

# The Effect of Kaolinite on Calcium Carbonate Water-Based Drilling Fluid

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## Abstract

This study evaluates the effect of kaolinite addition on calcium carbonate water-based drilling fluids (WBM) through systematic laboratory testing. Kaolinite was incorporated at concentrations of 42.8 kg/m<sup>3</sup> (15 lb/bbl), 85.6 kg/m<sup>3</sup> (30 lb/bbl), and 128.4 kg/m<sup>3</sup> (45 lb/bbl) into a standard CaCO<sub>3</sub>-based WBM, and its influence on density, pH, filtration, rheology, and viscoelastic behavior was analyzed. The density of the base mud (10.15 g/cm<sup>3</sup>) increased to 11.00 g/cm<sup>3</sup> with 128.4 kg/m<sup>3</sup> (45 lb/bbl) kaolinite, while pH rose proportionally with kaolinite content. Filtration tests at 93°C (200°F) and 2.07 MPa (300 psi) revealed that the base sample produced a filter cake thickness of 0.0098 in, which increased progressively with kaolinite addition. Rheological measurements showed Bingham plastic behaviour across all samples, with apparent viscosity increasing from 25 cP in the base mud to 33 cP at 128.4 kg/m<sup>3</sup> (45 lb/bbl). Yield point and gel strength also exhibited consistent growth, indicating improved suspension capacity. Viscoelastic testing confirmed enhanced storage modulus (*G'*) and gelling effect with higher kaolinite concentrations. These results demonstrate that kaolinite significantly enhances the density, filtration control, and rheological stability of CaCO<sub>3</sub> WBMs, supporting its application as a cost-effective and multifunctional additive in drilling operations.

## Keywords:

drilling fluids, kaolinite, calcium carbonate, WBM

## 1. Introduction

Drilling fluids are indispensable in hydrocarbon extraction, serving critical functions such as transporting cuttings, stabilizing the wellbore, cooling and lubricating the drill bit, and maintaining formation pressure (Adams 1985; Bourgoyne et al. 1986; Rabia 2001). Depending on the base fluid, drilling fluids are broadly categorized into oil-based muds (OBMs) and water-based muds (WBMs). OBMs offer superior thermal stability and lubricity but face limitations due to high costs and strict environmental regulations (Antia 2022; Mahmoud et al. 2024). Consequently, WBMs have gained increasing attention as more sustainable and cost-effective alternatives (Ahmed et al. 2021; Asad et al. 2024).

Typical WBMs are composed of water, bentonite, and various polymers and salts to control rheology, fluid loss, and wellbore stability (Dong et al. 2019; Gamal et al. 2019). However, in shale formations which account for more than 75% of drilled reservoirs these fluids often induce swelling and dispersion, causing wellbore instability and drilling inefficiencies (Muhammed et al.

2021; Ai et al. 2024). Therefore, continuous efforts are directed toward developing additives that improve the performance of WBMs under demanding conditions.

Calcium carbonate (CaCO<sub>3</sub>) is widely used in WBMs as a weighting and bridging agent due to its acid solubility, cost-effectiveness, and environmental compatibility (Ryabtsev et al. 2022; Basfar & Elkatatny 2023). It contributes to fluid-loss control and filter-cake formation, especially when appropriately sized (Dehghani et al. 2019; Villada et al. 2022). Meanwhile, kaolinite, a non-swelling clay mineral derived from feldspar and mica weathering, has shown potential for modifying drilling fluid properties without inducing the severe hydration issues associated with smectite clays (Ameloko et al. 2020; Zhang et al. 2020). Its platy structure and chemical stability make it an attractive candidate for improving fluid rheology and filtration characteristics (Omotioma et al. 2024; Uwaezuoke et al. 2024).

While previous studies have explored the use of kaolinite and other clays as viscosifiers or loss-control agents (Omary et al. 2023; Omotioma et al. 2024), limited research has focused on the combined performance of kaolinite with calcium carbonate in WBM formulations. The potential synergy between kaolinite's rheological influence and CaCO<sub>3</sub>'s bridging effect has not been fully characterized, particularly in terms of density, pH, filtration, rheological, and viscoelastic properties.

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The achievements of this work include the experimental characterization of kaolinite CaCO<sub>3</sub> WBM systems, the quantification of dose response relationships showing how increasing kaolinite concentrations systematically alter fluid properties, and the identification of a novel synergistic interaction between kaolinite and CaCO<sub>3</sub> that enhances filter-cake formation and viscoelastic performance. Unlike previous laboratory studies, this work establishes a new baseline for optimizing environmentally friendly and cost-effective WBMs.

In this study, we systematically investigate the influence of kaolinite addition on the performance of CaCO<sub>3</sub>-based WBMs. A comprehensive experimental program was designed to measure density, pH, filtration behaviour, rheological parameters, and viscoelastic properties across varying kaolinite concentrations.

## 2. Experimental Section

This section provides a detailed description of the materials used in the preparation of the drilling fluids. The study focuses on formulating water-based muds (WBMs) using kaolinite as a key additive. Each component was carefully selected based on its function in improving rheological and filtration properties. The specific purpose of each material and its role in this research are outlined below.

### 2.1. Materials

The present study focuses on water-based drilling muds (WBMs) formulated and tested to evaluate the effect of kaolinite as an additive on mud performance. WBMs were selected because they are the most widely used type of drilling fluid due to their environmental compatibility, cost-effectiveness, and ease of handling compared to oil-based muds (OBMs).

Water base mud: although water-based drilling fluids (WBDF) are frequently utilized with good technical and economic performance (Ahmed et al. 2021), their usage in extremely deep, divergent, and unconventional wells calls for particular considerations to conform to the high temperature and pressure circumstances (Khashay et al. 2025). The water-based system is the mud system that is most frequently employed in the sector (Alcheikh & Ghosh 2017). Water is the continuous phase, but the discontinuous phase may also include air or oil (emulsion muds or aerated mud) (M-I Swaco 2009).

Defoamer: a substance added to mud to reduce interfacial tension and allow trapped gas to more easily escape (Bourgoyne et al. 1986). Along with defoamer, mechanical degassing equipment is frequently employed. Defoamers include octyl alcohol, aluminum stearate, different glycols, silicones, and sulfonated hydrocarbons.

XC-Polymer: anionic XC-Polymer with fair tolerance for hardness ions and tolerance for salinity (Blkooor & Fattah 2013). XC is a finely ground substance that can

vary in the amount of lingering bacterium debris and how easily it dissolves in water (Hamed & Belhadri 2009; Davoodi et al. 2024).

Starch: starch can act as an addition that can increase and improve the mud's viscosity while also regulating fluid loss (Talukdar et al. 2018; Joel et al. 2023). There are two significant ingredients in it: amylose and amylopectin (Taiwo et al. 2011).

KCl: drilling fluids containing potassium chloride are widely utilized to keep well bores stable (Al-Bazali 2021). To purchase additional time before water absorption caused the shales to collapse into the well bore, the potassium ion fits into the silicon tetrahedron matrix of clays and helps maintain the structure together (Muhammed et al. 2021; Ai et al. 2024).

KOH: potassium hydroxide is sometimes known as KOH informally. In potassium-based water muds, caustic potash is used to boost pH and alkalinity as well as to aid in maintaining the K<sup>+</sup> ion concentration (Otitigbe 2021). It is extremely caustic, as the name suggests, and when dissolved in water, it produces heat. It is dangerous to use caustic potash without the right training and tools (M-I Swaco 2009).

