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Optimization of Carbon Nanoparticles as a Novel Reinforcing Rheological and Filtration Agent for Water-Based Drilling Fluids

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ABSTRACT

Water-based drilling fluids (WBDFs) are extensively used in drilling operations owing to their environmental compatibility and cost-effectiveness. Nevertheless, WBDFs often exhibit limitations in rheological stability and filtration control, particularly under high-pressure and high-temperature (HPHT) conditions. This study presents an experimental evaluation of carbon nanoparticles (CNPs) as a multifunctional additive for improving the rheological and filtration performance of WBDFs and compares their performance with that of a conventional additive, starch. Drilling fluid samples were formulated using CNP concentrations of 4, 6, and 8 g, in addition to base mud and starch-treated samples. The densities, rheological characteristics, and filtration behaviors of the prepared fluids were tested under standard laboratory conditions. The CNPs imparted minimal influence on the fluid density, which remained within 10.3–10.4 ppg. However, the CNPs significantly improved the rheological performance, with the plastic viscosity increasing from 10.23 cP to 11.48 by starch addition and further to 14.82 cP due to 4 gm CNPs. Additionally, the yield point reached its highest value of 22.34 lb/100 ft^2 at 6 g, demonstrating enhanced suspension and cuttings transport capacity. Filtration tests further revealed that the 6 g CNP sample reduced fluid loss from 16 to 11.5 mL and lowered the filter cake thickness to 1.6 mm from 2.8 mm. Overall, the obtained results demonstrated that the incorporation of 6 g CNPs provided the most balanced improvement in WBDF performance, contributing to greater wellbore stability, efficient cuttings transport, and improved drilling efficiency. These findings highlight the practical potential of nanoparticle-based additives for advanced and sustainable drilling fluid formulations. The PV of the mud increased from 10.23 cP for the base mud to 11.48 cP after the starch addition; it further increased to 14.82 cP, 12.32 cP, and 12.74 cP upon the addition of 4, 6, and 8 g CNPs.

Keywords: water-based drilling fluids, carbon nanoparticles, filtration control, rheological properties

1. INTRODUCTION

Well drilling is a complex and demanding process that is crucial for reaching subsurface oil and gas reserves [1]. Drilling fluid, or drilling mud, is a key component of the drilling process. which is essential for the safety, efficiency, and overall success of well construction. Drilling fluids maintain wellbore stability, provide hydrostatic pressure to control formation fluids, and form a protective mud cake, directly affecting structural integrity and drilling cost-effectiveness [1–4]. Additionally, drilling fluids are responsible for wellbore cleaning, cuttings transport, and the cooling and lubrication of the drill bit and drill string, suspending solids during circulation stops, transmitting hydraulic power, and supporting the drill string weight through buoyancy [5,6].

In the oil and gas industry, drilling fluids are generally classified as either water-based drilling fluids (WBDFs) or oil-based drilling fluids (OBDFs). Owing to their lower cost and reduced environmental impact, WBDFs are the most commonly used. These fluids employ water as the continuous phase and incorporate additives to optimize rheological behavior, filtration control, and shale inhibition. [7,8]. In contrast, OBDFs use oil as the continuous phase and are preferred under more challenging geological conditions because of their superior lubricity, thermal stability, and shale inhibition properties; however, they are more expensive and less environmentally friendly [9,10].

Despite these advantages, WBDFs often face limitations under high-pressure and high-temperature (HPHT) conditions, where they may exhibit unstable rheological properties and increased fluid loss [11–14]. WBDFs are often modified with surfactants, polymers, and nanoparticles (NPs) to improve rheological performance and control fluid loss [15–18]. Viscosity, yield point (YP), and gel strength (GS) are key rheological properties that ensure effective cuttings suspension, efficient hole cleaning, and wellbore stability [19,20]. The control of these properties also improves pumpability and reduces operational issues, particularly in HPHT environments [20].

Fluid loss is a major challenge in WBDFs, which occurs when the fluid seeps into the formation during drilling. This can weaken the formation, particularly in shale and fractured reservoirs, leading to swelling, hydration, and microfractures, potentially causing wellbore collapse [21,22]. Fluid loss can also cause formation damage by reducing permeability and affecting hydrocarbon

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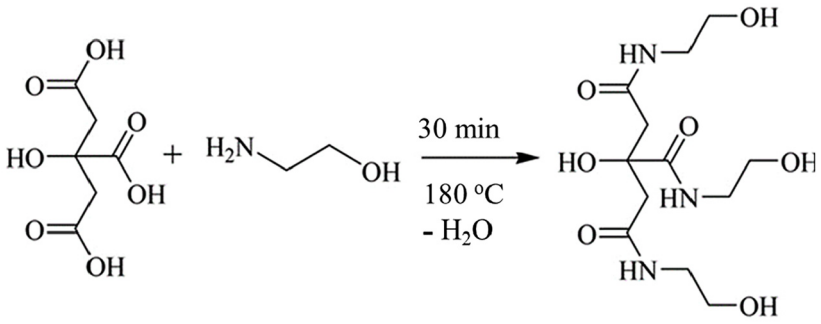

Figure 1. Synthesis of the CNDs

flow[23,24]. Changes in pressure and chemical interactions can also destabilize the wellbore[25]. Consequently, effective fluid-loss control is essential for maintaining wellbore stability, minimizing nonproductive time (NPT), and ensuring efficient drilling operations[25,26].

