THE INFLUENCE OF SiO$_2$ AND TiO$_2$ NANOPARTICLES ON THE PROPERTIES OF WATER-BASED MUD

Petar Mijić  
University of Zagreb  
Faculty of Mining, Geology and Petroleum Engineering  
Pierottijeva 6, 10 000 Zagreb, Croatia  
petar.mijic@oblak.rgn.hr

Nediljka Gaurina-Medimurec  
University of Zagreb  
Faculty of Mining, Geology and Petroleum Engineering  
Pierottijeva 6, 10 000 Zagreb, Croatia  
nediljka.gaurina-medimurec@oblak.rgn.hr

Borivoje Pašić  
University of Zagreb  
Faculty of Mining, Geology and Petroleum Engineering  
Pierottijeva 6, 10 000 Zagreb, Croatia  
borivoje.pasic@oblak.rgn.hr

ABSTRACT

About 75% of all formations drilled worldwide are shale formations and 90% of all wellbore instability problems occur in shale formations. This increases the overall cost of drilling. Therefore, drilling through shale formations, which have nanosized pores with nanodarcy permeability still need better solutions since the additives used in the conventional drilling fluids are too large to plug them. One of the solutions to drilling problems can be adjusting drilling fluid properties by adding nanoparticles. Drilling mud with nanoparticles can physically plug nanosized pores in shale formations and thus reduce the shale permeability, which results in reducing the pressure transmission and improving wellbore stability. Furthermore, the drilling fluid with nanoparticles, creates a very thin, low permeability filter cake resulting in the reduction of the filtrate penetration into the shale. This thin filter cake implies high potential for reducing the differential pressure sticking. In addition, borehole problems such as too high drag and torque can be reduced by adding nanoparticles to drilling fluids.

This paper presents the results of laboratory examination of the influence of commercially available nanoparticles of SiO$_2$ (dry SiO$_2$ and water-based dispersion of 30 wt% of silica), and TiO$_2$ (water-based dispersion of 40 wt% of titania) in concentrations of 0.5 wt% and 1 wt% on the properties of water-based fluids. Special emphasis is put on the determination of lubricating properties of the water-based drilling fluids. Nanoparticles added to the base mud without any lubricant do not improve its lubricity performance, regardless of their concentrations and type. However, by adding 0.5 wt% SiO$_2$-disp to the base mud with lubricant, its lubricity coefficient is reduced by 4.6%, and by adding 1 wt% TiO$_2$-disp to the base mud with lubricant, its lubricity coefficient is reduced by 14.3%.

Key words: torque and drag, silica and titania nanoparticles, lubricity, rheology, filtration

INTRODUCTION

The application of nanoparticles has become quite popular in different disciplines and has recently captured the attention of the oil industry. Nanoparticles are defined as structures with sizes in nm range ($10^{-9}$ m). One nanometer corresponds to the distance between 2 to 20 atoms, positioned one next to another [1]. Like any other industry, the oil industry can also acquire benefits from nanotechnology which deals with the usage of nanomaterials [2, 3]. Nanomaterials used in drilling fluids (muds) are those with particle sizes between 1 to 100 nanometers [1, 3, 4, 5]. According to literature, the idea of adding nanoparticles to drilling mud as an additive was
introduced in the oil industry a few years ago, but its application in the process of drilling is still in the initial stage [6]. Nanoparticles can be added to some fluid, usually water, to get a dispersion of nanoparticles or can be completely dry like powder. Based on the concentration of the nanoparticles in drilling fluids they can be classified as: (1) simple nanofluids with one nanosized additive added to drilling fluid and (2) advanced nanofluids with two or more nanosized additives [3, 4].

Recent research shows that nanoparticles suitable as drilling fluids additive include: (1) silica (SiO$_2$) [7, 8, 9, 10], (2) titania (TiO$_2$) [11], (3) aluminum oxide (Al$_2$O$_3$) [11], (4) copper oxide (CuO) [11, 12], (5) multi-walled carbon nanotube [10, 11], (6) hematite (Fe$_2$O$_3$) [9], (7) magnetite (Fe$_3$O$_4$) [13], (8) nano graphene [14], (9) boron-based nanoaditive [15], (10) calcium carbonate (CaCO$_3$) [10, 16], (11) iron (III) hydroxide (Fe(OH)$_3$) [16] and (12) ZnO [12].

