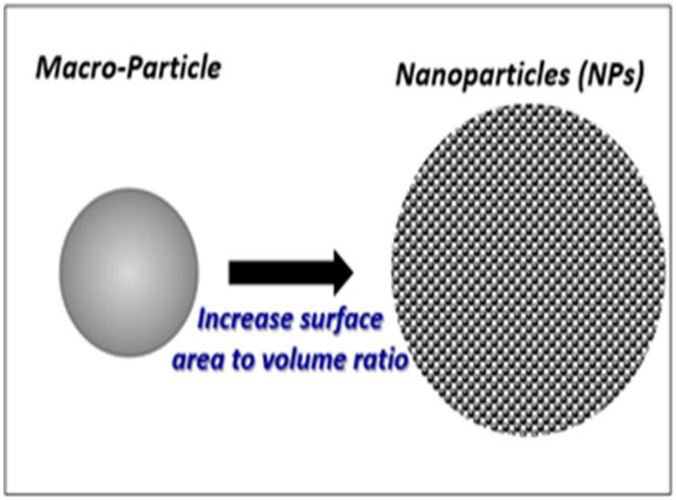


Figure 1: Surface Area to Volume Ratio of Nanoparticles (Salih et al. 2016)

Due to their features, they can change the internal link process and distribution of the clay particles, Bentonite platelets. The result is a wide range of drilling fluid behaviors and filtration properties that is also based on their types, concentrations, sizes, structure, pH, and charging types.

Recently, various nanoparticles were investigated and their performances were reported by many researchers such as Sharma et al. (2012), Sensoy et al. (2009), Cai et al. (2011), Li et al. (2012), Riley et al. (2012), etc. based on different methodologies. Hence, different performance of nanoparticles was described. For instance, some nanoparticles work as a perfect bridging agent due their tiny sizes. Therefore, they physically plug the nanometer-sized pores and shut off water loss in shale formations, thereby preventing shale swelling and its related problems. Properly formulated nanoparticles with water-based mud can replace the oil-based mud used as a shale swelling inhibitor.

For the same reason, the nanoparticles can reduce the filtration and enhance the associated mudcake properties—they result in thin, compacted, smooth, and plaster like mudcake ((Srivatsa & Ziaja 2011), (Javeri et al. 2011), (Salih et al. 2016), (Zakaria et al. 2012), and (Ismail et al. 2014)). However, selecting the optimum size and structure of nanoparticles that show superior plugging is challenging.

The water-based nano mud with hydrophilic film forming capability on the surface of drillbit can mitigate the bit balling problem— this is due to the high surface area to volume ratio and very low concentration requirements of the nanoparticles (El-Diasty and Ragab 2013). This occurs especially in sticky formations such as marl and shale rocks. As a result of minimizing the bit balling, the rate of penetration will increase.

The nanoparticles play significant roles in reducing the torque and drag forces throughout drilling operations. They work as lubricants, reducing the friction between the drill string and the well wall interface. Similarly, this feature helps in reducing the plastic viscosity—they work as ball bearings to facilitate the solids movement in the mud. Hence, the stuck pipe, equivalent circulation density (ECD), and circulation pressure loss can be reduced. By reducing the ECD, the mud circulation loss problem can be minimized. Proper shape and size of the nanoparticles should be selected for high performance.

Interestingly, only few amounts of the nanoparticles can enhance the rheological properties of the WBM due to high sensitivity and superior interaction with the Bentonite particles. However, based on their properties, they may increase or decrease the rheological properties such as the yield point and gel strength. Therefore, critical concentrations must not be exceeded in order to avoid damage to rheological properties ((Amanullah et al. 2011), (Contreras et al. 2014 a&b), (Jung et al. 2011), (Fakoya and Shah 2013), and (Nasser et al. 2013)).

It has been reported by Amanulah et al. (2011) that the nanoparticles have less kinetic energy impact, thereby increasing the life of the downhole tools. It is well known that wear and tear decrease the life of the tools. They are caused by the forces created due to the extreme kinematic energy associated with the large particles continuously added to the mud either naturally such as drilled cuttings or by rig crew for specific purposes during drilling operations (Salih et al. 2016). These forces can be minimized by replacing the large quantities of micro particle additives with a small amount of nanoparticles for the same purposes. By replacing the big particles with tiny particles, the plastic viscosity will decrease which is desirable.

According to the above-cited researches, it is obvious that the nano-based drilling fluids are regarded as a new generation of drilling fluids—they have been recently discovered. This implies the possibility of a wide range of further studies and improvements using nanoparticles with drilling fluids. In addition, it is seen that not all the used nanoparticles enhanced all the mud properties simultaneously. Therefore, the researchers need to attain the optimum filtration, hydraulic, and rheological properties of the water-based mud by finding the proper types, concentrations, and sizes of the nanoparticles.

The current goal is to explore more about the potentiality of nanoparticles in order to design efficient and economic water-based muds. This is achieved by investigating the impact of very low concentrations of two types of nanoparticles on the rheology, filtration, and hydraulics of high pH, flocculated, muds. Then, the general behavior trend of each nanoparticle type is determined and compared. Finally, selecting and recommending the best types and concentrations that enhance the properties and lead to an economic mud is targeted.

Research Methodology

Based on the objective of this study, the lab experiments included the API rheological, filtration, and hydraulic tests for several water-based mud samples with and without nanosilica or nanotitanium. The samples without nanoparticles are regarded as the basic samples, and they are used as references for comparison purposes. Based on the comparisons with the basic muds, the best type and concentrations are selected. The workflow shown in Figure 2 was used to achieve the objective of study.

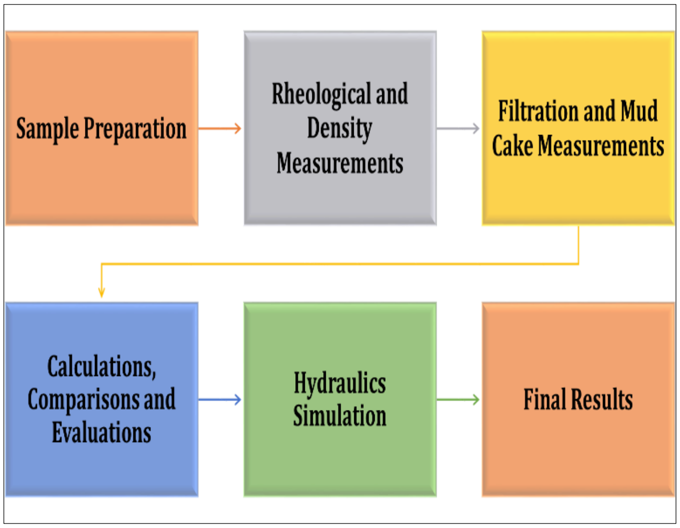


Figure 2: The Workflow of Research

The basic mud samples were prepared by mixing the common raw materials used for water-based mud preparation such as Aquagel Bentonite, Barite, water, and caustic soda (NaOH). Table 1 shows the composition and measured rheological properties of the basic muds. The nano-muds were prepared by individually and respectively adding four concentrations (0.1%, 0.3%, 0.5%, or 0.7% by weight) of nanosilica and nanotitanium to the basic muds. Table 2 shows the specifications of the used nanoparticles.

