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Lubricating Properties of Water-Based Drilling Fluid Improvement Using Lignite NPs as well as Their Effect on Rheological and Filtration Properties

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Abstract— In the process of drilling directional, extended-reach, and horizontal wells, the frictional forces between the drill string and the wellbore or casing can cause severe problems including excessive torque which is one of the most important problems during drilling oil and gas well. Drilling fluid plays an important role by reducing these frictional forces. In this research, an enhancement of lubricating properties of drilling fluids was fundamentally examined by adding Lignite NPs into the water-based drilling fluid. Lubricity, Rheology and filtration properties of water-based drilling fluid were measured at room temperature using OFITE EP and Lubricity Tester, OFITE Model 900 Viscometer, and OFITE Low-Pressure Filter Press, respectively. Lignite NPs were added at different concentrations (0.05 %, 0.1 %, 0.2 %, 0.5 %, and 1 %) by weight into water-based drilling fluid. Lignite NPs showed good reduction in COF of water-based drilling fluid. The enhancement was increased with increasing Lignite NPs concentrations; 23.68%, 35.52%, and 45.3 % reduction in COF were obtained by adding 0.2%, 0.5%, and 1% by weight Lignite NPs concentration, respectively.

Keywords— Water based drilling fluid, COF, Nanomaterials, Rheological and Filtration properties.

1. Introduction

While drilling problematic formations with non-smooth well profiles, directional, extended-reach, and horizontal wells, the frictional forces between drill string and wellbore or casing can cause severe drilling problems, waste of equipment, time and money. High torque and drag may exceed the capabilities of drill string and casing and can cause pipe sticking and loss of the well .[16]

To minimize the friction between the drill string and inside of the wellbore or casing, drilling fluids plays an important role in reducing the frictional forces. Surface interactions between drill string, drilling fluid, casing, filter cake and formation affect the coefficient of friction which is an indicator of torque and drag .[12]

Oil-based drilling fluids have low COF between drill string and wellbore or casing compared to that of water-based drilling fluids, the typical COF for oil-based drilling fluids is less than 0.1 when measured between metal to metal surfaces in laboratory, while that of water-based drilling fluids is ranging from 0.2 to as high as 0.6 [14]. However, the use of oil-based drilling fluids is severely limited as a result of high costs and environmental concerns. As a solution, it was seen that it would be advantageous to identify a water-based drilling fluid system with the addition of lubricants which is environmentally friendly, cost effective and as lubricious as oil-based and synthetic-based drilling fluid systems .[17]

Researchers had shown that using Nanomaterials in drilling fluids enhanced the lubricity of the water-based drilling fluid system. [8] investigated that Titania ($TiO2$) and Silica Nanoparticles effectively reduced the friction factor of drilling fluids. [18] studied the improvement of drilling fluids performance by using Nano Graphene, they reported 80% torque reduction using 5% by volume Nano Graphene engineered product. [9] improved the lubricity of water-based drilling fluid by using Boron-based Nanomaterial enhanced additive (PQCB), they showed that addition of 5% by volume of this additive gives 80%

torque reduction. [3] studied the effect of Barite Nanoparticles on the lubricity of water-based drilling fluid, they indicated a reduction in the coefficient of friction of more than 34 % with the concentration of 3% by weight of chemically generated Barite Nanoparticles and 15% with the mechanically generated Nanoparticles. [1] showed the effect of using Nano-Sepiolite (NSP) on lubricity of drilling fluids, they investigated that friction is reduced by about 34 % at HTHP when 4 wt. % NSP is added to water-based Lignosulfonate drilling fluid. [2] evaluated the effect of TiO2 Nanoparticles addition on rheology, filtration and lubricity characteristics of drilling fluid, they reported an average torque reduction of 24% with concentrations lower than 1gm of TiO2 in water-based drilling fluid. [4] investigated the impact of different Nanoparticles on various drilling fluid properties, including rheology, filtration, and lubricity. [19] and [20] showed the effect of Titanium Nitride (TiN), MoS2 and Graphene Nanoparticles on the properties and performance of water-based drilling fluid.

In this research, experimental work had been conducted to minimize COF of water-based drilling fluid using Lignite NPs.

