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# An Approach to Curbing Wellbore Instability in Shales through Nanoparticles-Augmented Water-Based Drilling Muds

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**Abstract**

Among the several problems encountered in drilling, wellbore instability has been regarded as the most adverse and the problem becomes more peculiar when the drilled formation is shale. Because of the predominance of clay minerals in shale there is much tendency for water absorption and swelling in clays which causes wellbore instability. Oil-based mud has good potential as a remediation for wellbore instability but its cost and environmental implication has affected the choice of its usage. In this study, three shale samples from shale formation of Niger Delta were utilized. Three mud samples were formulated: mud sample SK1 without nanoparticles (NPs), mud samples SK2 and SK3 with 6 wt% and 12 wt % of NPs addition respectively. Mud rheology, measurement of density, filtration loss, spontaneous imbibition (SI) and rate of swelling tests were conducted on the prepared mud samples. The results showed that, addition of NPs to water-based drilling muds (WBDM) did not significantly changed the mud density before and after barite addition but addition of NPs to WBDMs increased yield point and plastic viscosity, and gave better filtration control with improved mud capacity to lift extra cuttings and enormous shear stress provided for circulation in the space of the annulus.. Also addition of NPs to the WBDM decreases the amount of imbibition of shale. NPs showed great capacity to swiftly plug the pore throats and decrease rate of swelling of shale when added to WBDMs.

***Keywords*** *Shale formation; Drilling mud; Filtrate; Nanomaterials; Borehole; Filtration loss.*

## 1. Introduction

Shale reservoirs over the past decades have received huge attention. Shales are argillaceous rocks which contains clay-minerals that are water-sensitive [1] and have permeabilities usually in nanodarcy [2]. Shale formation being rich in clay most abundantly forms sedimentary rocks and this makes shale very prominent [1]. Estimates carried out by researchers have shown that shale formations make up over 75% of formations drilled globally. Additionally, over 90% of drilling problems generally encountered has a relationship with issues of wellbore integrity in shale formations [3] and because of this, conclusion has been drawn that shales present extremely troublesome situation in all drilled formations for gas and oil [4]. This problem which is mostly encountered when drilling shales is termed wellbore instability. Wellbore instability has been described as the inability of the open hole interval to maintain its normal shape, gauge size, as well as structural integrity. The situation is highly undesirable during any drilling operation because of several wellbore problems like sticky hole, stuck pipe, hole fill, tight hole, etc. it causes which in turn increases drilling cost and time needed to carry out drilling operations [5-7]. Wellbore instability causes have been classified into three broad groups which are Mechanical (due to in-situ stresses), Erosion (due to fluid circulation), and Chemical (due to interaction of borehole fluid with the formation) [8]. Among these causes of wellbore instability problems, those related to shale-fluid interactions are very common and the main reasons are drilling-fluid filtrate absorption and subsequent swelling and sloughing of the wellbore [9]. Many techniques have been identified to control wellbore instability in shales, some of these techniques are, bulged tube, slime hole, well cooling and drilling fluid technology. Among the techniques mentioned, drilling fluid technology offers a more economical, effective and practical approach to tackle wellbore instability problems [10-11]. Operators have utilized the inherent characteristics of oil-based muds as solution to wellbore instability. Oil-base muds was viewed as the first choice due to its relatively strong plugging and inhibitive property due to non- interaction between oil and shales [12]. However, due to environmental and economic implications of oil-base muds, WBDMs are more often preferred (due to low cost and pollution free) as long as there is a way to minimize the interaction between the drilling fluid and the shale. Due to the inherent problems associated with water-base muds in drilling shales, researchers are developing efficient WBDMs for shale formations [13]. Particle diameter of most additives like bentonite and barite used for conventional DM are much larger than the effective pore throat size of many shales. It was discovered that most bentonite and barite have particle diameters in the ranges of 0.1 µm to 100 µm while the effective pore throat size of varieties of shales are in the range of 10 nm to 30 nm [14]. Because of the larger sizes of the conventional additives relative to shale pore throat sizes, mud cakes cannot be formed by conventional additives on shale surfaces and thus cannot reduce filtrate invasion. The only particles that can fit in to shale particle size with the prospects of reducing filtrate invasion through the formation of mud cakes on shale surfaces are NPs [15-17]. Previous researches have demonstrated that NPs have good tendencies at plugging the pore throats, and considerably reducing the permeability of shales. Furthermore, when NPs are used alongside other drilling fluid additives, a synergetic formulation is achieved which has the capacity to further plug micro-cracks aside plugging the pore throat [18]. In this study, WBDMs were formulated by addition of NPs to stabilize active shale layers during drilling of shale formations and thus, reduce wellbore instability. Filtration tests were conducted to ascertain whether the formulated muds had the capacity to lower filtration loss. SI tests were also conducted to determine the amount of imbibition that would occur due to exposure of shale samples to different WBDMs filtrates. Swelling tests were as well conducted on the formulated WBDMs to ascertain the rate of swelling of shale and then find out whether NPs have the capacity of resolving wellbore instability problems during drilling of shale formations.

