University of Baghdad
College of Engineering
JE
JOURNAL OF ENGINEERING

Journal of Engineering

journal homepage: www.joe.uobaghdad.edu.iq
Number 2 Volume 25 February 2019

Chemical, Petroleum and Environmental Engineering

Enhancement in Lubricating, Rheological, and Filtration Properties of Unweighted Water-Based Mud Using XC Polymer NPs

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ABSTRACT

In this research, an enhancement in lubricating, rheological, and filtration properties of unweighted water-based mud is fundamentally investigated using XC polymer NPs with 0.2gm, 0.5gm, 1gm, 2gm, and 4gm concentrations. Bentonite, that had been used in the preparation of unweighted water-based mud, was characterized using XRF-1800 Sequential X-ray Fluorescence Spectrometer, XRD-6100/7000 X-ray Diffractometer, and Malvern Mastersizer 2000 particle size analyzer, respectively. Lubricating, rheology and filtration properties of unweighted water-based mud were measured at room temperature (35°C) using OFITE EP and Lubricity Tester, OFITE Model 900 Viscometer, and OFITE Low-Pressure Filter Press, respectively. XC Polymer NPs show a good enhancement in lubricating, rheology and filtration properties of unweighted water-based mud. The effect of XC Polymer NPs on lubricating properties was denoted at 4gm concentration, where the reduction percentage in COF was 30%. An increase in PV, YP, AV, gel strength of unweighted water-based mud was obtained due to the addition of XC Polymer NPs at concentrations up to 4gm. A reduction in filtrate volume and mud cake thickness of unweighted water-based mud was obtained due to the addition of XC Polymer NPs at 2gm and 4gm concentrations, the best result was obtained with using 4gm concentration, the reduction percentage of filtrate volume was 20.7% and mud cake thickness was 41%.

Keywords: unweighted water-based mud, nanomaterials, COF, rheological and filtration properties.

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Peer review under the responsibility of University of Baghdad.
https://doi.org/10.31026/j.eng.2019.02.07

Article received: 17/1/2018
Article accepted: 29/4/2018

تحسين خواص التزييت، الخواص الريولوجية، و خواص الترشيح لسائل الحفر ذو الاساس المائي الغير مثقل باستخدام جزيئات البوليمر النانوية

الخلاصة

في هذا البحث تم دراسة امكانية تحسين خواص التزييت والخواص الريولوجية ووخواص الترشيح لسائل الحفر ذو الاساس المائي الغير المثقل باستخدام جزيئات البوليمر النانوية بتراكيز 0.2gm, 0.5gm, 1gm, 2gm, and 4gm . تم قياس خواص البنتونايت الذي استخدم في تحظير سائل الحفر باستخدام الاجهزة المختبرية XRF-1800 Sequential X-ray Fluorescence Spectrometer, XRD-6100/7000 X-ray Diffractometer, and Malvern Mastersizer 2000 particle size analyzer. 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. اضهرت جزيئات البوليمر النانوية تحسين في خواص التزييت، الخواص الريولوجية، وخواص الترشيح لسائل الحفر ذو الاساس المائي الغير المثقل. يمكن ملاحظة تاثير جزيئات البوليمر النانوية على خواص التزييت لسائل الحفر ذو الاساس المائي الغير المثقل عند تركيز 4gm حيث كانت نسبة انخفاض معامل الاحتكاك لسائل الحفر تساوي 30%. اضهرت النتائج زيادة في الخواص الريولوجية عند اضافة جزيئات البوليمر النانوية بمختلف تراكيزه المستخدمة. كما اضهرت النتائج انخفاض في حجم الراشح و سمك كعكة الطين عند اضافة جزيئات البوليمر النانوية بتراكيز 2gm و 4gm ، ان افضل نتيجة تم الحصول عليها عند اضافة جزيئات البوليمر النانوية بتركيز 4gm، حيث كانت نسبة انخفاض حجم الراشح 20.7% ونسبة انخفاض سمك كعكة الطين 41%.

الكلمات الرئيسية: سائل الحفر ذو الاساس المائي الغير مثقل، المواد النانوية، معامل الاحتكاك، الخواص الريولوجية و خواص الترشيح.

1. INTRODUCTION

Drilling fluid is used in drilling operations to coal the bit, lubricate the rotating drill pipe, clean the hole effectively, and control formation pressure, but if the fluid lacks in any of functional requirements could lead to severe drilling problems such as lost circulation, pipe sticking, formation damage, erosion of the borehole, poor hole cleaning and torque and drag that significantly reduces the efficiency of drilling, **Nabhani**, and **Emami**, **2012**.
Nanotechnology generates products that have many unique characteristics, which can play an active role in improving mud cake quality, maintaining borehole stability, protecting the reservoir, and meeting the needs of drilling operations under complicated geological conditions. Nanomaterials have the potential of revolutionary impact in the fields of drilling fluids and reservoir protection. Currently, nanomaterials are considered to be the most promising matter of choice for design and development of novel drilling fluids as well as materials for reservoir protection, and may offer a better solution to petroleum industry problems that cannot be solved with traditional methods, so they have a bright prospect in oil and gas development and production, **Long**, **et al.**, **2012**. The desire to either solve problems that have been outstanding for years or just develop products that perform more effectively and efficiently has motivated drilling fluids′ researchers to look towards nanotechnology and see what benefits it may bring in the area of lubricity, rheology, filtration, and shale stability, **Friedheim**, **et al.**, **2012**.