Polymers like Polyanionic Cellulose (PAC) and Carboxymethyl Cellulose (CMC) are also common additives for filtration control and rheology modification (Saadi et al. 2025; Khan et al. 2024; Li et al. 2020a; Li et al. 2020b).

Calcium carbonate CaCO<sub>3</sub>: oil- and water-based drilling fluids, work-over fluids, and completion fluids all use CaCO<sub>3</sub> as a bridging agent and/or weighing material (Ryabtsev et al. 2022; Basfar & Elkatatny 2023). There are several different particle sizes available, ranging from 325 mesh (35 µm) to 30 mesh (550 µm). Applications can also be sized to order. During drilling, workover, and completion operations, it is utilized to keep fluid from entering permeable zones and to prevent circulation loss (Siddig et al. 2020). Both aqueous and non-aqueous drilling fluids can use calcium carbonate (Villada et al. 2022; Dehghani et al. 2019).

Kaolinite: a common clay mineral used in drilling fluids, sometimes as a primary viscosifier or as a contaminant from drilled formations (Ameloko et al. 2020; Omary et al. 2023; Omotoma et al. 2024; Zhang et al. 2020; Basfar et al. 2025; Uwaezuoke et al. 2024).

Sodium sulfite: effective removal of soluble oxygen from water-based drilling fluid systems is made possible by sodium sulfite (Rabia 2001). By removing factors that encourage organic polymers' heat deterioration, sodium sulfite also contributes to their longevity (Davoodi et al. 2024).

In this study, four water-based mud samples were prepared using the chemical precipitation method, following the procedures outlined in the American Petroleum Institute (API) standards (API, 2010; API, 2014). The final compositions of the drilling fluids are presented in Table 1.

Table 1. The WBDF Formulation

Component	Function	Ingredients	Mixing Time
Water	Base Fluid	308 ml	-
Defoamer	Antifoam	0.1 ml	1
XC-Polymer	Viscosifier	1.5 g	20
Starch	Fluid loss controller	6 g	20
KCL	Shale swelling controller	80 g	10
KOH	pH controller	0.3 g	1
Sodium Sulfite	Scavenge soluble oxygen	0.25 g	1
CaCO <sub>3</sub> (50 M)	Weighting material	80 g	10

## 2.2. Drilling Fluid Preparation

To prepare drilling fluid, kaolinite clay with different concentrations 42.8 kg/m<sup>3</sup> (15 lb/bbl), 85.6 kg/m<sup>3</sup> (30 lb/bbl), and 128.4 kg/m<sup>3</sup> (45 lb/bbl), were added to the base drilling fluid, and mixed with electric stirrer. Using a filter press apparatus, according to API requirements (American Petroleum Institute 2014), the filtration properties of drilling fluid, such as fluid loss and filter cake thickness, were measured using a filter pressure set at 2.07 MPa (300 psi) and 93°C (200°F), fluid loss over time was observed. **Table 1** shows the formulation of the WBDF.

To examine the effect of the kaolinite additive, SEM images of the filter cake were taken for the base drilling fluid and for drilling fluids with different kaolinite concentrations (**Rugang et al. 2014**). Although the primary focus of this study is the overall influence of kaolinite on drilling mud parameters, the SEM analysis was conducted to provide supporting evidence through the observation of filter-cake morphology following API standards (**American Petroleum Institute 2010; American Petroleum Institute 2014**).

## 3. Characterization of drilling fluids

This section describes the experimental methodology used to evaluate the performance of the prepared water-based drilling fluids. All procedures were conducted in accordance with the American Petroleum Institute (API) standards to ensure consistency and reliability of results. Tests were performed to measure rheological, density, and filtration properties, as well as pH control. The experimental design aims to quantify how varying kaolinite concentrations affect overall drilling fluid performance.

### 3.1. Particle Size Analysis

The analysis of the kaolinite powder revealed that the particle size distribution ranged from D<sub>10</sub> = 0.68 μm, D<sub>50</sub> = 2.8 μm, to D<sub>90</sub> = 10.63 μm, with a median (D<sub>50</sub>) value of 2.8 μm. Particle size measurements were performed using a laser diffraction particle size analyzer, which employs a dual-laser system with two detectors to accurately characterize a broad range of particle sizes, from fine to coarse fractions. Prior to measurement, all samples underwent wet dispersion to ensure proper deagglomeration and to improve measurement accuracy. The particle size distribution (PSD) of the sample is illustrated in **Figure 1**.

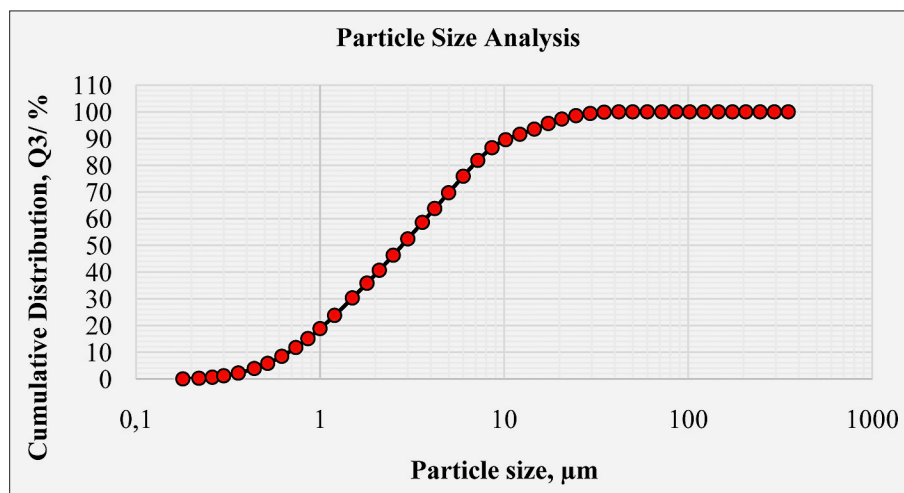
**Figure 2** illustrates the morphology of kaolinite. The synthesized CaCO<sub>3</sub> made up semi-spherical particles with a particle size of less than 10 μm.

The XRD analysis (see **Figure 3**) reveals the mineral composition of kaolinite, with oxygen as the predominant element at 57.4 wt%. This is followed by silicon (24.1 wt%) and aluminum (10.8 wt%), consistent with the expected SiO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub> components of kaolinite. Minor constituents include iron (5.6 wt%) and potassium (2.2 wt%).

## 4. Results and Discussion

The results obtained from the laboratory experiments are presented and discussed in this section. The data il-

Figure 1. PSD Curves of The Drilled Cutting



illustrate how the addition of kaolinite influences the key physical and chemical properties of the water-based drilling muds. Comparisons are made between the base mud and the kaolinite-modified muds to assess changes in rheology, density, and filtration behaviour. The find-

ings are further analyzed to identify correlations and practical implications for drilling operations.

4.1. Density and pH Measurement

The density (weight) of the base mud, measured using a mud balance apparatus at room temperature, was 1,216 kg/m<sup>3</sup> (10.15 lbm/gal). Introducing kaolinite led to a proportional increase in fluid density, reaching 1,318 kg/m<sup>3</sup> (11.00 lbm/gal) at a concentration of 128.4 kg/m<sup>3</sup> (45 lb/bbl). Furthermore, Figure 4 and Figure 5 illustrate that the addition of kaolinite enhanced the pH of the base fluid.