For all mud samples, a digital weighing scale, a mud multi-mixer, and an ultrasonic processor were used for preparing all samples. Sonic VCX130PB Ultrasonic Processor was used to mix the nanoparticles with the WBM samples in order to avoid nanoparticle aggregations from the mechanical blender. The pH measurements were conducted with a digital pocket pH meter.

For the rheological and density measurements, the Fann RheoVADR® Variable Automated Digital Rheometer was used to study the impact of the nanosilica and nanotitanium on the API rheological properties for each prepared mud sample. For this purpose, six dial readings (shear stress) were measured at six rotational speeds of 600 rpm, 300 rpm, 200 rpm, 100 rpm, 6 rpm, and 3 rpm. For mud density, a standard mud balance was used.

Table 1: Raw Materials and Rheology of the Basic WBMs

Materials	Composition
Water (cc)	500
Bentonite (% by weight)	5.6
Barite (% by weight)	5.2
Caustic Soda (NaOH) (gm)	0.5
Rheological Properties	
Plastic Viscosity (PV) (cp)	22
Yield Point (YP) (lb/100 ft2)	76
Apparent Viscosity (cp)	60
10 seconds Gel (lb/100 ft2)	38
10 minutes Gel (lb/100 ft2)	57
pH	11.5-12
Mud Density (lb/gal)	~ 9

Table 2: Physical & Chemical Properties of Nanoparticles

Chemical	Silica Dioxide	Titanium Dioxide
Physical State	Colloidal	Colloidal
Color	Milky	White
Density	1.106	1.41
Particle Size	5 nm	~100 nm
Charging	Negative	Negative
pH	10	7-8

More so, two gel strength measurements were carried out. The first measurement was carried out by stopping the fluid's movement for 10 seconds, then measuring the maximum dial reading (shear stress) at 3 rpm. The second measurement was carried out by stopping the fluid's movement for 10 minutes, then measuring the maximum dial reading (shear stress) at 3 rpm.

Finally, mud density in gm/cc for each prepared sample was measured by using the conventional Mud Balance. The mud densities were always around 9 gm/cc for the samples with and without nanoparticle additives.

Next, the API standard low pressure and low temperature (LPLT) filtration test was carried out by using the Multiple Unit Filter Press for each prepared mud sample. This device permits simultaneous running of six filtration tests. At the lab temperature (75 ºF), 100 psi was applied on the mud sample, which was in the filter press cup, to inforce the water component to pass through a piece of filter paper. The water was collected in a graduated cylinder as the filtrate loss. A mudcake was built on the filter paper during this process. The test was run for 30 minutes, which is the standard API time duration for filter press measurements. During the 30-minutes time interval, filtrate loss was measured at every minute. This test was repeated for each mud sample. At time zero, the spurt loss was measured and recorded. After 30 minutes, the filter press' parts were disassembled and the filter paper was taken off, then the filter cake thickness was measured in millimeters.

For the rheological property calculations, the measured rheological readings were used to calculate the mud properties such as the plastic viscosity (PV), apparent viscosity (AV), Bingham yield point (YP), shear rate (γ), flow behavior index (n), consistency index (K), effective viscosity (μe), and actual yield point. The properties were calculated using standard formulations. Based on the comparisons with the basic mud properties, the best concentrations and type were selected.

Finally, the enhanced rheological properties were used as input data to evaluate the impact of the nanoparticles on the equivalent circulation density (ECD) and the drillpipe circulation pressure. A hydraulic software and typical operational parameters were used for this investigation. Several runs were applied on a 9000 ft long-12 ¼ inches deviated wellbore. Table 3 shows the operational parameters used for this purpose.

Table 3: The Hydraulics Operational Parameters

Operational Parameter	Specifications
Drill Bit	12 ¼" PDC
Nozzles	3*13/32" & 3*12/32"
Drilled Cuttings Diameters	0.13"
Cuttings Mode	Slip
Cuttings Density	22 lb/gal
Cuttings Concentration	(10-20) %
Rate of Penetration (ROP)	100 ft/hr
Rotational Speed (RPM)	100 R/min
Pump Rate	850 gal/min
Rheology Model	Modified Power Law
Geothermal Gradient	0.012 °F/ft

Results and Discussions

Impact of Nanoparticles on Rheology

1. Rheological Profiles

The rheological profiles of the drilling muds with and without nanosilica and nanotitanium are shown in Figures 3 and 4, respectively. The figures show flow behaviors of a flocculated and deflocculated muds. Hence, the basic mud (untreated mud) exhibits flocculation due to high pH while the treated muds based on both nanoparticle types (nanomuds) exhibit deflocculation. For the flocculated mud, Sodium ions from caustic soda (NaOH) are adsorbed between the Bentonite particles leading to more attraction and flocculation. Regardless of the reasons behind flocculation, it is a negative phenomenon because of the resulted excessive gel strength, viscosity, and surge and swab pressures (Salih et al. 2016).

Based on the comparison of the rheological profiles, significant variances in the flow behaviors can be seen between the basic and treated muds. However, the behaviors of the nanomuds follow the same trend since the current nanoparticle types are anionic, but the shear rate/stress values are different since the other properties are different. It is believed that the concentration, charge types and density, shape, size, and pH of the nanoparticles control their performance by changing the linking process between the Bentonite particles in the WBM. Accordingly, the results show a reduction trend in the essential shear stresses used to maintain specific shear rates as the concentration of nanoparticles increases. In summary, the chemical interaction between the Bentonite's particles and the nanoparticles determines the trend shown in the figures.

