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RHEOLOGICAL MODELLING AND VALIDATION OF GRAPHENE OXIDE-ENHANCED WATER-BASED DRILLING FLUIDS FOR SURGE AND SWAB PRESSURE MITIGATION: A COMPARISON OF POWER LAW AND YIELD POWER LAW MODELS

Umar Nabil Sabo[1,2,3]*, Syahrir Ridha[1,2], Mohammad Yusuf[4]. Hafsa Bano[2], Bolade Agboola[3], Isioma Nwadike[3].

[1]Department of Petroleum Engineering, Universiti Teknologi PETRONAS, Bandar Seri Iskandar, Perak, 32610, Malaysia.
[2]Institute of Sustainable Energy & Resources, Universiti Teknologi PETRONAS, Bandar Seri Iskandar, Perak, 32610, Malaysia.
[3]Department of Petroleum Chemistry & Physics, American University of Nigeria, Yola, Adamawa State. Nigeria.
[4]Clean Energy Technologies Research Institute (CETRI), Process Systems Engineering, Faculty of Engineering and Applied Science, University of Regina, 3737 Wascana Parkway, Regina, SK, S4S 0A2, Canada.
Corresponding author: Umar Nabil Sabo (umar.sabo@aun.edu.ng).

Abstract
This study examines the rheological properties of graphene oxide (GO)-modified water-based drilling fluids (WBDFs) and assesses their performance by means of Yield Power Law (YPL) and Power Law (PL) models. Experimental findings confirm substantial improvements in yield stress, plastic viscosity, and shear-thinning behaviour. Mutually, the models signify high predictive accuracy ($R^2 > 0.79$ for YPL, and 0.95 for PL). The YPL model excellently captures the yield stress and non-Newtonian behaviour of the fluids, offering exceptional prediction of surge and swab pressures. These improvements contribute to better wellbore stability, cut non-productive time (NPT), and boosted safety margins. The results highlight a probable optimization during drilling operations by improving surge and swab pressure control. Forthcoming studies will encompass testing the fluids under high-pressure, high-temperature (HPHT) environments and integrating them into Computational Fluid Dynamics (CFD) models for multifaceted drilling scenarios.

Keywords: Graphene Oxide, Nanoparticles, Rheological Modelling, Shear-Thinning Behaviour, Water-Based Drilling Fluids.

1. Introduction

Water-based drilling fluids (WBDFs) remain indispensable for the success during drilling operations, offering wellbore stability, improving drilling efficiency, and mitigating surge and swab pressures in tripping processes. Surge pressures, generated by the downward drive of drill pipes which leads to formation fracturing, whereas swab pressures, generated by the ascending movement of the pipe which can induce formation influxes [1-5]. These pressure instabilities pose substantial challenges, especially in shallow wells with slim pressure windows. In such wells, the inadequate pressure margin between the fracture gradient and pore pressure makes it decisive to precisely forecast and manage surge and swab pressures to avoid operational catastrophes [5-7].

Current developments have established that the integration of nanoparticles such as graphene oxide (GO), can substantially improve the rheological properties of WBDFs [8-11]. The large surface area and exceptional nanosheet structure of GO improve key features such as yield stress, plastic viscosity, and shear-thinning behaviour [12-14]. Nevertheless, while GO-modified fluids have presented capable improvements, there is a limited body of study that relates comprehensive rheological modelling, especially in forecasting dynamic pressure behaviour such as surge and swab pressures [15-17].

Orthodox rheological models, such as Bingham Plastic (BP) and Power Law (PL) models, remain broadly used to define the flow properties of drilling fluids. But these models frequently fail to capture the intricate, non-Newtonian behaviour and yield stress displayed by GO-modified fluids [18, 19]. The Yield Power Law (YPL) model, which combines both yield stress and shear-thinning behaviour thereby offering a more precise representation of the rheological properties of GO-modified WBDFs [20, 21]. This model is principally suitable for fluids like GO-modified WBDFs, where the initial resistance to flow (yield stress) is crucial in predicting performance under dynamic circumstances such as surge and swab pressures [21-23]. Through the YPL model, this study aims to advance the prediction of surge and swab pressures, a task that traditional models often fail to accomplish with similar level of precision [24, 25]. This investigation addresses the gap by engaging both the YPL and PL models to meticulously assess the rheological properties of GO-modified WBDFs. By comparing these models, the study not only improves rheological understanding of GO-modified WBDFs but correspondingly contributes to enhanced surge and swab pressure predictions, improving wellbore stability and operational competence in challenging drilling settings like shallow wells with narrow pressure windows.