4.2. Drilling Fluids Filtration

Filtration tests performed at 93°C (200°F) and 2.07 MPa (300 psi) over 30 minutes demonstrated a direct correlation between filtration cake thickness and both the duration of the test and the concentration of kaolinite. This indicates that higher kaolinite concentrations lead to a thicker filter cake. The relationship between filtration volume and time is visually represented in Figure 6.

In drilling, a thin filter cake is crucial for borehole stability and minimizing fluid loss. Filtration tests re-

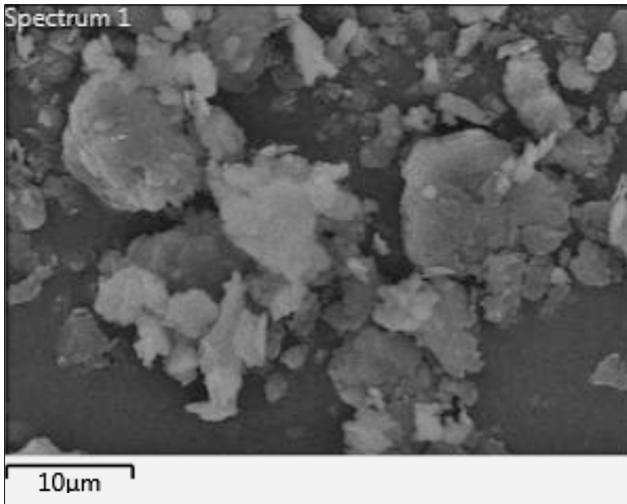


Figure 2. Kaolinite Particles Shape from SEM Image

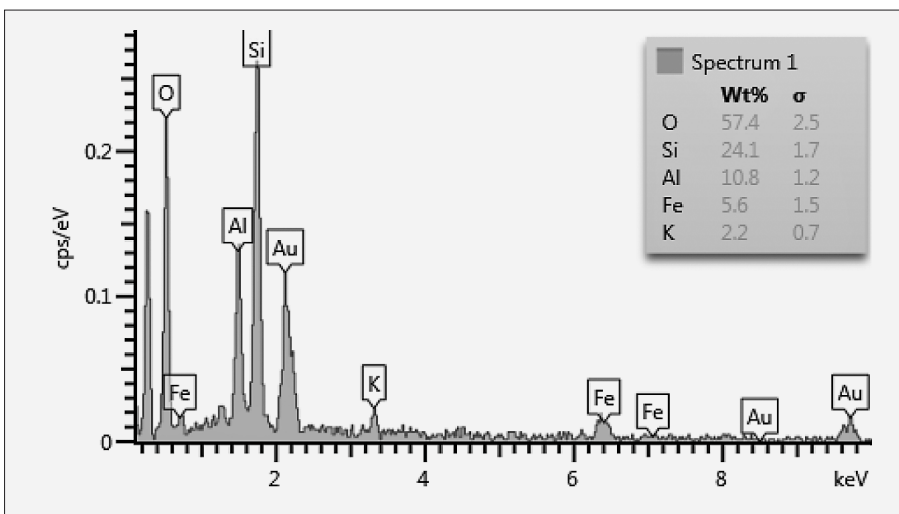


Figure 3. XRD Chart Showing the Mineral Composition of Kaolinite

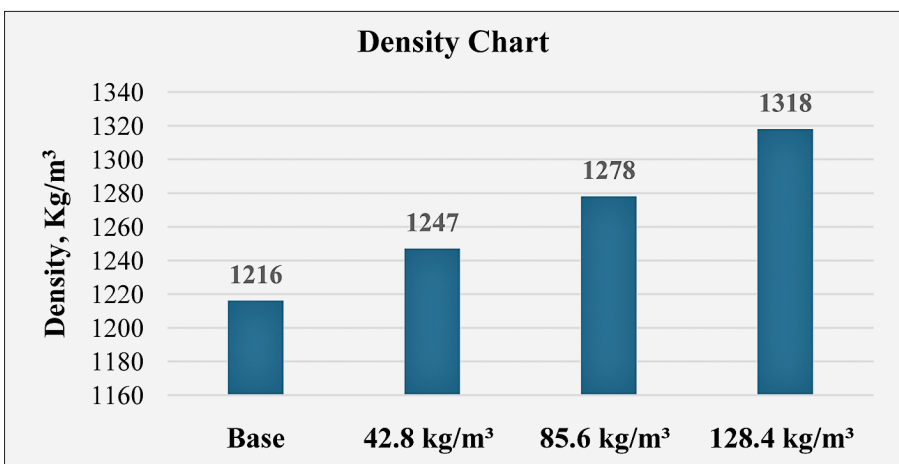


Figure 4. The Results of Density Measurements

vealed that the base sample exhibited a filtration volume of 0.5 cubic in and a cake thickness of 0.0098 in. However, as shown in **Figures 6** and **7**, the addition of kaolinite led to an increase in both filtration volume and filter cake thickness, deviating from the desired thin and low-permeable characteristics.

Expanding on the filtration test results, **Figure 8** provides visual evidence of the filter cake thickness immediately after the experiments. These photos, depicting

the base sample and samples with varying kaolinite concentrations, further illustrate the increasing trend in filter cake thickness with higher kaolinite content, complementing the quantitative data presented in **Figure 6**.

### 4.3. Rheological Test

The rheological behaviour of drilling fluid with kaolinite concentrations of 42.8 kg/m<sup>3</sup> (15 lb/bbl), 85.6 kg/m<sup>3</sup> (30 lb/bbl), and 128.4 kg/m<sup>3</sup> (45 lb/bbl) was evaluated at 93°C (200°F), as depicted in **Figure 9**. All fluids exhibited Bingham plastic behaviour, typical of drilling fluids. While improvements were observed in filter cake thickness and filtration, the rheological properties showed no significant alteration. This lack of substantial change may be attributed to the low kaolinite concentrations required to achieve the noted filtration enhancements. Notably, the addition of kaolinite at these concentrations had a negligible effect on the drilling fluid’s pH and mud density.

Although several rheological models have been developed to describe the flow behaviour of drilling fluids, such as the Herschel–Bulkley, Vom Berg, and Hahn–Eyring models, the present study employs the Bingham