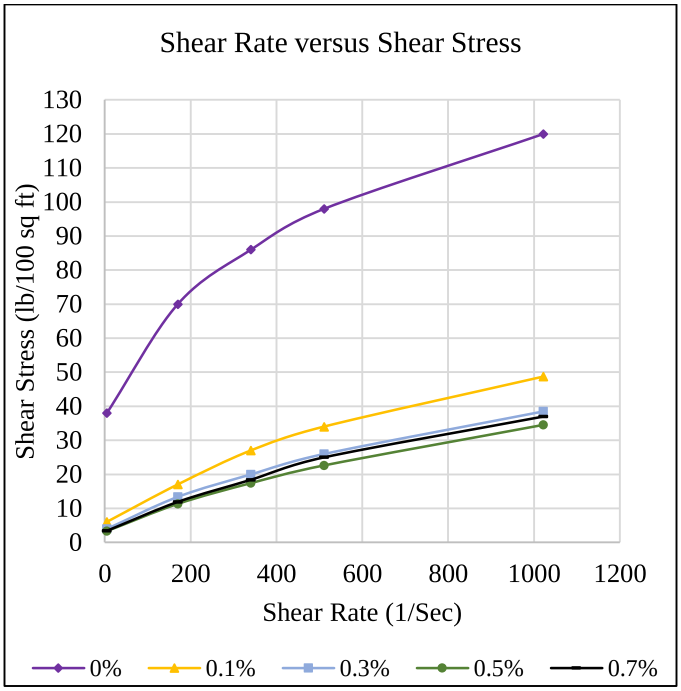


Figure 3: Rheological Profiles for Muds with Nanosilica

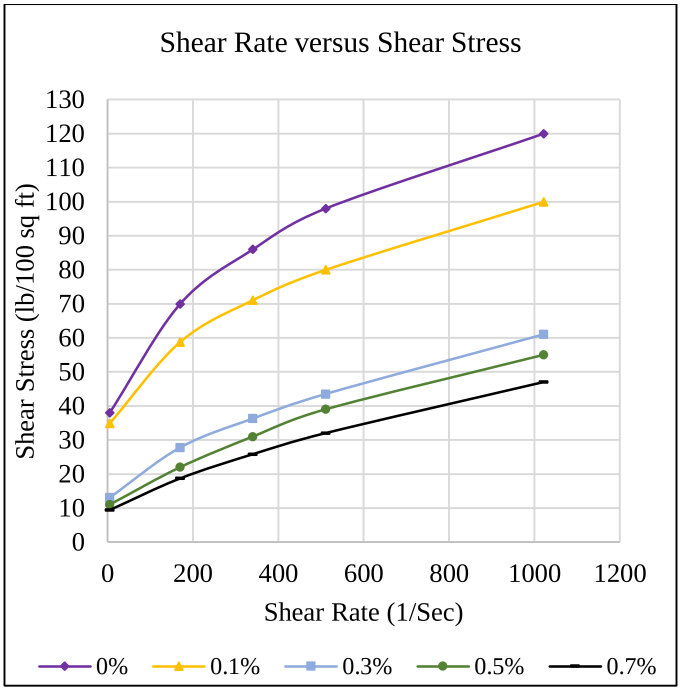


Figure 4: Rheological Profiles for Muds with Nanotitanium

Similar to the anionic nanosilica, the flow behavior for the muds with and without the anionic nanotitanium can be described by the Bingham Plastic model for the higher shear rates (>500 sec^{-1}) and/or by the Modified Power Law model for all shear rates. Further, the treated muds keep the non-Newtonian behavior after adding nanotitanium or nanosilica, which is a necessary property for the drilling fluids.

Unlike nanosilica, nanotitanium with concentration less or equal to 0.1% wt. does not significantly influence the mud behavior. This means the smaller amounts of nanotitanium are not enough to impact the mud behavior. However, 0.3% wt. of nanotitanium is enough to make a huge change in the rheological properties. The less surface area to volume ratio, thereby the less sensitivity, makes nanotitanium differ from nanosilica in terms of performance.

However, the clear difference between the behaviors obtained based on different amounts of nanotitanium is another observation that is missed in the nanosilica muds. Hence, each concentration results in a different fluid behavior though the difference in the concentrations was low. Thus, nanotitanium provides a wider range of rheological properties that can be used for different drilling conditions. For instance, this difference will facilitate the possibility of obtaining turbulent or laminar flow regimes, as needed, by using small amounts of nanotitanium based on different drilling conditions.

Overall, both nanoparticle types aids in increasing the mud pumpability by reducing the shear stress of the mud. This is desirable in the drilling operations in terms of saving the energy exerted by the mud pumps. Also, the flocculation in the mud is overcome.

2. Rheological Properties

Diverse rheological properties can be extracted based on different concentrations of nanoparticles. Different rheological property values for the corresponding concentrations are observed according to different types of nanoparticles. As stated earlier, the properties of nanoparticles control their performance.

2.1. Plastic Viscosity

Figure 5 shows the impact of nanosilica and nanotitanium on the plastic viscosity of the flocculated mud. Plastic viscosity of a mud depends mainly on the friction between the solids in the mud (Bentonite particles and other inerts) and secondarily on the electro-chemical attractions between the reactive particles. In turn, the friction depends on the solids' shape, size, distribution, arrangement, and distance interface (Salih et al. 2016). From Figure 5, it is seen that the basic mud exhibits higher plastic viscosity than the nanomuds do. This is due to the flocculation that causes a poor distribution, more attraction, and small distances between the moveable solids.

The anionic nanosilica and nanotitanium (negatively charged nanoparticles) reduce the plastic viscosity as the concentration increases. They are distributed between and around the Bentonite platelets, thereby neutralizing the original forces at the edges of the Bentonite particles (positive charges). This leads to domination of the original negative charges that are located on the wider surface of Bentonite platelets. This will increase the repulsive forces between the Bentonite particles, thereby increasing the distances. In addition, the nanoparticles work as lubricants or "ball bearings" that facilitate the movement. Accordingly, the current nanoparticles overcome the flocculation, thereby changing the link process between the bentonite particles and rearranging the bigger particles in ways that cause less friction.

Unlike the nanosilica, however, the nanotitanium decreases the plastic viscosity almost linearly. In addition, it generally results in less plastic viscosity decrease than the nanosilica does. It seems the smaller nanoparticles with higher density of charges are characterized by high sensitivity, interaction, and lubricity.

The minimum plastic viscosity is always required in the drilling operations to increase the rate of penetration, save the energy required to circulate the mud, cool and lubricate the down hole equipment, and reduce the mud circulation loss due to excessive equivalent circulation density that causes formation fractures.

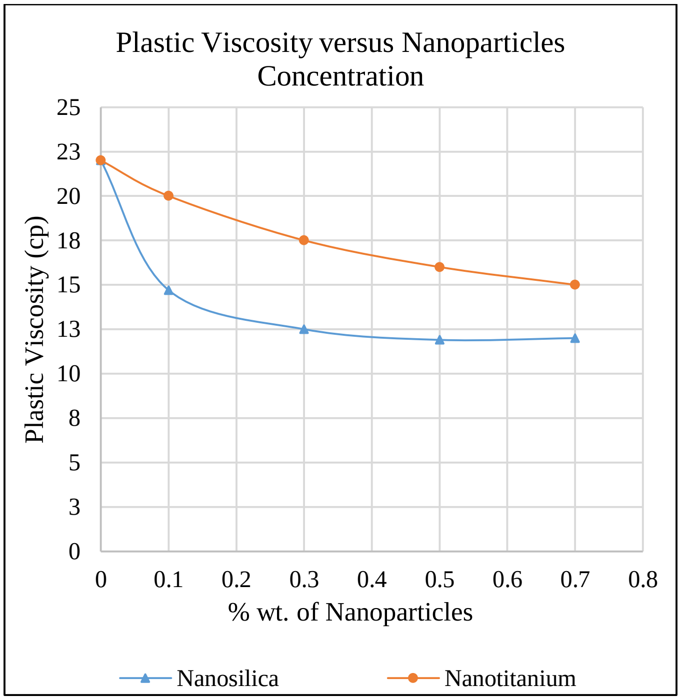


Figure 5: Impact of Nanoparticles on Plastic Viscosity

2.2. Yield Point

Similarly, Figure 6 shows significant reductions in the yield points based on 0.1% wt. or less of nanosilica and 0.3% wt. or less of nanotitanium. The yield point depends mainly on the electro-chemical attractive force and secondarily on fractional force, and both of them depend on the distance between the Bentonite particles (Salih et al. 2016). Anionic nanoparticles increase the distance, reduce the friction, and increase the repulsion. Hence, these concentrations are enough to affect these parameters and then reduce the yield point significantly.

Unlike nanosilica, however, the general yield points based on nanotitanium are in higher range, that allows less solids sagging and higher drilled cuttings carrying capacity.

