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ENHANCING FLUID INVASION MITIGATION IN WATER-BASED DRILLING FLUIDS: THE ROLE OF GRAPHENE OXIDE ON FILTRATION LOSS AND MUD CAKE FORMATION

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Abstract

This study investigates the effect of graphene oxide (GO) on two critical parameters; filtration loss and mud cake thickness of water-based drilling fluids (WBDFs), essential for maintaining wellbore stability during drilling operations. Experimental results demonstrate that incorporating 0.1 wt.% GO reduces filtrate volume by 16% and increases mud cake thickness by 12.2%. At 0.45 wt.% GO, filtrate loss decreases by 22%, and mud cake thickness increases by 18%. These improvements significantly enhance wellbore stability, especially in shallow wells with narrow pressure windows. By reducing fluid invasion and improving the sealing properties of the mud cake, GO-modified WBDFs offer a cost-effective solution to mitigate common drilling challenges such as lost circulation and wellbore collapse, ultimately enhancing operational efficiency and safety. The scalability of GO-modified fluids for commercial drilling projects holds great potential, offering a promising, environmentally friendly alternative to traditional fluid systems. This study highlights GO's potential as an additive to improve WBDF performance in real-world drilling scenarios. Future research could explore the optimization of higher GO concentrations and investigate hybrid formulations with other additives to further enhance filtration control and fluid sealing properties.

Keywords: Graphene Oxide, Fluid Loss Control, Mud Cake Thickness, Water-Based Drilling Fluids, Wellbore Stability, Nanoparticles, Nanotechnology.

1. Introduction

In the oil and gas industry, drilling operations are indispensable for meeting the rising global demand for energy, yet they display numerous challenges in terms of operational efficiency, safety, and environmental sustainability [1-4]. Among the most dangerous of these challenges is managing wellbore stability, as problems such as lost circulation, wellbore collapse, and blowouts often lead to operational delays, increased costs, and safety hazards [5-7]. These issues arise mostly from poor management of filtration loss and mud cake formation, particularly in shallow wells where pressure margins are narrow. Effective management of these parameters is important towards ensuring safe and cost-effective drilling operations, especially in situations where wellbore stability is experienced [8-11].

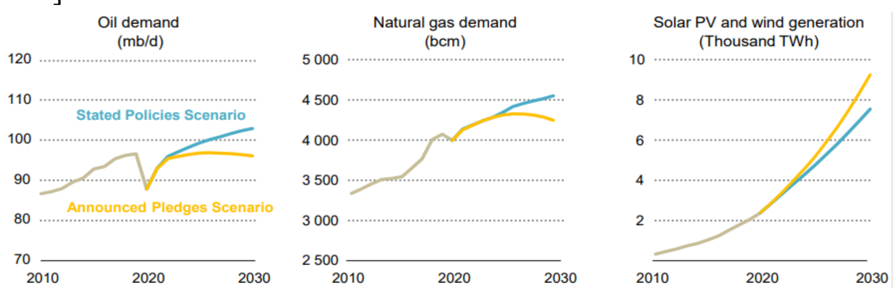

Figure 1. Oil, natural gas and renewable energy demand by 2030, *IEA report* [4].

As the global energy demand continues to grow, the oil and gas industry experiences pressure rise not only to advance drilling effectiveness but also to lessen its ecological effect. This has led to an increasing attention in the development of ecologically friendly and efficient water-based drilling fluids (WBDFs). The developments offer a more sustainable substitute to traditional oil-based drilling fluids [12-14]. Nano-enhanced WBDFs, especially those improved with graphene oxide (GO), appear as promising solution. GO's exceptional nanosheet structure, large surface area, and functional groups permit better interactions with fluid components, making it suitable for enhancing the performance of drilling fluids [13, 15-18]. Compared to orthodox fluids, GO-modified WBDFs provide numerous potential benefits, such as improved filtration control, enhanced rheology, and better lubricity, all of which can meaningfully increase operational performance and safety [13, 19-21].