Rheological properties, including viscosity, yield point (YP), and gel strength (GS), characterize the flow and deformation behavior of drilling fluids under applied stress. These properties play a critical role in transporting drill cuttings, maintaining wellbore stability, and controlling fluid loss.[7,20], these properties also influence pumpability, torque, drag, and drilling efficiency, especially under HPHT conditions[20]. Rheological models, such as the Herschel–Bulkley model, are used to predict fluid behavior under varying downhole conditions[7].

To reduce fluid loss and improve flow properties, starch is commonly used as an additive in WBDFs because of its biodegradability, cost-effectiveness and the formation of a thin, impermeable filter cake that protects the reservoir formation. Crosslinked starch nanospheres, measuring ~100–300 nm in size, can maintain stable filtration control at temperatures up to 150 °C due to their ability to effectively deform and plug micropores[27]. Moreover, modified starches and graft copolymers improve filtration control by reducing the filtrate volume and filter cake thickness while maintaining rheological properties[28,29]. Additionally, different starch types exhibit varying performance, with potato starch demonstrating greater thermal stability than other starches[30]. Despite these advantages, such conventional additives exhibit limitations under extreme drilling conditions, particularly in HPHT environments. This has led to increasing interest in nanomaterials as alternative/complementary additives to further enhance drilling fluid performance.

Carbon nanoparticles (CNPs) are a class of nanomaterials incorporating carbon black, graphene, and carbon nanotubes, and are widely recognized for their high surface area, mechanical strength, and chemical stability[31]. In recent years, carbon-based nanomaterials have attracted significant attention for drilling fluid applications owing to their capacity to improve rheological properties and mitigate fluid loss by forming a reinforcing network that enhances viscosity, suspension capacity, and filtration control. Despite these advantages, few studies have focused on the systematic optimization of CNPs as multifunctional additives in WBDFs. Accordingly, this study aims to investigate the use of carbon nanoparticles (CNPs) as a novel multifunctional additive for water-based drilling fluids. The study focuses on optimizing the CNP concentration and evaluating its combined effects on the rheological and filtration properties of the drilling fluid. Unlike previous studies[32–34] that primarily focused on single-property enhancement or specific nanomaterials, this study provides a comparative assessment with starch as a conventional additive and identifies the optimal formulation for balanced drilling performance. This work is expected to contribute to enhancing wellbore stability, mitigating fluid loss, and enhancing the overall drilling efficiency. Notably, the current CNPs (4–10 nm diameter) are significantly smaller than those reported in the literature for drilling fluid applications (20–100 nm)[32–34]. The CNPs (i.e., carbon nanodots, CNDs) employed herein were synthesized using citric acid and ethanolamine, as detailed in Figure 1[35].

2. METHODOLOGY

2.1. Materials and Methods. Under ambient conditions, a Hamilton Beach mixer (HMD-200) was used to prepare five drilling fluid formulations and evaluate the effectiveness of the filter loss agent (FLA). The composition of the base drilling fluid is listed in Table 1. A commercial FLA (starch)[36] was added, and its density, rheological properties, and filtration properties were measured. The results were compared with those obtained using CNPs as an innovative rheology and FLA, and a comparison was also performed with the base mud formulation in the absence of FLA additives. The experimental methodology is summarized in Figure 2, and the optimization parameters are presented in Table 2.

2.2. Test Prototypes and Parameters. Drilling fluid formulations containing different CNP loadings (4, 6, and 8 g) were used to assess the effect of CNPs on rheological performance

Table 1. *Composition and function of the base WBDF formulation*

Component	Quantity (g)	Mixing time (mins)	Function
Water	300	-	Base fluid
Deformer	0.08	5	Property control
XC polymer	1.5	15	Viscosifier
KCl	80	10	Clay inhibitor
KOH	0.3	5	pH control
Sodium sulfide	0.25	5	Oxygen scavenger
$CaCO_3$	80	10	Weighting agent
Starch	6	10	Filter loss agent