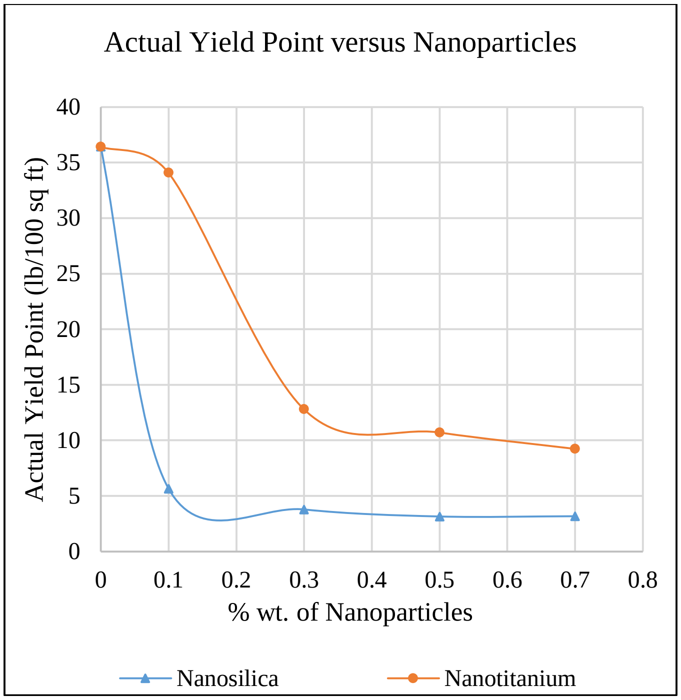


Figure 6: Impact of Nanoparticles on Yield Point

It is well known that drilling fluids with high yield point due to flocculation cause excessive pump pressure loss, decrease the rate of penetration, and increase the surge and swap pressures. Therefore, it is important to design suitable fluid rheology by using nanosilica and nanotitanium with proper amounts to improve the drilling performance and overcome these problems.

The current nanoparticles can be used as deflocculant agents, which are needed, for example, to condition the drilling muds after the cement jobs or during drilling formations containing chemicals such as magnesium hydroxide, potassium hydroxide, and anhydrite that increase flocculation.

2.3. Apparent Viscosity

Like plastic viscosity and yield point, the apparent viscosity shown in figure 7 illustrates the same trend.

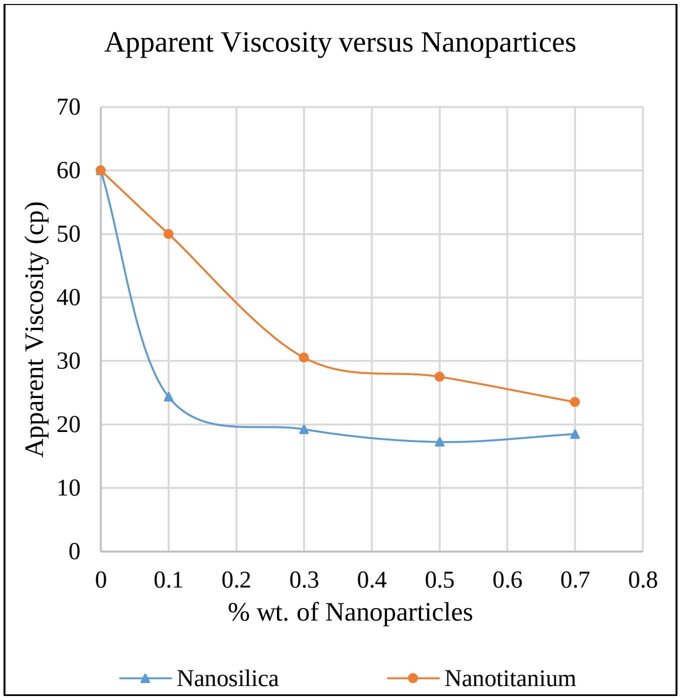


Figure 7: Impact of Nanoparticles on Apparent Viscosity

2.4. Shear Thinning

Anionic nanosilica and nanotitanium enhance the shear thinning of the flocculated mud. Usually, the well-designed fluids exhibit high shear thinning so that the effective viscosity—the mud viscosity at a specific shear rate (mud velocity)—decreases with increase in the shear rate.

Figures 8 and 9 show that the basic mud, which is flocculated mud, exhibits the lowest shear thinning, highest effective viscosities at low and high shear rates. That implies the lowest mud pumpability and highest energy required to displace the mud at low and high shear rates due to the flocculation. Contrary, the water-based nano muds exhibit lower effective viscosities (higher shear thinning) at different shear rates for all concentrations.

The anionic nanoparticles with different amounts weaken the attraction between the flocculated Bentonite’s particles differently. Breaking the bonds becomes easier at higher concentrations than lower concentrations when the mud velocity increases. The result is a wide range of effective viscosities based on different concentrations of nanoparticles. This restores the deflocculated mud’s behavior, thereby enhancing the mud pumpability.

Shear thinning for the nanomuds has very important applications in the drilling operations. At high mud velocities in the drill string and through the bit, the nanomud shear thins to low viscosities. This reduces the circulating pressure loss and saves the mud pumps’ energy. At low mud velocities in the annulus, the water-based nano mud has high viscosities which aids in hole cleaning and suspension capacity. At static conditions, the water-based nano mud exhibits a thixotropic behavior.

