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Multi-Functional Enhancement of Water-Based Drilling Fluid Using Copper Nanoparticles: A Study on Lubricity, Rheology, and Filtration Properties

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Article Info	ABSTRACT
<p>Received: 24 Nov 2025 Revised: 19 Jan 2026 Accepted: 08 Mar 2026 Available online: 31 March 2026</p>	<p>Nanoparticle additives emerge as a modern solution to eliminate the performance gap between conventional water-based drilling fluids (WBDFs), and more superior but environmentally challenging oil-based drilling fluids (OBDFs). This study focuses on the enhancement of KCl polymer mud using nano-additives. While nano-additives like copper oxide (CuO NPs) were studied and showed promising results, another form of copper (elemental copper nanoparticles, Cu NPs) with a potential as a multifunction mud additive remains largely unexplored. This research systematically investigates the impact of Cu NPs (0.04–0.8 wt%) on the lubricity, rheology, and filtration properties of KCl polymer mud. All the measurements were done in the lab at room temperature, using lubricity tester, viscometer, and low-pressure filter press. Most additives tend to enhance one property of the mud, but the Cu NPs acted as a more superior properties enhancer, as it didn't enhance only one aspect of KCL polymer mud, but acted as multifunctional additive. For the lubricity, the effect of Cu NPs was significant on the coefficient of friction (CoF), with maximum reduction of 41.68% observed at 0.8% concentration, however at the 0.2% concentration, a relatively similar result of CoF reduction was observed with 39.78% making it the optimal concentration for the lubricity aspect. For the rheological properties, the addition of Cu NPs to the KCL polymer mud enhanced the overall rheological properties, increasing the plastic viscosity (PV), yield point (YP), apparent viscosity (AV), and gel strength, the highest values [PV (44.5 cP), YP (69.4 lb/100ft²), AV (77.35 cP)] were observed at 0.2% concentration. Unlike its beneficial effects on lubricity and rheology, the addition of Cu NPs to KCl polymer mud resulted in increased fluid loss and thicker filter cakes. The study concludes that a concentration of 0.2 %wt of Cu NPs is optimal for the simultaneous enhancement of lubricating and rheological properties in KCl polymer mud. This study highlights the potential of Cu NPs as a multifunctional additive that can be used in advanced water-based drilling fluids systems.</p>
<p>Keywords:</p> <p>KCl Polymer Mud Copper Nanoparticles Lubricity Rheology Filtration</p>	

1. Introduction

The drilling fluid has become an important component in drilling operations, with several

functions that are to be optimized, such as controlling the formation pressures, the removal of drill cuttings from the wellbore, maintaining stability of the wellbore, transmitting hydraulic energy to downhole tools and bits, cooling and



lubrication, and sealing permeable formations. Failure in these functions leads to a major economic impact, affecting resources and time, compromising success, and causing major drilling problems [1, 2].

While oil-based drilling fluids (OBDFs) give superior performance, their high cost and environmental challenges have pushed the industry towards advanced water-based systems (WBDFs). KCl polymer mud is key here for inhibiting shale, but it still falls short of OBDFs in lubricity, rheology and filtration control. This gap is the reason for researching novel additives [3].

Nano-additives have emerged as a modern solution here. Their high surface area and unique properties can alter fluid behavior. Specifically, copper oxide nanoparticles (CuO NPs) have been widely studied. Previous works show they enhance rheology [4-10], improve high-pressure high-temperature (HPHT) filtration [6, 8, 11, 12], work as shale inhibitors [11, 13], and boost thermal stability [4, 8].

On the other hand, its elemental or metallic counterpart, namely copper nanoparticles (Cu NPs), is far less understood; the oxide usually covers most of the literature landscape. Only one previous study has been conducted on Cu NPs up until now, to the best of our knowledge [14], and that too concerning extreme-pressure lubricity in simple WBM.

This study directly targets that gap. Where the prior work [14] focused on lubricity at extreme-pressure conditions in simple WBM, we provide a full, multi-functional evaluation of Cu NPs in KCl polymer mud. We systematically test their impact on lubricity, rheology, and filtration together. This approach shows the broader potential and the trade-offs. The novelty is in this first integrated assessment of Cu NPs as a multifunctional additive, establishing a foundation for their optimized use in WBDFs.

2. Materials and Methods

2.1. Materials

Raw Materials. The additives used in the preparation process of KCl polymer mud were the following: Commercial Bentonite, Potassium Chloride (KCl), Caustic Potash (KOH), Low Viscous Poly Anionic Cellulose (PAC-LV),

Xanthan Gum (XC-Polymer), and Barite. All of the above additives were provided by Oren Hydrocarbons Middle East Incorporation.

