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# An Experimental Study to Assess The Impact of Inorganic Additives on Water-Based Drilling Fluid Performance

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**ABSTRACT** - Drilling mud plays a crucial role in ensuring safe and cost-effective drilling operations, but it is often contaminated during the process and can significantly impact the mud's properties. Previous studies have largely addressed drilling mud contamination in a general sense, this work provides direct comparative insight into how sodium hydroxide (NaOH) alone and in combination with barite, lime, and calcium sulphate alters key rheological and physical properties of water-based muds (WBM) at a constant temperature of 25 °C. This paper investigates the effects of inorganic additives, specifically NaOH, on the properties of WBM. In this experimental study, six mud samples were prepared alongside a base mud, with three samples contaminated with varying concentrations of NaOH and the other three with different amounts of barite, lime, and calcium sulphate. The study focused on evaluating the rheological and physical properties of the mud at 25°C. The results showed that NaOH positively increased the mud alkalinity up to 12.75, but this was less pronounced as a result of the combinations with other additives like barite and

calcium sulphate, reduced to 9.8. This trend is evident when higher NaOH concentrations result in increased fluid loss ( $\approx 40$  ml at around 6 minutes) and decreased gel strength ( $\approx 13$  lb/100 ft<sup>2</sup> after 10 minutes), which can negatively impact the mud's capacity to retain water and uphold structural integrity. However, the moderate doses of NaOH help in accelerating flocculation in the muds and increases the stability as well.

**Keywords:** WBM, sodium hydroxide, inorganic additives, rheological, physical properties.

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## INTRODUCTION

In rotary drilling operations for oil and gas, drilling fluids serve multiple critical functions, including cooling and lubricating the drill bit, transporting rock cuttings to the surface, and suspending these cuttings when circulation is paused. By applying the right amount of hydrostatic pressure, the drilling mud also helps to prevent the possible collapse of unstable strata into the borehole and the intrusion of unwanted fluid from potentially present permeable water-bearing strata. Drilling fluid systems are designed and formulated to work well under expected wellbore conditions (Amanullash 2007). Drilling fluid is classified into three categories: gas-based, oil-based, and water-based. The conditions around the drilling operations have a significant impact on the choice of which category to select. Water-based drilling fluid is the most efficient due to its low preparation and maintenance costs and environmental friendliness, even if all drilling fluids have their uses. Therefore, consumer interest in water-based drilling fluid has increased in comparison to other options due to these facts and environmental friendliness (Alderman et al., 1988).

The ability to sustain high enough stress to maintain cuttings suspended, particularly when fluid flow is stopped, and obtaining a lower viscosity profile to enable efficient pumping are the two fundamental rheological characteristics

thought to be required of drilling fluid for respectable functioning performance. To effectively carry out the aforementioned tasks in steady shear flow, the fluid needs to possess high-yield stress and shear-thinning properties (Moore 1986). The drilling fluid's design must be appealing to economically achieve the necessary rheological and filtration qualities. For the drilling fluid to function as intended, fluid loss and mud cake development must occur. In the oil and gas sector, needless additional fluid loss during drilling operations is becoming a bigger issue. By creating an appropriate drilling fluid that will create a thin, low-permeable mud cake on the borehole wall, this issue can be resolved. If the mud cake on the borehole wall has a high permeability, the formation will lose a lot of fluid. Therefore, designing and preparing a drilling fluid that reduces fluid loss volume is crucial in the drilling process. To prevent excessive fluid loss, filtration loss is managed with the use of certain chemical additives, including starch, carboxymethyl cellulose, low viscosity polyan-ionic cellulose, and bentonite (Moore 1986; & Shakib et al., 2016). Furthermore, at the laboratory level, cellulose nanomaterials (Zhou et al., 2023) and nano-particles have previously demonstrated their potential for regulating fluid loss (Bayat et al., 2018).