In recent times, investigators have shown interests in using GO in several industries, including oil and gas [22-24]. The unique characteristics of GO has caught the attention of researchers to improve DF's performance. Studies have shown the capabilities of GO in reducing spurt and filtrate loss [25-28], due to their ability in occupying Nano pores between conventional additives, generating less-permeable filter cake. Graphene oxide is a particle known to have at least one of its dimensions to be between 1nm-100nm. GO has shown its significant advantage towards improving rheological properties of WDFs [29-35]. Research has verified that GO can improve the viscosity, shear-thinning behaviour, and lubricity of drilling fluids, which leads to friction reduction and better drilling efficiency [16, 36, 37]. For example, studies by AlBajalan, *et al.,* [14], have demonstrated that GO-modified fluids show enhanced rheological properties that assists in improved pressure control during drilling operations. Likewise, Lalji, *et al.,* [38] emphasised the potential of GO to decrease friction between the drill bit and wellbore, improving drilling performance and dropping energy consumption. Nevertheless, in spite of these promising discoveries, most research focus on the rheological properties of GO, with inadequate consideration given to its influence on filtration loss and mud cake formation for sustaining wellbore stability [16, 39-42] .

Although some findings, such as Lalji, *et al.,* [42] have advised that GO can influence filtration properties and mud cake formation positively, the impacts are not well-understood, predominantly in the context of WBDFs. Additionally, there is an absence of research to address the optimal concentration of GO for an equilibrium improved filtration control with practicable mud cake thickness. This awareness is particularly significant in shallow well scenarios, where wellbore stability is life-threatening due to narrow pressure windows [43]. The current gap in the literature points out the need for further studies that investigate the twin effects of GO on both filtration loss and mud cake thickness, along with its overall influence on wellbore stability.

This study intends to fill this gap by systematically assessing the effect of GO on both filtration loss and mud cake thickness in WBDFs. By testing two variable formulations of GO (i.e. 0.1 wt.% and 0.45 wt.%), this study pursues to find the optimal formulation that advances filtration control, mud cake formation, and wellbore stability. Through this examination, the research aims to offer valuable understandings into the likelihood of GO-modified drilling fluids to boost operational efficiency and safety in the petroleum industry.

2. Materials and Methods

2.1 Preparation of Drilling Fluids:

The GO material, sourced from Sigma-Aldrich Malaysia, consisted of 15-20 graphene layers with 4-10% edge oxidation and a molecular weight of 4,239.48 g/mol. It was designed for dispersion in polar solvents like water, which makes it particularly suitable for use in aqueous systems like drilling fluids. The material's structure comprises exfoliated graphene nanoplatelets with functional organic groups, with hydroxyl content below 5%, allowing for chemical modification without compromising its intrinsic properties.

WBDFs were prepared by incorporating graphene oxide (GO) nanoparticles, bentonite, and barite according to the guidelines outlined in API 13B-1 for field testing WBMs. GO nanoparticles, selected for their exceptional rheological properties, were used at two distinct concentrations (0.1 wt.% and 0.45 wt.%) to enhance the fluid's performance [44]. The GO nanoparticles had an average sheet size of 1-5 μm and a thickness ranging from 1 to 10 nm, with oxygenated functional groups (–OH, –COOH) that promote strong interactions with the fluid's other components, improving stability and dispersion [45]. To incorporate the GO nanoparticles, they were pre-dispersed in deionized water before being added to the base fluid. This process was carried out using high shear mixing to ensure uniform dispersion of the GO nanosheets and to prevent aggregation, which could negatively affect the fluid's filtration and rheological properties. This high-shear technique was critical for achieving a stable dispersion and ensuring the fluid's optimal performance under dynamic drilling conditions.

[46]. This high shear mixing technique was vital for attaining a uniform dispersion and averting nanoparticle aggregation, which could distort the fluid's performance during filtration and rheological testing [47]. Detailed specifications of the GO nanoparticles used in this research are presented in Table 1.