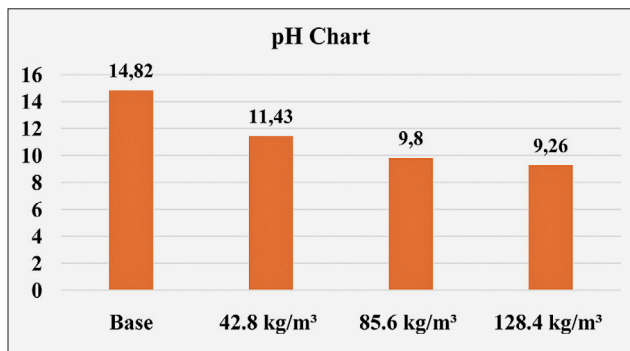


Figure 5. The Results of pH Measurements

Figure 6. Filtration Time vs. Filtration Volume for the Drilling Fluids Samples

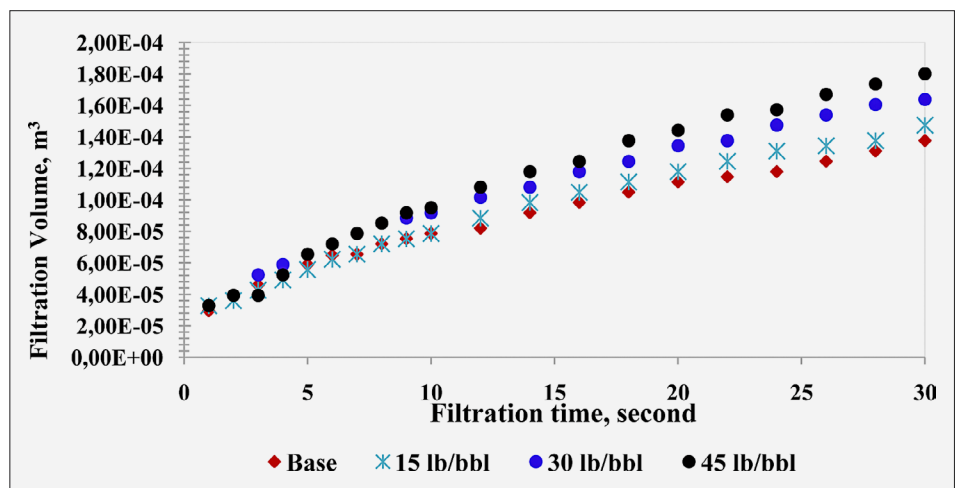
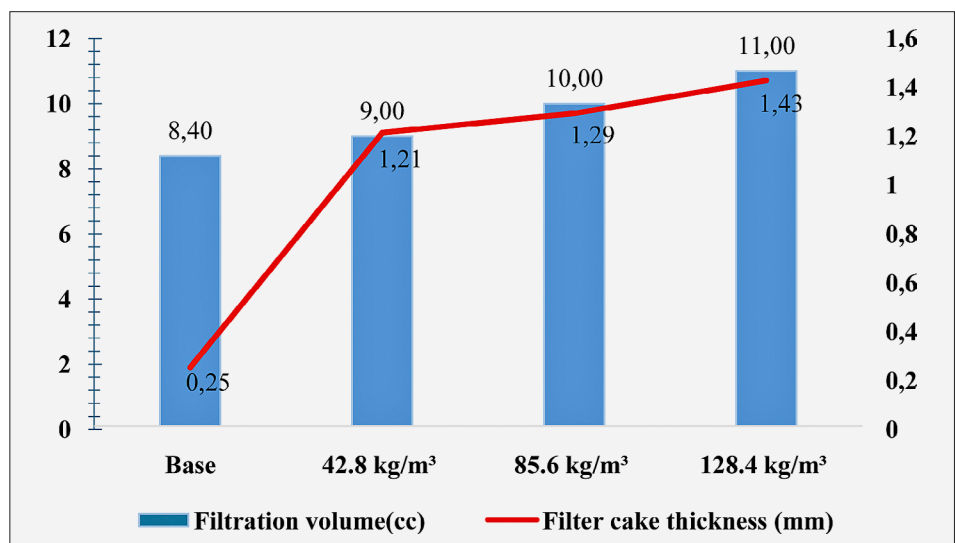


Figure 7. Filtration Volume and Cake Thickness



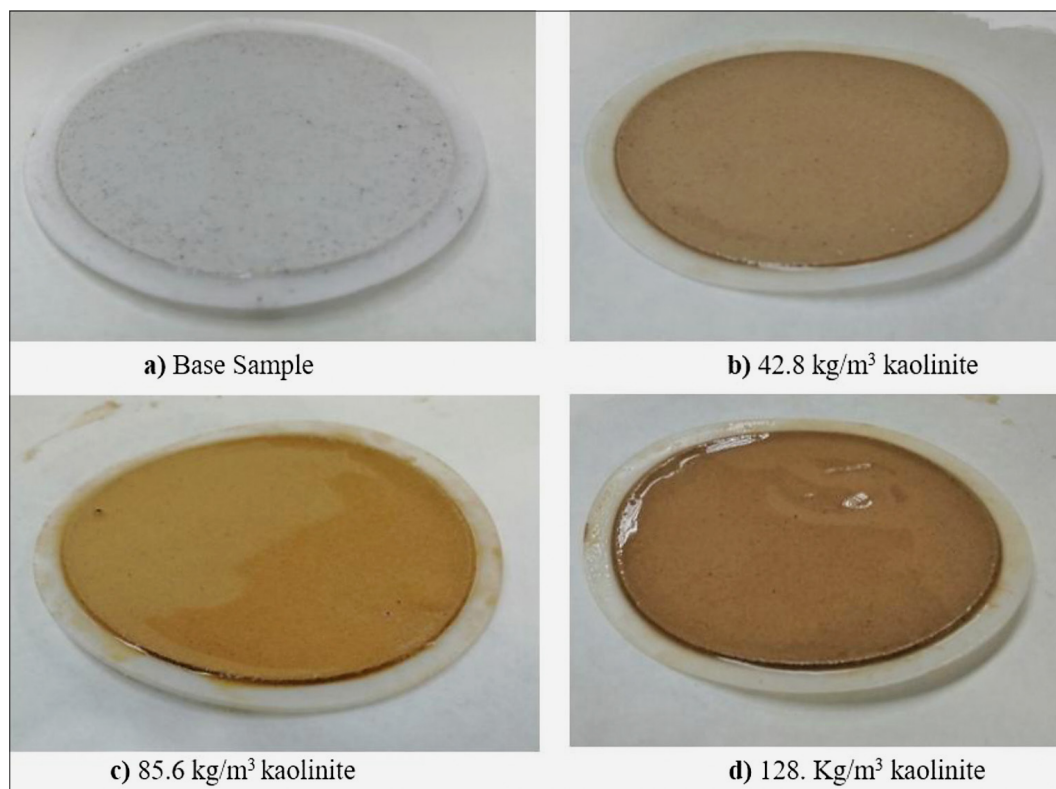


Figure 8. Filter Cake Thickness

Plastic model because it is the most commonly applied and recommended by the American Petroleum Institute (API RP 13D 2010) for field and laboratory analyses. The Bingham model provides a simple and practical approximation for water-based muds exhibiting moderate yield-stress behaviour under standard testing conditions. However, other advanced models have been shown to provide a more accurate representation of non-Newtonian and viscoplastic fluids. For example, the Vom Berg model (Vom Berg 1981; Coussot et al. 2002) has been successfully applied to describe drilling muds and other complex fluids by incorporating both yield stress and shear-thinning characteristics, often achieving higher correlation coefficients than the Bingham or Herschel-Bulkley models. Similarly, the Hahn-Eyring model (Hahn & Eyring 1937) has been used to represent the viscoelastic and plastic deformation behaviour of complex fluid systems and has demonstrated improved prediction of viscosity variation with shear rate. Recent investigations (Ahmed et al. 2021) have further confirmed that such advanced rheological models can provide more realistic characterization of water-based drilling fluids, particularly under high-pressure and high-temperature (HPHT) conditions. Therefore, while the Bingham Plastic model was adopted in the present study for its simplicity and industry relevance, future work should include a comparative evaluation using the Vom Berg and Hahn-Eyring models to achieve a more comprehensive understanding of the rheological behaviour of kaolinite-modified calcium carbonate muds.