Researchers had shown that using nanomaterials as additives can enhance lubricity, rheology, and filtration properties of drilling fluids. **Fereydouni**, **et al.**, **2012**, studied the effect of bulk and nano-size Polyanionic Cellulose on water loss volume and mud-cake thickness in water-based mud. **Jahns**, **2014**, investigated the effect of alumina, titania and silica nanoparticles on the tribological and rheological properties of water-based mud at different temperature conditions (25°C, 50°C, and 75°C). **Jabrayilov**, **2014**, studied the effect of titania and silica nanoparticles on the tribological and rheological properties of oil-based mud at different temperature conditions (25°C, 50°C, and 100°C), also presented the advantage of using nano-scale additives in the drilling fluid by making a comparison between the effect of microparticles and nanoparticles of silica on the friction factor of oil-based mud. **Ragab**, and **Noah**, **2014**, investigated the impact of the addition of silica nanoparticles on the filtration properties of water-based mud, also studied the effect of the size and concentration of silica nanoparticles on these properties of water-based mud. **Ismail**, **et al.**, **2014**, investigated the influence of different concentrations of nanoparticles (multi-walled carbon nanotube, titanium oxide nanoparticles, aluminum oxide nanoparticles, and copper oxide nanoparticles) on the rheological properties of water-based drilling fluid at room and elevated temperatures (250°F). **Ismail**, **et al.**, **2014**, studied the improvement of rheological properties of water-based and ester-based drilling fluids using multi-walled carbon nanotubes (MWCNTs) at different temperature conditions (80°F, 200°F, 250°F), also determined the optimum concentration of MWCNTs to produce better rheological properties in both water-based and ester-based drilling fluids. **Taha**, and **Lee**, **2015**, estimated the impact of Graphene-enhanced product which is a blend of proprietary surfactants engineered with Nano Graphene on the lubricity, rheology, filtration and shale compatibility of water-based drilling fluid. **Krishnan**, **et al.**, **2016**, studied the efficiency of boron-based nanomaterial enhanced additive in improving the water-based drilling fluid performance. **Caldarola**, **et al.**, **2016**, surveyed improvement of weighted water-based drilling fluid's lubricity coefficient using chemically and mechanically generated barite nanoparticles. **Abdo**, and **Al-Sharji**, **2016**, investigated the enhancement of lubricity and rheological properties of water-based drilling fluids by using nano-sepiolite at normal and HTHP conditions. Also, the influences of various sizes and compositions (4 samples of size range 30-60 nm and 4 samples of size range 60-90 nm with different dispersion behavior) of the nano-sepiolite on the stability of drilling fluids on HTHP conditions were investigated. **Al-Ogaili**, and **Suripis**, **2016**, analyzed the effect of TiO_2 nanoparticles with different concentrations (0.05ppb, 0.1ppb, 0.5ppb, and 1ppb) on rheology, filtration and lubricity characteristics of water-based drilling fluid and oil-based drilling fluid. **Dhiman**, **2016**, studied the effect of nanoparticles on various drilling fluid properties, including lubricity, rheology, and filtration, considering several influence factors, such as the concentration of nanoparticle, size of the nanoparticle, type of nanoparticle, temperature, and aging. **Al-Zubaidi**, **et al.**, **2016**, studied the feasibility of using Iraqi clay as a source of drilling fluid, also investigated the effect of nano commercial bentonite and nano chemical materials (MgO, TiO_2, Graphene) on rheological and filtration properties of water-based mud. **Ismail**, **et al.**, **2016**, investigated the applicability of multi-walled carbon nanotubes (MWCNTs), nano silica and glass beads (GBs) as primary additives for enhancing rheology, lubricity and filtration properties of water-based drilling fluid. Also, effect of GBs of different sizes such as (90–150 μm) and (250–425 μm) was investigated at different concentrations (2ppb, 4ppb, 6ppb, 8ppb, 10ppb, 12ppb) on the properties of water-based drilling fluid. **Salih**, **et al.**, **2016**, studied the effect of silica dioxide nanoparticles on the rheological and filtration properties of high pH water-based drilling fluid and low pH water-based drilling fluid. **Aftab**, **et al.**, **2017**, revealed the improvement of rheological properties and shale inhibition of water-based drilling fluid using nano silica, multi-walled carbon nanotube, and Graphene nanoplatelet. **Vegard**, and

Belayneh, **2017**, and **Wrobel**, and **Belayneh**, **2017**, showed improving performance of polymer/salt treated bentonite drilling fluid system using titanium nitride (TiN), MoS_2 and Graphene nanoparticles. Summary of experimental studies on the effect of Nanomaterials on lubricity, rheology, and filtration properties of drilling fluids is illustrated in **Table1**.

Table 1. Summary of experimental studies on the effect of nanomaterials on lubricity, rheology, and filtration properties of drilling fluids.

References	Nanomaterials	Concentrations	Base Fluid	Observations
Fereydouni, et al., 2012	Nano size Polyanionic Cellulose	1 gm - 10 gm	Water-based drilling fluid	The addition of Polyanionic Cellulose Nanoparticles to the water-based mud resulted in a desirable reduction of water loss volume and mud cake thickness
Jahns, 2014	Alumina, Titania, and Silica Nanoparticles	0.1% - 0.5% by weight	Water-based drilling fluid	Titania, and Silica Nanoparticles reduced friction factor effectively, while Alumina Nanoparticles had a limited friction reduction
Jabrayilov, 2014	Titania and Silica Nanoparticles	0.1% - 0.5% by weight	Oil-based drilling fluid	47% reduction in friction factor was obtained by using 0.25% by weight of Silica Nanoparticles at the temperature of 50°C
Ragab and Noah, 2014	Silica Nanoparticles	10% - 60% wt./vol.	Water-based drilling fluid	56% reduction in fluid loss was obtained by using concentration of 20% - 30% wt./vol.
Ismail, et al., 2014	Multi-Walled Carbon Nanotube, Titanium Oxide, Aluminum Oxide, and Copper Oxide Nanoparticles	0.001 gm - 1 gm	Water-based drilling fluid	Increasing the concentration of MWCNT and aluminum oxide in water-based drilling fluid resulted in higher plastic viscosity, yield point, and gel strength. On the other hand, titanium oxide and copper oxide resulted in decreased plastic viscosity, yield point, and gel strength
Ismail, et al., 2014	Multi-Walled Carbon Nanotubes	0.001 ppb - 0.1 ppb	Water-based drilling fluid & ester-based drilling fluid	Rheological and filtration properties showed better improvement with the addition of MWCNTs
Taha and Lee, 2015	Nano Graphene	1% - 5% by volume	Water-based drilling fluid	80% torque reduction in salt polymer water-based drilling fluid and 50% torque reduction in HTHP water-based drilling fluid was obtained by using 4% - 5% by volume of the product
Krishnan, et al., 2016	boron-based Nanomaterial enhanced additive	1% - 5% by volume	Water-based drilling fluid	80% torque reduction in 10 lb/gal water-based drilling fluid and 52% torque reduction in 13.5 lb/gal water-based drilling fluid was obtained by using 5% by volume of the product
Coldarola, et al., 2016	chemically and mechanically generated Barite Nanoparticles	3% by weight	Water-based drilling fluid	A reduction in the friction coefficient of more than 34 % was achieved using a concentration of 3% by weight of chemically generated Barite Nanoparticles and that mechanically generated Nanoparticles reduced the friction coefficient by more than 15 %