2. Materials and Methods

2.1 Fluid Preparation

Duo concentrations of GO 0.1 wt.% and 0.45 wt.%, were selected for this investigation to assess the impact of GO concentration on rheological properties of WBDFs. The lower concentration (i.e. 0.1 wt.%) was chosen to observe the initial effects of GO adjustment [14, 26, 27], whereas the higher concentration (i.e. 0.45 wt.%) was incorporated to examine the potential for supplementary enhancement in fluid properties and evaluate any possible opposing effects at higher concentrations [28, 29]. These concentrations were selected based on earlier investigations and their significance to typical drilling fluid formulations utilized in the oil and gas industry.

The graphene oxide nanoparticles were dispersed into a base fluid incorporated with xanthan gum (XG) and barite by means of a high-shear mixer, unambiguously the Five-Spindle Multi-Mixer® Model 9B. The mixer ran at 11,500 RPM in deionized water to reach even dispersal of the GO particles. The high shear mixing procedure is crucial for realising an even dispersion of GO, as it excellently disrupts any agglomerates and guarantees that the GO sheets are well-dispersed in the fluid [30-32]. This even dispersion is critical for precisely characterizing the rheological properties of the GO-modified WBDFs and warranting reliable performance throughout testing [33-35]. The mixture was afterwards stirred at 1000 RPM for 30 minutes to further confirm homogeneity and complete distribution of the GO nanoparticles. This technique was repeated for both GO concentrations.

2.2 Rheological Testing

Rheological properties, comprising yield point (YP), plastic viscosity (PV), and gel strength (at 10 seconds and 10 minutes), were determined by means of a standard Fann 35 viscometer at 25°C [36, 37]. Measurements were recorded at 600, 300, 200, 100, 6, and 3 RPM to create shear stress vs. shear rate data. Each sample was verified in triplicate to ensure precision and reproducibility, and the viscometer was calibrated prior to use [36, 38]. The model's precision is ±0.5 of the dial reading. Rheological parameters for water-based drilling fluids (WBDFs) were determined using the following equations:

$$AV = \Phi600 + 2\Phi300 / 3 \quad (1)$$

$$PV = \Phi_{600} - \Phi_{300} \quad (2)$$

$$YP = 0.5 \times (\Phi_{300} - PV) \quad (3)$$

2.3 Model Fitting and Validation

The experimental data obtained from the rheological measurements were fitted to the two models (i.e. PL and YPL). The PL was used to illustrate the fluid's shear-thinning behaviour, while the YPL was selected to account for the yield stress displayed by the fluids, as well as their non-Newtonian features [39-41]. The experimental statistics were fitted using nonlinear regression, and the goodness of fit was measured by calculating the coefficient of determination (R^2) and root mean square error (RMSE) for each drilling sample [20] [21, 42].

The subsequent equations were used to model the shear stress (τ) as a function of shear rate (γ̇) for both models:

Yield Power Law Model:

$$\tau = \tau y + K \cdot \dot{\gamma} n \quad (4)$$

Where *K* is consistency index, γ is share rate, τ is share stress, n is the flow behaviour index, and τy is Yield stress.

Power Law Model:

This two-parameter model relates shear stress to shear rate, where k is the consistency index and n represents the degree of shear-thinning or thickening behaviour. Equation (5) shows the model form.

$$\tau = K \cdot \dot{\gamma} n \quad (5)$$

Where *K* is consistency index, γ is share rate, τ is share stress and n is the flow behaviour index.

3. Results and Discussion

3.1 Rheological Properties of GO-Modified WBDFs

The integration of GO into WBDFs caused substantial improvements in the rheological features of the drilling fluids, especially at the lower concentration (0.1 wt.%). At lower concentration, the fluid showed enhanced yield stress, plastic viscosity, and shear-thinning behaviour, these are crucial for maintaining stability throughout drilling operations. At 200 RPM, the viscosity was 39 cp, and at 6 RPM, it was 25 cp, signifying the shear-thinning nature of the drilling fluid. This behaviour is mainly significant in mitigating surge and swab pressures, where the fluid requires easy flow under high shear rates while keeping sufficient viscosity at low shear rates to avert wellbore instability [42-44].

Likewise, at the higher concentration of 0.45 wt.% GO, the fluid displayed improved rheological properties but with a minor reduction in viscosity related to the 0.1 wt.% GO formulation. At 200 RPM, the viscosity was noted at 30 cp, and at 6 RPM, it was 18 cp. This drop in viscosity at higher GO concentrations is probably due to the increased particle concentration, which can lead to accumulation or variations in the fluid's microstructure. This phenomenon can interrupt the anticipated shear-thinning behaviour of the fluid, potentially upsetting its flow properties. The gel strength measurements at 10 seconds (15) and 10 minutes (21) also exhibited a reasonable increase in fluid stability at the higher GO concentration, even though the enhancements were less noticeable than at the lower concentration [18, 26].