Drilling operations may result in cement contamination, which could alter the properties of the mud. Cement amount, deflocculant type and

concentration, and solids content are some of the variables that affect the degree of contamination (Rig worker 2020). For drilling operations to be both safe and efficient, the mud must have low calcium levels. Numerous issues might arise from elevated calcium levels brought on by cement contamination. Chemical treatment with sodium bicarbonate is proposed to address this issue, as it generates insoluble calcium carbonate, facilitating the extraction of calcium and lime from the drilling mud while preserving pH stability (Rig worker 2020).

Chikwe & Nwakanma (2020) studied the impact of the pollutants on the rheological properties of the oil-based mud. The research focused exclusively on how varying concentrations of salt impurities and cement contamination impact the performance of drilling mud samples gathered from the Niger Delta in Nigeria. The samples were maintained at 49°C to ensure temperature consistency before their rheological properties were recorded. The rheological properties of drilling mud samples showed a decrease as contaminant concentration increased. Their investigation showed that cement contamination emerged as the most harmful among eight previously studied salt impurities to mud consistency.

Broni-Bediako & Amarin (2019) studied the effects of cement contamination in water-based mud of cement. Out of four mud samples, three showed contamination with varying amounts of Class G cement. The mud was analyzed for pH, density, fluid loss, and rheological properties, which were measured at three temperatures: 20, 40, and 60 °C. Increasing cement concentration resulted in greater yield point, augmented gel strength, as well as enhanced viscosity and solid suspension. On the other hand, opposing effects of cement content and temperature are observed on plastic viscosity. High cement concentrations could further increase the density pH and fluid loss of the mud compromising its stability as well as performance during drilling operations. Mahmud et al. (2020) studied the effect of bicarbonate and sodium carbonate impurities on the rheological properties of WBM. They concluded that cement contamination controlled the viscosity of the mud

and pumping pressure required for circulation. Contaminants affect chemical properties, illustrated by increased pH in mud correlating with increased sodium carbonate content and decreased pH corresponding to bicarbonate levels. As the levels of cement contamination and treatment agent increased, plastic viscosity decreased, while the yield point increased accordingly. As the concentration of harmful compounds rose, fluid loss also increased, which indicates a diminished ability to retain fluid. The study concludes that additional research is needed to fully explore the rheological properties of water-based muds used in HPHT drilling (Mahmud et al., 2020).

Sylvester et al. (2022) explored the impact of different contaminants on the performance and rheological characteristics of water-based mud being studied. They examined the mud system, focusing on cement, carbonate, silica sand, and salt. Through their experimental study, they identified that sodium salt in the mud system was responsible for increased fluid loss into the formation. In other words, sodium salt contaminates water/asphalt mud, impacting its performance. They also discovered that the presence of contaminants could alter the rheological properties of the drilling mud system, which in turn affected the drilling rate (Dankwa et al., 2018).

Dankwa and colleagues (2018) further investigated the effect of monovalent and divalent salts such as potassium chloride (KCl), calcium chloride (CaCl<sub>2</sub>), and magnesium chloride (MgCl<sub>2</sub>) on the rheological characteristics of a polluted WBM system. Sixteen mud samples were contaminated with varying amounts of salt at room temperature, with fifteen samples affected. The results of the mud tests showed that as salt content increased, rheological parameters like plastic viscosity, apparent viscosity, and yield point decreased. The study concluded that contamination of drilling mud with monovalent and divalent salts significantly impacts its performance, particularly in terms of flocculation, hydration, and particle dispersion. The effects were most pronounced with CaCl<sub>2</sub> and MgCl<sub>2</sub> salts, and less so with KCl salt. Recently, Suhascaryo and co-authors have studied the effect