Abdo and Al-Sharji, 2016	Nano-Sepiolite	2% - 5% by weight	Water-based drilling fluid	A 34 % reduction in the friction force was observed at HTHP conditions (175°C and 14 Kpsi) by using 4% by weight of Nano-Sepiolite with size range 30-60 nm
Al-Ogaili and Suripis, 2016	TiO_2 Nanoparticles	0.05 ppb - 1 ppb	Water-based drilling fluid & Oil-based drilling fluid	34% torque reduction in water-based drilling fluid and 28% torque reduction in oil-based drilling fluid was obtained by using a concentration of 0.5 ppb
Dhiman, 2016	Al_2O_3, Fe_3O_4, and SiO_2 Nanoparticles (with and without KH550 coating)	0.01% - 1% by weight	Water-based drilling fluid	Lubricity of drilling mud was improved with the addition of SiO2 Nanoparticle with and without coating, performing of SiO2 Nanoparticle with KH550 coating was better than SiO2 Nanoparticle without coating
Al-Zubaidi, et al., 2016	Nano Commercial Bentonite, MgO, TiO_2, and Graphene Nanomaterials	0.005% - 0.4% by weight	Water-based drilling fluid	MgO Nano additives gave the best rheological and filtration results
Ismail, et al., 2016	Multi-Walled Carbon Nanotubes (MWCNTs) & Nano Silica	0.001 ppb - 0.2 ppb	Water-based drilling fluid	MWCNTs could be a better choice as a drilling fluids additive for water-based drilling fluid
Salih, et al., 2016	Silica Dioxide Nanoparticles	0.1% - 0.7% by weight.	Water-based drilling fluid	Silica Dioxide Nanoparticles improved the rheological and filtration properties of water-based drilling fluids with very small concentrations (0.1% - 0.3%) by weight
Aftab, et al., 2017	Nano Silica, Multi-Walled Carbon Nanotube, and Graphene Nanoplatelet	0.1 ppb	Water-based drilling fluid	0.1 ppb Graphene increased PV by 5% and YP by 8%, also it decreased API and HPHT filtrate loss volume by 8% and 12.5%, respectively
Belayneh, et al., 2017	Titanium Nitride (TiN), MoS_2 and Graphene Nanoparticles	0.05 gm - 0.4 gm	Water-based drilling fluid	46%, 34% and 44% reduction in the coefficient of friction was obtained using 0.05 gm Titanium Nitride, 0.1gm Graphene, and 0.2 gm MoS2 Nanoparticles, respectively

2. EXPERIMENTAL WORK

2.1 Materials

2.1.1 Bentonite

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

2.1.2 XC Polymer NPs

Xanthan Gum (XC-Polymer) was supplied by OREN HYDROCARBONS MIDDLE EAST INC. XC Polymer NPs (Cream color free-flowing powder, 100% purity, and 10.68 - 339.68 nm sizes) was prepared mechanically by grinding it for three weeks using ceramic ball miller. The particle size distribution of XC Polymer NPs is shown in **Fig. 1**.

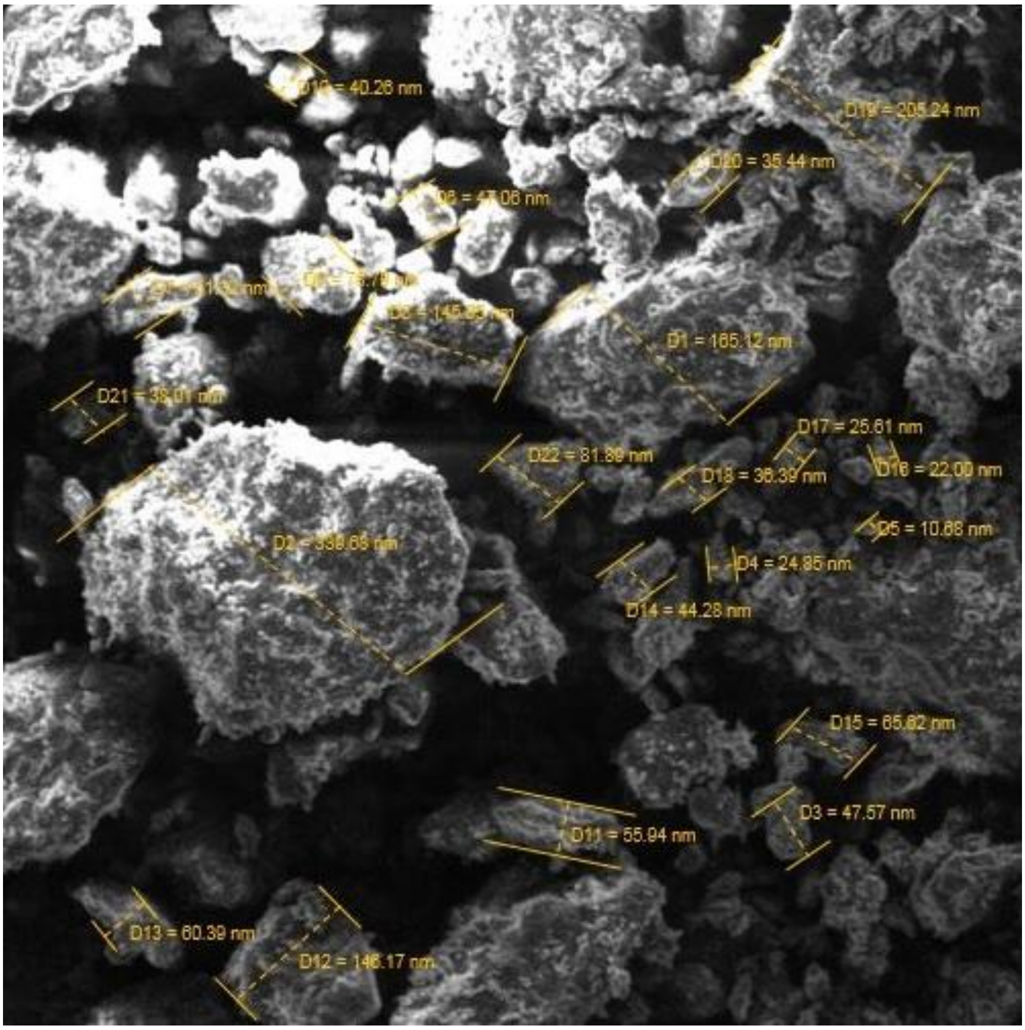

Figure 1. SEM image of XC Polymer NPs.

2.2 Procedure of Experiments

2.2.1 Drilling fluid preparation

To prepare the blank sample of water-based mud, the 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. XC Polymer NPs with concentrations of 0.2, 0.5, 1, 2, 4 gm were added to unweighted water-based mud and mixed for 10 minutes using Hamilton Beach Mixer then the samples were continued to mix using Ultrasonic Bath for 10 minutes to ensure a good dispersion of nanomaterials in the drilling fluid samples.

It is important to mention that the blank sample of unweighted water-based mud doesn’t have any other chemicals, just water, and bentonite, in its formulation. This is in order to investigate the effect of XC Polymer NPs on the drilling fluid properties without the side effect of chemicals.

Before any testing, the drilling fluid samples are remixed for a period ranging from 5 to 15 minutes.