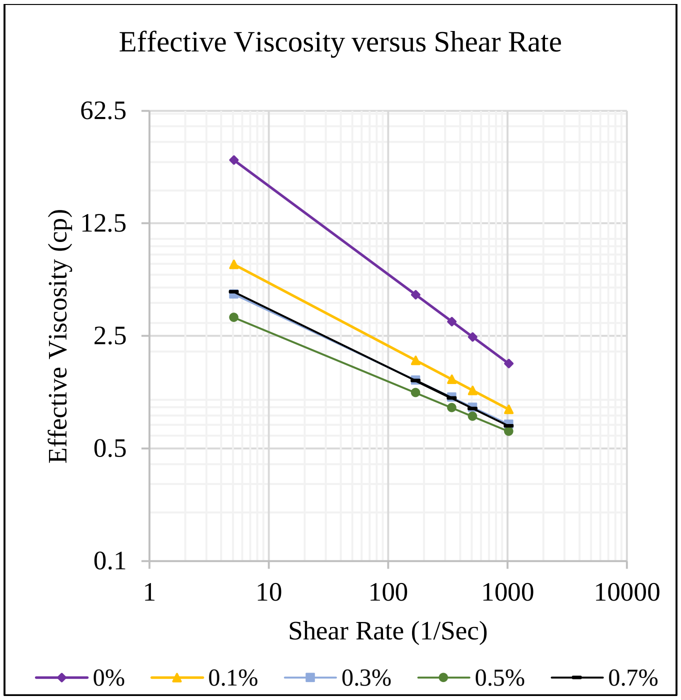


Figure 8: Impact of Nanosilica on the Effective Viscosity

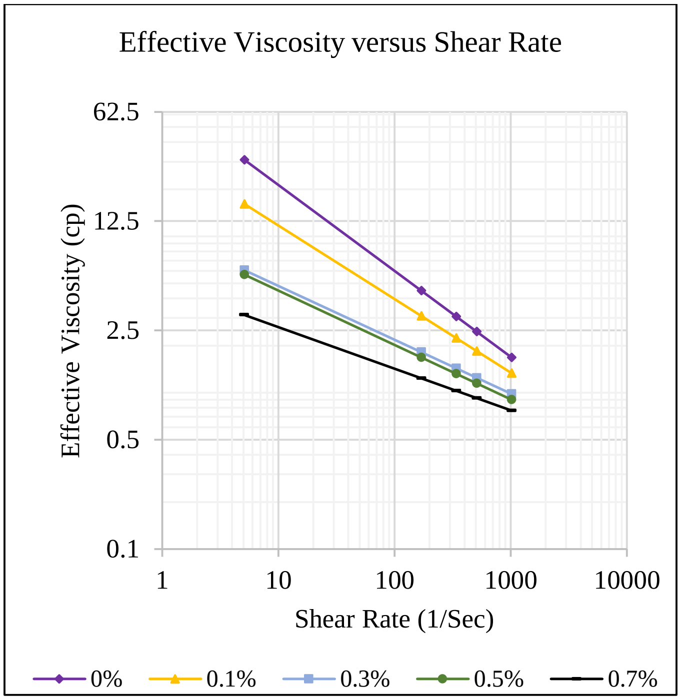


Figure 9: Impact of Nanotitanium on Effective Viscosity

2.5. Gel Strength

Figures 10 and 11 show the impact of the anionic nanoparticles on the API gels. Gel strength is controlled by the electro-chemical attractive forces between the Bentonite particles at static conditions. It is seen that the basic mud (0% wt.) develops a progressive type of gel due to the flocculation of the mud—attraction between the Bentonite particles—after increasing the pH. In contrast, the nanomuds exhibit gradual reduction in the gel strength as the concentration of the anionic nanoparticles increases. This is due to the continuous magnification of the repulsive forces between the Bentonite particles. More fragile gels can be obtained, but the gel values differ according to the nanoparticle types and properties. Fragile gel is mostly required for resuming the mud circulation easily, cutting suspension, reducing surge and swap pressures, and cuttings removal at the shale shakers (Salih et al. 2016).

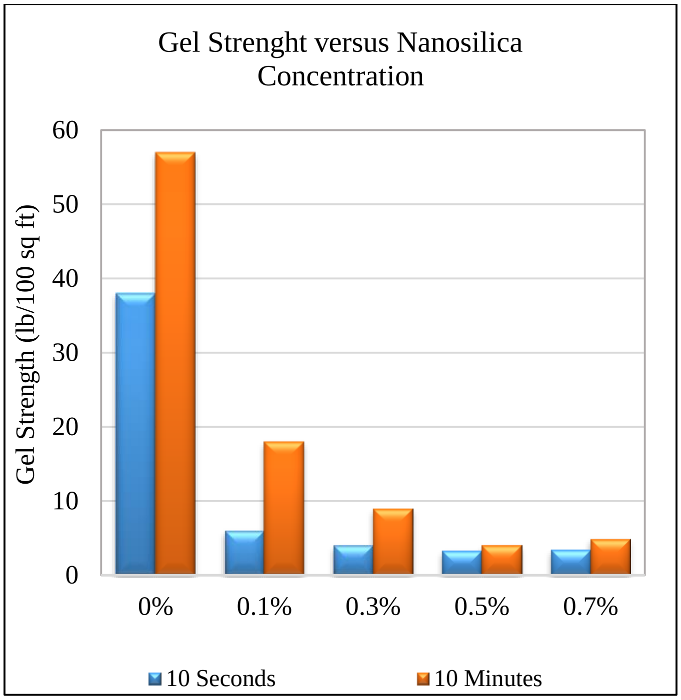


Figure 10: Impact of Nanosilica on Gel Strength

Figure 10 shows that the best concentrations of nanosilica that resulted in the fragile gels are 0.1% and 0.3% wt. However, the results show the negative impacts of 0.5%-0.7% wt. These concentrations result in very low flat gels that are undesirable. They cause solids to sag, such as Barite sag. In addition, flat gels do not allow sufficient cutting suspension capacities while the mud pumps are off. This makes nanosilica with few amounts a suitable material to treat the high pH water-based muds used to drill deeper formations where the smaller cuttings exist and more fragile gels is needed.

Unlike nanosilica, Figure 11 shows that 0.1% wt. of nanotitanium does not significantly enhance the gel strength. However, 0.3%-0.7% wt. developed more fragile gel than the basic mud does. In addition, it is noticed that nanotitanium develops quicker gels than nanosilica since the difference between the 10 seconds and 10 minutes' gels are bigger for the corresponding concentrations.

Nanotitanium does not result in low flat gels. Considering the economics and no more influence of the nanotitanium on the gel strength for the concentrations greater than 0.3% wt., 0.3% wt. is recommended for the current mud system. The drilled cuttings suspension requirements feature makes nanotitanium a suitable chemical to treat the high pH water-based muds used to drill surface holes where the larger cuttings exist and the less fragile gel is needed.

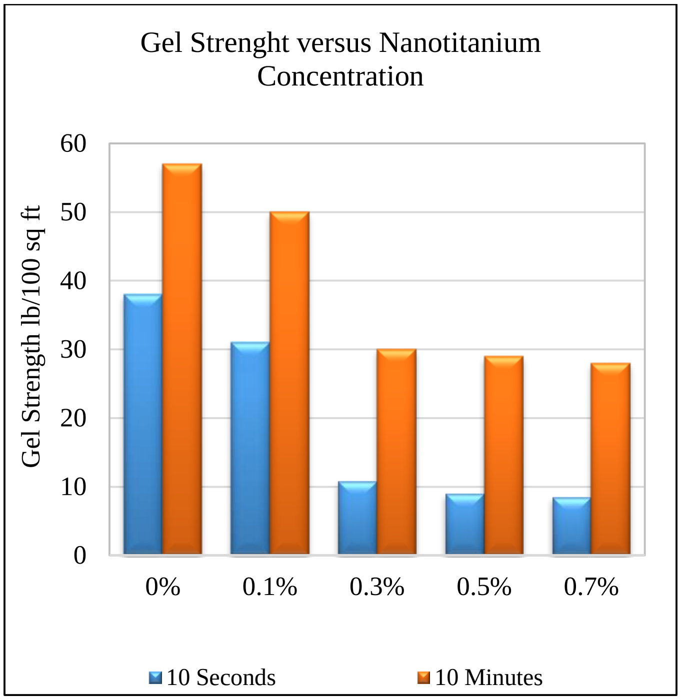


Figure 11: Impact of Nanotitanium on Gel Strength

The current wide range of gels provide flexibility in designing the water-based mud according to different drilling requirements.

Impact of Nanoparticles on the Filtration Properties

1. Filtration Volume

Figure 12 shows the impact of the anionic nanosilica and nanotitanium on the filtration of the flocculated water-based mud. It is seen that both reduce the filtration, but with different levels. Nanosilica is superior while nanotitanium enhances the filtration slightly as the concentration increases. For example, around 44% and 20% filtrate reductions were obtained at 0.7% wt. of nanosilica and nanotitanium, respectively. For the filtration properties, the particle size and charge density affect the filtration volume developed by the current nanomuds. Accordingly, the nanosilica and nanotitanium change the link process and physically occupy the spaces between the Bentonite particles.

It is well known that the flocculated muds always develop higher filtration. In this case, the attracted Bentonite particles link in edge-to-edge or edge-to-face position forming open network structures, thereby easing the water loss. The degree of flocculation dominates the filtration volume and higher clay flocculation leads to more filtration and thicker mudcake that increase the probability of differential stuck pipe problems. On the other hand, more dispersion and deflocculation of the Bentonite particles results in less filtration due to forming of roof-like structures and parallel interface connections between the Bentonite platelets (Salih et al. 2016).