## 2. Materials and methods

### 2.1 Materials

Silica NPs, shale samples, deionized water, Nanodarcy permeameter (Grace M9190 model), bentonite, multi mixer, helium porosimeter, K-PAM, $NH_4NPAN$, LV-CMC, mud balance, viscometer, press machine, swelling instrument, personal computer, Fann Series 300, Fann model 175CT, XR Diffractometer

#### *2.1.1. Nanoparticles (NPs)*

The NPs used in this study is silica spheres. The diameter of the silica NPs ranges from 10-20nm without magnification. Silica NPs has been proven to have splendid compatibility of ions, temperature and stability in drilling muds. Furthermore, silica NPs has been shown to have no adverse effects on drilling fluids properties.

#### *2.1.2. Shale samples*

The shale samples used in this work were gotten from shale formation of Niger Delta, Nigeria. The shales used were gotten from one location and thus have same properties even though three shale core samples were prepared. Porosity measurement was carried out with Helium porosimeter and it ranges from 3.24% to 3.81% while permeability measurement was carried out with the aid of Grace M9190 nanoperm with shale samples permeabilities ranging from 0.0004 to 0.00046mD. The length and diameter of the shale samples are 38.1mm and 25.4mm respectively. Thereafter, shale sample mineral components were determined using XRD technique. Some samples were crushed to obtain its powdered form. XR diffractometer had the samples packed in it's sample holder and mineral components identification test was carried out involving sample scanning using XR diffractometer. When the sample's mineral components identification has been concluded, application of Rietveld Analysis was utilized for XRD spectrum modeling through reference spectra weight. Many samples were used for uncertainty reduction. The Table 1 shows the sample's mineral components while Table 2 shows shale samples and their properties. Evidently from the table, total clay content in the shale stood at 50.9% with clay minerals constituents shown in table.

Table 1. Mineral composition of the Niger Delta Shale used in this study

| S/N | Constituents | Concentration | S/N | Constituents | Concentration |
|---|---|---|---|---|---|
| 1 | Quartz | 27.1 | 7 | Smectite | 8.6 |
| 2 | Calcite | 4.2 | 8 | Oglioclase Feldspar | 3.2 |
| 3 | Dolomite | 3.4 | 9 | Albite | 1.2 |
| 4 | Illite | 21.5 | 10 | Anhydrite | 2.7 |
| 5 | Kaolinite | 4.4 | 11 | Siderite | 3.2 |
| 6 | Chlorite | 16.4 | | Total clay present | 50.9 |

Table 2. Shale samples and their parameters

| Sample number | Length, mm | Diameter, mm | Permeability, mD | Porosity, % | Usage |
|---|---|---|---|---|---|
| SN1 | 38.1 | 25.4 | 0.0004 | 3.35 | Water-base drilling fluid filtrate |
| SN2 | 38.1 | 25.4 | 0.00046 | 3.81 | Water-base drilling fluid filtrate + 6% NPs |
| SN3 | 38.1 | 25.4 | 0.00044 | 3.24 | Water-base drilling fluid filtrate + 12% NPs |