2.2.2 Lubricity measurements

The lubricating properties of unweighted water-based mud with and without XC polymer 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 the correction factor (CF) using the following equation:

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

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

$$COF = \frac{CF * meter\ reading}{100} \tag{2}$$

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

2.2.3 Rheology measurements

Rheological properties of unweighted water-based mud with and without XC polymer 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, while AV is calculated manually using the data obtained from the apparatus as follows:

$$AV = \frac{\emptyset 600}{2} \tag{3}$$

- The variation of shear stress and effective viscosity with shear rate is 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

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

2.2.4 Filtration measurements

Filtrate loss volume (at 7.5 and 30 minutes) and mud cake thickness were measured using OFITE Low-Pressure Filter Press with Dead Weight Hydraulic Assembly.

3. RESULTS AND DISCUSSION

3.1 Bentonite Characterization Analysis

The X-Ray fluorescence (XRF) analysis of the Bentonite that is used in the preparation of unweighted water-based mud is shown in **Table 2**.

Table 2. XRF analysis of commercial bentonite.

SiO_2 %	Fe_2O_3 %	Al_2O_3 %	CaO %	MgO %	SO_3 %	LOI %	P_2O_5 %	Na_2O %	K_2O %
49.98	10	17.5	4.4	4.9	0.16	8.49	0.62	2.24	0.12

LOI: Loss on Ignition

The X-Ray diffraction (XRD) analysis of the bentonite is shown in **Fig. 2** and illustrated in **Table 3**.

Table 3. XRD analysis of commercial bentonite.

Minerals	
Major	Montmorillonite, Quartz
Minor	Palygorskite, Calcite

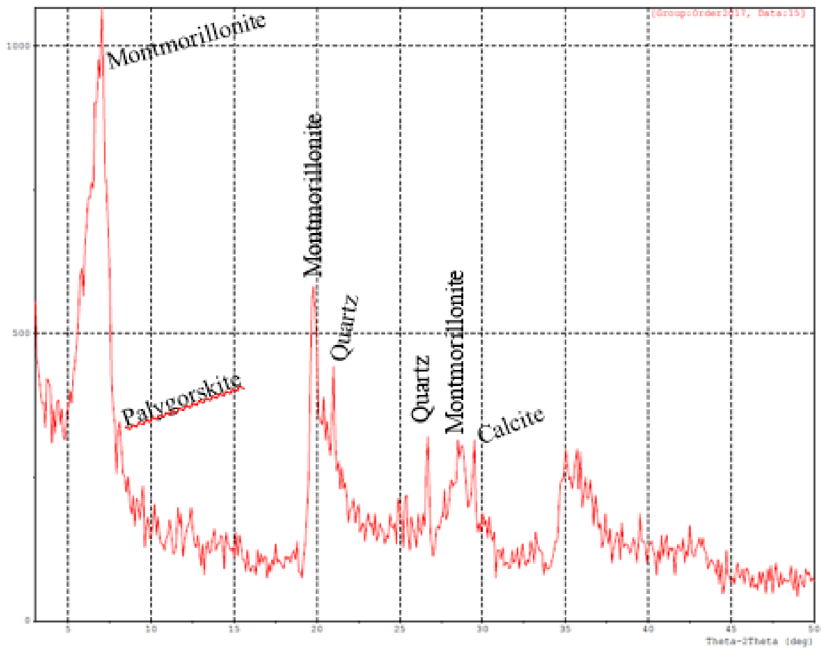

Figure 2. XRD analysis of commercial bentonite.

The particle size distribution of bentonite is shown in **Fig. 3**. The result of the particle size distribution analysis showed that the average size of bentonite is 238 nm.

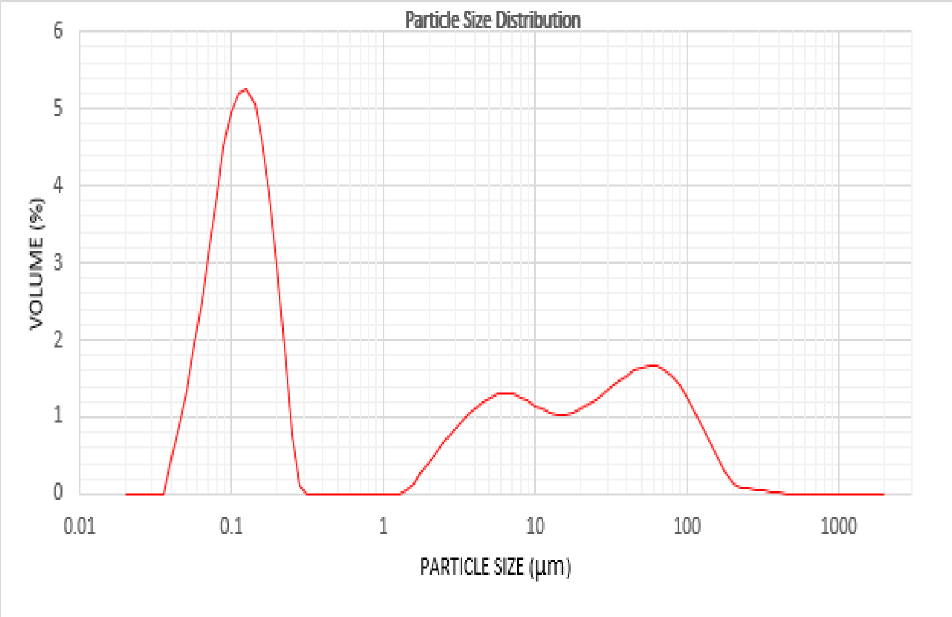

Figure 3. Particle size distribution of bentonite.

3.2 Lubricating Properties

Effect of XC polymer NPs addition to unweighted water-based mud with different concentrations on COF is illustrated in **Table 4** and shown in **Fig. 4**. The highest COF reduction percentage (30.82 %) is obtained with 4 gm XC polymer NPs.

Table 4. COF and COF reduction % of unweighted water-based mud with XC polymer NPs.