Table 1: Physicochemical Characteristics of Graphene Oxide Nanoparticles Used in This Study.

MATERIAL	DENSITY (G/ML)	MOLECULAR WEIGHT (G/MOL)	APPEARANCE	DESCRIPTION
Graphene Oxide (GO)	1.8	4,239.48	Black (Powder)	20sheets, 4-10% edge-oxidized

The key tests of this investigation are mud thickness and filtration measurements. These measurements were achieved under room conditions utilizing American petroleum institute procedure to improve the accuracy and control the uncertainty to an acceptable limit of 2%. There are some critical factors in uncertainty of the experiments such as the contamination of the material, neatness of the laboratory supplies, the precision of the digital balance (±0.01gr), the accuracy of the thickness vernier calliper (±0.5 of dial reading), the pressure applied to the filter cell (±5 psi), and reading the filtrate volume in nearest ±0.1 ml.

2.2 Filtration Testing

Filtration tests were conducted according to the procedures outlined in API RP 13B-1 using a standard filter press (Series 300, Fann Instrument Company) at a pressure of 100 psi for 30 minutes. To ensure the accuracy of the measurements, all instruments were meticulously calibrated before the tests. The tests were performed under atmospheric conditions using Whatman quantitative ashless filter paper (Grade 42), with a particle retention size of 2.5 μm [48, 49].

The filtration loss of the drilling fluids was assessed using the API Low-Pressure Low-Temperature (LPLT) filter press, maintaining standard test settings to evaluate the filtration characteristics of the fluids. To ensure consistency and comparability, all formulations were tested under identical conditions. The filtrate volume is a crucial measure of the fluid's ability to form a solid filter cake and resist fluid invasion into the formation.

2.2 Mud Cake Thickness Measurement

The thickness of the mud cake formed during filtration testing was measured using a calibrated micrometre. At the conclusion of the LPLT test, the filter press was carefully disassembled, and the mud cake that had accumulated on the filter paper was gently removed. The micrometre allowed for precise measurement of the cake thickness to the nearest hundredth of a millimetre. These measurements provided valuable insights into the ability of the drilling fluid to form a solid, impermeable filter cake, which is crucial for preventing fluid invasion into the formation during drilling operations. The ability to form a well-structured mud cake plays a significant role in ensuring wellbore stability and optimizing fluid efficiency in real-world drilling environments [50].

3. Results and Discussion

The LPLT filtration assessment was conducted for 30 minutes to assess the consequence of variable GO concentrations (i.e. 0.0, 0.1, and 0.45 wt.%) on the filtration and mud cake characteristics of WBDFs. The findings, summarized in Table 2, establish a strong concentration-dependent trend. As GO concentration increased, filtration loss decreased, from 10.0 mL for the base fluid to 7.8 ml at 0.45 wt.% GO, signifying a 22% decrease. At the same time, mud cake thickness increased from 2.45 mm (base fluid) to 2.89 mm (0.45 wt.% GO), an 18% increase.

Table 2: Filtration Loss and Mud Cake Thickness for GO- WDF's (0.1 wt.% and 0.45 wt.%): COMPARATIVE Analysis with Base Fluid (LPLT, 30-Minute Test).

GO Concentration	Filtration Loss (mL)	% Reduction	Mud Cake Thickness (mm)	% Increase
0.0wt% (Base)	10.0	–	2.45	–
0.1wt%	8.4	16.0%	2.75	12.2%
0.45wt%	7.8	22.0%	2.89	18.0%