#### *2.1.3. Mud sample preparation*

To prepare mud sample of the WBDM, 350 ml of deionized water was gotten, 3wt% of bentonite was then added to the deionized water and mixed thoroughly with a multi mixer. Furthermore, 0.75 wt% of K-PAM, 0.55 wt% of $NH_4$NPAN and 0.5 wt % of CMC- LV were also added. These additives were added successively to the mixture to obtain conventional water-based mud prior to addition of NPs. K-PAM was added to retard dispersion and hydration of shale, $NH_4$NPAN was added to inhibit fluid loss and as well prevent borehole collapse through viscosity reduction and CMC- LV was added to improve the control of fluid loss. Thereafter, NPs addition was made to the drilling fluid with NPs added by 6-wt% and 12-wt% to the drilling fluid. The mixture was properly stirred to ensure proper dispersion of the NPs. In general three mud samples were prepared, one without NPs called mud sample SK1, 6 wt% NPs addition to the mud system called mud sample SK2 and 12 wt% NPs addition to the mud system called mud sample SK3. After the addition of the NPs, the densities of the three mud samples were determined. This was necessary to ascertain the mud samples densities without any weighting agent. After this stage, barite was finally added and again the muds densities determined. Depicted in Table 3 are the additives utilized in WBDM formulation.

Table 3. Main additives of the WBDM

| Addictives | Mud sample SK1 | Mud sample SK2 | Mud sample SK3 |
|---|---|---|---|
| Deionized Water (mL) | 350 | 350 | 350 |
| Bentonite (wt %) | 3 | 3 | 3 |
| K-PAM (wt %) | 0.75 | 0.75 | 0.75 |
| $NH_4$NPAN (wt %) | 0.55 | 0.55 | 0.55 |
| CMC- LV (wt %) | 0.5 | 0.5 | 0.5 |
| NPs (wt %) | - | 6 | 12 |
| Barite (g) | 65 | 65 | 65 |

### 2.2. Experimental procedures

#### *2.2.1. Density measurement*

The densities of the mud samples were measured to ensure that there is no integrity issues that will emanate from the additives used. Mud balance (Fann model 140) was used in measurement of the mud density. The densities of the basic water-based mud and the NPs-augmented water-based mud were measured. In the measurement procedure, the cup was cleaned and fully filled with the prepared mud samples. The cup was then sealed at the top and pressurized with the lid to release air trapped within. Furthermore, the mud sample was placed on the measurement balance and density readings taken and recorded. The readings were taken in ppg.

### *2.2.2. Mud rheology*

In the mud rheology test, Fann 35 viscometer was used for each mud sample preparations and measurements were done at different rotational speeds. From the rheology readings, plastic viscosity as well as yield point was determined for the different mud samples prepared. Also, the mud samples' gel strengths were determined. In determining the gel strength, the mud samples were stirred for about 10 seconds at 600 RPM speed. Then the sample was left undisturbed for about 10 with maximum reading taken at 3RPM rotational speed. Thereafter, the mud was re-stirred at 600RPM speed and again left undisturbed for 10minutes with the final maximum readings taken at another 3rpm as the gel strength for 10minutes.

### *2.2.3 Filtration control*

The Mud samples' filtration loss characteristics were measured under the conditions of LPLT and HPTP. The test condition for the HPTP was 650 psi pressure and 255°F temperature while the LPTP test conditions was at 100 psi pressure and 77°F temperature in adherence to the API standard practice [19]. In measuring the fluid loss, Fann 175CT model with 300 Series were used. The bottom valve was made open for collection of the fluid loss for a period of 30minutes which was followed by the collection of the filter cake as the cell cooled down. The mud cake collected was then washed with low running water and measurement taken afterwards.

### *2.2.4. SI experiment*

SI experiments were carried out by testing the fluid amount imbibed into shale samples under exposure to diverse fluids at 30°C in adherence with API standard practice [19]. Shale core plugs drilled in the same direction of bedding plane were dried and suspended underneath the weighing balance and thereafter immersed into the test fluid. The amount fluid imbibed into the shale plug with increase in time was automatically recorded with the system for acquisition of data.

### *2.2.5. Swelling experiment*

Shale swelling was determined with the aid of linear swell grace meter (M4600 grace linear swell meter). 12-g of powered dry shale sample were placed into the test container, then compacted with press machine at 580.15psi for 5 min. The compacted sample had the displacement sensor attached on its top surface. The experimental fluid filled the test container remaining space. The data acquisition system was then utilized to record the sample's swelling rate.