2. Experimental Work

2.1 *Materials*

2.1.1 Bentonite

The bentonite that had been used in preparation of water-based drilling fluid was supplied by OREN HYDROCARBONS MIDDLE EAST INC.

2.1.2 Nano Materials

Lignite was supplied by OREN HYDROCARBONS MIDDLE EAST INC. Lignite NPs (Black free-flowing powder, 100% purity, 63 nm sizes) was mechanically generated using ceramic ball mill, where the grinding period was two weeks. The particle size distribution of Lignite NPs is shown in Figure 1.

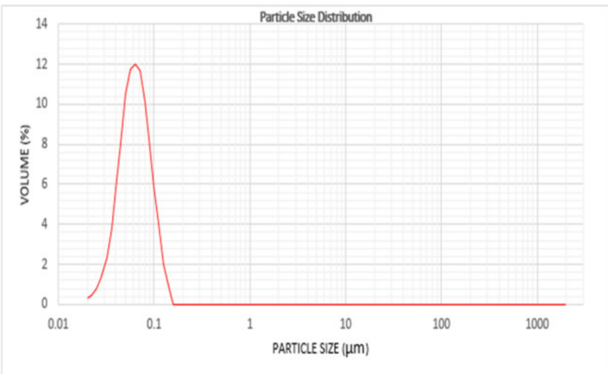

Figure 1: Particle Size Distribution of Lignite NPs.

2.2 *Experiments*

Water-based drilling fluid (350 ml distilled water + 22.5 gm bentonite) was used in these experiments. To prepare the blank sample of water-based drilling fluid, bentonite was mixed with distilled water using Hamilton Beach Mixer for 20 minutes and then the suspension was aged in a sealed container for 16 hours to ensure good hydration of bentonite. The Lignite NPs with concentrations of 0.05%, 0.1%, 0.2%, 0.5%, and 1% by weight were added to the blank sample of water-based drilling fluid and mixed for 10 minutes using Hamilton Beach Mixer then continued to mix using Ultrasonic Bath for 10 minutes to ensure a good dispersion of Lignite NPs in water-based drilling fluid samples.

Before any testing, water-based drilling fluid samples were remixed for a period ranging from 5 to 15 minutes.

Lubricating properties of water-based drilling fluid with and without Lignite NPs had been measured by using OFITE EP and Lubricity Tester as following:

- Before any test the apparatus device was calibrated with distilled water so as to calculate the value of correction factor (CF) using the following equation:

$$CF = \frac{34}{meter\ reading\ (32-34)} \quad (1)$$

- The Coefficient of friction of the drilling fluids was calculated manually using the data obtained from apparatus as follows:

$$COF = \frac{CF * meter\ reading}{100} \quad (2)$$

Each test was repeated twice in order to verify the accuracy of the results.

Rheological properties of water-based drilling fluids with and without Lignite NPs had been measured using OFITE Model 900 Viscometer as follows:

- Before any test, the apparatus was calibrated with calibration fluid that is attached originally with the apparatus to get offset degree value ranging from ± 0 to ± 0.1 so as to ensure the obtaining of accurate data.

- The rheological properties including PV, YP and gel strength were measured directly from the apparatus. Also, they can be calculated manually using the data obtained from the apparatus as follows:

$$PV = \varphi 600 - \varphi 300 \quad (3)$$

$$YP = \varphi 300 - PV \quad (4)$$

- while AV was calculated manually using the data obtained from the apparatus as follows:

$$AV = \frac{\varphi 600}{2} \quad (5)$$

- The variation of shear stress and effective viscosity with shear rate was measured directly from the apparatus at the rotational speeds (600, 300, 200, 100, 60, 30, 20, 10, 6, 3, 2, 1) RPM. Where 1RPM = 1.7 1/s

Also, the variation of effective viscosity with shear rate can be calculated manually using the data obtained from the apparatus as follows:

$$\mu e = \frac{dial\ reading\ at\ certain\ rpm \times 300}{rpm} \quad (6)$$

Finally, tests were repeated three times and the average has been taken to ensure the accuracy of the results.