Weight (gm)	Wt.%	COF	COF reduction %
Blank	----	**0.532**	----
0.2	0.05	0.632	- 18.79
0.5	0.1	0.595	- 11.84
1	0.2	0.528	0.75
2	0.5	0.516	3
4	1	**0.368**	**30.82**

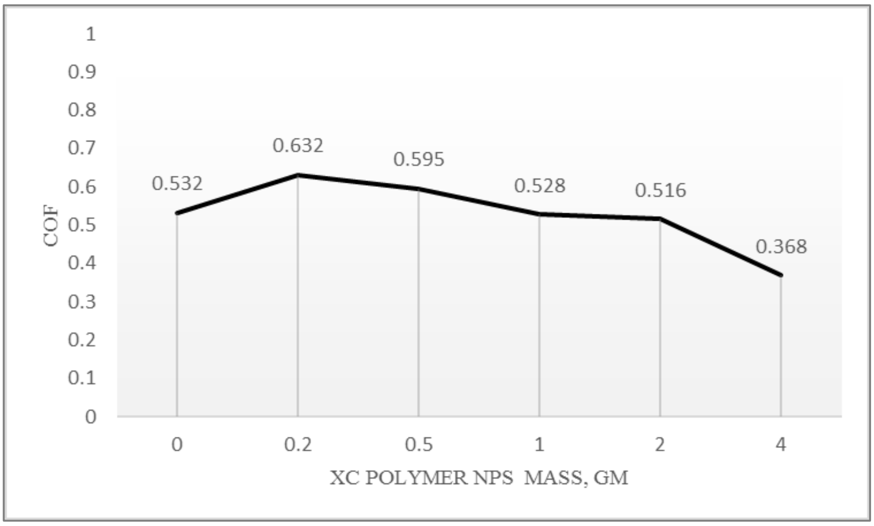

Figure 4. COF of unweighted water-based mud with different concentrations of XC polymer NPs.

As the concentration of XC polymer NPs increased, the COF value of unweighted water-based mud decreased. With the exception that unweighted water-based mud with low concentration (0.2gm and 0.5gm) showed an increase of COF value compared to that of a blank sample.
XC polymer NPs show a mixed lubrication regime, that means it will act as a boundary lubricant and establish high strength thin film on the contacting surfaces when the speed is too low and the load is too high. When the load is decreased and speed increased, it will be able to act as a hydrodynamic or elastohydrodynamic lubricant and form a wedge-shaped film between the contacting surfaces. At both situations, it will completely separate the contacting surfaces and reduce the frictional forces between them, **Vicente, et al., 2005**.

3.3 Rheological Properties

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 the 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, (Ismail, Seong, Buang, & Sulaiman, Improve Performance of Water-Based Drilling Fluids Using Nanoparticles, 2014) **Salih**, **et al.**, **2016**.
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. The yield point is increased with the addition of nanomaterials, this may be due to dispersion ability of nanomaterials to be well distributed and 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, **M-I SWACO**, **1998**, and **M.** and **M.**, **2015**.

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 were taken at 10-sec (called initial gel strength) and 10-min intervals, and in critical situations at 30 min intervals, **M-I SWACO**, **1998**.

The rheological properties (including PV, YP, AV, gel strength) of unweighted water-based mud are illustrated in **Table 5** and shown in **Figs. 5** to **8**.

Table 5. Rheological properties of unweighted water-based mud with different concentrations of XC polymer NPs.

weight (gm)	Wt.%	PV (cP)	YP (lb_f/100 ft^2)	AV (cP)	YP/PV (lb_f/100 ft^2/cP)	10 sec gel (lb_f/100 ft^2)	10min gel (lb_f/100 ft^2)
Blank	----	**7.1**	**43.7**	**27.55**	6.154	**41.8**	**88.5**
0.2	0.05	7.6	48.3	30.25	6.355	45.9	107.4
0.5	0.1	11.2	60.5	39.6	5.401	50.7	100.1
1	0.2	12.2	79.7	49.55	6.532	61.5	97.9
2	0.5	12.5	108.4	63.5	8.672	72.9	90.4
4	1	**20**	**209.9**	**119.3**	10.495	**119.6**	**125.5**

The results show that the addition of XC polymer NPs to unweighted water-based mud caused an increase in plastic viscosity (PV), yield point (YP), apparent viscosity (AV), and gel strength compared with the blank sample. Due to the effect of adding 4 gm of XC polymer NPs, high values of PV (20 cP), YP (209.9 lbf/100 ft^2), AV (119.3 cP), 10 sec gel (119.6 lbf/100 ft^2), and 10 min gel (125.5 lbf/100 ft^2) were observed. However, **Figs. 5** to **8** show that the trend of XC polymer NPs increases when the concentration increases.

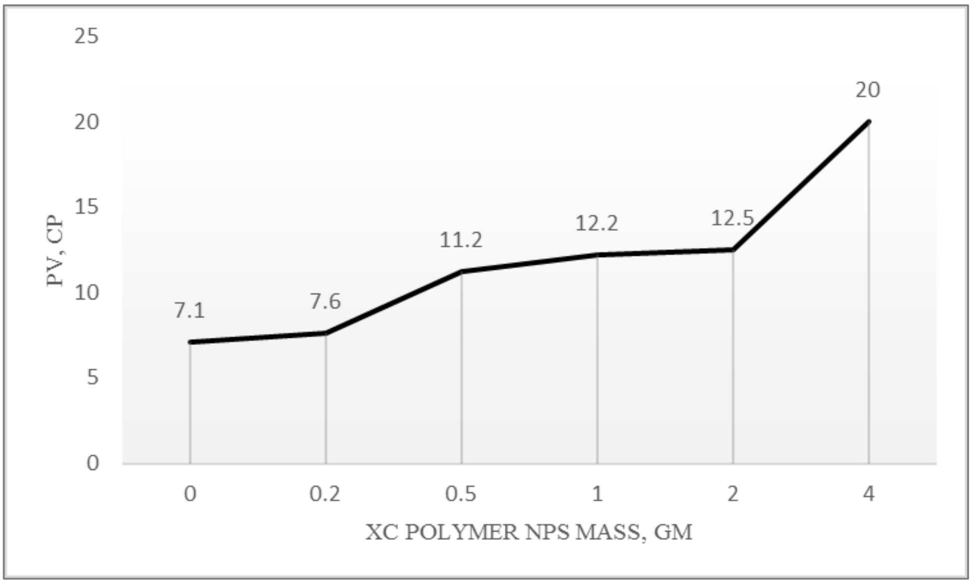

Figure 5. The plastic viscosity of unweighted water-based mud with different concentrations of XC polymer NPs.