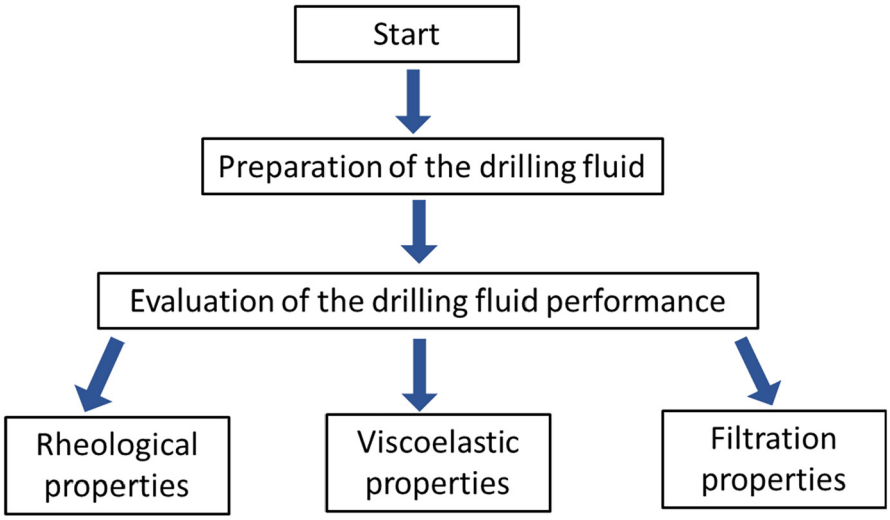

Figure 2. Schematic representation of the experimental methodology used for preparing and evaluating the drilling fluid formulations

Table 2. *Compositions of the drilling fluid formulations with varying CNP contents*

Component	CNPs 4 (g)	CNPs 6 (g)	CNPs 8 (g)
Water	300	300	300
Deformer	0.08	0.08	0.08
XC polymer	1.5	1.5	1.5
KCl	80	80	80
KOH	0.3	0.3	0.3
Sodium sulfide	0.25	0.25	0.25
$CaCO_3$	80	80	80
CNPs	4	6	8

and compare it with that of starch, a conventional FLA. After measuring the density using Humboldt mud balance of each formulation, rheological tests were conducted using a Fann VG-35 rheometer to measure the viscosity and GS under controlled shear rates relevant to drilling operations. Subsequently, filtration performance was evaluated under API standard conditions (100 psi and 75 °F). Fluid loss was measured over 30 min, followed by measurement of the filter cake thickness.

2.3. Experimental. The effects of CNP loading (4, 6, or 8 g) and starch (6 g) on the WBDF properties were evaluated as follows. The drilling fluid was prepared at ambient temperature using a Hamilton Beach mixer at 10,000 rpm and subsequently aged for 16 h to ensure complete polymer hydration and chemical equilibrium. After this time, the drilling fluid density was measured using a standard mud balance, and rheological tests were performed with a rotational viscometer. (Fann VG-35) to measure the shear stress at 600, 300, 200, 100, 6, and 3 rpm. The plastic viscosity (PV), YP, and GS (at 10 s and 10 min) were calculated. Filtration tests were performed using an API filter press at 100 psi and ambient temperature for 30 min.

2.4. Density Measurements. The density of the water-based drilling fluid was measured to evaluate its capacity to provide adequate hydrostatic pressure for well pressure control and to assess the effect of the added materials on the fluid properties. Mud density is directly related to maintaining the downhole hydrostatic pressure and preventing formation influx, thereby contributing to wellbore stability and safe drilling operations. Thus, a Humboldt mud balance (model ASTM D4380) was used to measure the fluid density of the base mud, commercial starch-containing mud, and CNP-containing mud at three additive levels (i.e., 4, 6, and 8 g). The results are reported in pounds per gallon (ppg).

2.5. Rheological Measurements. Rheological measurements were performed to assess the drilling fluid's ability to transport drill cuttings, minimize formation damage, and maintain wellbore stability. To evaluate the effect of CNP addition and compare its performance with that of commercial starch, the rheological properties of the water-based drilling fluids (WBDFs), including plastic viscosity (PV), yield point (YP), and apparent viscosity (AV), were measured at 75 °F and a differential pressure of 14.7 psi using a Fann VG viscometer. The same instrument was also used to determine the gel strength (GS) of the drilling fluids. and store. The GS was estimated from readings at 3 rpm after 10 s and 10 min. The following equations A Fann VG viscometer, which is a concentric-cylinder rotational viscometer, was used to determine the rheological properties of the drilling fluids. The instrument measures fluid viscosity at selectable rotational speeds of 3 rpm (for gel strength determination), 100, 200, 300, and 600 rpm. During testing, the drilling fluid sample is placed in a cylindrical cup while the inner rotor rotates at the selected speed. The resistance generated by the fluid against the rotating spindle produces a torque that is measured by the instrument. By recording dial readings at different rotational speeds, the Fann VG viscometer enables the determination of key rheological parameters, including plastic viscosity (PV), yield point (YP), and apparent viscosity (AV).