of KCl contamination on WBM performance. They concluded that the nanosilica enhanced rheological characteristics and decreased shale swelling. In the meantime, the 1% KCl formulation performed well in erosion and Linear Swelling Meter testing (Suhascaryo et al., 2025). Ebikapaye (2018) investigated the influence of temperature on WBM density utilized during drilling operations. Density measurements were made at each temperature after the mud was heated to between 28 – 70°C. The results revealed a reverse relationship between mud weight and temperature, meaning density was reduced with an increase in temperature. This reduction in density was attributed to the degradation of the mud fraction under the effects of high temperatures. WBM consists of numerous temperature-sensitive components, including polymers, clays, and weighing agents. At high temperatures, they have the potential to destroy the organic molecules and polymers that mud is made of, imparting undesirable characteristics to it. Khamis and co-authors (2020) studies the impact of cement contamination on rheological characteristics of WBM. They prepared both cement-contaminated mud and cement- contaminated mud treated with sodium bicarbonate, as well as fresh mud. Measurements of apparent viscosity, annular viscosity, gel strength, and yield point were made using rheological analysis. Cement suspension logic and sodium bicarbonate's role in reducing the viscosity, gel strength, and yield point of cement - contaminated mud.

Increasing pH, which is frequently accomplished with NaOH, dramatically changes viscosity, yield point, and fluid loss in bentonite-based WBMs, according to earlier research such as Gamal et al. (2019). The results show optimal rheology within a specified pH range, confirming the significance of pH adjustment in mud formulation. In 2022, Ohia and co-authors contrasted the usage of classic NaOH with local pH modifiers (such plant extracts) showed that NaOH is still a benchmark agent for pH control even when other additives are investigated, confirming its significance in mud stability and formulation (Ohia et al., 2022). NaOH is still utilized in contemporary rheological assessments of drilling fluids, as evidenced by studies on drilling mud rheology

(e.g., formulations with NaOH to adjust pH to ~9.5 for better colloidal stability), reinforcing its influence on plastic viscosity and yield point relevant to drilling performance (Martin et al., 2022). Studies have demonstrated that NaOH raises the alkalinity of mud and affects the rheological behavior of drilling muds, mainly concentrating on its impacts on pH, fluid loss, and gel strength. However, there has not been enough systematic research done on how NaOH concurrently influences mud characteristics in the presence of certain inorganic additives (such as barite, calcium salts like CaCO<sub>3</sub>, and sulphate compounds like CaSO<sub>4</sub>) under various field-relevant conditions.

The purpose of this study is to examine how different NaOH concentrations and specific inorganic additions affect the rheological and filtration characteristics of WBM. It specifically aims to compare the performance of treated mud systems with that of the base mud and assess how these additives affect important rheological parameters, filtration loss, and mud cake features, such as surface roughness. The purpose of this comparison is to determine appropriate additive doses that enhance mud performance without sacrificing stability and to evaluate how well NaOH improves WBM qualities.

## METHODOLOGY

### Materials

The raw materials used in the formulation of WBM include water, bentonite, and sodium hydroxide. Lime, barite, and calcium sulfate were chosen as the three inorganic additives and mixed with the base mud. NaOH is purposefully supplied in this work to control pH and alter the water-based mud's electrochemical environment, which affects clay hydration, electrical double layer behaviour, and inorganic additive performance. NaOH is therefore seen as a controlled experimental variable rather than an uncontrolled contaminant, and it is purposefully employed to investigate both the spectrum of beneficial conditioning and the boundaries at which mud qualities decrease. This method improves the applicability of the experimental results to actual drilling fluid management situations, allows a

thorough assessment of WBM sensitivity to pH variations, and sheds light on the relationship between alkalinity and inorganic additions.

### Drilling mud preparation

The preparation method (API RP 13I Standard for drilling fluids laboratory testing) and equipment used were outlined in the earlier publication by Mahmud et al. (2020). To create mud sample A, 350 ml of water was placed in a Hamilton mixer cup. A uniform mixture was achieved by prehydrating 15g of bentonite for 30 minutes while stirring. The sample was then aged for 15 hours in a sealed jar. After aging, the bentonite was mixed with 1g of NaOH for 5 minutes using an electric hand mixer, followed by the addition of 4g of calcium sulfate, which was mixed for another 10 minutes. Then, 7.5ml of lime and 3g of barite were added, and the mixture was stirred for an additional 5 minutes to ensure homogeneity before evaluating its rheological and physical properties.