## 3. Results and discussion

### 3.1. Density of mud system

Mud samples densities were determined to ensure that these mud samples possess adequate hydrostatic pressure to avoid the occurrence of kick and or mud loss during drilling. The result for the density experiment is given in table 4 and from the result; the addition of NPs does not significantly change the mud density before and after barite addition. This was attributed to minor interaction occurring between the additives and water. In reality, it is desirable to add more weighting agents such as barite to the mud samples to increase the mud systems' density and this was carried out to enable deeper wells' sections to be drilled; and to investigate whether NPs-barite interaction could significantly cause a change in the mud densities of the samples. From Table 4, mud sample SK1has a density of 8.5ppg while mud samples SK2 and SK3 had densities of 8.6 and 8.7 respectively before barite addition. After the addition of barite, the mud density significantly increased to 9.6ppg for sample SK1, 9.7ppg for sample SK2 and 9.85ppg for sample SK3 respectively as depicted in table 4. Drilling mud density always is in most cases, the first barrier put in place to prevent well kick; significantly it helps in wellbore stabilization and drilling mud stability for transport of cuttings. Therefore, higher mud density entails better mud stability for transport of cuttings to the surface and as such a great control against the occurrence of well kick. The addition of barite was carried to investigate whether NPs-barite interaction could significantly cause a change in the mud densities of the samples

Table 4. Mud density results for the various mud samples

| Mud Samples | Mud type | Density b/4 barite addition (ppg) |
|---|---|---|
| SK1 | Basic Water-base drilling mud Filtrate | 8.5 |
| SK2 | Water-base drilling mud Filtrate + 6% NPs | 8.6 |
| SK3 | Water-base drilling mud Filtrate + 12% NPs | 8.7 |
| Mud samples | Mud type | Density after barite addition (ppg) |
| SK1 | Basic Water-base drilling mud Filtrate + barite | 9.6 |
| SK2 | Water-base drilling mud Filtrate + 6% NPs+ barite | 9.7 |
| SK3 | Water-base drilling mud Filtrate+12% NPs+barite | 9.85 |

### 3.2. Mud rheology

The muds' rheological behaviour and its knowledge are necessary for proper provision of hole cleaning and ensure that mud losses are not initiated by ECD. Figure 3 and table 5 depicts the rheological test results on the WBDM samples. From Figure 1, higher shear rates were obtained for samples SK2 and SK3 which are NPs augmented WBDMs. Higher addition of NPs concentration causes an increase in the needed shear stress necessary for mud circulation in the annulus. NPs greatly changed the mud rheology with Sample SK3 having the highest PV and YP values. This is attributable to NPs size and also because the ratio of surface-to-volume is quite high and this causes an increase in the friction between the absorbed water and particles. [20-22], stated that NPs based mud samples' should have PV not exceeding 18-29 cP at temperature of 78°F so as to enable proper circulation of the NPs in the annulus. From Table 5, sample SK2 and Sk3 which are NPs augmented-WBDMs had PV that never exceeded this threshold. Also there could be a reaction between silica NPs and $OH^-$ in WBDMs as given by Eqns. (1) and (2), [22-23]. There could be a decrease in the $OH^-$ concentration as a result of these reactions and this could lower NPs-WBDMs' pH value.

$$SiO_2(s) + NaOH + H_2O \rightarrow NaH_3SiO_4 \quad (1)$$

$$SiO_2 + 2NaOH \rightarrow Na_2SiO + H_2O \quad (2)$$

The DM's particles of colloids with their electrochemical activities change the YP. As such, dispersed particles' surface charges changes the YP in diverse ways: the YP may be increased by the repulsive force strongly existing between bentonite particles which are negatively charged and nanomaterials which are also negatively charged. [22-24] posited that electrostatic repulsion strongly existing between particles which are negatively charged (nanomaterials and clay) hinders coagulation thereby creating a strong network of platelets of clay in the DM system, thus increasing the YP and PV. From Table 5, silica-NPs improved the mud capacity to lift extra cuttings but enormous shear stress needed for circulation in the space of the annulus. From Figure 1, evidently this enormous shear stress is provided by mud sample SK3. An indication whether cuttings suspension can be achieved by the mud as soon as pump is put off for any work-over or tripping operations is gel strength. [21-22] stated that DMs with NPs should have 10 seconds gel strength between 6 lb/100ft$^2$-10 lb/100ft$^2$. From Table 5, mud sample SK2 is within the stated threshold and therefore will be good for any drilling operations.