Nanomaterials. The Nanomaterials that had been used in this research was Cu NPs (10 – 30 nm size, 99.99% purity, supplied by Nanjing Nano Technology Co., Ltd.).

2.2. Drilling Fluid Preparation

The effect of Cu NPs with different concentrations was explored in a water-based drilling fluid system, namely KCl polymer mud. And to understand the behavioral changes of the additive on the drilling fluid system, a blank sample of KCl polymer mud was prepared using the procedure described in **Table 1**, All mixing was performed using a Hamilton Beach Mixer, with rotational speeds of (13,000 RPM).

Table 1. The preparation of KCl polymer mud blank sample.

Additives	Concentration	Mixing Procedure
Bentonite	8 gm/350ml of distilled water	20 minutes of mixing, then the suspension was aged in a sealed container for 16 hrs.
KCl	10 gm/350ml	2 minutes of mixing
KOH	0.5 gm/350 ml	2 minutes of mixing
PAC polymer	2 gm/ 350ml	2 minutes of mixing
XC polymer	1 gm/350ml	2 minutes of mixing
Barite	100 gm/350ml	2 minutes of mixing, then after the last additive, the whole mixture was mixed for 10 minutes.

The Cu NPs with concentrations of 0.04, 0.1, 0.2, 0.4, 0.8 %wt were added to blank sample of KCl polymer mud, then each slurry was mixed for 10 minutes, to guarantee the homogenous dispersion of the nano-additive within the sample, an Ultrasonic Bath was used for another 10 minutes (the desparation was carried out at frequency of 40 kHz and a power of 100 W, the water bath temperature was monitored and maintained below 35°C to prevent thermal

degradation of drilling fluid components). Before any testing, KCl polymer mud samples were remixed for an extra period of time (5 - 15 min.).

2.3. Lubricity Measurements

The lubricating properties of the KCl Polymer mud samples were measured using OFITE EP and Lubricity Tester in the lab and as following:

- To ensure the reliability of the measurements, OFITE EP and lubricity tester was calibrated with distilled water before each test, in accordance with the equipment's standard calibration protocol, then the correction factor (CF) was calculated using Equation 1.

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

where the constant 34 is defined by the equipment manufacturer as the reference meter reading for distilled water under standard calibration conditions [15].

- Then the coefficient of friction (CoF) for each sample was calculated manually using the obtained values for apparatus, using Equation 2.

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

2.4. Rheology Measurements

Rheological properties of KCl Polymer mud samples were measured using OFITE Model 900 viscometer, and the procedure of the test is as follows:

- To ensure accurate results, the apparatus was calibrated before each test with a special calibration fluid (provided by the device manufacturer), to get offset values that were ranging from 0 to ± 0.1 .
- Plastic viscosity (PV), yield point (YP), and gel strength values were measured using OFITE Model 900 viscometer. But for the apparent viscosity (AV), it was calculated

manually for each sample using Equation 3.

$$AV = \frac{\phi 600}{2} \quad (3)$$

To ensure the repeatability and the accuracy of the results, each test was repeated three times, and the average values were taken into account to ensure the reliability of the results.

2.5. Filtration Measurements

OFITE low-pressure filter press with dead weight hydraulic assembly was used for the filtration loss measurements. The filtrate loss volume was measured at 7.5min (V7.5), and 30 min (V30).

All measurements (lubricity, rheology, and filtration properties) were conducted at room temperature (approximately 35°C).

The overall experimental procedure for evaluating the effect of Cu NPs on KCl Polymer mud is summarized in Error! Reference source not found..

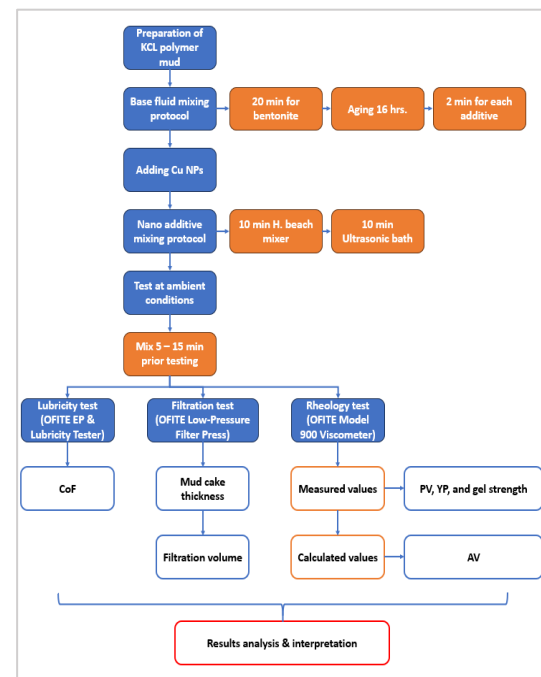


Figure 1. Experimental workflow for evaluating the effect of Cu NPs on KCl polymer mud.