Filtration properties (filtrate volume and mud cake thickness) were measured using OFITE Low-Pressure Filter Press with Dead Weight Hydraulic Assembly.

3. Results and Discussion

3.1 *Effect of Lignite NPs on Lubricity of Water-Based Drilling Fluid*

The COF and COF reduction percentage values of water-based drilling fluid are illustrated in Table 1 shown in Figure 2 & Figure 3.

Table 1: COF and COF Reduction % of Water-Based Drilling Fluid with Different Concentrations of Lignite NPs.

Weight (gm)	Wt.%	COF	COF reduction %
Blank	----	0.532	----
0.2	**0.05**	**0.546**	**- 2.63**
0.5	0.1	0.449	15.6
1	0.2	0.406	23.68
2	0.5	0.343	35.52
4	**1**	**0.291**	**45.3**

According to the results, water-based drilling fluid with concentration of 1% shows 45.3 % reduction in the COF .

As the concentration of Lignite NPs increases, the COF value of water-based drilling fluid decreases. With the exception that water-based drilling fluid with concentration of 0.05 % shows an increase of COF value compared to that of a blank sample.

According to the XRD study of Lignite, it has random layer lattice structure (graphite-like structure), for this reason Lignite may act as graphite (self-lubricating solid material) and form film on the contacting surfaces and as a result of the film formation, it will reduce the friction between the contacting surfaces [13].

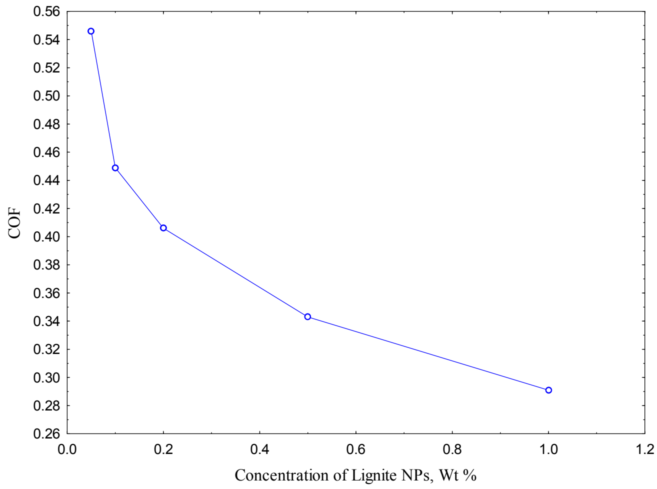

Figure 2: COF of Water-Based Drilling Fluid with Different Concentrations of Lignite NPs.

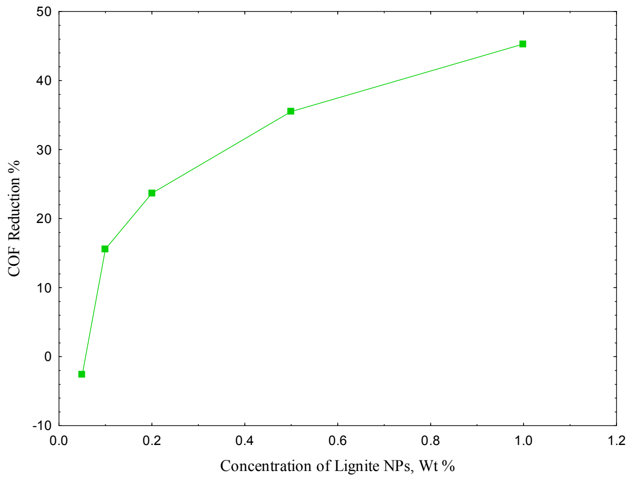

Figure 3: COF Reduction % of Water-Based Drilling Fluid with Different Concentrations of Lignite NPs.

3.2 *Effect of Lignite NPs on Rheological Properties of Water-Based Drilling Fluid*

After the addition of Nanomaterials to the drilling fluids, the rheological properties (including plastic viscosity, yield point, apparent viscosity, and gel strength) may go through some changes.