This drop in viscosity at higher GO concentrations could be attributed to the cluster of GO nanoparticles. As the concentration of GO increases, the nanoparticles may start to network more strongly, leading to particle aggregation. This aggregation can interrupt the even dispersion of the nanoparticles, in that way altering the shear-thinning behaviour of the fluid. While this trend was observed, further investigation is needed to optimize the concentration of GO and prevent agglomeration, possibly through advanced dispersion techniques like ultrasonication.

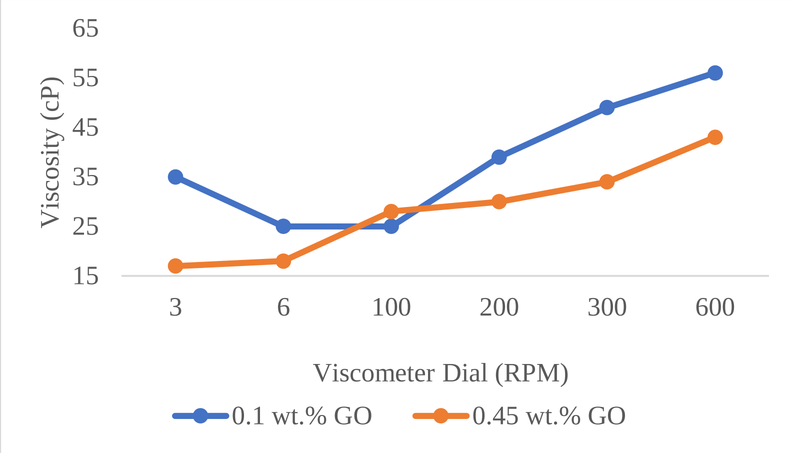

Figure 1: Viscometer Readings for 0.1 wt.% and 0.45 wt.% GO-modified WBDFs.

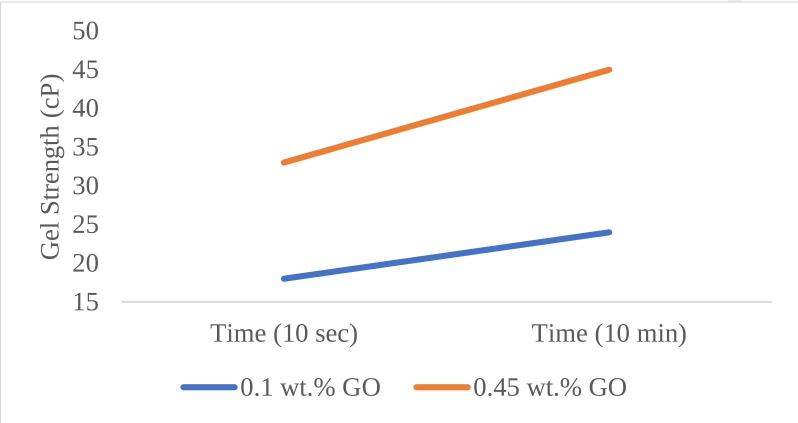

Figure 2: Gel Strength Measurements for 0.1 wt.% and 0.45 wt.% GO-modified WBDFs at 10 sec and 10 min.

Table 1: Rheological Data for GO-Modified WBDFs.

Viscometer Reading	0.1 wt.% GO	0.45 wt.% GO	Gel Strength (10 sec)	Gel Strength (10 min)
200 RPM	39	30	18	15
6 RPM	25	18	25	21
600 RPM	56	43	-	-
Low RPM	-	-	-	-
100 RPM	25	28	-	-
3 RPM	35	17	-	-
300 RPM	49	34	-	-

3.2 Model Fitting and Validation

The experimental data for both 0.1 wt.% and 0.45 wt.% GO-modified WBDFs were accurately represented by both the Power Law (PL) and Yield Power Law (YPL) models. As shown in Table 2, the YPL model demonstrated superior fit accuracy for both concentrations, with R^2 values of 0.795 (for 0.1 wt.%) and 0.992 (for 0.45 wt.%), compared to R^2 values of 0.519 (for 0.1 wt.%) and 0.954 (for 0.45 wt.%) for the PL model. Additionally, the RMSE values were consistently lower for the YPL model, indicating a better prediction of shear-thinning behaviour and yield stress characteristics of the fluids.