3. Results and Discussion

All the measurements in this study (lubricity, rheology, and filtration) were conducted in ambient temperature (approximately 35 C). This

approach was used to understand the fundamentals of how Cu NPs can affect KCl polymer mud behavior without adding complex variables like high temperature. Although this approach is helpful to understand the base behavior of the additive, it acts as a limitation for this study, where the drilling fluid is subjected to a higher temperature during drilling operations. The observed behavior for (lubricity, rheology, and filtration) are specific to the tested conditions of this study, and future work should validate the results in high temperature conditions.

3.1. Lubrication Behavior

The effect of Cu NPs addition to KCl polymer mud across the selected concentrations range on the CoF can be found in **Table 2** and to have a better view of the additive behaviors across different concentrations, the results are illustrated in **Error! Reference source not found.**

Table 2. Lubricity performance of KCl polymer mud with varying concentrations of Cu NPs.

Cu NPs Concentration, wt%	CoF	CoF Reduction, %
0	0.367	----
0.04	0.235	35.96
0.1	0.221	39.78
0.2	0.221	39.78
0.4	0.25	31.88
0.8	0.214	41.68

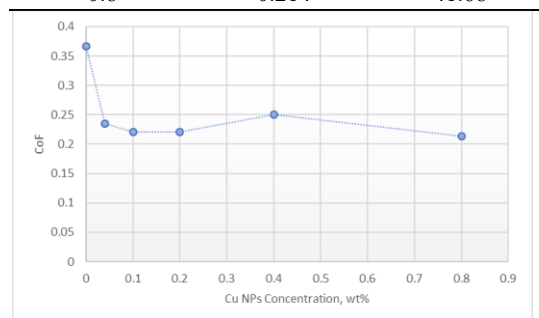


Figure 1. Effect of Cu NPs concentration on CoF of KCl polymer mud.

The addition of Cu NP caused a reduction in the CoF value across all of the concentrations. A reduction in CoF up to 35.96% was observed at the lowest concentration of 0.04 wt%. The CoF decreased further with increasing nanoparticle concentration, reaching a minimum value of 0.221 (a 39.78% reduction) at concentrations between 0.1 and 0.2 wt%.

However, a non-regular behavior was observed at a higher concentration (0.4 wt%) where the CoF increased to a value of 0.25, making it higher than the lower concentrations, but still an enhanced value compared to the blank sample. This behavior may be due to a process known as nanoparticle agglomeration, where individual nanoparticles, in some concentrations, start to group together and form a large cluster of particles that can change how the additive behaves. At the highest concentration (0.8 wt%) the CoF improved again, reaching the maximum enhancement across all the concentrations, and gave a CoF value of 0.214.

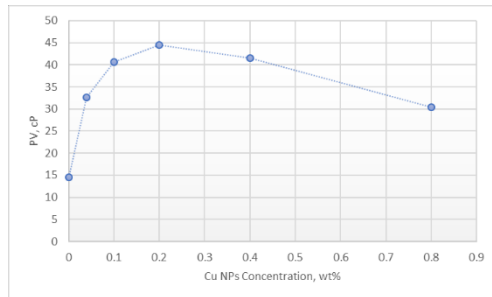
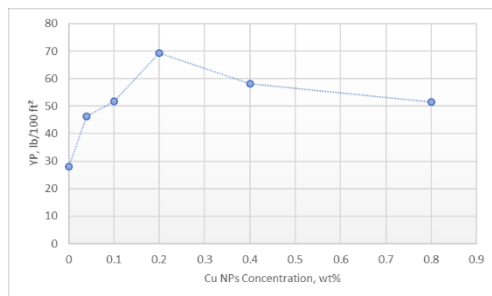
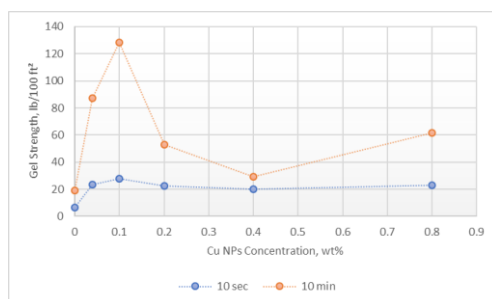
The mechanism behind the lubricity improvement is attributed to the formation of soft and low shear strength film on the metal surfaces. This soft and low shear film separates the contacting surfaces, thus reducing the frictional forces between them [16-19].