$$PV = \phi_{600} - \phi_{300} \quad (1)$$

$$YP = \phi_{300} - PV \quad (2)$$



Figure 3. Standard API filter press used to measure fluid loss and filtration behavior of the drilling fluids under controlled pressure (100 psi) and temperature (75 °F) conditions

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

2.6. Filtration Tests. The HPHT filter loss test is an important laboratory test for assessing the fluid loss performance of WBDFs under simulated downhole conditions. Fluid loss control is crucial for maintaining wellbore stability, reducing formation damage, and evaluating the efficiency of drilling operations. The HPHT filter loss test was performed using a calibrated HPHT filter press that exposed the WBDF samples to controlled pressure and temperature conditions. An HPHT filter press is a type of filtration equipment designed to assess the filtration properties of drilling fluids under HPHT conditions. The API filtration test (Figure 3) was performed at 75 °F under a differential pressure of 100 psi. Filtrate volume was recorded throughout the 30 min test period to evaluate fluid-loss performance. The filtration apparatus consisted of a cylindrical cell fitted with a filter medium that permitted the passage of the liquid phase while retaining solid particles. The water-based drilling fluid (WBDF) sample was introduced into the cell, and pressure was applied to simulate drilling conditions. Filter paper served as the filtration medium for the formation of the filter cake. At the end of the test, the total filtrate volume was determined, and the thickness of the resulting filter cake was measured in millimeters (mm).

3. RESULTS AND DISCUSSION

3.1. Density Measurements. The effects of starch and CNP addition on the WBDF density were evaluated, as shown in Figure 4. Relative to the base mud (10.60 ppg), starch addition reduced the density slightly to 10.30 ppg, while CNP addition (4, 6, and 8 g) yielded comparable densities of 10.3–10.4 ppg.

Previous studies have demonstrated that higher quantities of NPs may lead to agglomeration in aqueous drilling mud, thereby affecting the homogeneity of the colloidal system[37]. This phenomenon could explain the observed fluctuations in density, such as the slight increase at 8 g compared with that at 6 g[33].

3.2. Rheology Measurements. The influence of carbon nanoparticles (CNPs) on the rheological behavior of the drilling fluid was evaluated and compared with that of the base mud and the starch-treated formulation. As illustrated in Figure 5, the incorporation of CNPs enhanced both the shear stress and viscosity of the drilling fluid. Furthermore, all formulations exhibited typical non-Newtonian shear-thinning behavior,