3.1 Filtration Loss of Testing Drilling Fluids

The integration of GO into WBDFs caused in a substantial, concentration-dependent drop in filtration loss. For the 0.1 wt.% GO formulation, a 16% reduction in filtrate volume was observed compared to the base fluid, indicating an improvement in the fluid's ability to form a stable filter cake. At a higher concentration of 0.45 wt.% GO, the reduction in filtrate volume increased to 22%, further highlighting the potential of GO to enhance fluid sealing properties. These reductions suggest that GO effectively enhances the fluid's filtration control, contributing to better wellbore stability by minimizing fluid invasion into the formation. The ability of the GO-modified fluid to limit filtrate loss is crucial in maintaining formation integrity and preventing issues such as lost circulation or wellbore collapse during drilling operations. Figure 2 presents the influence of graphene oxide (GO) concentration on filtration loss. An increasing GO concentration led to a steady reduction in filtrate volume, with the most pronounced effect observed at 0.45 wt.% (figure 3).

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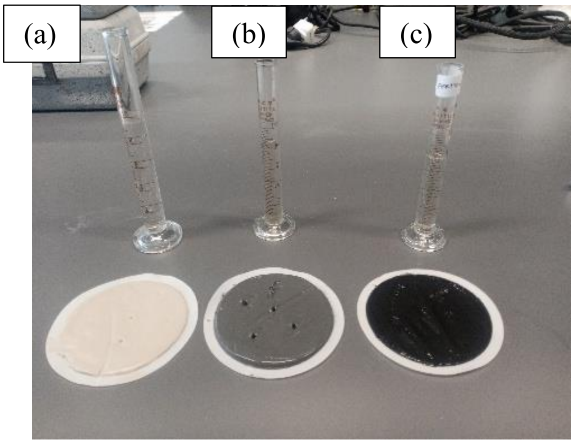

Figure 2: Comparison of Filtrate Loss and Filter Cake Deposition: (a) Base Fluid, (b) GO 0.1 wt.%, (c) GO 0.45 wt.%, in Graduated Cylinders and Filter Papers.

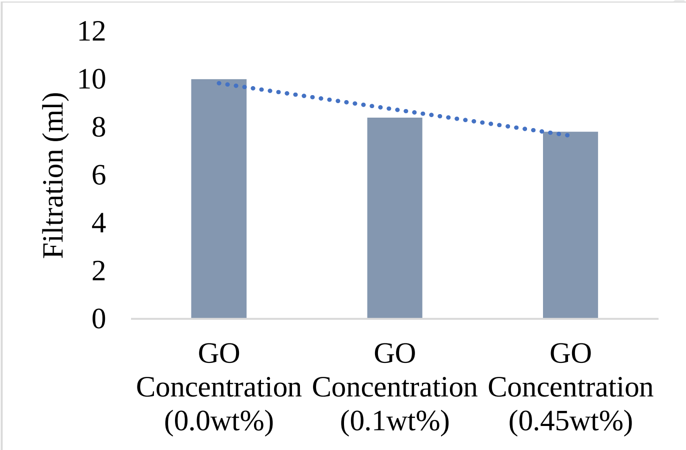

Figure 3: Effect of Graphene Oxide Concentration (0.1 wt.% and 0.45 wt.%) on Filtration Loss.

Figure 3 shows the impact of GO on filtration loss in WDF's, showing a clear reduction in filtrate volume with increased GO concentration. The greatest significant reduction transpires at 0.45 wt.%, attributed to the formation of a dense, low-permeability filter barricade by GO nanosheets, which limits fluid migration into the formation.

3.2 Mud Cake Thickness of Testing Drilling Fluids

A comparable concentration-dependent trend was detected for mud cake thickness. At 0.1 wt.% GO, the mud cake thickness increased by 12.2%, while at 0.45 wt.% GO, the increase was even more pronounced, with an 18% rise in cake thickness. The increase in mud cake thickness can be attributed to the enhanced ability of GO to form a denser, more impermeable filter cake. This thicker cake plays a critical role in reducing fluid invasion into the formation, thus improving wellbore stability. The higher concentration of GO likely results in the formation of a more compact and tightly packed cake, which enhances the sealing capabilities of the fluid. This is especially important in shallow well drilling, where narrow pressure margins make it essential to control filtration and mud cake formation to avoid formation damage or influxes. Figure 4 presents the influence of graphene oxide (GO) concentration on mud cake thickness.