3.2. Rheological Properties

Cu NPs additive had a significant effect on the rheological properties of KCL polymer mud. The results, including PV, YP, AV and gel strength are presented in **Table 3** and for better understanding of how significant the change in these properties across different concentrations, the results are illustrated in **Figure 2Figure 3Figure 4.**

Table 3. Rheological properties of KCl polymer mud with varying concentrations of Cu NPs.

Cu NPs Concentration, wt%	PV, cP	YP, lb/100 ft ²	AV, cP	YP/PV, lb/100 ft ² /cP	Gel Strength, lb/100 ft ²	
					10 sec	10 min
0	14.6	27.9	29.65	1.91	6.4	19.2
0.04	32.7	46.2	56.15	1.412	23.2	87.2
0.1	40.6	51.7	66.55	1.273	27.9	128.2
0.2	44.5	69.4	77.35	1.559	22.5	52.9
0.4	41.6	58.2	70.45	1.399	20	29.2
0.8	30.4	51.5	57.6	1.694	22.7	61.7

**Figure 2.** Effect of Cu NPs concentration on PV of KCl polymer mud.**Figure 3.** Effect of Cu NPs concentration on YP of KCl polymer mud.**Figure 4.** Effect of Cu NPs Concentration on Gel Strength of KCl Polymer Mud.

The addition of Cu NPs to KCl polymer mud results in enhanced rheological properties (PV, YP, AV and gel strength) across all of the tested concentrations compared to the blank sample. For the tested range, the 0.2% concentration delivered the optimal enhancement combination for the rheological properties [PV (44.5 cP), YP (69.4 lb/100 ft²), and AV (77.35 cP)].

PV is an important property of drilling mud, and can be defined as the resistance to flow in a fluid, caused by the internal friction between particles (solids and liquids) of drilling fluid, and the increase of solids in the mud, will therefore increase the PV. The addition of nanoparticles, that are characterized with large surface area to volume ratio (Cu NPs in our case), and this special characterization of nanomaterials will cause an increase in the interaction between the nanoparticles and the drilling fluid particles, that can cause increase in internal friction, leading to an increase in PV [20-22].

YP is a measurement of the electrochemical attraction forces between particles of the drilling fluid at low shear rates. The addition of nanoparticles (Cu NPs in our case) showed an increase of yield point values, and this can be due to fact that the nano-additives characterized by a large surface area to volume ratio, which allow the particles to carry more surface charges, making the electrochemical attraction forces between nanoparticles and other drilling fluid particles stronger, which directly increases the YP of the fluid.

Gel strength is the ability of the drilling fluid to form a network between particles when the mud sits in static conditions, and this property is caused because of the electrostatic forces between drilling fluid particles. The nano-additives can form a stronger network structure, increase surface charges due to its large area to volume ratio, and it may form a crosslink with the KCl polymer chains, to thicken the structure of the mud at static conditions. The 10-second gel strength of the blank sample was 6.4 lb/100 ft². The addition of Cu NPs enhanced this property, with the highest value of (27.9 lb/100 ft²) observed at 0.1% concentration. The 10-minute gel strength showed a more dramatic increase, surging from 19.2

lb/100 ft² for the blank to 128.2 lb/100 ft² at the 0.1% wt. concentration. The subsequent decrease in 10-minute gel strength at higher concentrations may be due to a repulsive force occurring between the nanomaterials, water molecules, and bentonite particles, or due to agglomeration which can disrupt the fluid's microstructure [20, 23].

In conclusion, the addition of Cu NPs enhanced the rheological properties of the KCl polymer mud. The concentration of 0.2% by weight can be considered an effective concentration, providing high values of YP and AV, which are essential for good hole cleaning.

3.3. Filtration Properties

Filtration measurements for KCl polymer mud across the selected range of Cu NPs concentrations are presented in **Table 4** and **Figure 5** **Figure 6**.

Table 4. Filtration properties of KCl polymer mud with varying concentrations of Cu NPs.