Conversion of macroparticles into nanoparticles results in a multiple increase (more than a million fold) in the specific surface area to the volume of particles. Because of that, a desired change in properties of drilling fluid is usually obtained by adding nanoparticles only in small concentrations (< 1%) [5].

Using fluids, which contain nanoparticles can be beneficial in solving other drilling problems such as borehole instability, lost circulation, pipe sticking problems and bit balling [17, 18, 19, 20].

In this paper authors focused on measuring the lubricity performance of tested drilling fluids to show the impact of adding SiO$_2$ and TiO$_2$ nanoparticles. Also, the impact of adding SiO$_2$ and TiO$_2$ nanoparticles on other properties of selected drilling fluids was tested.

TORQUE AND DRAG

Nowadays, with the intention to drill deeper and longer, and with the rapid increase in the number of directional, horizontal and extended reach wells, excessive values of torque and drag while drilling can cause many problems. Regarding directional or extended reach drilling, the main assumption is that both torque and drag, are the result of frictional force caused by contact between the drill string and wellbore, which can be expressed by using coefficient of friction (CoF). High friction between the drill string and wellbore may cause higher hookload while tripping, which reduces the lifespan of drilling equipment, shortens the well length substantially, and may also cause many other problems that occur during the drilling of the wellbore [21, 22]. One of the functions of the drilling fluid is to minimize the coefficient of friction between the drill string and wellbore, and thus minimize torque and drag problems [4, 19]. The conventional micro and macro-material based fluid used for reducing drag and torque has limited capability to minimize torque and drag [4, 19]. Because of that, drilling nanofluids have been developed and applied in oil industry [21]. It is believed that nanoparticles produce continuous and thin lubricating film at the pipe-wall interface, which causes significant reduction of the coefficient of friction and thus easy sliding of the drill string along the wellbore surface [4, 19]. For example, according to Hareland et al. (2012) it is shown that adding nickel-based nanoparticles to drilling mud results in reduction of the coefficient of friction by more than 25%.

LUBRICITY

As it was mentioned, significant function of drilling fluid is the reduction of frictional forces between the drill string and the wellbore. The reduction in coefficient of friction (CoF) is a function of fluid composition [23, 24]. Standard drilling fluid composition includes a conventional lubricant to improve its lubricity. Lubricity is a very important parameter, especially in cases when curved or horizontal section of the wellbore has been drilled, as well as long drillstring is used to achieve the target (for example, drilling an extended reach well). The choice of the type of lubricant can be changed depending on the availability and location of the well [7]. It is already known that oil-based drilling fluids improve lubricity better than water-based drilling fluids. This finding can be explained by the superior lubricating ability of an oil-based drilling fluid. According to Amorim et al. (2011) [25] the most efficient lubricants are the ones that operate through several mechanisms, depending on their chemical composition and on their dispersion state in the fluid. The lubricants that are used in water-based fluids consist of active-surface compounds with affinity for metallic surfaces, which are in constant contact with other metallic surfaces or geological formations [25]. Recent research shows that nanoparticles could act as an additive for improving lubricity and reduce friction between the drill string and wellbore. The reason is that nanofluids have the potential to form slightly lubricating film at the wellbore and pipe interface [3]. Nasser et al. (2013) [26], researched the use of nanographite, whose average particle size was 40 nm, in concentration of 3% by weight. They researched the impact of nanoparticles on density, viscosity, filtrate loss and lubricity of a drilling fluid. The drilling fluid tested consisted of water, bentonite, barite and starch. Their experimental work showed that nanoparticles can enhance the properties of drilling fluids. In 2014, Jabrayilov [19] conducted tribological and rheological experiments using titania and silica nanoparticles as an additive to examine the lubricity and rheology of the mud. In his research, silica nanoparticles were added to fluids in concentration of 0.25 wt% and reduced coefficient of friction by 47% at the temperature of 50°C. Taraghikhah et al. (2015) [8] tested the adding of silica nanoparticles (1-60 nanometer range) to water-based and polymer-based drilling fluids in concentrations of 0.25 wt%, 1 wt% and 2 wt%. Their research showed that the increase in content of SiO$_2$ nanoparticles in the drilling fluid decreases the coefficient of friction during drilling. Consequently, they achieved an acceptable enhancement in lubricity (69%) by adding only 1 wt% of nanoadditve. Taha and Lee (2015) [14] conducted a laboratory test of nano
Nanographene was used as an additive to reduce torque and compared it to a well-known ester-based lubricant. The nanographene lubricant had been evaluated in several different types of water-based drilling fluids using standard lubricity tester. Laboratory tests indicated that the nanographene reduces torque in a 1200 kg/m³ (10 lb/gal) conventional salt polymer mud by 70–80%, whereas the ester-based lubricant achieved torque reduction of 30–40%. In a 1620 kg/m³ (13.5 lb/gal) HTHP water-based mud torque reduction was 50%. All tests in the laboratory had indicated that the nanographene achieved higher torque reduction, thus improving mud properties. According to Taha and Lee (2015) [14], the optimum additive concentration was 5% by volume. In 2016 Krishnan et al. [15] conducted tests under extreme pressure using the standard 1200 kg/m³ (10 lb/gal) and 1620 kg/m³ (13.5 lb/gal) water-based muds. They focused on the application of boron-based nanomaterial enhanced additive. Addition of 5% by volume of boron-based nanomaterial in 1200 kg/m³ (10 lb/gal) water-based mud provided torque reduction of 80% while for 1620 kg/m³ (13.5 lb/gal) mud the torque reduction was 52%. Also, they noticed an increase in rheology of the mud with the addition of this additive showing higher plastic viscosity (PV), yield point (YP) and gel strength as compared to the commercially available lubricant. After their research, boron-based nanomaterial was used in the field in Myanmar and performed excellently with torque reduction of 36.36% while the commercial lubricant provided torque reduction of approximately 13.64%. Caldarola et al. (2016) [27] investigated the lubricity of a fluid sample containing normal sized barite and two fluid samples, containing chemically and mechanically generated barite nanoparticles. The results indicated a reduction in friction coefficient of more than 34% by substituting normal sized barite with a concentration of 3 wt% of chemically generated barite nanoparticles. The friction coefficient was reduced by more than 15% by substituting normal sized barite with a concentration of 3 wt% of mechanically generated nanoparticles.