Plastic viscosity (PV) is that part of the resistance to flow caused by mechanical friction. An increase in the concentration of solids, a reduction in the size of the solid particles, increase in total surface area of solids exposed will increase the plastic viscosity. Nanomaterials have large surface area per volume, this will increase the interaction of nanomaterials with drilling fluid matrix, where the nanomaterials may link or bond directly or through intermediate chemical linkage with the drilling fluid matrix and that will cause an increase in plastic viscosity. While the reduction of plastic viscosity is due to a repulsive force between nanomaterials and drilling fluid matrix [7] [15].

Yield point (YP) is a measurement of the attractive forces (resulting from negative and positive charges located on or near the particle surfaces) in a drilling fluid under flow conditions. Yield point is increased with the addition of Nanomaterials, this may due to dispersion ability of Nanomaterials to be well distributed more effectively on the surface of the bentonite and thus increase the attractive force between them. Sometimes yield point decreased with the addition of Nanomaterials, this may be due to a repulsive force occurring between the Nanomaterials, water molecules, and bentonite particles [11] [10].

Gel strength is caused because of electrostatic forces between different mud particles. Attractive forces link Nanomaterials and mud particles and may cause an increase in gel strength of the mud. Gel strength readings taken at 10-sec (called initial gel strength) and 10-min intervals, and in critical situations at 30 min intervals [11].

The effect of Nanomaterials is sometimes unstable during the addition of them at different concentrations, so the discussion of the rheological properties is based on the concentration of Lignite NPs that had yielded good results in improving the lubrication properties. Rheological properties of water-based drilling fluid with different concentrations of Lignite NPs at room temperature (35 °C) are illustrated in **Table 2** and shown in **Figures 4** to **6**.

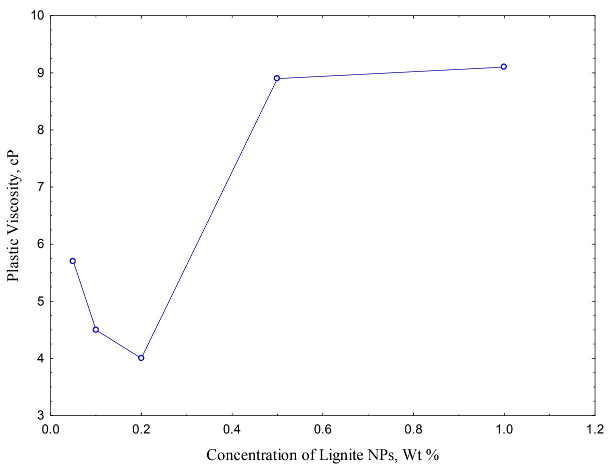

Figure 4: Plastic Viscosity of Water-Based Mud Drilling Fluid with Different Concentrations of Lignite NPs.

The effect of Lignite NPs on water-based drilling fluid causes unstable changes in the rheological properties as shown in Table 2. The best results in COF is obtained when 4 gm of Lignite NPs is added, and this addition causes a decrease in YP and AV to 31.5 lbf/100 ft² and 23.7 cP, respectively. Gel strength results showed different trend, as discussed below.

Lignite is a deflocculant but also referred to as thinner for water based mud, serves for filtration reduction, oil emulsification, and stabilization of properties against high temperature effects. It is an organic acid that also supplies anions to the fluid, thus causing clay particles to repel one another and reduce the yield point, gel strength and flow index of the drilling fluid [4].

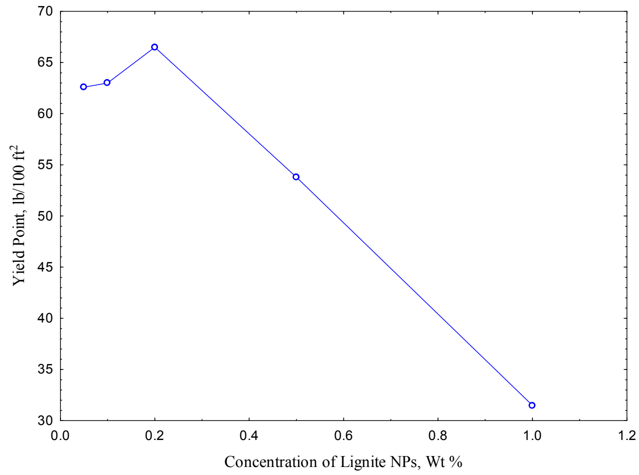

Figure 5: Yield Point of Water-Based Drilling Fluid with Different Concentrations of Lignite NPs.