In general, the mixing procedure for six samples from A to E were performed as that of sample A by applying different masses of NaOH and volumes of lime as shown in Table 1 as well as the respective amount of lime and NaOH was blended into the respective mud formulations. In WBM formulation experiments, additives are frequently added gradually to find the concentration at which they start to significantly affect fluid characteristics. Many studies look at effects from about 0.5 weight percent upward. The use of 1 g, 3 g, and 5 g additions is justified by this stepwise strategy, which permits the evaluation of both minor and more prominent impacts without jeopardizing the stability of the mud system (Mahmud et al., 2020; Ndubuisi et al., 2020; Rasan et al., 2023; Suhascaryo & Dhaffa 2024).

The rheological and a few physical characteristics were then ascertained. Before the cakes were allowed to cure, a tactile inspection of their textures was done, and a millimeter scale was dipped into the mud cake to measure its thickness. Figure 1 displays the mud cake samples that were investigated in this study. The pictures of the mud

cakes in Figure 1 were taken immediately after any extra fluid that was not essential to the cakes was removed, and before the cakes' thickness was measured.

### Rheology test

The study of a matter's flow and deformation properties is known as rheology. Drilling fluid rheology offers pertinent data needed for circulation system design. Rheology is important, as shown by analyses of fluid flow velocity profiles, fluid viscosity, friction pressure losses, and annular wellbore cleaning. All drilling hydraulics analyses and evaluations of mud system performance are based on rheological characteristics (Darley & Gray 1988; Dhiman 2012; Nasser et al., 2013; Awele 2014). The Fann viscometer was used to measure the rheology of each drilling fluid sample. Equations 1 and 2 were utilized to calculate the samples' yield point (YP) and plastic viscosity (PV) based on the viscometer's results (Ogbeide & Igbinere 2016; Yunita et al., 2016).

$$PV: cP = \theta_{600} - \theta_{300} \quad (1)$$

$$YP: lb/100ft^2 = \theta_{300} - PV \quad (2)$$

Table 1. Quantity of additives to treat NaOH contaminationa

Drilling fluid	Sample ID	Contaminant	Additives
Water Base Mud	Sample A	1 g NaOH	N/A
	Sample B	1 g NaOH	3 g Barite 4 g Calcium Sulphate 7.5 ml Lime
	Sample C	3 g NaOH	N/A
	Sample D	3 g NaOH	10 g Barite 3 g Calcium Sulphate 10 ml Lime
	Sample E	5 g NaOH	N/A
	Sample F	5 g NaOH	20 g Barite 2.5 g Calcium Sulphate 13 ml Lime

### Fluid loss test

The amount of filtrate that enters a porous permeable formation from drilling mud is measured as fluid loss. A good drilling mud should build a thin filter cake on the sides of the wellbore

to prevent excessive fluid from seeping into the formation. Good drilling fluids have low fluid loss, which is essential to the wellbore's integrity. Several factors include temperature, time, cake compressibility, and the nature, amount, and size of particles in the drilling fluid that impact the fluid loss characteristics (Khodja & Khodja-Saber 2010; Nasser et al., 2013). A filter press was used to measure the fluid loss of each drilling fluid.

## RESULT AND DISCUSSION

### Mud pH

The pH results presented in Figure 2 indicate a clear increase in alkalinity with the addition of NaOH to the cement samples. The base mud exhibits a pH of approximately 10, while sample A, sample C, and sample E show progressively higher pH values, reaching around 12.5 to 13. This is consistent with other studies including Gamal et al. (2019) on the alkaline additives that modified the drilling and cement slurries to higher pH increased the stability and mitigated corrosion in well bore. In high pH values the dispersion of the clay size and avoidance of undesirable flocculation are enhanced as it was also observed by Caenn et al. (2017), who studied drilling fluid additives. However, excessive alkalinity can influence rheological and filtration characteristics, and it is therefore desirable to control the pH to optimize performance (Ahmed et al. 2019). These results reinforce the well-documented role of NaOH in modifying cement chemistry and electrochemical balance in drilling fluids.