According to all the above-mentioned authors, nanoparticles in water-based drilling fluids act as lubrication additives. Oil-based drilling fluid compared to water-based drilling fluid has superior lubricating characteristics and is commonly used in demanding environments. However, it is more expensive and not environmentally friendly. Therefore, the testing of new types of lubricants, such as nanoparticles, is of increasing interest to the oil industry with the intention of improving lubrication performance of water-based drilling fluids.

LABORATORY TESTING

Laboratory testing was performed in Drilling Fluids Laboratory at the Faculty of Mining, Geology and Petroleum Engineering, University of Zagreb, Croatia. In order to better understanding the impact of the addition of particular additives on the properties of the drilling mud, simple bentonite drilling fluid was chosen as base drilling mud. Preparation of base mud was carried out following American Petroleum Institute Standards, API Specifications 13A (1993) and API 13B-1 (1997). The high-yield bentonite is used for adjusting rheological and filtration properties, NaOH to maintain alkalinity and PAC LV to maintain filtration. Base mud formulation is shown in Table 1.

### TABLE 1. BASE MUD FORMULATION

<table>
<thead>
<tr>
<th>Base mud formulation</th>
<th>Quantity</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>-</td>
<td>base fluid</td>
</tr>
<tr>
<td>Bentonite</td>
<td>30 g/l</td>
<td>rheological and filtration properties</td>
</tr>
<tr>
<td>NaOH</td>
<td>2 g/l</td>
<td>alkalinity</td>
</tr>
<tr>
<td>PAC LV</td>
<td>2 g/l</td>
<td>filtration</td>
</tr>
</tbody>
</table>

The research procedure is presented in Fig. 1.

![Fig. 1. Research Procedure](image)

According to Fig. 1, ten types of drilling fluid systems were prepared and subjected to laboratory testing. One drilling fluid system contains only lubricant (Halliburton Torq-Trim II), six drilling fluid systems contain different types of nanoparticles (designated TiO₂-disp; SiO₂-disp and SiO₂-dry) in different...
concentrations, while another two drilling fluid systems contain both lubricant and nanoparticles. Nanoparticles used for laboratory research are shown in Fig. 2. and in table 2. The desired concentration of nanoparticles (0.5 wt% or 1 wt%) was added to 1 liter of base drilling mud (table 3). It was added slowly to minimize the agglomeration of nanoparticles and mixed for 30 more minutes. To differentiate between the dry SiO$_2$ and the SiO$_2$ from dispersion, the samples were marked as SiO$_2$-dry and SiO$_2$-disp, respectively. The content of nanoparticles, in volume of dispersion added in mud, is expressed as wt% and in grams.