The results show that the anionic nanosilica and nanotitanium cause more dispersion between the Bentonite particles, and then causing more parallel contacts. This helps in narrowing the pathways between the clay platelets within the developed mudcakes. It is believed that nanosilica causes more Bentonite particle dispersion due to providing more charges to the mud, since it has higher surface area to volume ratio.

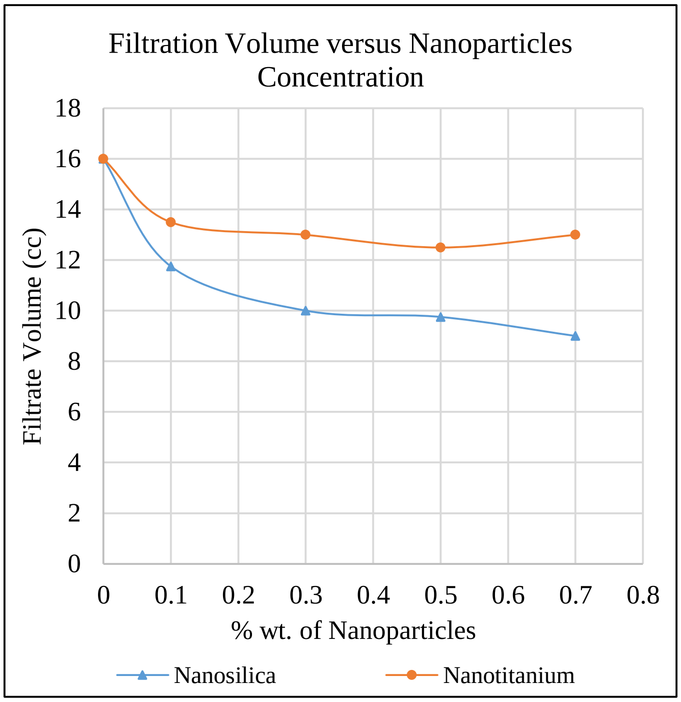


Figure 12: Impact of Nanoparticles on Filtration Volume

The distributed nanoparticles physically occupy the spaces between the clay particles leading to more sealing and less filtration. The size of the nanoparticles affects their performance to reduce the filtration. It seems that the smaller nanoparticles cause more occupation, thereby leading to less filtration. This is noticed from the performance of the smaller nanosilica particles. The bigger nanotitanium particles arrange the Bentonite platelets in the parallel position instead of the point type position. This results in a shingle roof-like structure. However, they occupy fewer spaces between the clay particles. Practically, reducing the filtration of the water-based mud is always required to mitigate the wellbore instability and its associated problems.

The results show no big difference in the spurt loss between the nano and basic muds. However, it was totally stopped after adding nanosilica or nanotitanium. The spurt loss is one of the famous causes of solids invasion that causes formation damage (Zakaria et al. 2012). Therefore, the current nanomuds play significant roles in reducing the reservoir damage and increasing the hydrocarbon productivity.

2. Mudcake Properties

Figure 13 and Table 4 show the impact of nanoparticles on the thickness and structure of the deposited mudcakes. It shows that the nanosilica and nanotitanium reduce the thickness and enhance the structure of mudcake as the concentration increase gradually. In this case, the nanoparticles plug the very small holes existed on the surface of the mudcake leading to smooth, compacted, thin, and plaster-like cakes.

However, nanosilica is superior in the performance. It reduces the thickness more than the nanotitanium due to its smaller particle sizes and higher particles dispersion. Nanosilica forms about 1 mm cake at 0.7% wt.—70 % thickness reduction, while nanotitanium forms about 2.4 mm cake—28% cake thickness reduction. Interestingly, these nanoparticles do not increase the thickness of mudcake, as extra solid additives, because they are trapped in the spaces located on cake surfaces.

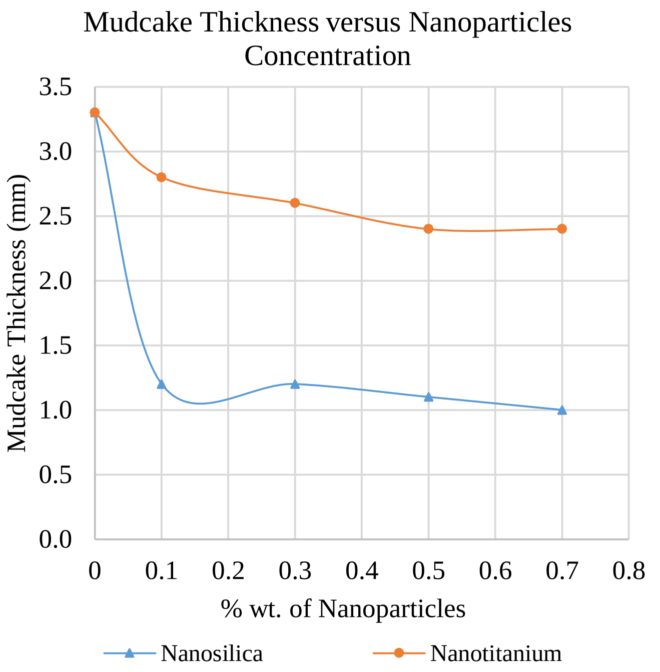
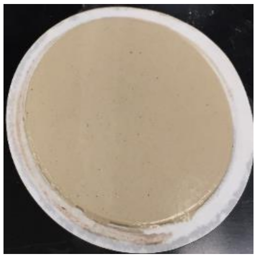
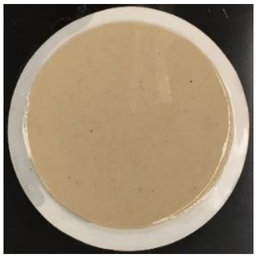


Figure 13: Impact of Nanoparticles on Mudcake Thickness

Hence, the wall of a drilled well in unconsolidated formations can be strengthened by the very smooth, compacted, thin, and plaster-like mudcakes. In addition, the mudcakes deposited by the deflocculated water-based nano muds can be removed easily due to the weak links between the clay particles. The negatively charged ions from the anionic nanoparticles are attracted to the positive charges on the clay particles leading to force equilibrium and then weak connections.

As described in our previous research (Salih et al. 2016), these properties work hand in hand with the erosion action of the cementing washers to effectively displace the entire mudcake from the borehole walls before the cement jobs, thereby allowing an efficient bond between the cement and the formations.

Table 4: Mudcakes Developed by Basic and Nano Muds

Description	WBM w/Nanosilica	WBM w/Nanotitanium
WBM with 0.0% wt. of Nanoparticles		
WBM with 0.1% wt. of Nanoparticles		
WBM with 0.3% wt. of Nanoparticles		
WBM with 0.5% wt. of Nanoparticles		
WBM with 0.7% wt. of Nanoparticles		

Impact of Nanoparticles on the Hydraulics Properties

As hydraulic parameters, equivalent circulation density (ECD) and drillpipe circulation pressure (DPP) were studied to reflect the impact of the anionic nanoparticles on the hydraulics optimization in the selected hole using the enhanced rheological data. The ECD is equal to the mud density plus the density due to the pressure loss in the annulus portion of a wellbore. The ECD is a viscosity-dependent parameter since rheology and hydraulics are directly related. Therefore, it can be improved by enhancing the mud rheology. The drillpipe circulation pressure represents the energy exerted by the mud pumps to circle the mud. Mud hydraulics optimization can be achieved by making a balance between well control, hole cleaning, pump pressure, ECD and pressure drop across the drill bit based on the best rheological properties of the muds (Salih et al 2016).