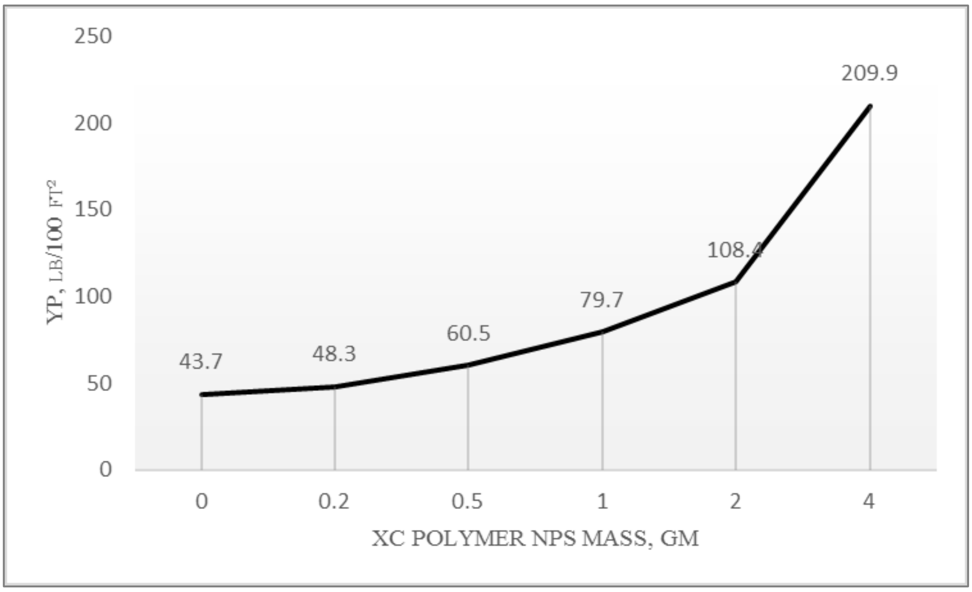

Figure 6. Yield point of unweighted water-based mud with different concentrations of XC polymer NPs.

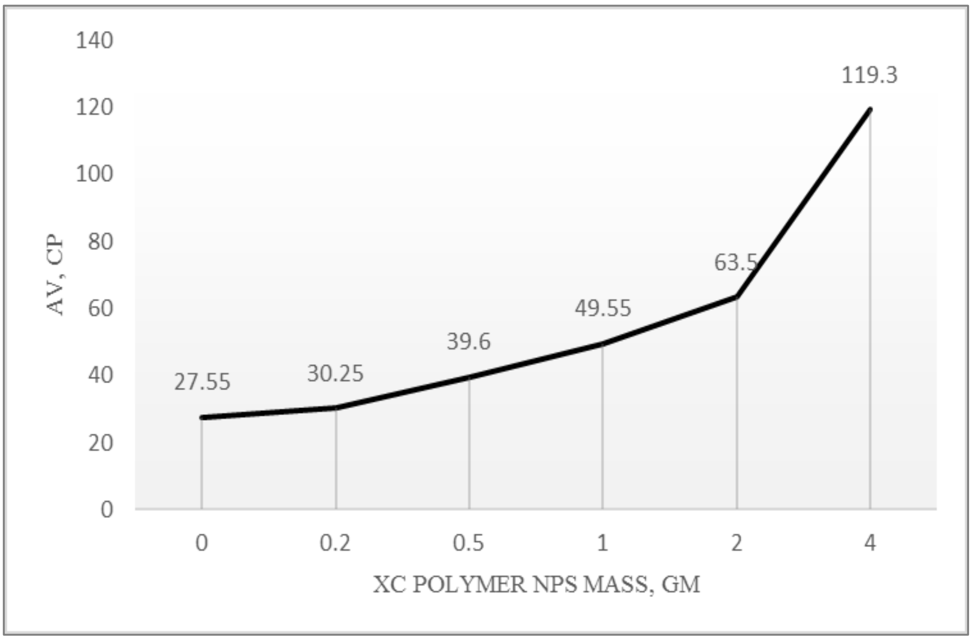

Figure 7. The apparent viscosity of unweighted water-based mud with different concentrations of XC polymer NPs.

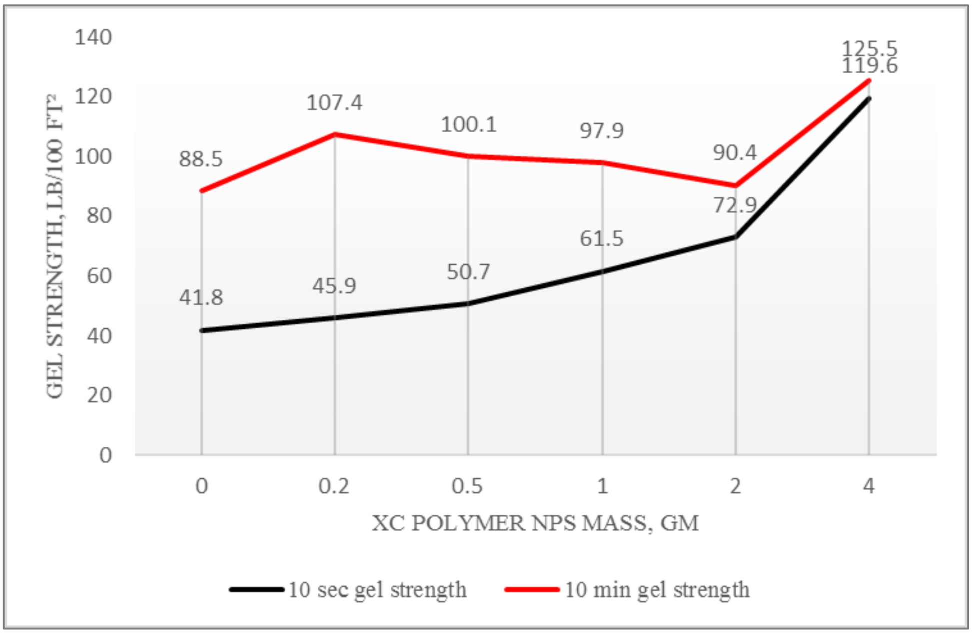

Figure 8. Gel strength of unweighted water-based mud with different concentrations of XC polymer NPs.

A *rheological model* is described as a relationship between the shear stress and shear rate, which is called a consistency curve, unweighted water-based mud with different concentrations of XC polymer NPs exhibit Herschel-Bulkley model as shown in **Fig. 9**. 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, **M-I SWACO**, **1998**:

$$\tau = \tau_0 + K\,\Upsilon^{n} \quad (4)$$

$$n = 3.32 \log\left(\frac{\emptyset 600 - \tau_0}{\emptyset 300 - \tau_0}\right) \quad (5)$$

$$K = \frac{\emptyset 300 - \tau_0}{511^{n}} \quad (6)$$

The behavior of unweighted water-based mud with different concentrations of XC polymer NPs is illustrated in **Table 6** and shown in **Fig. 9**. Whereas, H-B parameters are illustrated in **Table 7**.

Table 6. Shear stress of unweighted water-based mud with different concentrations of XC polymer NPs.