Table 2: Rheological Parameters and Model Fitting for 0.1 wt.% and 0.45 wt.% GO-modified WBDFs

Model	0.1 wt.% GO - K	0.1 wt.% GO - n	0.1 wt.% GO - τ_0	0.1 wt.% GO - R^2	0.1 wt.% GO - RMSE	0.45 wt.% GO - K	0.45 wt.% GO - n	0.45 wt.% GO - τ_0	0.45 wt.% GO - R^2	0.45 wt.% GO - RMSE
Power Law	21.743	0.127	N/A	0.519	7.970	12.643	0.180	N/A	0.954	1.932
Yield Power Law	0.049	1.003	28.193	0.795	5.208	1.161	0.494	15.227	0.992	0.828

The improved fit of the YPL model can be directly linked to its ability to capture the yield stress behaviour, which is crucial in real-world applications like surge and swab pressure mitigation. The yield stress represents the minimum stress required to initiate flow, which is important in controlling pressure fluctuations during tripping operations. The YPL model's capability to more precisely predict yield stress means it is well suited for forecasting fluid behaviour in dynamic drilling circumstances, where surge and swab pressures can vary significantly.

3.3 Comparative Analysis of 0.1 wt.% vs. 0.45 wt.% GO

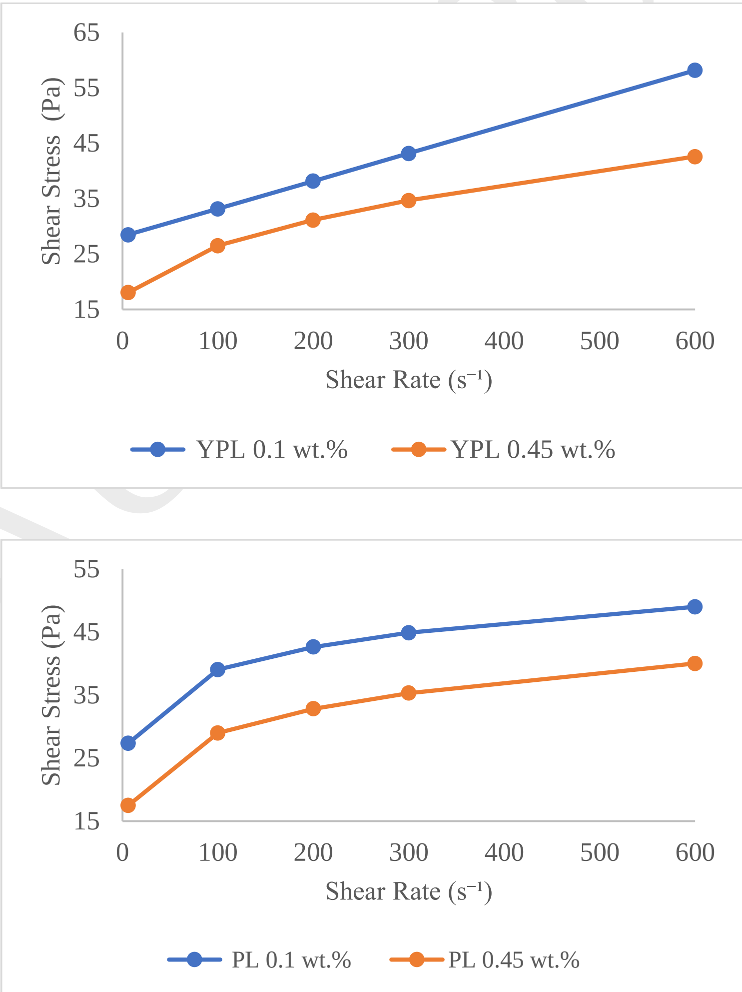

Figure 3: Shear stress vs. shear rate plots for (a) PL and (b) YPL models.

Figures 3(a) and 3(b) display the shear stress vs. shear rate plots for both the PL and YPL models, evidently showing the superior fit of the YPL model, especially at lower shear rates where yield stress is most important. The YPL model correctly captures the fluid's resistance to flow beforehand, which is a crucial feature for controlling surge and swab pressures. Contrastingly, the PL model underestimates this resistance, leading to less precise predictions of pressure behaviour.

The decrease in viscosity detected at higher GO concentrations (i.e. at 0.45 wt.%) signifies the importance of optimizing GO concentrations to avoid potential agglomeration problems. While higher concentrations of GO lead to enhancements in yield stress and plastic viscosity, disproportionate concentration may disrupt the fluid's shear-thinning behaviour, eventually distressing its performance. More studies are required to fine-tune the concentration and dispersion of GO to realise optimum fluid properties without compromising performance.