![Image of nanoparticles](https://example.com/image.png)

**TABLE 2. TYPICAL DATA FOR NANOPARTICLES USED IN LABORATORY RESEARCH**

<table>
<thead>
<tr>
<th>No.</th>
<th>Brand name</th>
<th>Manufacturer</th>
<th>Appearance</th>
<th>Nanoparticles content</th>
<th>Density @20$^\circ$ C (kg/m$^3$)</th>
<th>Stabilizing agent</th>
<th>Average particle size (D50)</th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>AERODISP® W 740 X</td>
<td>Evonik Industries</td>
<td>water-based dispersion</td>
<td>39-41 wt% of titania (TiO$_2$)</td>
<td>1410</td>
<td>-</td>
<td>70 nm</td>
<td>5-7</td>
</tr>
<tr>
<td>2</td>
<td>AERODISP® W 7330 N</td>
<td>Evonik Industries</td>
<td>water-based dispersion</td>
<td>30 wt% of silica (SiO$_2$)</td>
<td>1200</td>
<td>NaOH</td>
<td>120 nm</td>
<td>9.5-10.5</td>
</tr>
<tr>
<td>3</td>
<td>Elite NSiP20</td>
<td>Anhui Elite Industrial Co., LTD.</td>
<td>white powder</td>
<td>99.9% silica (SiO$_2$)</td>
<td>-</td>
<td>-</td>
<td>20 nm</td>
<td>6-8</td>
</tr>
</tbody>
</table>

**TABLE 3. DRILLING FLUID FORMULATIONS**

<table>
<thead>
<tr>
<th>No.</th>
<th>Drilling fluid systems</th>
<th>Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Base mud (BM)</td>
<td>1 liter</td>
</tr>
<tr>
<td>2</td>
<td>BM+lub, 2 vol%</td>
<td>20 ml lubricant (2% by volume of base mud)</td>
</tr>
<tr>
<td>3</td>
<td>BM+0.5 wt% SiO$_2$-disp</td>
<td>0.5 wt% SiO$_2$ nanoparticles, 5 g SiO$_2$ nanoparticles (14 ml dispersion)</td>
</tr>
<tr>
<td>4</td>
<td>BM+0.5 wt% TiO$_2$-disp</td>
<td>0.5 wt% TiO$_2$ nanoparticles, 5 g TiO$_2$ nanoparticles (9 ml dispersion)</td>
</tr>
<tr>
<td>5</td>
<td>BM+0.5 wt% SiO$_2$-dry</td>
<td>5 g SiO$_2$-dry</td>
</tr>
<tr>
<td>6</td>
<td>BM+1 wt% SiO$_2$-disp</td>
<td>1 wt% SiO$_2$ nanoparticles, 10 g SiO$_2$ nanoparticles (28 ml dispersion)</td>
</tr>
<tr>
<td>7</td>
<td>BM+1 wt% TiO$_2$-disp</td>
<td>1 wt% TiO$_2$ nanoparticles, 10 g TiO$_2$ nanoparticles (18 ml dispersion)</td>
</tr>
<tr>
<td>8</td>
<td>BM+1 wt% SiO$_2$-dry</td>
<td>10 g SiO$_2$-dry</td>
</tr>
<tr>
<td>9</td>
<td>BM+lub, 2 vol%+0.5 wt% SiO$_2$-disp</td>
<td>20 ml lubricant (2% by volume of base mud), 0.5 wt% SiO$_2$ nanoparticles, 5 g SiO$_2$ nanoparticles (14 ml dispersion)</td>
</tr>
<tr>
<td>10</td>
<td>BM+lub, 2 vol%+1 wt% TiO$_2$-disp</td>
<td>20 ml lubricant (2% lubricant by volume of base mud), 1 wt% TiO$_2$ nanoparticles, 10 g TiO$_2$ nanoparticles (18 ml dispersion)</td>
</tr>
</tbody>
</table>