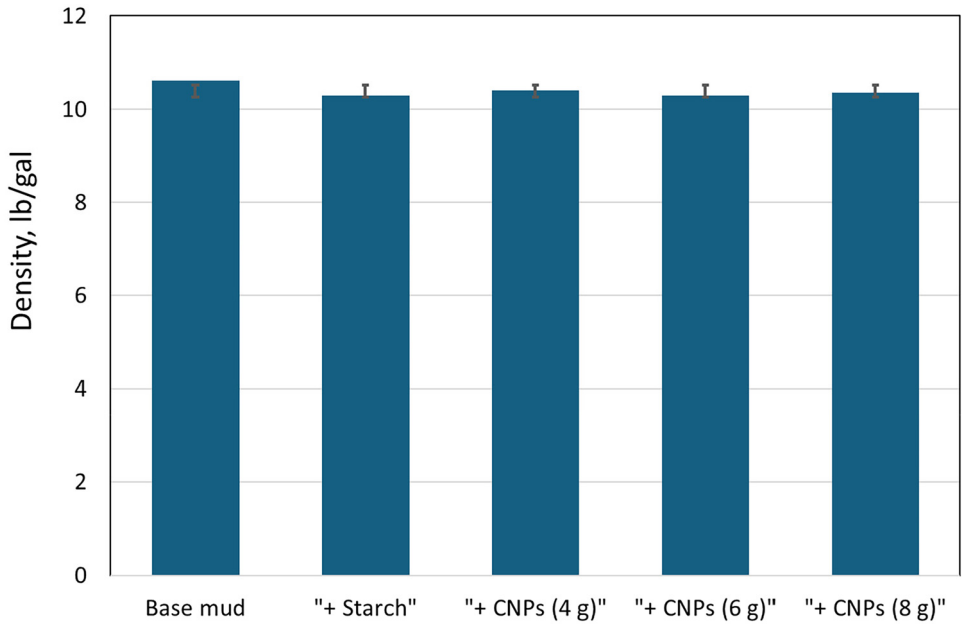

Figure 4. Effects of starch and CNP addition on the drilling fluid density

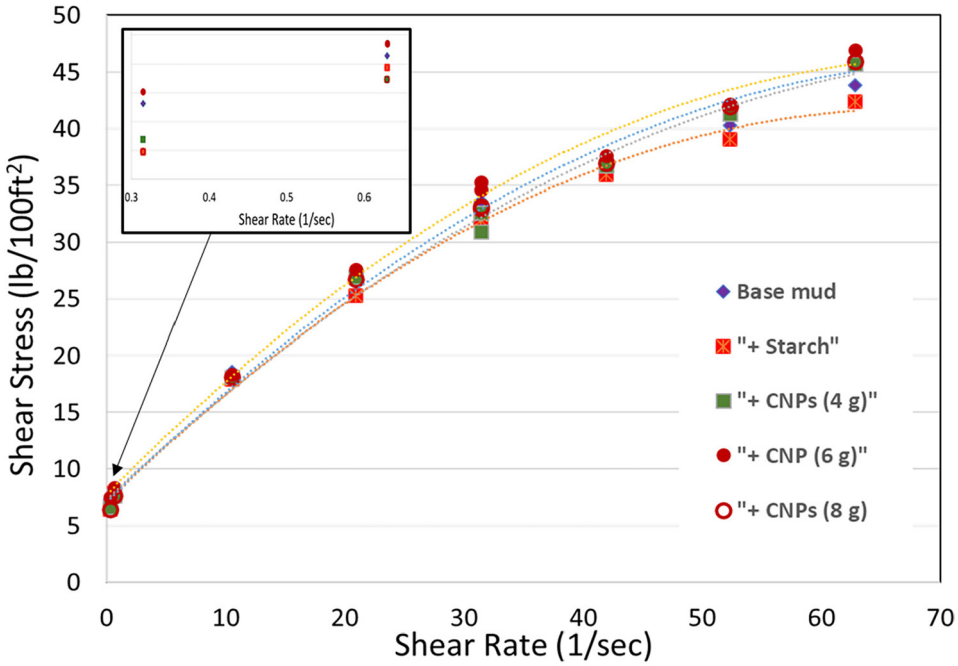

Figure 5. Shear stress–shear rate correlation for drilling fluids containing different CNP quantities at 75 °F

characterized by a reduction in apparent viscosity with increasing shear rate. At the highest shear rate, the CNP (6 g) formulation exhibited the greatest shear stress (46.98 lb/100 ft^2), followed by the CNP (8 g) (45.94 lb/100 ft^2), and CNP (4 g) (45.73 lb/100 ft^2) formulations. The base mud showed a lower shear stress (43.85 lb/100 ft^2) and the lowest value was obtained for the starch-based fluid (42.39 lb/100 ft^2). These results reveal that CNP incorporation enhanced the rheological structure of the drilling fluid, thereby improving the cuttings transport efficiency. Although the fluids exhibited lower shear stress values at low shear rates (i.e., 6.47–9.19 lb/100 ft^2), the CNP (6 g) formulation maintained slightly higher stress levels. This behavior results in enhanced suspension capacity, improved GS, and reduced risk of cuttings sag. Similar enhancements in rheological performance resulting from NP addition have been widely reported in drilling fluid systems [38].

As shown in Figure 6, the PV of the mud increased from 10.23 cP for the base mud to 11.48 cP after starch addition, further increasing to 14.82, 12.32, and 12.74 cP upon the addition of 4, 6, and 8 g CNPs, respectively. This increase in viscosity can be attributed to the formation of a CNP network structure within the mud system. This behavior is facilitated by the relatively uniform dispersion of NPs within the fluid during continuous mixing, thereby enhancing the particle–fluid interactions. This