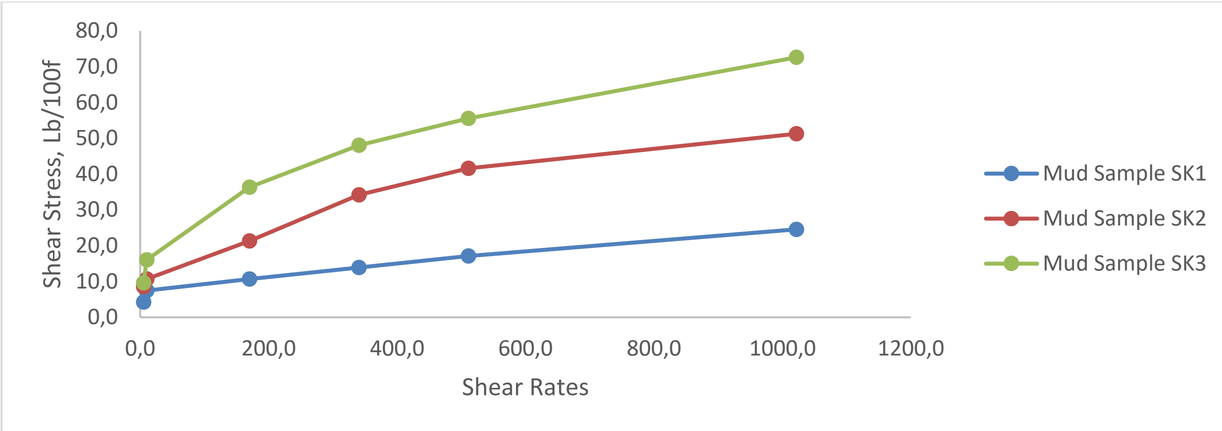


Figure 1. Shear stress and shear rate for mud samples SK1, SK2 and SK3

Table 5. Mud rheology results

| Mud samples | 3 rpm | 6 rpm | 100 rpm | 200 rpm | 300 rpm | 600 rpm | Plastic viscosity, cP | Yield Point, lb/100ft$^2$ | Gel strength (10 sec.), lb/100ft$^2$ | Gel strength (10 Min.), lb/100ft$^2$ |
|---|---|---|---|---|---|---|---|---|---|---|
| SK1 | 4 | 7 | 10 | 13 | 16 | 23 | 7 | 9 | 4 | 7 |
| SK2 | 8 | 10 | 20 | 32 | 39 | 48 | 9 | 30 | 8 | 11 |
| SK3 | 9 | 15 | 34 | 45 | 52 | 68 | 16 | 36 | 15 | 21 |

### 3.3. Filtration control

Tests on filtration loss were conducted under the conditions of LPLT and HPHT in order to determine the quantity of mud invasion/loss into permeable formations and then get the mud cake thickness produced during drilling of the formations. Thus, improvement in mud samples fluid control can be achieved through the addition of fluid loss additives like CMC-LV which can cause formations' pore throats closure and provision of encapsulation. These additives have surface-charges with chain structure that are not long. These surface-charges can aid deflocculation of particles of bentonite (clay). Consequently, proper dispersion of particles of bentonite (clay) in the solution is crucial thereby reducing filtration loss through the creation of mud cake with little thickness. NPs can achieve the same through the blockage of subsurface formations' pore throats and reduction of negatively charged surface charges of the solutions of colloids. From Table 6, nanosilica particles had great effect on filtration control since addition of NPs reduced the fluid loss volume drastically for both HPHT and LPLT tests, thus; a remarkable improvement on filtration control can be achieved with it.

Table 6. Volume of filtrate and thickness of mud cakes for HPHT and LPLT tests

| Mud samples | LPLT Filtration at 30min | | HPHT Filtration at 30min | |
|---|---|---|---|---|
| | Filtrate volume (mLs) | Mud cake thickness (/32 inch) | Filtrate volume (mLs) | Mud cake thickness (/32 inch) |
| SK1 | 20.1 | 3 | 18.7 | 1 |
| SK2 | 16.8 | 2 | 15.9 | 1 |
| SK3 | 14.2 | 2 | 13.6 | 1 |

### 3.4. NPs Effect on amount of imbibition

Invasion of filtrate into shale can take place through SI. Amounts of Imbibition that occurred due to exposure of shale samples to three different filtrates of both basic WBDM and NPs-augmented –WBDMs were tested. Filter tester was utilized to get the filtrates with WBDM filtrate as the basic fluid. Depicted in Figure 2 is the Imbibition amount versus time for basic WBDM (samples- SK1) filtrate and NPs-augmented WBDM (samples SK2 and SK3) filtrates.