Cu NPs Concentration, wt%	V7.5, ml	V30, ml	Mud Cake Thickness, mm
0	4	8	0.622
0.04	4.4	8.8	0.71
0.1	5.4	10.8	0.712
0.2	6.6	13.2	0.814
0.4	6.2	12.4	0.8
0.8	5.8	11.6	0.872

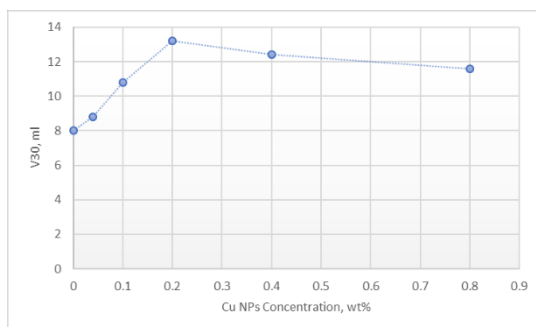


Figure 5. Effect of Cu NPs concentration on V30 of KCl polymer mud.

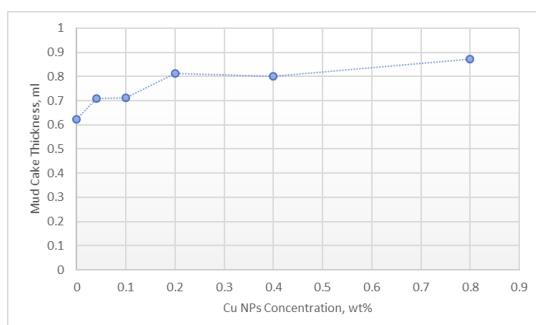


Figure 6. Effect of Cu NPs concentration on mud cake thickness of KCl polymer mud.

The addition of Cu NPs caused an increase in both V30 and mud cake thickness compared to the blank sample.

The blank sample had a V30 of 8 ml and a mud cake thickness of 0.622 mm. With the addition of 0.2 wt% Cu NP, the V30 increased to 13.2 ml and the mud cake thickness increased to 0.814 mm. This represents a 65% increase in V30 and a 30.9% increase in mud cake thickness.

Nano-additives in general, can increase the filtrate loss volume of drilling fluid; this may be explained due to solid accumulation which makes the mud cake less stable, making it harder for the mud with nano-additives to form an impermeable, low porosity mud cake layer, that prevents more filtrate to pass through [24, 25]. The increase in mud cake thickness with the addition of Cu NPs supports this explanation, indicating the formation of a more permeable and less compact filter cake.

The non-regular response of the V30 to Cu NPs concentration may be due to nanoparticle agglomeration at higher concentrations, which can disrupt the mud cake structure.

4. Conclusions

This study provides a comprehensive evaluation of metallic Cu NPs on KCl polymer mud. The key findings reveal Cu NPs as a multifunctional additive for lubricity and rheology enhancement, though with a negative impact on filtration control.

The Cu NPs significantly enhanced lubricity, reducing the CoF by up to 40%. The rheological properties (PV, YP, AV, and gel strength) were also enhanced, giving the mud superior lubricity and improved hole cleaning capacity. However, these enhancements came with increased filtration volume and thicker filter cakes.

Within the tested concentration range (0.04–0.8 wt%), the 0.2 wt% concentration is recommended. This value delivered optimal lubricity improvement and the peak rheological properties increase, albeit alongside elevated fluid loss. Therefore, using Cu NPs is highly recommended in a careful and controlled way, specifically for scenarios where lubricity and cuttings lifting capacity are critical and where the filtration increase can be managed.

This work distinguishes the role of metallic Cu NPs from the widely studied oxide form and establishes a foundation for their application. Future research must focus on validating these findings under high-temperature conditions and developing strategies to mitigate the filtration drawback.

Abbreviations

AV	Apparent viscosity
CF	Correction factor
CoF	Coefficient of friction
Cu	Copper
CuO	Copper oxide
KCl	Potassium chloride
KOH	Caustic potash
NPs	Nanoparticles
OBDFs	Oil-based drilling fluids
PAC	Poly anionic cellulose
PV	Plastic viscosity
V30	Filtrate loss volume at 30 min
V7.5	Filtrate loss volume at 7.5 min
WBDFs	Water-based drilling fluids
XC	Xanthan Gum
YP	Yield point

Conflict of interest

The authors declare no conflicts of interest concerning this research.

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Author Contribution

The manuscript was written by **M.S. Hameed**, who also performed the experiments and analyzed the results. **N.S. Al-Zubaidi** contributed to data analysis and supervision. **A.A. Alwasiti** provided supervision. All authors discussed the results and contributed to the final manuscript.

AI Declaration Statement

The authors confirm that the manuscript has been written without the assistance of generative AI or AI-based writing tools.

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