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

الخلاصة
في هذا البحث تم دراسة امكانية تحسين خواص التزييت والخواص الريولوجية وخصائص الترشيح لسائل الحفر ذو الأساس المائي الغير مثقل باستخدام جزيئات البوليمر النانوية بتراكيز 0.2gm، 0.5gm، 1gm، 2gm، و 4gm. تم قياس خواص البنتونايت الذي استخدم في تحضير سائل الحفر باستخدام الأجهزة المختبرية XRF-1800 Sequential X-ray Fluorescence Spectrometer، XRD-6100/7000 X-ray Diffractometer، و Malvern Mastersizer 2000 particle size analyzer. تم قياس كل من التزييت و الخواص الريولوجية والترشيح لسائل الحفر عند درجة حرارة الغرفة باستخدام الأجهزة OFITE EP and Lubricity Tester، OFITE Model 900 Viscometer، و OFITE Low-Pressure Filter Press، على التتابع. اظهرت جزيئات البوليمر النانوية تحسين في خواص التزييت، الخواص الريولوجية، وخصائص الترشيح لسائل الحفر ذو الأساس المائي الغير مثقل. يمكن ملاحظة تأثير جزيئات البوليمر النانوية على خواص التزييت لسائل الحفر ذو الأساس المائي الغير المثقل عند تركيز 4gm حيث كانت نسبة انخفاض معامل الاحتكاك لسائل الحفر تساوي 30%. اظهرت النتائج زيادة في الخواص الريولوجية عند اضافة جزيئات البوليمر النانوية بمختلف تركيزات المستخدمة. كما اظهرت النتائج انخفاض في حجم الرشح و سمك كعكة الطين عند اضافة جزيئات البوليمر النانوية بتركيز 2gm و 4gm، ان أفضل نتيجة تم الحصول عليها عند اضافة جزيئات البوليمر النانوية بتركيز 4gm حيث كانت نسبة انخفاض حجم الرشح 20.7% و نسبة انخفاض سمك كعكة الطين 41%. 

الكلمات الرئيسية: سائل الحفر ذو الأساس 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 influence 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 Surapis, 2016**, analyzed the effect of TiO₂ 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, TiO₂, 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), MoS2 and Graphene nanoparticles. Summary of experimental studies on the effect of Nanomaterials on lubricity, rheology, and filtration properties of drilling fluids is illustrated in Table 1.

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 % |
| Authors                  | Nanocarrier                     | Concentration          | Fluid Type                        | Results                                                                 |
|-------------------------|---------------------------------|------------------------|-----------------------------------|------------------------------------------------------------------------|
| 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$_2$O$_3$, Fe$_3$O$_4$, 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.
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:

\[
CF = \frac{34}{\text{meter reading} (32-34)}
\]  

(1)

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

\[
COF = \frac{CF \times \text{meter reading}}{100}
\]  

(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:

\[
AV = \frac{\phi_{600}}{2}
\]  

(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$_2$O$_3$ | Al$_2$O$_3$ | CaO | MgO | SO$_3$ | LOI | P$_2$O$_5$ | Na$_2$O | K$_2$O |
|-------|---------|-------------|-------------|-----|-----|--------|-----|------------|---------|-------|
| %     | 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.
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           |
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/100 ft²) | AV (cP) | YP/PV (lb/100 ft²/cP) | 10 sec gel (lb/100 ft²) | 10 min gel (lb/100 ft²) |
|-------------|-------|---------|-----------------|--------|-----------------------|-------------------------|-------------------------|
| 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 ft²), AV (119.3 cP), 10 sec gel (119.6 lbf/100 ft²), and 10 min gel (125.5 lbf/100 ft²) 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.
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*:

\[
\tau = \tau_0 + K Y^n 
\]

\[
n = 3.32 \log \left( \frac{\phi_{600} - \tau_0}{\phi_{300} - \tau_0} \right) 
\]

\[
K = \frac{\phi_{300} - \tau_0}{511^n} 
\]

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

| Wt (gm) | \(\tau_0\) (lb/100 ft²) | n       | K        |
|---------|------------------------|---------|----------|
| 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) |
|------------|-------------------------|
|            | Blank                   | 0.2 gm | 0.5 gm | 1 gm  | 2 gm  | 4 gm  |
| RPM 1/sec  | Blank                   | 11175.1| 13403.1| 16227.6| 19419.9| 17487.6| 21281.4|
| 1          | Blank                   | 5535.5 | 6640   | 8007.6 | 9981.8 | 11799.1| 13671.9|
| 2          | BLANK                   | 3682.1 | 4411.3 | 5288.2 | 6629.1 | 8159.8 | 11612.5|
| 3          | BLANK                   | 1831.8 | 2192.1 | 2640   | 3335.1 | 4222.9 | 7105.7 |
| 4          | BLANK                   | 1094.8 | 1313.6 | 1586.2 | 2009.4 | 2568.7 | 4462.2 |
| 5          | BLANK                   | 549.4  | 659.4  | 807.8  | 1024   | 1328.2 | 2340   |
| 6          | BLANK                   | 363.5  | 437.7  | 544    | 695.5  | 893.8  | 1591.5 |
| 7          | BLANK                   | 204    | 236.9  | 287.7  | 368    | 471.3  | 845.3  |
| 8          | BLANK                   | 125.3  | 148.8  | 181.3  | 231.6  | 297.3  | 532.7  |
| 9          | BLANK                   | 71.5   | 76.4   | 101.3  | 128.8  | 166    | 293.9  |
| 10         | BLANK                   | 47.9   | 52.7   | 68.6   | 87.8   | 115.6  | 210.7  |
| 11         | BLANK                   | 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.
**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 ft^2  
n = flow behavior index, Dimensionless  
V_{30} = filtrate volume at 30 min, ml  
V_{7.5} = filtrate volume at 7.5 min, ml  
y' = shear rate, 1/s  
φ_{300} = viscometer dial reading at 300 rpm, lbf/100 ft^2  
φ_{600} = 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