From Figure 2, the amount of imbibition of basic WBDM filtrate was the highest in all the shale smples, but with addition of NPs to it, the amount of imbibition of WBDM filtrate significantly reduced in comparison with the basic mud. The addition of 6% wt of NPs decreased the total imbibition of the WBDM by 50% while the addition of 12 wt% NPs decreased the imbibition by 70%. The results has evidently shown that NPs addition could cause a decrease in the amount of imbibition of shale and this reduction in amount of imbibition becomes more visibly remarkable with increase in the concentration of NPs. For the mud samples- SK1, SK2 and SK3, the amount of imbibition speedily increased initially, thereafter it gradually became constant. In the case of the basic WBDM (sample SK1) filtrate, there was fast increase in amount of imbibition within 12 hours while for the NPs-augmented WBDM filtrates; there was fast increase in amount of imbibition for sample SK2 and sample SK2 filtrates within 2 hours, which is an indication that NPs can swiftly plug the pore throats of shale.

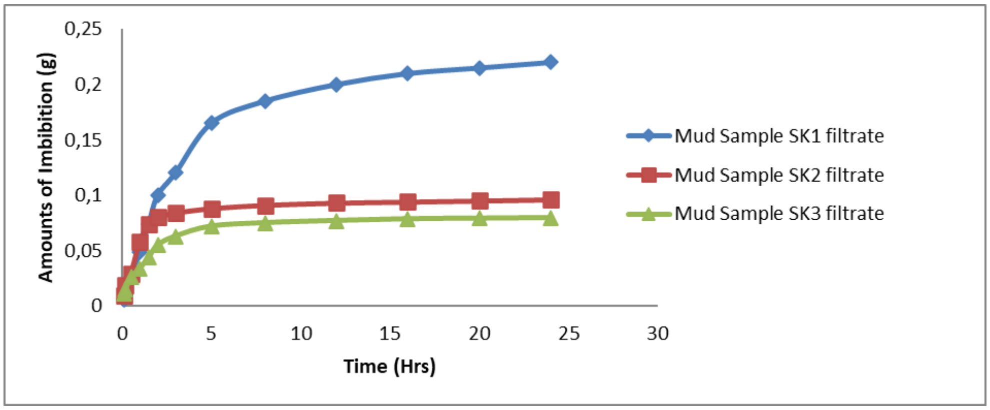


Figure 2. Imbibition amount vs time for various DM filtrates

### 3.5. Effect of NPs on swelling rate of shales

The shales' clay minerals are known to undergo hydration leading to swelling once they come into contact with the water present in drilling fluid and this can destroy the shale [25]. Low rate of swelling is desired as it is beneficial in reduction of problems associated with wellbore instability during drilling of shale formations. Depicted in Figure 3 is rate of swelling vs time for various DMs. From Figure 3, rate of swelling of shale's exposure to mud samples SK1 was 9% while rate of swelling was 3.91% and 2.77% with shale's exposure to mud samples SK2 and SK3 respectively. It is obvious that, NPs-augmented WBDMs greatly decreased rate of swelling of shale in comparison with basic DM. The result has evidently revealed that addition of NPs in WBDMs will effectively reduce problems associated with wellbore instability during drilling of shale formations.