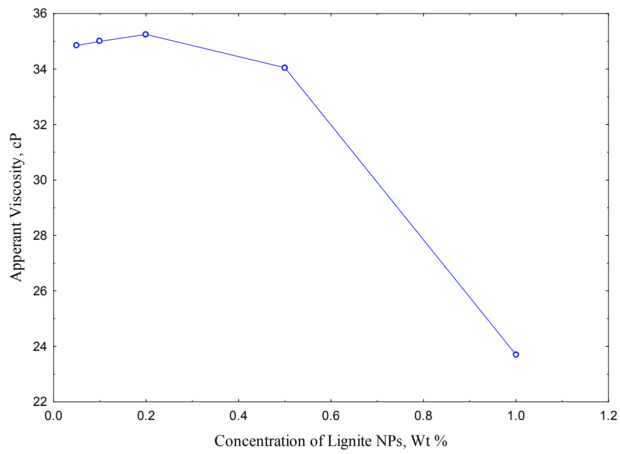

Figure 6: Apparent Viscosity of Water-Based Drilling Fluid with Different Concentrations of Lignite NPs.

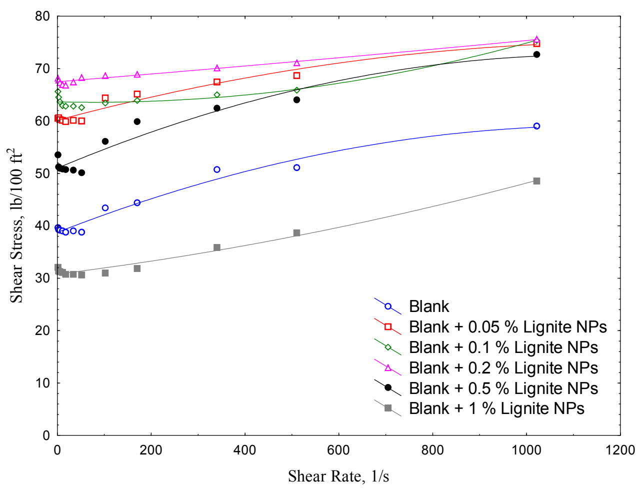

Figure 7: Consistency Curves of Water-Based Drilling Fluid with Different Concentrations of Lignite NPs.

A **rheological model** is described as a relationship between the shear stress and shear rate, which is called a consistency curve. Water-based drilling fluid with different concentrations of Lignite NPs exhibit Herschel-Bulkley model (using statistical analysis) as shown in **Figure 7**. The Herschel-Bulkley model completely describes drilling fluids because it closely matches the flow profile of a typical drilling fluid.

The equations for the Herschel-Bulkley model are [11]:

$$\tau = \tau_0 + K\,\Upsilon^{n} \quad (7)$$

$$n = 3.32 \log\left(\frac{\emptyset 600 - \tau_0}{\emptyset 300 - \tau_0}\right) \quad (8)$$

$$K = \frac{\emptyset 300 - \tau_0}{511^{n}} \quad (9)$$

The behavior of water-based drilling fluid with different concentrations of Lignite NPs is illustrated in **Table 3** and shown in **Figure 7**, while Herschel-Bulkley parameters are illustrated in **Table 4**. Water-based drilling fluid with different concentrations of Lignite NPs exhibit **shear-thinning behavior** so that the effective viscosity decreases as the shear rate increases, as illustrated in **Table 5** and shown in **Figure 8**.

3.3 *Effect of Lignite NPs on Filtration of Water-Based Drilling Fluid*

Filtration properties of water-based drilling fluid with different concentrations of Lignite NPs are illustrated in **Table 6** and shown in **Figures 9** and **10**.

The discussion of the effect of Lignite NPs on filtration properties is based on the concentration of Lignite NPs that has yield good results in improving the lubrication properties.