1. Equivalent Circulation Density

The ECD profiles are shown in the Figures 14 and 15 for the water-based mud systems and with nanosilica and nanotitanium. The comparison to the flocculated mud shows clear enhancements in the mud hydraulics system due to a decrease in the ECD based on both nanoparticles types. This is undoubtedly desirable, considering the other hydraulics optimization requirements. However, nanosilica reduces the ECD in a way that is more significant. Figure 14 shows a gradual ECD decrease, from 9.7 lb/gal to 9.2 lb/gal. The biggest enhancement was obtained after adding 0.1% wt. of the nanosilica to the mud. Use of nanosilica with a small concentration was sufficient to change the drilling fluid viscosity and rheological properties.

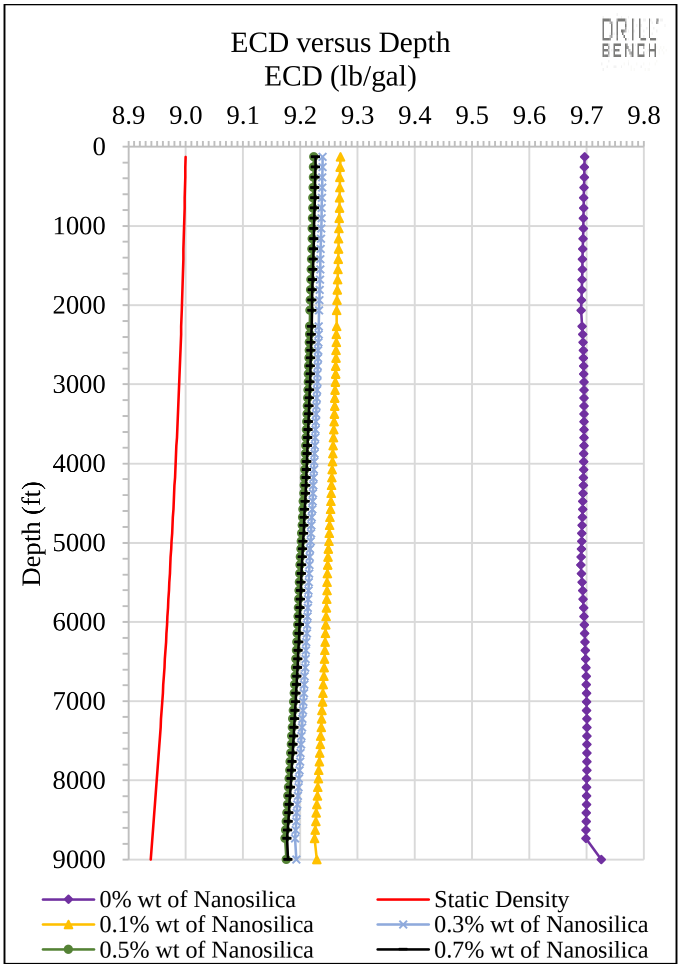


Figure 14: Impact of Nanosilica on the ECD

On the other hand, Figure 15 shows a gradual ECD decrease from 9.7 lb/gal to 9.3 lb/gal with nanotitanium. Unlike nanosilica, the biggest enhancement was obtained after adding 0.3% wt. of the nanotitanium to the mud. This supports the previous observation that implies the use of nanotitanium with 0.3% wt. is sufficient to change the drilling fluid rheological properties.

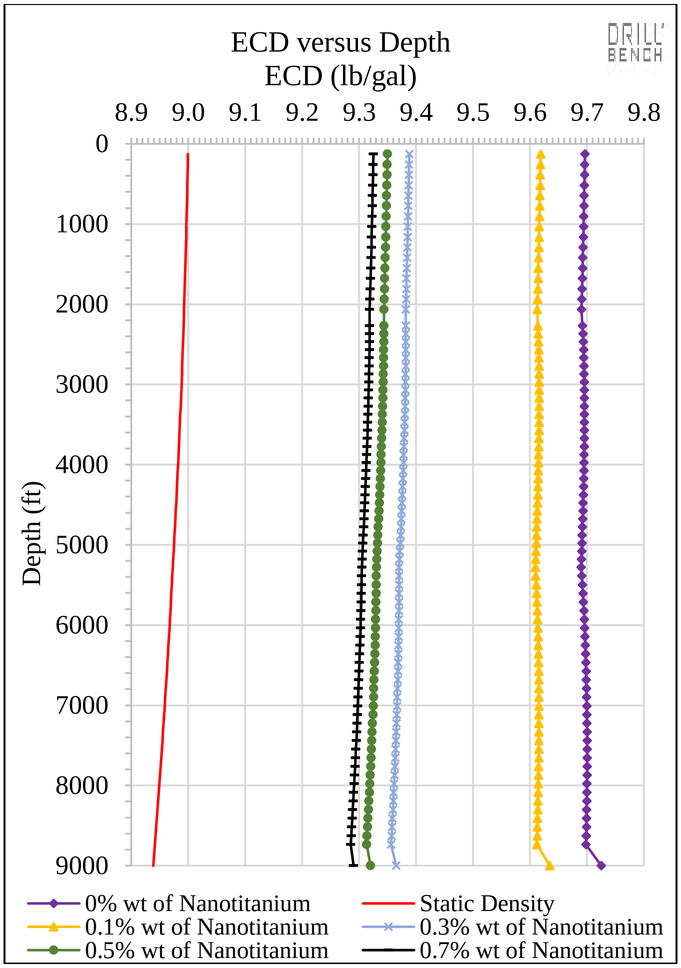


Figure 15: Impact of Nanotitanium on the ECD

2. Drillpipe Pressure

Figures 16 and 17 show the impact of nanoparticles on the circulation pressure measured at the rig floor. Results show an overall reduction in the drillpipe pressure required for displacing the mud into and out of the well after treating the basic mud with nanosilica or nanotitanium. This is always required for more flexibility to increase the flow rate of the mud to fulfil some specific conditions.

Figure 16 shows the reduction of the pressure by approximately 300 psi based on the current nanosilica formulation and 0.1% wt. of nanosilica is enough to make the major reduction in the pump pressure loss throughout the 9000 ft directional well. Figure 17 shows that the nanotitanium reduces the surface drillpipe pressure by approximately 270 psi and 0.3% wt. makes the largest reduction. As anionic nanoparticles, nanosilica and nanotitanium reduce the friction component of the pressure. In this case, nanotitanium and nanosilica work as lubricants in the water-based mud.