On the other hand, adding NaOH, increases the alkalinity of the cement samples, but this effect is apparently suppressed by the presence of the other additives, barite, calcium sulfate, and lime. The base mud has a pH of about 10, however, sample A with only 1 g NaOH has a much higher pH of about 12. On the other hand, it can be observed that samples B, D, and F, which contain barite, calcium sulfate, and lime in a varying proportion in addition to NaOH, have the pH quite similar to the pH of the base mud and hence these labelControl experiments with a range of pH similar to the base mud, suggesting that these additional components may act as pH buffers or neutralizers.

This result agrees with those related to the change in the pH balance in cementitious systems by Caenn, Darley & Gray (2017) who found that calcium sulphate and barite can modify the pH balance by reacting with the alkaline additives. Additionally, Ahmed, et al. (2019) commented that lime can control the availability of hydroxyl ions in drilling and cement slurries and play a role in the pH sustainability. This indicates that the inorganic additives will help buffer pH excursions, and is significant as it is required to maintain the electrochemical balance in cement slurry and drilling fluids. Proper control of pH is essential to ensure the stability of cement formulations, prevent excessive flocculation, and optimize performance in wellbore applications (Gamal et al. 2019).



Figure 1. Mud cake thickness of sodium hydroxide contaminant used in this study.

## Density

The density values (in pounds per gallon, ppg) of the samples are affected by the varying compositions of additives such as sodium hydroxide, barite ( $\text{BaSO}_4$ ), calcium sulphate ( $\text{CaSO}_4$ ), and lime ( $\text{Ca}(\text{OH})_2$ ). The density test results for each mud sample using a mud balance are displayed in Figure 3. According to Figure 3, the density of the mud sample reduced somewhat as more NaOH (a contaminant) was added to the WBM. Sample A density was 8.55 ppg (63.96 lb/ft<sup>3</sup>), and when contaminated with 3 g, and 5 g of NaOH, respectively, leading to a noticeable density reduction to 8.3 ppg (62.09 lb/ft<sup>3</sup>) and 8.1 ppg (60.59 lb/ft<sup>3</sup>), as NaOH does not significantly contribute to the weight increase and indicating that higher NaOH content lowers mud weight.

The additional quantity of 3 g barite, 4 g calcium sulphate, and 10 ml lime to sample B has led to maintaining the base mud density, 8.6 ppg (64.33 lb/ft<sup>3</sup>), likely due to the weight-balancing effect of barite. Furthermore, sample D additives (10 g barite, 3 g calcium sulphate, and 10 ml lime) have led to maintaining density due to the substantial addition of barite. A similar trend was observed in sample F, which includes 5 g sodium hydroxide, 20 g barite, 2.5 g calcium sulphate, and 13 ml lime, showing that a high concentration of barite offsets the density loss from NaOH.

Therefore, higher sodium hydroxide concentrations reduce density, as seen in samples C and E.

Barite addition compensates for density loss, explaining why samples B, D, and F maintain the base mud density, while calcium sulphate and lime have moderate effects, likely acting as stabilizers.

## Rheological properties

The experiment concentrated on contaminated WBM's rheological characteristics at room temperature.

## Plastic viscosity

PV is a key rheological parameter that influences the flow behavior of cement slurries. It represents the internal resistance of the fluid to flow and is primarily affected by solid content, particle interactions, and chemical additives (Nelson & Guillot 2006). Figure 4 presents the plastic viscosity of base mud and six modified samples (A–F), each containing different compositions of NaOH,  $\text{BaSO}_4$ ,  $\text{CaSO}_4$ , and  $\text{Ca}(\text{OH})_2$ .

From Figure 4, it can be observed that the base mud sample provides a reference viscosity with a value of 3.5 cP, while sample A with 1 g NaOH, PV increased significantly to 6.5 cP due to sodium hydroxide, which alters the electrostatic interactions in the slurry, increasing resistance to flow (Jooybari et al., 2019). PV of sample B remained similar to the base mud value (3.5 cP) because of barite that acts as a weighting agent and can reduce excessive thickening by improving particle dispersion (Ahmed et al., 2019).