Plastic Viscosity (PV), a parameter in the Bingham plastic model, refers to the flow resistance resulting from mechanical friction within the fluid. Experts in drilling fluids often consider PV a crucial indicator of the mud's solids content. Yield Point (YP) quantifies the minimum stress required to initiate fluid flow, reflecting the electrochemical and/or attractive forces between particles due to their orientation and concentration (colloidal size) (Ahmed et al. 2021). Apparent Viscosity (AV), based on the Bingham plastic rheology model, is determined using a direct-indicating rotational viscometer at 600 rpm ( $\approx 62.8 \text{ rad/s}$ ) (a shear rate of  $1,022 \text{ s}^{-1}$ ) and is calculated as half of the dial reading. For example, a dial reading of 50 at 600 rpm corresponds to an AV of  $25 \text{ mPa}\cdot\text{s}$  ( $25 \text{ cP}$ ). The results of this analysis, presented in Figure 10, illustrate the increasing trends of apparent viscosity, yield point, and plastic viscosity with increasing kaolinite concentration.

Figure 11 illustrates the relationship between gel strength and time for all drilling fluid samples. It suggests that the base sample exhibits a relatively small gelling effect over time in terms of viscoelasticity. However, the addition of kaolinite at different concentrations to the base sample clearly increases this gelling effect.

#### 4.4. Amplitude, frequency and time sweep tests

To complement the rheological and filtration analyses, Scanning Electron Microscopy (SEM) was employed to investigate the surface morphology of the filter cakes. SEM images provide visual confirmation of the

Figure 9. Rheological Behaviour of Both Drilling Fluids Samples

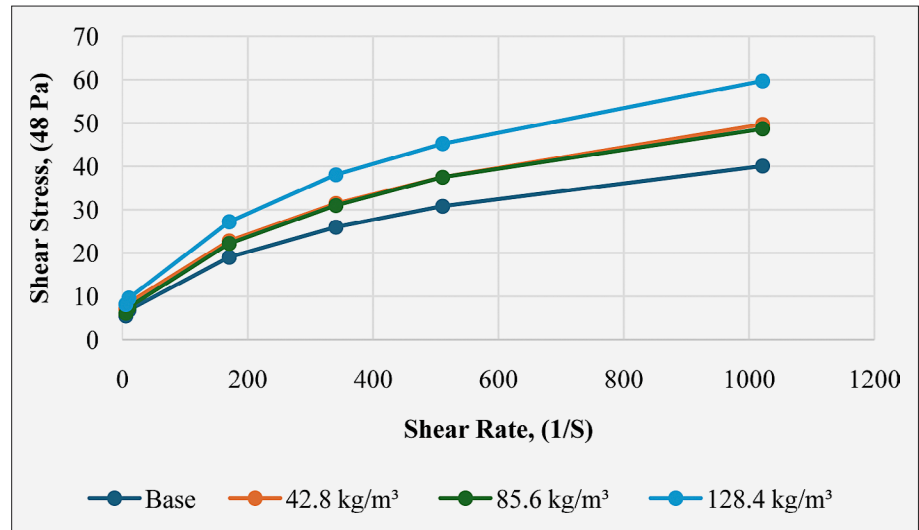


Figure 10. AV, PV, and YP for All Drilling Fluids Samples

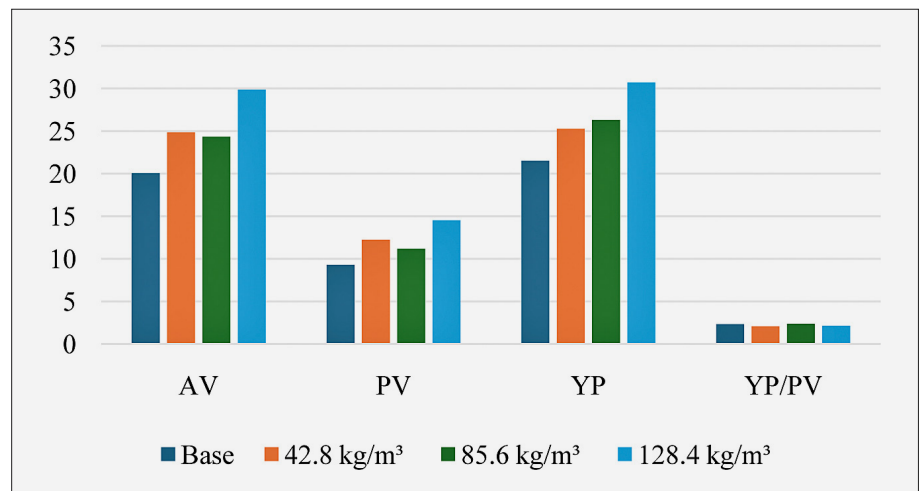
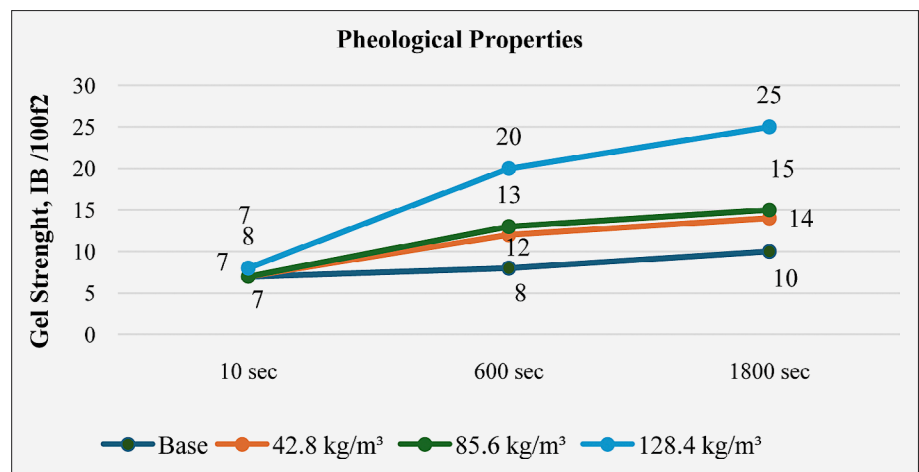


Figure 11. Gel Strength Over Time for All Drilling Fluid Samples



microstructural changes caused by the addition of kaolinite. This analysis helps to better understand how kaolinite particles influence the compactness and uniformity of the filter cake, which are important for controlling fluid loss and maintaining wellbore stability. The key observations are presented and discussed in the following figures.

#### 4.4.1. Amplitude Test

Amplitude sweep tests were conducted to determine the linear viscoelastic domain by increasing the amplitude over time at a constant frequency. This can be performed using either controlled stress or controlled strain. Amplitude sweep is also known as strain sweep or stress