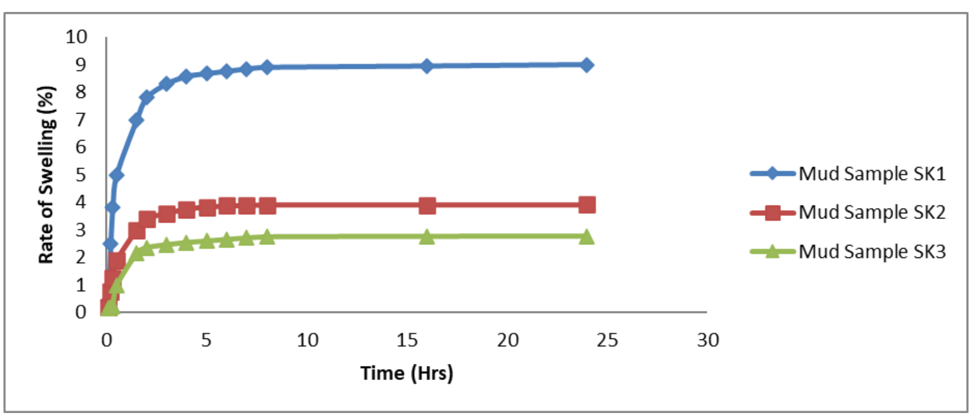


Figure 3. Rate of swelling rate vs time for various DMs

## 4. Conclusions

The density tests revealed that the addition of NPs to the NP- augmented WBDM did not significantly change the mud density before and after barite addition The addition of silica-NPs to WBDM increases the PV and YP in comparison to basic WBDM without NPs. NPs-augmented WBDMs show lower fluid loss than basic WBDM. Thus, there is better filtration control with the addition of NPs to the WBDM.

Addition of NPs to the WBDM decreases the amount of imbibition when compared with the basic WBDM and increase in concentration of NPs further decreases the amount of imbibition of shales. NPs have the ability to swiftly plug the pore throats of shale and plugging effect can be better induced by increasing the concentrations of the NPs in the WBDM system. The rate of swelling of shale decreased with the addition of NPs to the WBDM. Thus, NPs addition in WBDMs will effectively reduce problems associated with wellbore instability during drilling of shale formations.

### *Nomenclature*

| | |
|---|---|
| *HPHT* | *High pressure high temperature* |
| *LPLT* | *Low pressure low temperature* |
| *Ppg* | *Pounds per gallon* |
| *API* | *American Petroleum Institute* |
| *NPs* | *Nanoparticles* |
| *K PAM* | *Potassium Polyacrylate* |
| *NH4 HPAN* | *Ammonium Hydrolyze polyacrylonitrile* |
| *CMC LV* | *Carboxy Methyl Cellulose* |
| *WBDM* | *Water based drilling mud* |
| *WBDMs muds* | *Water based drilling* |
| *XRD* | *X ray diffraction* |
| *XR* | *X ray* |
| *Nanoperm* | *Nanodarcy permeameter* |
| *ECD* | *Equivalent circulating density* |
| *PV* | *Plastic viscosity* |
| *YP* | *Yield point* |
| *OH* | *Hydroxyl ions* |
| *SI* | *Spontaneous imbibitions* |
| *DM* | *Drilling mud* |
| *DMs* | *Drilling muds* |

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### *Conflicts of interest*

*The authors declare no conflicts of interest regarding the publication of this paper.*

### References

[1] Gholilou A, Behnoud Far P, Vialle S, Madadi M. Determination of safe mud window considering time-dependent temperature variations and pore pressure: analytical and numerical approaches. J. of Rock Mechanics and Geotech. Eng., 2017; 9(5):900e11.

[2] Kerunwa A, Okereke NU, and Tasiewojiewhor I. Enhancing the Productivity of Niger Delta Shale Formation through Matrix-Stimulation: An Experimental Study. Open J. of Yangtze Gas and Oil, 2020; (5): 117-130.

[3] Zhang Qiangui, JiaWenyu, Fan Xiangyu, Liang Yongchang, Yang Yang (2015). Shale wellbore stability mechanism Review based on mechanical/chemical coupling theories. Petroleum 1, Ke Ai publishers, pp. 91-96

[4] Zeynali ME. Mechanical and physico-chemical aspects of wellbore stability during drilling operations, J. Pet. Sci. Eng., 2012;(82): 120-124.

[5] Zhong R, Miska SZ, Yu M Modeling of near-wellbore fracturing for wellbore strengthening. J. Pet. Sci. Eng., 2018; (38): 475-84.

[6] Gao C. and Gray KE. A workflow for infill well design: wellbore stability analysis through a coupled geomechanics and reservoir simulator. J. Pet. Sci. Eng., 2019; (176): 279-90.

[7] Singh A, Rao KS. and Ayothiraman R. A closed-form analytical solution for a circular opening using Drucker-Prager criterion under plane strain condition. Indian Geotech. J., 2019; (49): 437-54.