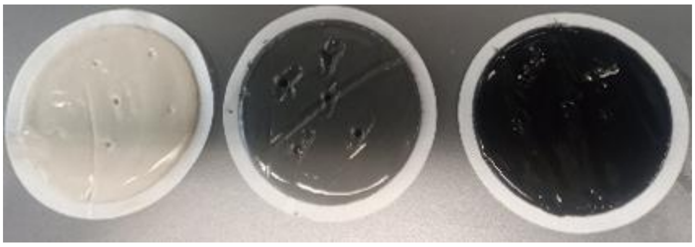

Figure 4: Close-up of Fresh Filter Cakes Post-Filtration: (a) Base Fluid, (b) GO 0.1 wt.%, (c) GO 0.45 wt.%.

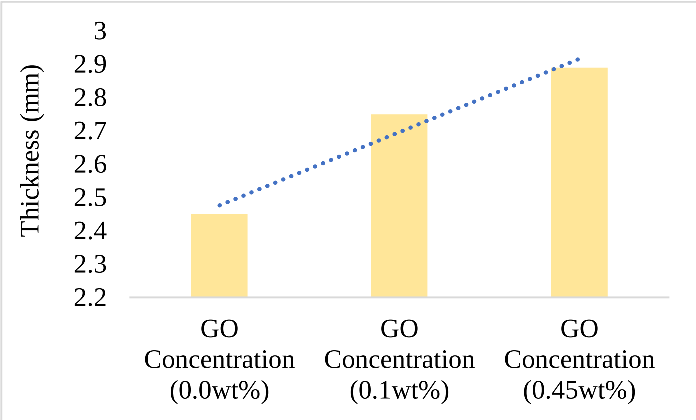

Figure 5: Effect of Graphene Oxide Concentration (0.1 wt.% and 0.45 wt.%) on Mud Cake Thickness in Water-Based Drilling Fluids.

Figure 5 reveals a steady increase in mud cake thickness with higher GO concentrations. Whereas this thickening may raise equivalent circulating density (ECD) and surge pressures, the decrease in filtrate volume suggests improved sealing properties, advantageous for formations with high permeability or fractures. Conversely, mud cake thickness showed a consistent increase with higher GO concentrations. While the thicker mud cakes may raise concerns about equivalent circulating density (ECD) and surge pressures, their enhanced compactness contributes to improved sealing properties. This is particularly advantageous in formations with fractures or high permeability, where effective sealing is critical.

3.3 Results and Discussion:

GO is a highly versatile nanomaterial with unique properties that allow it to significantly enhance the performance of WBDFs. At the molecular level, GO's impact on filtration loss and mud cake formation can be explained by its structure and chemical functionality, which enable strong interactions with the other components of the drilling fluid.

3.3.1 Molecular Structure of GO and Its Role in Filtration Control

GO is composed of graphene sheets that are oxidized, with oxygen-containing functional groups such as hydroxyl (-OH), carboxyl (-COOH), and epoxy (-O-) located at the edges and on the surface. These functional groups are highly hydrophilic, providing the GO sheets with an ability to interact strongly with water molecules and other components of the fluid, such as bentonite or barite.

At low concentrations (e.g., 0.1 wt.%), GO's nanosheet structure begins to interact with the polymeric components of the drilling fluid, such as bentonite or barite. The high surface area of GO enables it to form a network of physical interactions with the fluid's polymers, resulting in a more cohesive and dense structure. This interaction improves the fluid's ability to form a stable and low-permeability filter cake during filtration tests. The GO nanosheets fill voids in the cake, increasing its compactness and reducing the flow of filtrate into the formation, thus enhancing filtration control. At higher concentrations (e.g., 0.45 wt.%), the number of GO nanosheets increases, leading to further strengthening of the filter cake. The intercalation of GO sheets within the cake forms a denser network, increasing the barrier properties of the mud cake. This compact structure significantly reduces the permeable pathways for filtrate, leading to a more pronounced reduction in filtration loss.