3.4 Limitations and Uncertainties in Model Predictions

Notwithstanding the superior performance of the YPL model, certain limits and doubts need to be recognised. One possible limitation of the YPL model is its dependence on the assumption that the yield stress is constant across changing shear rates. In real-world drilling environments, features such as temperature variations, pressure fluctuations, and the existence of contaminants could impact the yield stress in ways that the YPL model may not completely account for. This could lead to inconsistencies in forecasting surge and swab pressures in situations with fluctuating circumstances.

In addition, the YPL model assumes a steady relationship between shear rate and shear stress, which might not hold accurate in all forms of fluids or operational circumstances. For instance, during high shear rate procedures, such as in deep well drilling or when using high flow rates, the model might miscalculate the fluid's capacity to resist surge pressures due to the simplification of intricate fluid dynamics. In such cases, more advanced models that consider features like viscoelasticity or non-Newtonian behaviour outside the shear-thinning region may offer more precise predictions. Likewise, the PL model, while easier, may still assist as a valuable approximation for certain low-viscosity, shear-thinning fluids, nevertheless it fails to capture the yield stress required for exact surge and swab pressure prediction in more intricate fluids like GO-modified WBDFs. This makes the PL model less appropriate for fluids with substantial yield stress, as established in this study.

3.5 Practical Implications and Future Work

The enhanced rheological properties of GO-modified WBDFs, especially at the 0.1 wt.% concentration, have substantial consequences for drilling operations. The ability to correctly predict and control surge and swab pressures is crucial for improving wellbore stability, decreasing NPT, and improving safety margins in complex drilling environments, such as shallow wells with narrow pressure windows. By providing a more consistent technique for estimating these pressures, the YPL model can help in designing drilling fluids that guarantee constant wellbore conditions, averting costly formation damage and decreasing operational hazards.

Forthcoming research should put more attention on addressing the limitations detected with the YPL model, especially in situations with changing temperature, pressure, or fluid contamination. Also, additional optimization of GO concentrations and dispersion procedures should be followed to avoid aggregation and boost fluid performance. Trying the GO-modified WBDFs under HPHT settings will offer more understandings into their consistency in extreme environments, such as deep-water drilling procedures. Besides, integrating these fluids into real-time drilling procedures through Computational Fluid Dynamics (CFD) models will permit for more precise predictions and optimization of drilling fluid performance under dynamic circumstances.

4. Conclusion:

This study establishes that GO-modified WBDFs substantially improve rheological properties, especially at a concentration of 0.1 wt.%. The incorporation of GO enhances significant parameters such as yield stress, plastic viscosity, and shear-thinning behaviour, altogether are important for mitigating surge and swab pressures. The YPL and PL models were validated through experimental data, with the YPL model offering a superior fit for both concentrations of GO, precisely capturing yield stress and non-Newtonian fluid behaviour.

The enhanced rheological properties of GO-modified WBDFs contribute to improved pressure control, enhancing wellbore stability and operational effectiveness. The 0.1 wt.% GO-modified WBDFs have demonstrated to be both a cost-effective and ecologically sustainable answer, displaying potential for a wide range of drilling applications. Additionally, these discoveries could help cut NPT by offering more precise predictions of surge and swab pressures, thus improving safety and working efficiency during drilling processes. The environmental effect of using GO-modified fluids is also outstanding, as they could serve as an alternative to traditional synthetic-based fluids, which are often detrimental to the environment.

Future Recommendations

Future research should focus on the following significant areas:

1) Discover the effect of higher GO concentrations on fluid rheology, while tackling agglomeration problems through cutting-edge dispersion approaches like ultrasonication. This will support fluid stability and performance, especially in deep-well drilling scenarios.
2) Study the combination of GO with other nanoparticles or polymers (e.g. xanthan gum or polymer-clay composites) to further improve fluid properties and advance surge/swab pressure mitigation in dynamic drilling situations.
3) Trying GO-modified WBDFs under HPHT settings is key for evaluating their performance in extreme drilling conditions, such as deep-water or HPHT wells. These tests will advance the consistency of the results and ensure that the GO-modified fluids can resist the harsh environments faced in deep-drilling operations.
4) Fitting GO-modified fluids into real-time drilling operations by integrating results into CFD models will improve surge/swab pressure predictions, wellbore stability, and fluid behaviour under complex drilling situations. This incorporation will offer operators with improved decision-making tools, permitting them to optimize drilling fluid performance in real-time and cut the likelihood of costly operational delays or catastrophes.

Authorship Contributions:

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