**Lubricity measurement**

The lubricity coefficient of muds was determined using an OFITE EP-Lubricity Tester, according to the methodology of measurement recommended by the manufacturer’s manual [28]. Before any measurement of lubricity of drilling fluid systems was done, test was performed with deionized water to calibrate the instrument. The initial torque was zero and the speed was 60 rpm. Then a 150 in-pounds force was applied for 5 minutes to obtain the correction factor (CF). After mixing the drilling fluid system for 30 minutes, the fluid was transferred to the sample cup and torque reading was obtained. The testing was performed at room temperature. After 5 min the torque meter reading was obtained at 60 rpm and 150 in-pounds of load. Lubricity coefficient was calculated according to Eq. (1). [28]:

$$
\text{Lubricity Coefficient} = \frac{\text{Meter Reading} \times \text{Correction Factor}}{100 \text{ Pounds}} \quad (1)
$$

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Lubricity coefficient for tested drilling muds (No. 1-8 from table 3) is shown in Fig. 3.

According to Fig. 3, adding nanoparticles did not decrease lubricity coefficient. Only by adding the lubricant to the base drilling mud a positive impact on the mud’s lubricity has been attained. Adding 1 wt% of titania nanoparticles results in the decrease of lubricity coefficient to the value quite similar to the one achieved with the base mud without the addition of nanoparticles (0.37). Regardless of the type and concentrations, the usage of silica nanoparticles increases the value of lubricity coefficient. On the basis of these results it was decided to carry out additional tests with 0.5 wt% SiO$_2$-disp and 1 wt% TiO$_2$-disp, because they showed the best results. SiO$_2$-disp and TiO$_2$-disp were added to the base mud which already contained 2 vol% of lubricant. The results are shown in Fig. 4.

The addition of SiO$_2$-disp and TiO$_2$-disp into base drilling mud with lubricant decreases the value of lubricity coefficient, and thus additionally improves its lubricity. The percent of lubricity coefficient reduction was 4.6% by adding SiO$_2$-disp in concentration of 0.5 wt%, and 14.3% by adding TiO$_2$-disp in concentration of 1 wt%, relative to the values achieved with base mud with lubricant.

Rheological measurement

The rheological properties of different mud systems were measured using a rotational OFITE Model 900 viscometer. Viscometric data were obtained at fixed speeds of 600, 300, 200, 100, 6 and 3 rpm and two temperatures: 25°C and 50°C. The plots of shear rates and shear stresses (flow curves) were created for all tested muds at both temperatures (Fig. 5., 6., 7. and 8.).
According to Fig. 5., 6., 7. and 8. it can be noticed that all tested fluids behave as Herschel-Bulkley fluids. For smaller concentration of nanoparticles (0.5 wt%) at both temperatures, muds with SiO₂-dry and muds with SiO₂-disp provide higher shear stress than muds with TiO₂-disp at the same shear rate (Fig. 5. and 7.). Mud with TiO₂-disp in concentration of 0.5 wt% at the temperature of 25°C provides lower shear stress than the base mud at the same shear rates (Fig. 5.), but at the temperature of 50°C TiO₂-disp has higher values of shear stress than the base mud at higher shear rates (>500 s⁻¹) (Fig. 7.). For a higher concentration of nanoparticles (1 wt%), mud with SiO₂-dry nanoparticles, at a temperature of 25°C, has significantly higher values of shear stress than other muds at the same shear rate. At the same time, fluids with SiO₂-disp and TiO₂-disp have smaller values than the base mud (Fig. 6.). At 50°C, mud with 1 wt% of SiO₂-dry has the smallest values of shear rates at smaller shear rates (< 250 s⁻¹), but the highest at higher shear rates (> 500 s⁻¹) (Fig. 8.).

The results of plastic viscosity, yield point, strength of 10 sec gel and 10 min gel for all drilling muds are shown in Fig. 9., 10., 11. and 12.
According to Fig. 9, 10, 11, and 12, SiO$_2$-dry nanoparticles in both concentrations and at both temperatures increase the value of plastic viscosity. At the temperature of 25°C, SiO$_2$-disp and TiO$_2$-disp in concentration of 0.5 wt% have the similar value of the plastic viscosity as the base mud (Fig. 9.), while at the temperature of 50°C, their value is higher than the value of the base mud (Fig. 11.). Also, SiO$_2$-dry and SiO$_2$-disp in concentration of 0.5 wt% provide higher values of yield point, while TiO$_2$-disp in concentration of 0.5 wt% has the value of yield point less than that for the base mud (Fig. 9.). At a temperature of 50°C, the value of yield point decreases for all added nanoparticles in concentration of 0.5 wt% to the value below that of the base mud (Fig. 11.). At the temperature of 25°C, regardless of the type and concentrations of nanoparticles, the strength of 10 sec and 10 min gel decreases when compared to gel strengths of the base mud.