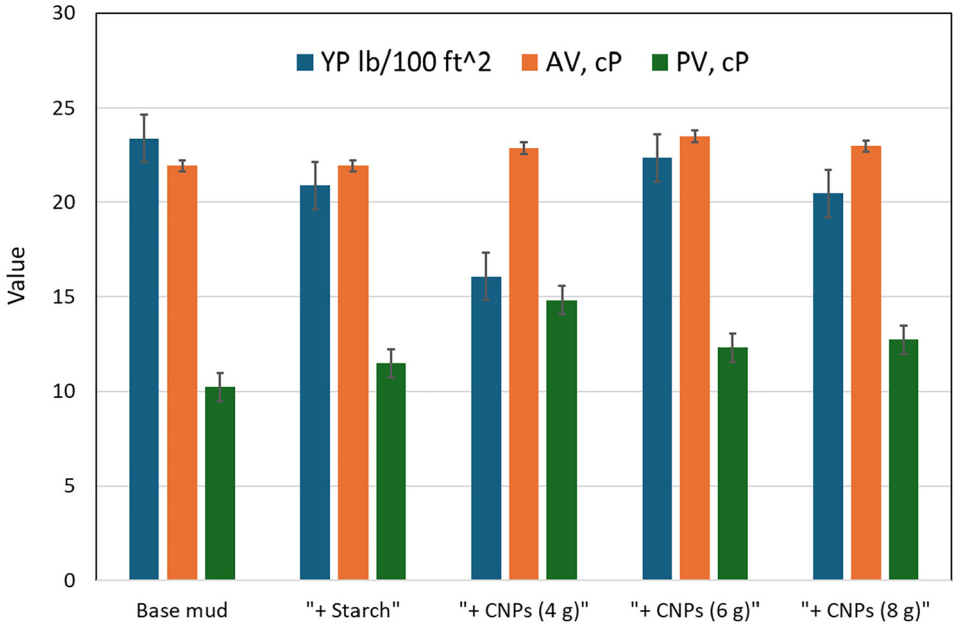

Figure 6. Variation in PV, YP, and AV for the drilling fluids incorporating different CNP quantities at 75 °F

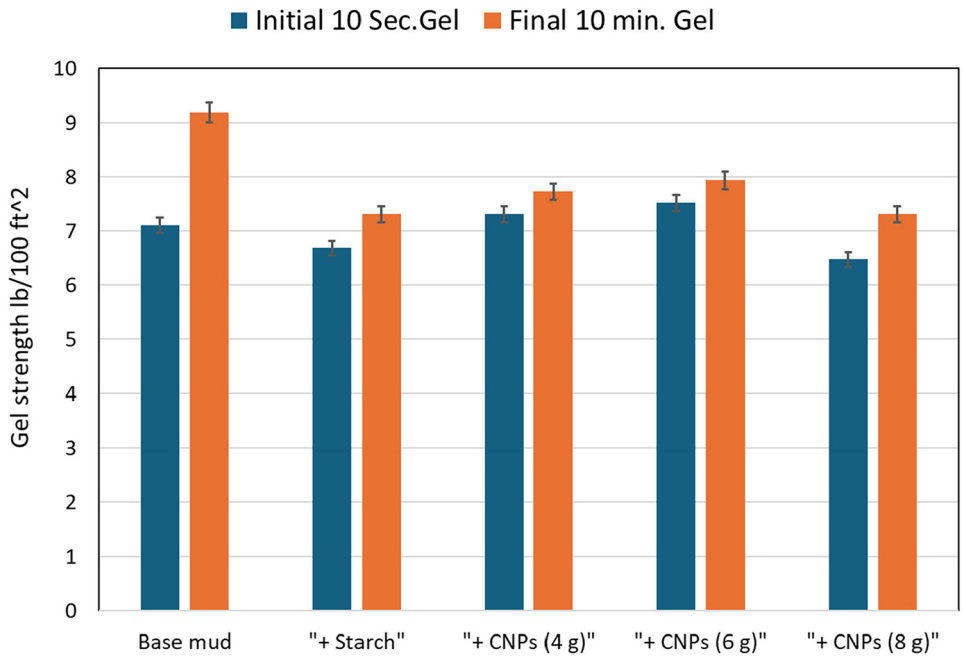

Figure 7. Comparison of the GS (10 s and 10 min) for drilling fluids with varying CNP quantities at 75 °F

internal network restricts fluid flow and promotes the transport of drill cuttings to maintain wellbore cleanliness.

A similar behavior has been reported in NP-enhanced drilling fluids, wherein the presence of NPs improves both fluid strength and viscosity[37]. However, at higher CNP loadings (i.e., >4 g), the PV decreased once again. This was somewhat unexpected, as an increase would typically be anticipated for higher NP loadings[38]. This behavior may therefore be attributed to NP agglomeration at higher loadings, which reduces the effective surface area and disrupts the internal fluid structure despite continuous mixing[34]. Notably, the YP, which represents a critical property of drilling fluids, is governed by the additive type and quantity. As shown in Figure 6, the base mud exhibited a YP of 23.39 lb/100 ft^2, decreasing to 20.88 lb/100 ft^2 upon the addition of starch. Lower YPs were recorded upon the addition of 4, 6, and 8 g CNPs (i.e., 16.08, 22.34, and 20.46 lb/100 ft^2, respectively). This trend indicates superior dispersion and stronger particle interactions within the fluid for the 6 g CNP system. In contrast, the reduced values at loadings of 4 and 8 g indicate insufficient structural development and NP agglomeration, respectively, both of which weaken the particle network. This highlights the importance of optimizing NP loading to balance dispersion and agglomeration effects and