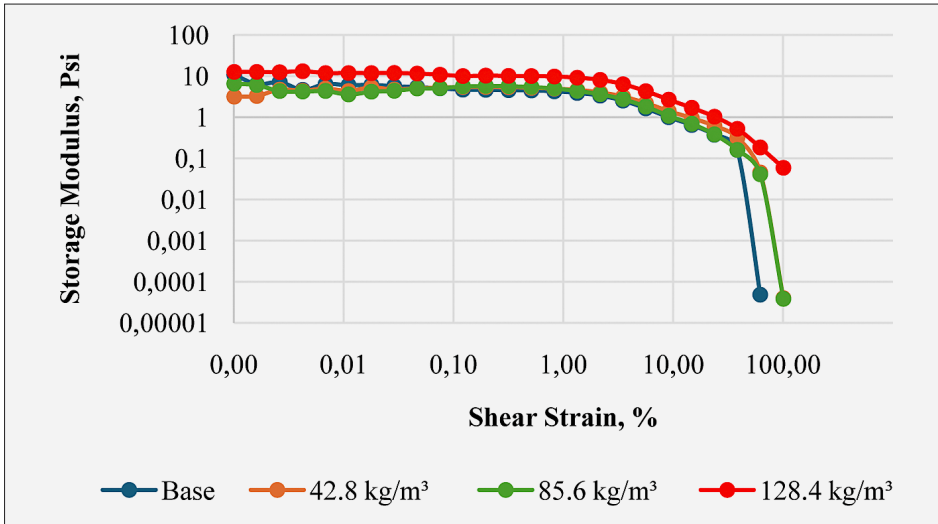


Figure 12. The Relationship Between Storage Modulus and Shear Strain

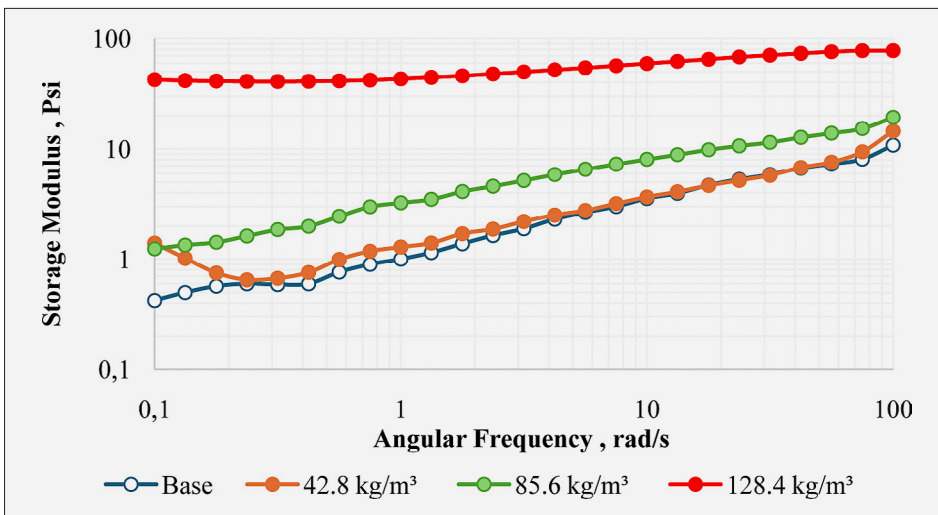


Figure 13. FRQ Sweep Plot

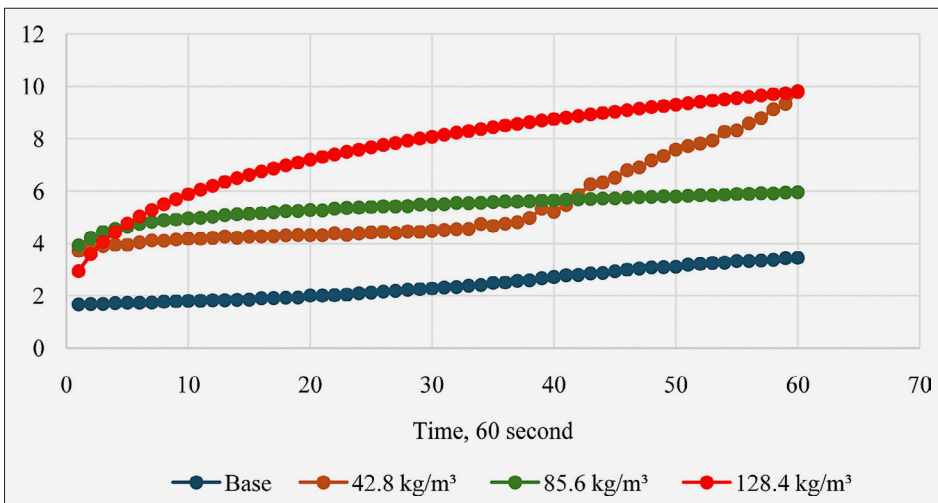


Figure 14. Time of Sweep

sweep. The linear viscoelastic range is defined as the stress or strain amplitude range within which the material's internal structure remains unchanged.

The linear viscoelastic (LVE) range was determined by plotting the storage modulus ( $G'$ ) and loss modulus

( $G''$ ) against strain (or stress) on logarithmic scales for both axes (see Figure 12). Within the LVE range,  $G'$  and  $G''$  exhibit constant values, indicating their independence from the stress or strain amplitude. Based on the results of this test, the LVE was found to be 1.94.

#### 4.4.2. FRQ Sweeps

Frequency sweep tests, another type of oscillatory test, involve varying the frequency while maintaining a constant amplitude to investigate the time-dependent viscoelastic properties of the material. Typically, the frequency is scanned from high to low values. High-frequency oscillations probe short-term behavior, whereas low-frequency oscillations examine long-term behaviour. The results of this test, shown in **Figure 13**, indicate that increasing the kaolinite concentration in the fluid enhances its viscoelasticity, as evidenced by an increase in the storage modulus.

#### 4.4.3. Time Sweep

Time sweep tests were conducted to monitor the evolution of the fluid's structure over time. By tracking changes in the elastic modulus, the formation and development of a gel-like structure can be studied. The results of this test, as shown in **Figure 14**, indicate that the base sample exhibits a limited gelling effect over time in terms of its viscoelastic viscosity.

### 5. Conclusions

This research provides a comprehensive investigation into the efficacy of kaolinite as a cost-effective, high-performance additive in calcium carbonate ( $\text{CaCO}_3$ ) water-based drilling fluids (WBM). While often viewed as a contaminant, this study reframes kaolinite as a valuable multifunctional material for enhancing drilling fluid properties. An extensive experimental program was conducted to quantify the effects of varying kaolinite concentrations on the rheological and filtration characteristics of a  $\text{CaCO}_3$  WBM.

- The results demonstrate that the addition of kaolinite yields significant improvements in key performance indicators. A systematic increase in kaolinite concentration leads to a desirable enhancement of the rheological profile, including increased Plastic Viscosity, Yield Point, and gel strengths. This improved rheology is essential for efficient hole cleaning and suspension of solids. More critically, the study reveals that kaolinite acts as a superior filtration control agent, substantially reducing both API and HTHP (High-Temperature, High-Pressure) fluid loss. This effect is attributed to the synergistic interaction between the platy kaolinite particles and the  $\text{CaCO}_3$  bridging particles, which co-operate to form a thin, robust, and low-permeability filter cake.
- A comparative analysis positions our findings within the context of existing literature, highlighting the unique advantages of kaolinite over conventional additives. Unlike swelling clays like bentonite, kaolinite provides controlled viscosity without exces-

sive gelation, and it exhibits greater stability in certain ionic environments. Compared to excellent viscosifiers like attapulgite that offer poor fluid loss control, kaolinite demonstrates a dual functionality that is highly advantageous. Furthermore, it presents a thermally stable and significantly more economical alternative to synthetic polymers like poly-anionic cellulose (PAC).

- The novel contribution of this work lies in its detailed characterization of the kaolinite/ $\text{CaCO}_3$  synergy and the establishment of a clear dose-response relationship, offering a valuable baseline for fluid engineering. The practical implications for the drilling industry are substantial. The use of kaolinite is particularly applicable for drilling in cost-sensitive areas, through depleted or high-permeability zones where fluid loss control is paramount, and in formulating more environmentally benign fluid systems. The tangible benefits include significantly reduced drilling fluid costs, improved wellbore stability by minimizing shale hydration, enhanced operational efficiency through better hole cleaning, and minimized formation damage, ultimately contributing to safer and more economical drilling operations.