Table 2: Rheological Properties of Water-Based Drilling Fluid with Different Concentrations of Lignite NPs.

weight (gm)	Wt.%	PV (cP)	YP (lb_f/100 ft²)	AV (cP)	YP/PV (lb_f/100 t²/cP)	10 sec gel (lb_f/100 ft²)	10min gel (lb_f/100 ft²)
Blank	----	7.1	43.7	27.55	6.154	41.8	88.5
0.2	0.05	5.7	62.6	34.85	10.912	63.4	91.4
0.5	0.1	4.5	63	35	14	66.5	116.2
1	0.2	4	66.5	35.25	16.625	75.1	120.7
2	0.5	8.9	53.8	34.05	6.044	66	115.9
4	1	9.1	31.5	23.7	3.461	42.4	107.2

Table 3: Shear Stress of Water Based-Drilling Fluid with Different Concentrations of Lignite NPs.

Shear Rate		**Shear Stress (lb/100 ft²)**					
		Lignite NPs Concentration, Wt.%					
RPM	**1/sec**	**Blank**	**0.05%**	**0.1%**	**0.2%**	**0.5%**	**1%**
1	1.7	39.7	60.5	65.6	68.2	53.5	32.1
2	3.4	39.3	60.6	64.5	67.8	51.3	31.4
3	5.11	39.2	60.3	63.7	67.3	51	31.2
6	10.21	39	60.2	63	67	50.9	31.1
10	17.02	38.8	59.9	62.8	66.8	50.7	30.8
20	34.05	39	60.1	62.8	67.5	50.6	30.8
30	51.07	38.8	60	62.6	68.3	50.2	30.6
60	102.14	43.4	64.4	63.5	68.7	56.1	31
100	170.23	44.4	65.1	63.9	68.9	59.9	31.8
200	340.46	50.7	67.5	65	70.1	62.5	35.9
300	510.69	51.1	68.7	65.9	71.1	64.1	38.7
600	1021.38	59	74.8	75.4	75.6	72.7	48.5

Adding 4gm of Lignite NPs to water-based drilling fluid caused a slight increase in filtrate volume to 12.8 ml and a decrease in mud cake thickness to 0.846 mm. The increase percentage was 10.34% for filtrate volume, while the reduction percentage was 34.32% for mud cake thickness.

Nanomaterials addition to the drilling fluid causes an increase in filtrate loss volume, this may be explained due to solid accumulation which makes the mud less stable, that means impermeable and low porosity mud cake cannot be obtained and more filtrate can pass through the mud cake [6].

Lignite NPs with 2gm and 4gm concentration caused a slight decrease in the **stability** of mud as a result of the formation of foam at the surface of the drilling fluid through two hours of the test.

Table 4: H-B Parameters of Water-Based Drilling Fluid with Different Concentrations of Lignite NPs.

	H-B Parameters		
	Lignite NPs		
Weight (gm)	**τ_0 (lb/100 ft²)**	**n**	**K (lb. sec^{-n} /100 ft²)**
Blank	39.5	0.8419	0.0456
0.2	60.6	1.3370	0.0008
0.5	62.9	1.7564	3.6738E-05
1	67.4	--------	---------
2	51.9	1.0912	0.0084
4	30.4	1.0337	0.0131

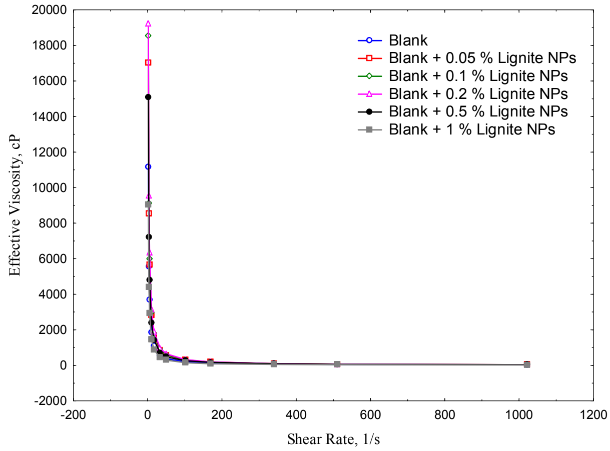

Figure 8: Effective Viscosity versus Shear Rate of Water-Based Drilling Fluid with Different Concentrations of Lignite NPs.