For higher concentrations (1 wt%), at the temperature of 25°C, only the mud with SiO$_2$-dry had significantly higher values of plastic viscosity, yield point and gel strengths than those achieved for all other tested muds (Fig. 10.). At the temperature of 50°C, plastic viscosity value of all tested muds with nanoparticles was higher than the plastic viscosity value of the base mud, but values of yield point and gel strengths were lower than those achieved in the base mud.

As the additional tests were carried out with 0.5 wt% SiO$_2$-disp and 1 wt% TiO$_2$-disp added to the base mud which already contained 2 vol% of lubricant, rheological properties of these mud systems were measured (No. 9 and 10 from table 3). The flow curves are shown in Fig. 13. and 14., while rheological parameters are shown in Fig. 15. and 16.
At the temperature of 25°C, mud with lubricant and SiO$_2$-disp in concentration of 0.5 wt% provides significantly higher values of shear stress than other muds at the same shear rates (Fig. 13). Also, for both temperatures, SiO$_2$-disp and TiO$_2$-disp added to the mud with lubricant provide higher values of shear stress than those achieved in muds which contain only nanoparticles (without lubricant) at the same shear rates (Fig. 14).

According to Fig. 15, and 16., it can be seen that adding SiO$_2$-disp in concentration of 0.5 wt% and TiO$_2$-disp in concentration of 1 wt% to the base mud with lubricant, at both temperatures increases its values of plastic viscosity, yield point and gel strengths.

**Filtration measurement**

The filtration characteristics of the drilling muds were obtained following the API procedures. Data was collected using a standard API filter press with a standard operating pressure of 700 kPa (100 psi) and at room temperature. The volume of the filtrate was measured after 30 min in a graduated cylinder. The results are shown in Fig. 17.

Regardless of the type and concentrations, adding silica and titania nanoparticles to the base mud without any lubricant increases its API filtration value. Adding SiO$_2$-disp in concentration of 0.5 wt% to the base mud with lubricant decreases the value of API filtration. At the same time, TiO$_2$-disp in concentration of 1 wt% added to the base mud with lubricant decreases its API filtration by 17%.

**Cake thickness**

Filter cake thicknesses were measured at the end of the 30-min filtration period using a micrometer. Measurements were repeated on multiple spots providing a larger number of results, which improved accuracy. The average value of cake thickness is shown in Fig. 18.

**pH measurement**

pH was measured using standard pH-meter. All tested muds had pH value between 11 and 11.5.
Density measurement

The density of all tested muds was slightly higher (1020 kg/m³) than the density of water, because there is no weighting additive in the base mud formulation.

CONCLUSIONS

The following conclusions can be drawn:

1. regardless of their concentrations and type, nanoparticles added to the base mud without any lubricant do not improve its lubricity performance,
2. adding of 0.5 wt% SiO₂-disp to the base mud with lubricant, reduced its lubricity coefficient by 4.6%,
3. adding of 1 wt% TiO₂-disp to the base mud with lubricant, reduced its lubricity coefficient by 14.3%,
4. at the temperatures of 25°C and 50°C, muds with 0.5 wt% SiO₂-dry and muds with 0.5 wt% SiO₂-disp provide higher shear stress than muds with 0.5 wt% TiO₂-disp at the same shear rate,
5. regardless of concentrations, SiO₂-dry provides the highest plastic viscosity values,
6. adding 0.5 wt% SiO₂-disp and 1 wt% TiO₂-disp to the base mud with lubricant results in higher plastic viscosity, yield point and gel strength values at both tested temperatures in comparison to muds containing only nanoparticles (without any lubricant),
7. adding of 0.5 wt% SiO₂-disp and 1 wt% TiO₂-disp to the base mud with lubricant decreases the value of API filtration,
8. adding 1 wt% TiO₂-disp to the base mud with lubricant reduced its API filtration by 17%,
9. all mud systems had mud cake thickness less than 0.16 mm, but the thinnest cake was recorded in the case of the base mud without any lubricant and the mud with both 0.5 wt% SiO₂-disp and lubricant.

In conclusion, in order to gain better insight into the impact of nanoparticles on lubricity performance of mud, it is necessary to perform further testing using other materials at different concentrations at higher pressure and temperature testing conditions.

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REFERENCES