#### List of Terms Glossary

WBM	Water Based Mud
OBM	Oil Based Mud
$\text{CaCO}_3$	Calcium Carbonate
pH	Potential of Hydrogen
AMP	Amplitude
FRQ	Frequency Sweep
PSD	Particle Size Distribution
XRD	X-Ray Diffraction
KCL	Potassium Chloride
KOH	Potassium Hydroxide
API	American Petroleum Institute
SEM	Scanning Electron Microscopy
PV	Plastic Viscosity
YP	Yield Point
AV	Apparent Viscosity
LVE	Linear Viscoelastic

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## 6. References

- Adams NJ (1985). *Drilling Engineering A Complete Well Planning Handbook*. PennWell Books, Tulsa
- Ahmed A, Alsaihati A, Elkatatny S (2021). An overview of the common water-based formulations used for drilling on-shore gas wells in the Middle East. *Arabian Journal for Science and Engineering* 46(7): 6867–6877. <https://doi.org/10.1007/s13369-021-05561-x>
- Ai E, Li Q, Liu Z, Zhang B, Wang L, Ma C (2024). Advanced trends in shale mechanical inhibitors for enhanced wellbore stability in water-based drilling fluids. *Minerals* 14(12): 1197. <https://doi.org/10.3390/min14121197>
- Al-Bazali T (2021). Insight on the inhibitive property of potassium ion on the stability of shale: a diffuse double-layer thickness ( $\kappa^{-1}$ ) perspective. *Journal of Petroleum Exploration and Production Technology* 11: 2709–2723. <https://doi.org/10.1007/s13202-021-01221-2>
- Alcheikh IM, Ghosh B (2017). A comprehensive review on the advancement of nondamaging drilling fluids. *International Journal of Petrochemistry and Research* 1 (1): 61–72. <https://doi.org/10.18689/ijpr-1000111>
- Ameloko AA, Ogologo CE, Daramola OC, Babalola AO (2020). Assessment of clay materials for suitability in drilling mud formulation from part of Ondo State, South-West Nigeria. *Journal of Petroleum Exploration and Production Technology* 10: 2815–2828. <https://doi.org/10.1007/s13202-020-00947-9>
- American Petroleum Institute (API) (2010). *Rheology and hydraulics of oil-well fluids, API recommended practice 13d, sixth edition*. API Publishing Services, Washington DC
- American Petroleum Institute (API) (2014). *Recommended practice for field testing water-based drilling fluids (API RP 13B-1 / ISO 10414-1:2008), 4th edn. Errata 1, August 2014*
- Antia M (2022). Environmental and public health effects of spent drilling fluid. *Environmental Challenges* 8: 100576. <https://doi.org/10.1016/j.envc.2022.100576>
- Asad MS, Jaafar MT, Rashid FL, Togun H, Rasheed MK, Al-Obaidi MA, Al-Amir QR, Mohammed HI, Sarris IE (2024). Sustainable Drilling Fluids: A Review of Nano-Additives for Improved Performance and Reduced Environmental Impact. *Processes* 12(10): 2180. <https://doi.org/10.3390/pr12102180>
- Basfar S, Elkatatny S (2023). Micronized calcium carbonate to enhance water-based drilling fluid properties. *Scientific Reports* 13: 18295. <https://doi.org/10.1038/s41598-023-45776-y>
- Basfar S, Shokry A, Iqbal A, Elkatatny S, Alajmi S (2025). Evaluation of the effects of kaolin clay on the performance of barite-weighted oil-based drilling fluid. *ACS Omega* 10(10): 9976–9985. <https://doi.org/10.1021/acsomega.4c07376>
- Blkooor SO, Fattah KA (2013). The influence of XC-polymer on drilling fluid filter cake properties and formation damage. *Journal of Petroleum & Environmental Biotechnology* 4(5): 157. <https://doi.org/10.4172/2157-7463.1000157>
- Bourgoyne AT Jr, Millheim KK, Chenevert ME, Young FS Jr (1986). *Applied Drilling Engineering*. Society of Petroleum Engineers, Richardson, TX
- Coussot P, Tocquer L, Lanos C, Ovarlez G. (2002). Rheological modeling of yield stress fluids: from Bingham to advanced viscoplastic models. *Journal of Non-Newtonian Fluid Mechanics* 102(2): 165–178.
- Davoodi S, Al-Shargabi M, Wood DA, Rukavishnikov VS, Minaev KM (2024). Synthetic polymers: A review of applications in drilling fluids. *Petroleum Science* 21: 475–518. <https://doi.org/10.1016/j.petsci.2023.08.015>
- Dehghani F, Kalantariasl A, Saboori R, Sabbaghi S, Peyvandi K (2019). Performance of carbonate calcium nanoparticles as filtration loss control agent of water-based drilling fluid. *SN Applied Sciences* 1: 1466. <https://doi.org/10.1007/s42452-019-1446-8>
- Dong W, Pu X, Ren Y, Zhai Y, Gao F, Xie W (2019). Thermoresponsive bentonite for water-based drilling fluids. *Materials* 12(13): 2115. <https://doi.org/10.3390/ma12132115>
- Gamal H, Elkatatny S, Basfar S, Al-Majed A (2019). Effect of pH on rheological and filtration properties of water-based drilling fluid based on bentonite. *Sustainability* 11(23): 6714. <https://doi.org/10.3390/su11236714>
- Hamed SB, Belhadri M (2009). Rheological properties of biopolymers drilling fluids. *Journal of Petroleum Science and Engineering* 67(3–4): 84–90. <https://doi.org/10.1016/j.petrol.2009.04.001>
- Hahn E, Eyring H. (1937). Theory of plastic deformation and flow in solids. *Journal of Chemical Physics* 5(11): 745–753.
- Joel OF F, Ndubuisi EC (2023). Evaluation of local starch as a filtration control additive in water-based mud as substitute for imported samples for drilling operations in Nigeria. *IOSR Journal of Engineering (IOSRJEN)* 13(11): 42–48.
- Khan MA, Li MC, Lv K, Sun J, Liu C, Liu X, Shen H, Dai L, Lalji SM, et al. (2024). Cellulose derivatives as environmentally-friendly additives in water-based drilling fluids: A review. *Carbohydrate Polymers* 342: 122355. <https://doi.org/10.1016/j.carbpol.2024.122355>
- Khashay M, Zirak M, Sheng JJ, Ganat T, Esmaeilnezhad E (2025). Elevated temperature and pressure performance of water based drilling mud with green synthesized zinc oxide nanoparticles and biodegradable polymer. *Scientific Reports* 15: 11930. <https://doi.org/10.1038/s41598-025-96900-z>
- Li MC, Tang Z, Liu C, Huang R, Koo MS, Zhou G, Wu Q (2020). Water-redispersible cellulose nanofiber and polyanionic cellulose hybrids for high performance waterbased drilling fluids. *Industrial & Engineering Chemistry Research* 59 (32): 14352–14363. <https://doi.org/10.1021/acs.iecr.0c02644>
- Li MC, Wu Q, Han J, Mei C, Lei T, Lee SY, Gwon J (2020). Overcoming salt contamination of bentonite water-based drilling fluids with blended dual-functionalized cellulose nanocrystals. *ACS Sustainable Chemistry & Engineering* 8 (31): 11569–11578. <https://doi.org/10.1021/acssuschemeng.0c02774>