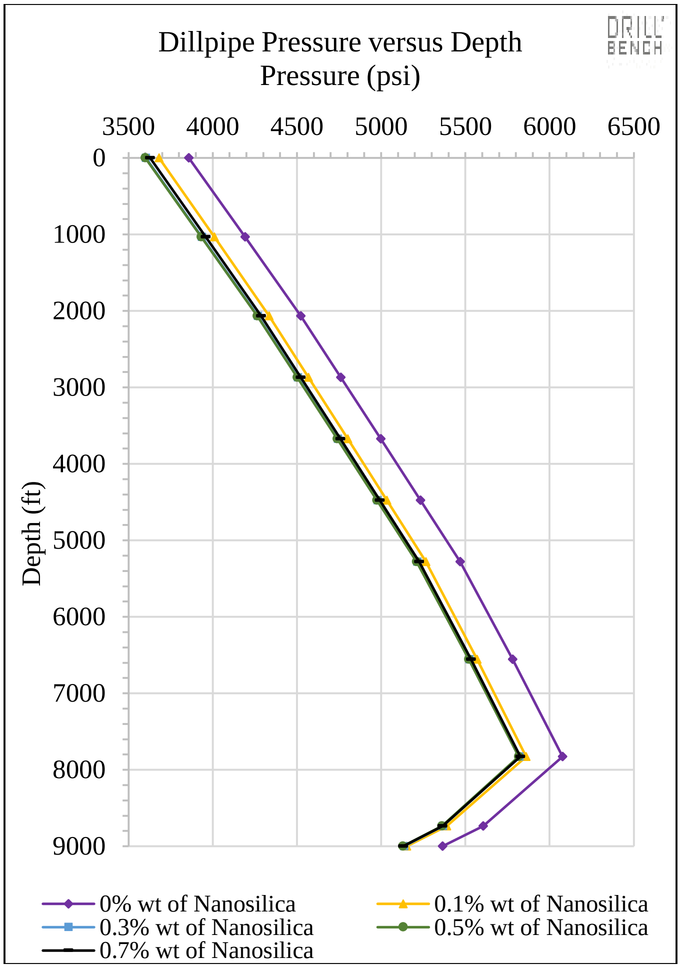


Figure 16: Impact of Nanosilica on Drillpipe Pressure

Thus, enhancing the rheological properties of water-based muds by using nanosilica and nanotitanium helps in optimizing the hydraulics. Minimizing pump pressure is always required to save the energy exerted by mud pumps and to increase the operational life of the surface and subsurface drilling equipment. Usually, minimizing the ECD helps in reducing loss circulation, formation fracture, and their related blowouts in the brittle and under pressure formations and in wells that have close values of the fracture and pore-pressure gradients.

It is important to note that the reductions in ECD and drillpipe pressure are based on addition of nanoparticles only, thereby on changing the rheology of the mud. Therefore, the possibility of obtaining different results is very high based on other independent parameters such as wellbore geometry, downhole tool dimensions, and subsurface temperature.

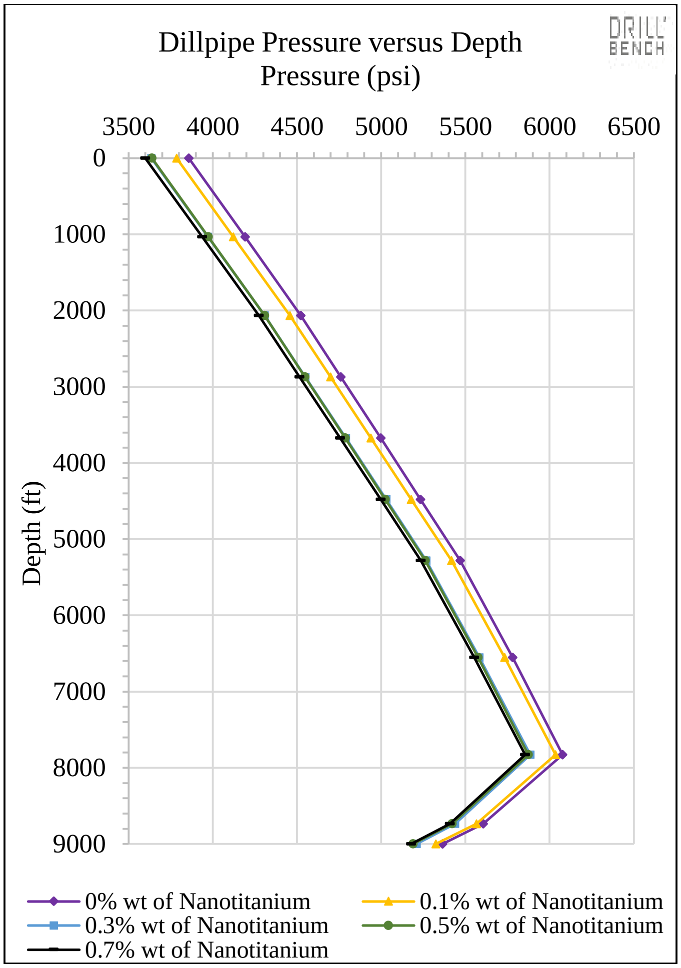


Figure 17: Impact of Nanotitanium on Drillpipe Pressure

Conclusions

Based on the results, the following conclusions are presented:

1. The current nanoparticles can be used to carefully design economic and qualified water-based drilling muds.
2. The smaller nanoparticles are superior than the bigger ones since they provide additional charges to the mud and occupy more spaces between the bentonite particles in the developed mudcakes.
3. The anionic nanosilica and nanotitanium change the link process, cause repulsion, reduce the friction, and cause dispersion between the flocculated Bentonite particles.
4. As multi-function additives, 0.1% wt. or less of nanosilica and 0.3% wt. or less of nanotitanium are the optimum concentrations. In this study, nanosilica is more efficient.
5. Regardless of the physical and chemical properties of the nanoparticles, they completely stop the spurt loss and enhance the structure of the mudcake since they distribute and fill the tiny holes on the mudcake surfaces.
6. Unlike the conventional filtration inhibitors, the

nanoparticles are expected to function at different downhole temperatures since they work based on a space plugging technique.

7. The current nanoparticles are very sensitive to the pH level and deflocculate the high pH muds without impacting the viscosity due to hydration. They can replace the conventional deflocculants used to treat the water-based muds.
8. Due to the very low concentrations used in this study and nano-scale dimensions of the nanoparticles, they do not increase the mud density and mudcake thickness as extra solids in the mud.
9. Hence, the smart water-based nano muds with nanosilica and nanotitanium can be used to replace the oil-based mud.

Acknowledgments

The authors of this study would like to acknowledge Dr. Victor A. Lifton of Evonik Corporation and Michael Donaty of Sonics & Materials, Inc. for providing the materials and equipment used in this research.

Nomenclature

API	American Petroleum Institute
AV	Apparent Viscosity, cp
cc	Cubic Centimeters
cp	Centipoise
ECD	Equivalent Circulation Density
F	Fahrenheit
ft	Foot
gm	Grams
gal	Gallons
hr	Hours
k	Consistency Index
LPLT	Low Pressure Low Temperature
LCM	Lost Circulating Materials
min	Minutes
n	Flow Behavior Index
nm	Nanometer
NaOH	Sodium Hydroxide
OBM	Oil-Based Mud
PV	Plastic Viscosity, cp
PDC	Polycrystalline Diamond Compact
ROP	Rate of Penetration
RPM	Rotation per Minutes
WBM	Water-Based Mud
Yp	Yield Point, lb/100 ft2
γ	Shear Rate, 1/sec
θ_{600}	Dial Reading at 600 rpm
θ_{300}	Dial Reading at 300 rpm
θ_{200}	Dial Reading at 200 rpm
θ_{100}	Dial Reading at 100 rpm
θ_{6}	Dial Reading at 6 rpm
θ_{3}	Dial Reading at 3 rpm
τ	Shear Stress, lb/100 ft2
μe	Effective Viscosity lb/100 ft2

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