Shear Rate		**Shear Stress (lb/100 ft²)**					
		XC Polymer NPs, gm					
RPM	**1/sec**	**Blank**	0.2 gm	0.5 gm	1 gm	2 gm	**4 gm**
1	1.7	**39.7**	47.5	57.8	69	62.5	**75.6**
2	3.4	**39.3**	47.1	56.8	70.8	83.7	**97.2**
3	5.11	**39.2**	46.9	56.2	70.5	86.8	**123.7**
6	10.21	**39**	46.6	56.2	71	89.9	**151.2**
10	17.02	**38.8**	46.6	56.3	71.3	91.1	**158.2**

20	34.05	**39**	46.8	57.3	72.6	94.2	**166**
30	51.07	**38.8**	46.5	57.9	74	95.1	**169.3**
60	102.14	**43.4**	50.4	61.2	78.3	100.2	**179.9**
100	170.23	**44.4**	52.8	64.3	82.2	105.4	**188.9**
200	340.46	**50.7**	54.2	71.9	91.4	117.8	**208.5**
300	510.69	**51.1**	56.3	73.2	93.6	123.2	**224.3**
600	1021.38	**59**	64.4	84.5	106.6	135.5	**252.8**

Table 7. H-B parameters of unweighted water-based mud with different concentrations of XC polymer NPs.

	H-B Parameters		
	XC Polymer NPs		
Wt (gm)	**τ_0 (lb/100 ft²)**	**n**	**K (lb. sec⁻ⁿ /100 ft²)**
Blank	**39.5**	**0.8419**	**0.0456**
0.2	47.1	1.1585	0.0043
0.5	57.3	1.0193	0.0187
1	72.1	0.8475	0.0759
2	88.3	0.5514	0.8471
4	**141.3**	**0.3448**	**8.9147**

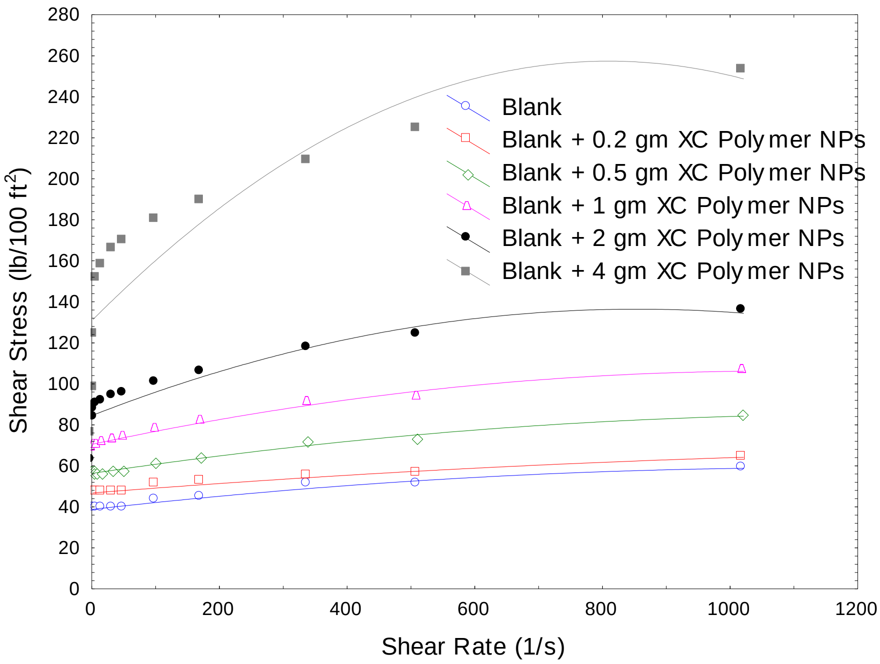

Figure 9. Consistency curves of unweighted water-based mud with different concentrations of XC polymer NPs.

Most of the non-Newtonian fluids exhibit "*shear-thinning*" behavior so that the effective viscosity decreases as the shear rate increases. Unweighted water-based mud different concentrations of XC polymer NPs exhibit shear-thinning behavior as illustrated in **Table 8** and shown in **Fig. 10**.

Table 8. Effective viscosity of unweighted water-based mud with different concentrations of XC polymer NPs.

Shear Rate		**Effective Viscosity (cP)**					
		XC Polymer NPs, gm					
RPM	**1/sec**	**Blank**	0.2 gm	0.5 gm	1 gm	2 gm	**4 gm**
1	1.7	**11175.1**	13403.1	16227.6	19419.9	17487.6	**21281.4**
2	3.4	**5535.5**	6640	8007.6	9981.8	11799.1	**13671.9**
3	5.11	**3682.1**	4411.3	5288.2	6629.1	8159.8	**11612.5**
6	10.21	**1831.8**	2192.1	2640	3335.1	4222.9	**7105.7**
10	17.02	**1094.8**	1313.6	1586.2	2009.4	2568.7	**4462.2**
20	34.05	**549.4**	659.4	807.8	1024	1328.2	**2340**
30	51.07	**363.5**	437.7	544	695.5	893.8	**1591.5**
60	102.14	**204**	236.9	287.7	368	471.3	**845.3**
100	170.23	**125.3**	148.8	181.3	231.6	297.3	**532.7**
200	340.46	**71.5**	76.4	101.3	128.8	166	**293.9**
300	510.69	**47.9**	52.7	68.6	87.8	115.6	**210.7**
600	1021.38	**27.6**	30.1	39.5	50	63.5	**118.9**

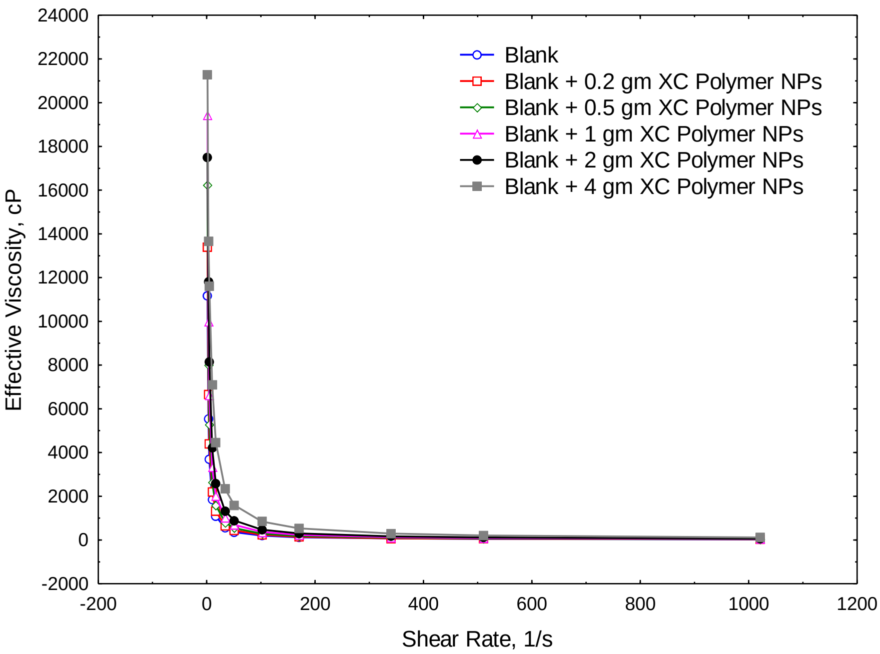

Figure 10. Effective viscosity versus shear rate of unweighted water-based mud with different concentrations of XC polymer NPs.