- M-I Swaco (2009). Drilling Fluids Engineering Manual, Version 2.2. M-I Swaco - A Schlumberger Company, Houston
- Mahmoud H, Mohammed AAA, Nasser MS, Hussein IA, El-Naas MH (2024). Green drilling fluid additives for a sustainable hole-cleaning performance: a comprehensive review. *Emergent Materials* 7: 387–402. <https://doi.org/10.1007/s42247-023-00524-w>
- Muhammed NS, Olayiwola T, Elkatatny S (2021). A review on clay chemistry, characterization and shale inhibitors for water-based drilling fluids. *Journal of Petroleum Science and Engineering* 206: 109043. <https://doi.org/10.1016/j.petrol.2021.109043>
- Omary PM, Ricky EX, Kasimu NA, Madirisha MM, Kilulya KF, Lugwisha EHJ (2023). Potential of kaolin clay on formulation of water based drilling mud reinforced with biopolymer, surfactant, and limestone. *Tanzania Journal of Science* 49(1): 218–229. <https://dx.doi.org/10.4314/tjs.v49i1.19>
- Omotioma M, Nkemdilim Dorothy O, Mbah GO, Okechukwu ES, Azuka EJ (2024). Effects of process factors on the characteristics of water based mud viscosified by kaolin and bentonite. *World Scientific News* 192: 270-288.
- Otitigbe FE (2021). Evaluation of pH of drilling fluid produced from local clay and additives. *Journal of Applied Sciences and Environmental Management* 25(4): 561-566. <https://dx.doi.org/10.4314/jasem.v25i4.11>
- Rabia H (2001). Well Engineering and Construction. Entrac Consulting Limited, London.
- Rugang Y, Guancheng J, Wei L, Tianqing D, Hongxia Z (2014). Effect of water-based drilling fluid components on filter cake structure. *Powder Technology* 262: 11-18. <https://doi.org/10.1016/j.powtec.2014.04.060>
- Ryabtsev P, Kuksov V, Khomutov A (2022). Smart bridging agent enhanced well productivity in depleted production formation. Paper AADE-22-FTCE-052 presented at the AADE Fluids Technical Conference and Exhibition, Houston, Texas, 19-20 April.
- Saadi R, Hamidi H, Wilkinson D (2025). Optimizing filtration properties of water-based drilling fluids: Performance of PAC variants and synergistic effects. *Colloids and Surfaces A: Physicochemical and Engineering Aspects* 715: 136590. <https://doi.org/10.1016/j.colsurfa.2025.136590>
- Siddig O, Mahmoud AA, Elkatatny S (2020). A review of different approaches for water-based drilling fluid filter cake removal. *Journal of Petroleum Science and Engineering* 192: 107346. <https://doi.org/10.1016/j.petrol.2020.107346>
- Taiwo A, Joel O, Kazeem A (2011). Investigation of local polymer (Cassava Starches) as a substitute for imported sample in viscosity and fluid loss control of water-based drilling mud. *ARPN Journal of Engineering and Applied Sciences* 6(12): 43–48
- Talukdar P, Kalita S, Pandey A, Dutta U, Singh R (2018). Effectiveness of different starches as drilling fluid additives in non damaging drilling fluid. *International Journal of Applied Engineering Research* 13(16): 12469-12474.
- Uwaezuoke N, Chukwuebuka UC, Muhammed AA, Duru U (2024). Evaluation of kaolin clay polymeric nanoparticles for improved water-based mud properties. *International Journal of Oil, Gas and Coal Engineering* 12(1): 36-45. <https://doi.org/10.11648/ogce.20241201.15>
- Villada Y, Busatto C, Casis N, Estenoz D (2022). Use of synthetic calcium carbonate particles as an additive in water-based drilling fluids. *Colloids and Surfaces A: Physicochemical and Engineering Aspects* 652: 129801. <https://doi.org/10.1016/j.colsurfa.2022.129801>
- Vom Berg R. (1981). A new rheological model for non-Newtonian fluids applied to drilling muds. *Journal of Petroleum Technology* 33(3): 657–662.
- Zhang JR, Xu MD, Christidis GE, Zhou CH (2020). Clay minerals in drilling fluids: functions and challenges. *Clay Miner* 55(1): 1–11. <https://doi.org/10.1180/clm.2020.10>

## SAŽETAK

### Utjecaj kaolinita na isplaku na bazi vode koja sadržava kalcijev karbonat

Ovim je istraživanjem sistematskim laboratorijskim ispitivanjima analiziran utjecaj dodavanja kaolinita na isplaku na bazi vode (engl. *Water Based Mud*, WBM) koja sadržava kalcijev karbonat. Kaolinit je u standardni WBM na bazi  $\text{CaCO}_3$  dodavan u koncentracijama od  $42,8 \text{ kg/m}^3$  (15 lb/bbl),  $85,6 \text{ kg/m}^3$  (30 lb/bbl) i  $128,4 \text{ kg/m}^3$  (45 lb/bbl) te je analiziran njegov utjecaj na gustoću, pH, filtracijska i reološka svojstva te viskoelastično ponašanje isplake. Sa  $128,4 \text{ kg/m}^3$  (45 lb/bbl) kaolinita gustoća osnovne isplake ( $10,15 \text{ g/cm}^3$ ) povećala se na  $11,00 \text{ g/cm}^3$ , dok je pH rastao proporcionalno s udjelom kaolinita. Filtracijski testovi na  $93,3 \text{ }^\circ\text{C}$  ( $200 \text{ }^\circ\text{F}$ ) i  $2,07 \text{ bar}$  ( $300 \text{ psi}$ ) pokazali su da uzorak osnovne isplake proizvodi debljinu filtarskoga kolača od  $0,0098 \text{ in}$ , koja se progresivno povećavala s dodatkom kaolinita. Mjerenja reoloških svojstava pokazala su Binghamovo plastično ponašanje u svim uzorcima, s prividnom viskoznošću koja se povećavala od  $25 \text{ cP}$  u osnovnoj isplaci do  $33 \text{ cP}$  pri  $128,4 \text{ kg/m}^3$  (45 lb/bbl) dodanoga kaolinita. Točka tečenja i čvrstoća gela također su pokazale dosljedan rast, što upućuje na poboljšani kapacitet suspenzije. Ispitivanja viskoelastičnosti potvrdila su povećan modul pohrane (engl. *enhanced storage modulus*) ( $G'$ ) i učinak geliranja pri višim koncentracijama kaolinita. Ovi rezultati pokazuju da kaolinit znatno poboljšava gustoću, kontrolu filtracije i reološku stabilnost  $\text{CaCO}_3$  WBM-ova, što ide u prilog njegovoj primjeni kao isplativoga i multifunkcionalnoga aditiva u operacijama bušenja.

#### Ključne riječi:

isplaka, kaolinit, kalcijev karbonat, isplaka na bazi vode (WBM)

#### Author's contribution

**Mohammed Abdalraheem** (M.Sc. in Petroleum Engineering from Institut Teknologi Bandung – ITB): conceptualization, methodology, theoretical modelling, simulation, writing – original draft preparation, literature review, experimental investigation, data analysis, and visualization. **Basfar** (Postdoctoral Researcher, Department of Petroleum Engineering, King Fahd University of Petroleum and Minerals – KFUPM): supervision, project administration, methodology, validation, writing – review and editing, and technical guidance in drilling fluid research. **Elkattatny** (Professor, Department of Petroleum Engineering, KFUPM; Associate Editor for Journal of Energy Resources Technology and Arabian Journal for Geosciences): conceptual supervision, provision of advanced laboratory facilities and research infrastructure, review and editing, technical oversight in drilling fluid and reservoir engineering, and strategic support for research implementation.

All authors have read and agreed to the published version of the manuscript.