3.3.2. Impact of GO on Mud Cake Formation

Mud cake formation plays a critical role in sealing the wellbore and preventing fluid invasion into the formation. The ability of GO to enhance mud cake formation stems from its physical and chemical characteristics.

- Intercalation and Reinforcement of the Cake Matrix: The layered structure of GO sheets enables them to intercalate in the mud cake, reinforcing the cake's structure and improving its impermeability. This intercalation effectively blocks the formation of large pore spaces in the mud cake, reducing the rate of fluid penetration into the formation. As a result, the mud cake thickness increases with higher GO concentrations, providing a stronger seal.
- Electrostatic Repulsion and Dispersion Stability: The oxygen-containing functional groups on the GO nanosheets also contribute to the electrostatic repulsion between GO sheets, preventing aggregation or restacking. This ensures that the GO nanosheets remain well-dispersed within the fluid and the mud cake, contributing to the homogeneity and uniformity of the mud cake. This uniformity is crucial for minimizing weaknesses in the filter cake, which could otherwise lead to fluid invasion into the formation.
- Hydration and Structural Integrity: The hydrophilic nature of GO also plays a role in maintaining the structural integrity of the mud cake. Upon hydration, the functional groups on GO nanosheets form strong hydrogen bonds with water molecules, which may increase the overall cohesion of the mud cake. The result is a more robust and impermeable filter cake, which reduces the risk of fluid migration into porous formations or fractures.

3.3.3. Mechanisms Behind Filtration Loss Reduction

- Increased Cake Compactness: As mentioned, the enhanced interaction between GO and the fluid’s polymer matrix results in the formation of a denser, more compact mud cake. The increased cake thickness reduces the permeability of the filter cake, thereby reducing the filtration loss. This is especially pronounced at higher concentrations of GO (e.g., 0.45 wt.%), where the increased number of nanosheets contributes to a much tighter, low-permeability filter cake.
- Particle Size and Surface Area Effect: The small size and large surface area of GO nanosheets also contribute to the reduction of filtration loss. The higher surface area provides more sites for interaction with the other fluid components, leading to a more stable fluid system. Moreover, the GO sheets themselves act as physical barriers to the flow of filtrate, obstructing the pathways through the cake and thereby reducing fluid invasion into the formation.

3.3.4. Comparative Mechanism with Other Nanomaterials

When comparing GO to other nanomaterials such as nanosilica or carbon nanotubes (CNTs), its mechanisms are more advantageous in terms of filtration control. Nanosilica and CNTs often improve rheology but do not significantly enhance filtration control or mud cake formation to the same degree as GO.

- Nanosilica: While nanosilica enhances the rheological properties of WBDFs, its effect on filtration loss is less pronounced. Nanosilica's smaller surface area and lack of significant functional groups mean that it does not interact as effectively with fluid components, limiting its impact on the filtration control and mud cake formation compared to GO.
- Carbon Nanotubes: CNTs also provide improved rheological properties but tend to require additional dispersing agents to prevent aggregation, which can complicate fluid formulation. GO, on the other hand, can be uniformly dispersed without the need for additional agents, offering a simpler and more efficient solution for improving filtration properties.

3.3.5. Potential Trade-offs and Limitations

While GO enhances filtration control and mud cake formation, it is important to acknowledge potential trade-offs at higher concentrations. As GO concentration increases, the viscosity of the fluid may rise, potentially impacting pumping efficiency. The increased viscosity could also lead to higher equivalent circulating density (ECD) and surge pressures, particularly in narrow-margin wells. These factors should be carefully considered when optimizing the concentration of GO for specific drilling operations.