3.4 Filtration Properties

Filtration properties of the unweighted water-based mud with different concentrations of XC polymer NPs are illustrated in **Table 9** and shown in **Fig. 11** and **Fig. 12**.

Table 9. Filtration properties of unweighted water-based mud with different concentrations of XC polymer 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	7.83	8	100	6.2	12.4	0.958
0.5	0.1	8.6	7.68	8	100	6.6	13.2	0.924
1	0.2	8.65	7.51	8	100	6.2	12.4	0.954
2	0.5	8.7	7.36	8	100	4.8	**9.6**	**0.9**
4	1	8.75	6.56	7	100	4.6	**9.2**	**0.76**

The effect of adding 4gm of XC Polymer NPs is very obvious, where a decrease in filtrate volume to 9.2 ml and mud cake thickness to 0.76 mm was observed, the reduction percentage is 20.7% for filtrate volume and 41% 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. On the other hand, nanomaterials may cause a decrease in filtrate loss volume, this may be explained due to the ability of nanomaterials to seal the nanopore throats of the wellbore formation and prevent water infiltration, **Ismail**, **et al.**, **2014**, and **Aftab**, **et al.**, **2017**.

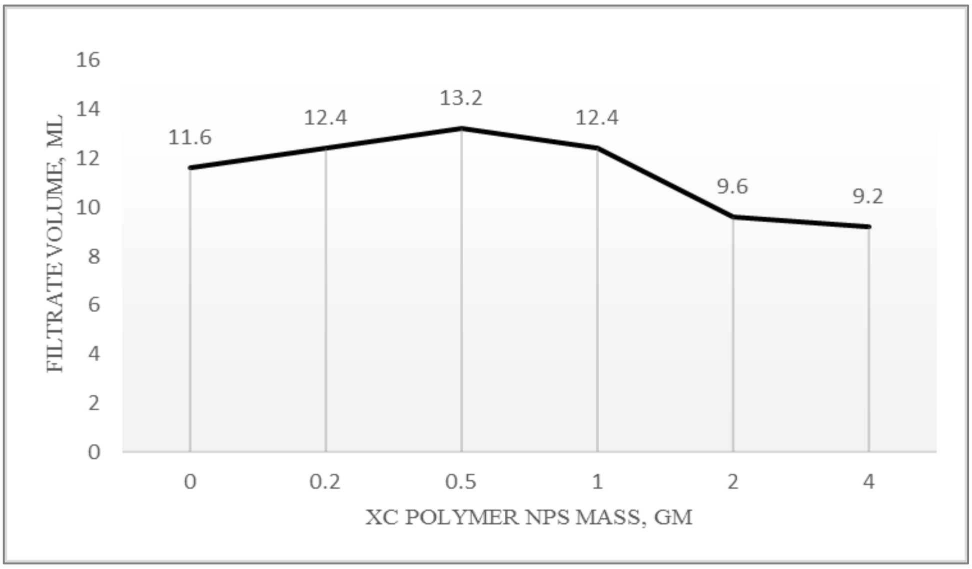

Figure 11. Filtrate volume of unweighted water-based mud with different concentrations of XC polymer NPs.

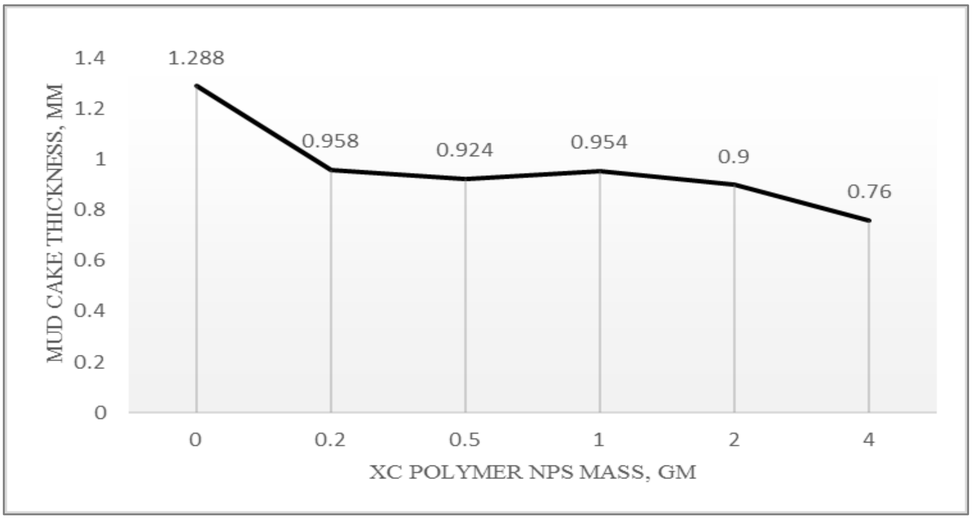

Figure 12. Mud cake thickness of unweighted water-based mud with different concentrations of XC polymer NPs.

4. CONCLUSION

- XC polymer NPs can be used to enhance the lubricating performance and reduce COF of unweighted water-based mud.
- The addition of XC polymer NPs with a concentration of 4gm to unweighted water-based mud can reduce COF by 30 %.
- The addition of XC polymer NPs with concentrations up to 4gm to unweighted water-based mud can enhance rheological and filtration properties.
- The addition of XC polymer NPs with a concentration of 4gm to unweighted water-based mud can increase PV by 181.6 %, YP by 380.3 %, AV by 333.8 %, 10 sec gel by 186 %, and 10 min gel by 41.8 %, which are very high values.
- The addition of XC polymer NPs with a concentration of 4gm to unweighted water-based mud can reduce filtrate volume by 20.7% and mud cake thickness by 41%.
- Unweighted water-based mud with different concentrations of XC polymer NPs exhibit Herschel-Bulkley model.
- Unweighted water-based mud with different concentrations of XC polymer NPs exhibit shear-thinning behavior.

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NOMENCLATURE

K = consistency index, lb.s^n/100 ft2
n = flow behavior index, Dimensionless
V_{30} = filtrate volume at 30 min, ml
$V_{7.5}$ = filtrate volume at 7.5 min, ml
γ = shear rate, 1/s
φ300 = viscometer dial reading at 300 rpm, lbf/100 ft^2
φ600 = viscometer dial reading at 600 rpm, lbf/100 ft^2
μ_e = effective viscosity, cP
τ = shear stress, lbf/100 ft^2
τ_0 = yield stress, lbf/100 ft^2

ABBREVIATIONS

AV = apparent viscosity
CF = correction factor
COF = coefficient of friction
NPs = nano particles
PV = plastic viscosity
YP = yield point