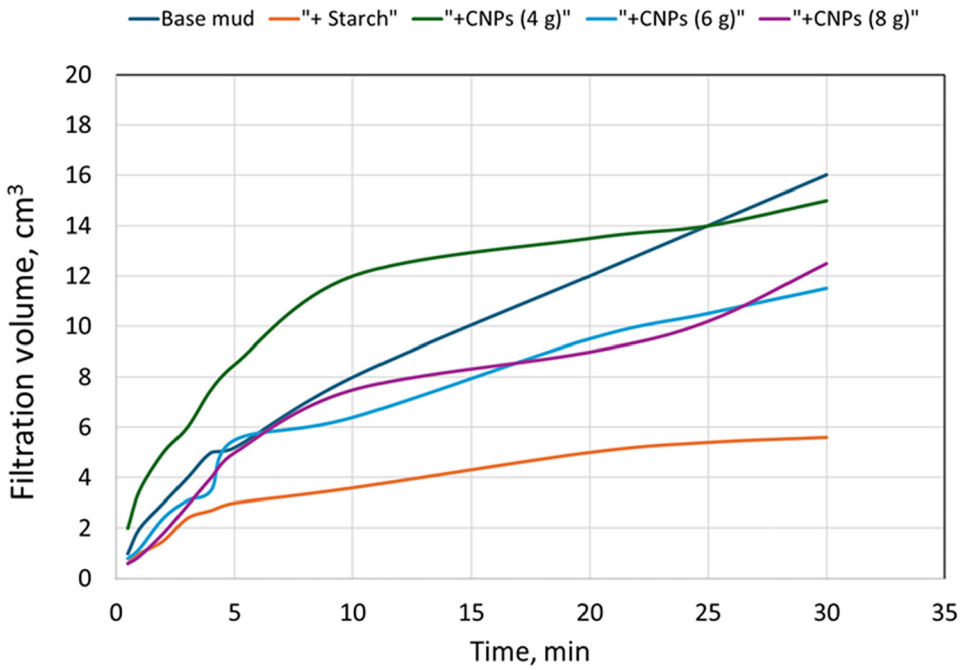

Figure 8. Effect of CNP loading on the drilling fluid filtration volume after 30 min at 100 psi and 75 °F

ultimately enhance rheological performance. A higher yield point (YP) is desirable because it improves the suspension and transport of drill cuttings, thereby promoting efficient hole cleaning and maintaining wellbore stability. Furthermore, an increased YP facilitates the formation of a stable, low-permeability filter cake, which helps reduce fluid loss and minimize formation damage [32].

With respect to the AV, the base mud and starch formulations exhibited consistent values of 21.92 cP (Figure 6), while increased AVs of 22.86, 23.49, and 22.97 cP were obtained for the formulations containing 4, 6, and 8 g CNPs, respectively. Although this increase is relatively small (~1–1.5 cP), it is significant in the context of drilling operations, as even minor improvements in viscosity can enhance the cuttings transport efficiency, reduce sedimentation, and improve wellbore stability, particularly under low shear rate conditions [39]. The highest AV was observed for a CNP content of 6 g, indicating optimal NP dispersion and improved fluid structure. This enhancement leads to superior carrying capacity and drilling efficiency, consistent with previous studies on NP-enhanced drilling fluids [32]. Additionally, the GS results presented in Figure 7 corroborate the observed rheological behavior of the drilling fluids. The GS at 10 s and 10 min decreased from 7.10 and 9.19 lb/100 ft^2 for the base mud to 7.52 and 7.93 lb/100 ft^2, respectively, for the CNP (6 g) formulation. Although the base mud exhibited a higher GS, this could lead to increased pump pressure during restart operations. The GS observed in the CNP system was sufficient to maintain adequate cuttings suspension while preserving favorable flow behavior. Moderate GS is desirable, as it supports the capacity of the fluid to suspend cuttings under static conditions while permitting efficient circulation, thereby contributing to wellbore stability.

3.3. Filtration Test Results. As shown in Figure 8, CNP incorporation improved the filtration performance of the WBDF relative to the base mud; however, the performance did not surpass that of the starch formulation. Based on the results obtained after 30 min, an optimal CNP loading of 6 g was identified, which resulted in a filtration volume of 11.5 mL, reflecting a noticeable reduction compared with the base mud (16 mL). This suggests that the CNP additive with an optimum lading of 6 gm reduces fluid loss by enhancing the internal structure of the fluid. The filtration performance of base mud is summarized in Table 3, which presents the filtrate volumes recorded over time under standard API conditions.