Table 5: Effective Viscosity of Water-Based Drilling Fluid with Different Concentrations of Lignite NPs.

Shear Rate		Effective Viscosity (cP)					
		Lignite NPs Concentration, Wt%					
RPM	**1/sec**	**Blank**	**0.05%**	**0.1%**	**0.2%**	**0.5%**	**1%**
1	1.7	11175.1	17034.4	18525.9	19205.4	15090.4	9055.1
2	3.4	5535.5	8540.5	9101.7	9558	7226.2	4423.7
3	5.11	3682.1	5669	5984.4	6328.4	4787.3	2927.5
6	10.21	1831.8	2826.4	2959.4	3145.5	2392.1	1459.8
10	17.02	1094.8	1687.3	1769.2	1884	1428.4	869
20	34.05	549.4	846.2	884.4	951.7	713.6	433.8
30	51.07	363.5	564.2	588.1	645.2	472	288
60	102.14	204	302.7	298.3	322.9	263.4	145.5
100	170.23	125.3	183.4	180	194.2	168.9	89.7
200	340.46	71.5	95.2	91.7	98.8	88.1	50.7
300	510.69	47.9	64.4	61.9	66.7	60.2	36.4
600	1021.38	27.6	34.8	35.1	35.3	34	22.8

Table 6: Filtration Properties of Water-Based Drilling Fluid with Different Concentrations of Lignite NPs.

Weight (gm)	**Wt. %**	**Density (ppg)**	**pH (pH-meter)**	**pH (pH-paper)**	**Stability %**	**V7.5 (ml)**	**V30 (ml)**	**Mud cake thickness (mm)**
Blank	----	8.6	8.45	9	100	5.8	11.6	1.288
0.2	0.05	8.6	8.13	9	100	6.4	12.8	1.108
0.5	0.1	8.62	8.02	9	100	6.4	12.8	1.044
1	0.2	8.65	7.86	8	100	5.8	11.6	1.036
2	**0.5**	**8.3**	7.81	8	**99**	6	12	0.908
4	**1**	**<8**	7.44	8	**98**	6.4	**12.8**	**0.846**

Lignite NPs with 2gm and 4gm concentration caused a decrease in the **density** of mud as a result of the formation of foam within the drilling fluid matrix.

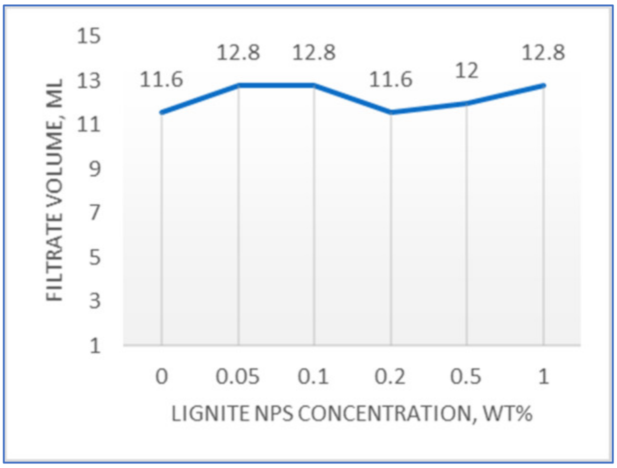

Figure 9: Filtrate Volume at 30 min of Water-Based Drilling Fluid with Different Concentration of Lignite NPs.

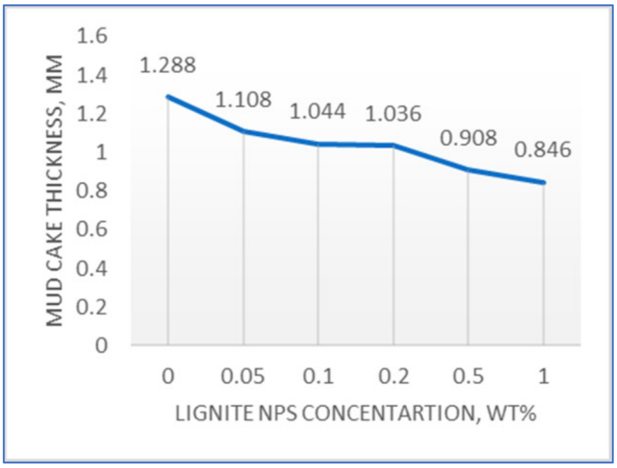

Figure 10: Mud Cake Thickness of Water-Based Drilling Fluid with Different Concentrations of Lignite NPs.