4. Conclusion

This study demonstrates that the incorporation of GO into WBDFs significantly enhances both filtration loss and mud cake thickness, which are crucial for improving wellbore stability, particularly in shallow well drilling operations. The experimental results show that the addition of 0.1 wt.% GO reduces filtrate volume by 16% and increases mud cake thickness by 12.2%. At 0.45 wt.% GO, the reduction in filtration loss increases to 22%, while the mud cake thickness rises by 18%. These findings underscore the potential of GO as a cost-effective and efficient additive for improving the performance of WBDFs.

The improvements in filtration control and mud cake formation, achieved through the addition of GO, pave the way for the development of new drilling fluid formulations or protocols tailored for shallow well drilling, where narrow pressure windows require precise fluid behaviour. This study highlights the importance of balancing GO concentration to optimize fluid properties, ensuring both improved sealing capabilities and manageable rheological behaviour. The results suggest that GO-modified WBDFs could become a standard additive in drilling operations, helping to address wellbore stability challenges and reduce operational risks.

Implications for Industry

The findings of this study provide several practical implications for the drilling industry. The significant reduction in filtration loss and the enhancement of mud cake thickness directly contribute to improving wellbore stability, minimizing risks such as lost circulation, wellbore collapse, and influxes. This is particularly important in shallow well environments where maintaining wellbore integrity is critical.

In terms of cost efficiency, the use of GO-modified fluids could result in substantial savings by reducing NPT due to wellbore instability and mitigating the need for costly remedial operations. The improved sealing properties of GO-modified WBDFs can reduce the occurrence of formation damage and fluid invasion, thereby decreasing the frequency of wellbore cleanups and pressure balancing operations. Moreover, GO's cost-effectiveness, coupled with its potential for improving operational efficiency, makes it a promising alternative to more expensive and environmentally harmful oil-based fluids.

A brief cost-benefit analysis could further solidify these findings, highlighting that the initial cost of incorporating GO into drilling fluids could be offset by the long-term reduction in NPT and wellbore remediation activities, leading to greater overall drilling efficiency and reduced operational costs.

Future Work

While this study has provided valuable insights into the benefits of GO-modified WBDFs, further research is needed to optimize the concentration of GO and its interactions with other additives. Future studies should explore the performance of higher concentrations of GO in WBDFs and investigate potential combinations with other nanomaterials or chemical additives, such as surfactants, polymers, or weighting agents, to achieve even more enhanced filtration control and mud cake formation. These combinations could offer a more tailored solution for different wellbore environments, optimizing fluid performance based on specific drilling conditions.

Additionally, testing GO-modified fluids under dynamic conditions, such as varying flow rates or the presence of specific contaminants (e.g., high salinity or high-temperature conditions), would provide a more comprehensive understanding of the fluid's behaviour under realistic operational scenarios. Field trials and long-term stability studies would also be necessary to assess the durability of GO-modified fluids and their effectiveness across a wider range of drilling environments. Such future work would help to fully realize the potential of GO-modified fluids in both conventional and unconventional drilling applications.

Authorship Contributions:

Umar Nabil Sabo: Conceptualization, Data Collection, Research, Methodology, Initial Draft Writing. Syahrir Ridha: Resources, Funding, Oversight, Validation, Manuscript Review & Editing. Bolade Agboola, Isioma Nwadike, Mohammad Yusuf, Hafsat Bano.: Data Analysis, Methodology, Manuscript Review & Editing.

Competing Interests Statement:

The authors declare no conflicts of interest, either financial or personal, that could have influenced the content of this paper.

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Nomenclature &Abbreviations

GO	Graphene Oxide
WBDF	Water-Based Drilling Fluid
XG	Xanthan Gum
LPLT	Low-Pressure Low-Temperature
API	American Petroleum Institute
NPT	Non-Productive Time
ECD	Equivalent Circulating Density
ml	Millilitres
mm	Millimetres
wt.%	Weight Percentage

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