[8] Halafawi IM, Avram IL. Wellbore instability prediction and performance analysis using Poroelastic modeling. J. of Oil, Gas and Petrochem. Sci., 2019; 2(2): 93-106.

[9] Rafieepour S, Zamiran S, Ostadhassan M A cost-effective chemothermo-poroelastic wellbore stability model for mud weight design during drilling through shale formations. J. of Rock Mechan. and Geotech. Eng.,2019; 2020; 12: 768-779.

[10] Rafieepour S, Ghotbi C, Pishvaie MR. The effects of various parameters on wellbore stability during drilling through shale formations. Pet. Sci. and Tech.; 2015; 33:1275-85

[11] Zamiran S, Rafieepour S, Ostadhassan M. A Geomechanical Study of Bakken Formation Considering the Anisotropic Behavior of Shale Layers. J. Pet. Sci. Eng., 2018; 165: 567-574.

[12] Shu H, Lixi L, Yinjin Z, Yi D, Yongxue L, Xiangjun L. The influence of water-based drilling fluid on mechanical property of shale and the wellbore stability. Petroleum, 2016; 2(1): 61-66.

[13] Song Jiwei, Yuan Ye, Gu Sui, Yang Xianyu, Yue Ye, CaiJihua and Jiang Guosheng. 2D Numerical Simulation of Improving Wellbore Stability in Shale using Nanoparticles-Based Drilling Fluid. Energies, 2017; 10, 651.

[14] Al-Bazali TM. Experimental Study of the Membrane Behavior of Shale during Interaction with Water-based and Oil-based Muds. PhD Dissertation) Univ. of Texas at Austin, Texas 2005.

[15] Jung CM, Zhang R, Chenevert ME, Sharma MM. High-performance water-based mud using nanoparticles for shale reservoirs. SPE/AAPG/SEG Unconventional Resources Technology Conference 2013, SPE 168799-MS / URTEC2013-106.

[16] Riley M, Stamatakis E, Young S, Hoelsher KP, Stefano G, Ji L, Friedheim J. Wellbore stability in unconventional shale- the design of nanoparticle fluid. SPE-153729-MS, https://doi.org/10.2118/153729-MS.

[17] Sharma MM, Chenevert ME, Guo Q, Ji L, Friedheim J, Zhang R. A new family of nanoparticle based drilling fluids. SPE-160045-MS. DOI:10.2118/160045-MS.

[18] Yili K, Jiping S, Hao Z, Lijun Y, Minggu S. Strengthening shale wellbore with silica nanoparticles drilling fluid. . Petroleum, 2016; 2(2): 189-195

[19] API-13B-1 (1997): Recommended practice for field testing water-based drilling fluids. API, Washington, DC.

[20] Jain R, Mahto V, and Sharma V. Evaluation of polyacrylamide-grafted-polyethylene glycol/silica nanocomposite as potential additive in water based drilling mud for reactive shale formation. J. Nat. Gas Sci. Eng.,2015; (26): 526-537.

[21] Ismail A, Aftab A, Ibupoto Z, and Zolkifile N. The novel approach for rheological properties of water-based drilling fluids enhancement by using multi-walled carbon nanotube, nanosilica and glass beads. J. Pet. Sci. Eng., 2016; (139): 264-275.

[22] Gholami R, Raza A, Rabiei M, Nikoo Fakhari N., Balasubramaniam P, Rasouli V, and Nagaraja R. An Approach to Improve Wellbore Stability in Active Shale Formations using Nanomaterials. Petroleum, https://doi.org/10.1016/j.petlm.2020.01.001.

[23] Yu YF, Kang YL, You LJ, Chen Q, and Yang B. Alkali corrosion: a new mechanism of shale borehole instability. Acta Pet. Sin., 2016; 34 (5): 983-988.

[24] Barry MM, Jung Y, Lee JK, Phuoc TX, and Chyu MK. Fluid filtration and rheological properties of nanoparticle additive and intercalated clay hybrid bentonite drilling fluids. J. Pet. Sci. Eng., 2015. 127: p. 338-346.

[25] Soroush H, Sampaio JH, and Nakagawa EY. Investigation into strengthening methods for stabilizing wellbores in fractured formations. SPE-101802-MS, ISBN: 978-1-55563-149-9.

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