4. Conclusion

- Lignite NPs can be used to enhance the lubricating performance and reduce COF of water-based drilling fluid system.
- The addition of Lignite NPs with concentrations up to 1% by weight to water-based drilling fluid can reduce COF up to 45.3 %.
- The effect of Lignite NPs on water-based drilling fluid causes unstable changes in the rheological properties.
- The best result in COF is obtained when 4 gm of Lignite NPs is added, and this addition causes a decrease in YP and AV with a decrease percentage of 27.9% and 13.9%, respectively.
- Adding 4gm of Lignite NPs to water-based drilling fluid causes a slight increase in filtrate volume with an increase percentage of 10.34% and a decrease in mud cake thickness with a decrease percentage of 34.32%.
- Water-based drilling fluid with different concentrations of Lignite NPs exhibit shear-thinning behavior.

Nomenclature

Symbol	Description	Unit
k	Consistency index	lb.s^n/100 ft^2
n	Flow behavior index	Dimension-less
V_{30}	Filtrate volume at 30 min	ml
$V_{7.5}$	Filtrate volume at 7.5 min	ml
$\dot{\gamma}$	Shear rate	1/s
$\varphi 300$	Viscometer dial reading at 300 rpm	lb_f/100 ft^2
$\varphi 600$	Viscometer dial reading at 600 rpm	lb_f/100 ft^2
μ_e	Effective viscosity	cP
τ	Shear stress	lb_f/100 ft^2
τ_0	Yield stress	lb_f/100 ft^2

Abbreviations

AV	Apparent Viscosity
CF	Correction Factor
COF	Coefficient of Friction
NPs	Nano Particles
PV	Plastic Viscosity
YP	Yield Point

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تحسين خواص التزييت لسائل الحفر ذو الاساس المائي باستخدام جزيئات اللكنايت النانوية بالاضافة الى دراسة تاثيرها على الخواص الريولوجية و الترشيح

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الخلاصة – في مرحلة حفر الابار الموجهة و الابار الافقية, تتولد قوى الاحتكاك بين عمود الحفر و السطح الداخلي للبئر او البطانة والتي تؤدي الى حدوث عدة مشاكل من ضمنها زيادة عزم الدوران بشكل كبير والذي يعد من اهم المشاكل التي تحدث اثناء عمليه حفر الابار النفطية. سائل الحفر له دور مهم في تقليل قوى الاحتكاك المتولدة بين عمود الحفر و السطح الداخلي للبئر او البطانة. في هذا البحث سيتم تحسين تزييت سائل الحفر ذو الاساس المائي باستخدام جزيئات اللكنايت النانوية. تم قياس كل من التزييت و الخواص الريولوجية والترشيح لسائل الحفر عند درجة حرارة الغرفة باستخدام الاجهزة المختبرية OFITE EP and Lubricity Tester, OFITE Model 900 Viscometer, and OFITE Low-Pressure Filter Press,على التعاقب. اضيفت جزيئات اللكنايت النانوية بتراكيز مختلفة (0.05%, 0.1%, 0.2%, 0.5%,1%) كنسبة وزنية الى سائل الحفر ذو الاساس المائي. اضهرت جزيئات اللكنايت النانوية تحسين ملحوظ في معامل الاحتكاك لسائل الحفر ذو الاساس المائي. حيث ان نسبه انخفاض معامل الاحتكاك تزداد بازدياد تراكيز جزيئات اللكنايت النانوية, اعلى نسب انخفاض لمعامل الاحتكاك كانت % 45.3 ,35.52%, 23.68% تم الحصول عليها باضافة جزيئات اللكنايت النانوية بتراكيز 1% ,0.5%, 0.2%, على التعاقب.

الكلمات الرئيسية – سائل الحفر ذو الاساس المائي، معامل الاحتكاك، المواد النانوية، الخواص الريولوجية، خواص الترشيح.