Table 3. *API filtration test conditions and recorded filtrate volumes*

Time (mm:ss)	Volume (mL)
00:30	1
1:00	2
2:00	3
3:00	4
4:00	5
5:00	5.2
10:00	8
20:00	12
25:00	14
30:00	16
*MCT 1/32	2.8/32

*MCT: Mud cake thickness in 1/32 inches

The improvement of filtration due to aid of 6 g of CNPs, the starch formulations exhibited lower filtration volume values, indicating superior fluid loss control. This behavior can be attributed to the ability of starch to effectively seal the pore spaces and reduce filtrate invasion through wall formation [29]. In contrast, the CNP formulation primarily acts as a structurally enhancing agent. While it improves rheological properties, such as viscosity and GS, it provides less efficient pore sealing. The filter cake thickness

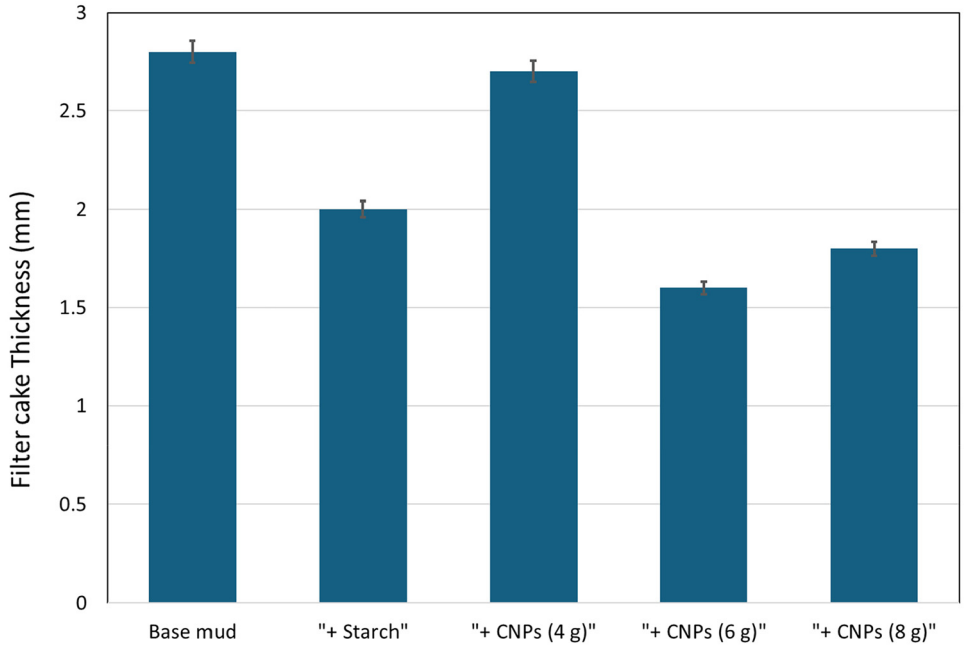

Figure 9. Effect of CNP loading and starch addition on the filter cake thickness under API filtration conditions

results shown in Figure 9 support this observation. Specifically, the CNP (6 g) sample produced the thinnest filter cake (1.6 mm), while the base mud and starch formulation demonstrated thicknesses of 2.8 and 2.0 mm, respectively. This indicates that CNPs promote the formation of a thinner filter cake. Notably, a well-formed filter cake with appropriate thickness is crucial for ensuring efficient drilling operations by minimizing excessive filtrate invasion into the formation and reducing the risk of formation damage.

4. CONCLUSIONS

A thorough experimental investigation was carried out to examine the influence of CNP addition on the characteristics of WBDFs. The resulting enhancements were evaluated with respect to those of a starch-based formulation. It was revealed that CNP addition had no significant effect on mud density, which ranged between 10.3 and 10.4 ppg across all CNP quantities, comparable to the value obtained for starch. With respect to the rheological properties, CNP addition clearly improved the performance of the drilling fluid compared with both the base mud and starch formulations. Specifically, the PV increased from 10.23 cP (base mud) to a maximum of 14.82 cP for the CNP (4 g) formulation, while the starch formulation exhibited a lower value of 11.48 cP. However, the most balanced performance was observed for the CNP (6 g) formulation, where the fluid exhibited enhanced viscosity without excessive thickening, indicating superior structural stability. Additionally, the YP exhibited a nonlinear trend with increasing CNP loading. The optimal value was observed for the CNP (6 g) formulation (22.34 lb/100 ft^2), surpassing the corresponding value for the starch formulation and approximating that of the base mud system. These findings therefore revealed that a CNP loading of 6 g maintained effective cuttings transport capacity. In terms of the GS, the CNP formulations exhibited superior structural control compared with the base mud. Although the base mud exhibited a higher GS, this can lead to an elevated pump pressure during restart operations. Overall, the CNP (6 g) formulation provided superior balance between the suspension capacity and ease of restart, rendering it more suitable for practical drilling operations. Despite these promising results, this study had several limitations. Specifically, the experiments were conducted under standard laboratory conditions and the effects of HPHT conditions were not considered. Additionally, detailed CNP characterization and statistical analyses of the experimental variability are lacking. Future studies should therefore focus on addressing these gaps to further validate the findings and enhance the applicability of such systems in field operations.

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