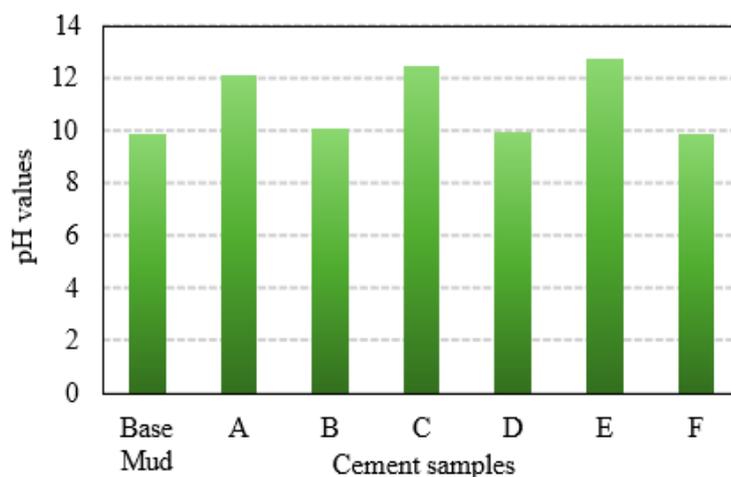


Figure 2. Shows comparing pH values of NaOH contaminated mud before and after being treated with additives.

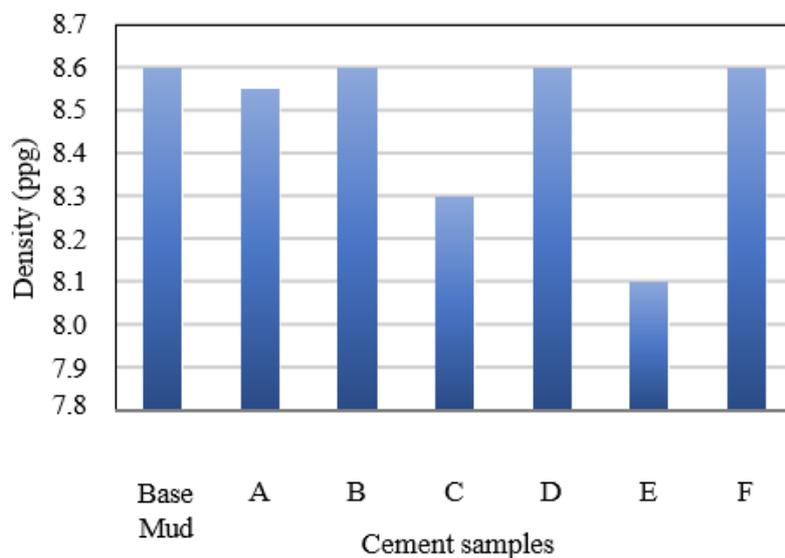


Figure 3. WBM density with changed cement concentrations

On the other hand, sample C shows significant increase of PV value with 6.0 cP, indicating that higher NaOH concentration enhances particle flocculation, increasing viscosity (Caenn et al. 2017), but sample D recorded PV value of 4.0 cP, which is slightly increased compared to the base mud but lower than sample C, suggesting that Barite and Lime help to stabilize the system and limit excessive thickening (Nelson et al., 2006).

Sample E, PV is elevated with value of 5.5 cP, confirming that high NaOH content increases the flocculation effect, making the slurry more resistant to flow (Nelson et al., 2006), but when inorganic additives were added, sample F plastic viscosity reduced to 4.0 cP compared to sample E, indicating that a high concentration of barite can counteract the thickening effect of NaOH (Caenn et al., 2017). The flocculation and deflocculation behavior of WBM is affected by the presence of  $\text{Ca}^{2+}$  ions produced from lime ( $\text{Ca}(\text{OH})_2$ ), which alter the electrostatic and interparticle interactions in the suspension. Divalent  $\text{Ca}^{2+}$  ions more efficiently compress the electrical double layer than monovalent ions, allowing for controlled particle bridging that can lessen excessive flocculation and stabilize particle networks. Clay and other fine particles in mud typically carry negative surface charges. The ionic interaction processes controlling the clay electrical double layer (EDL) can account for the rise in plastic viscosity seen in samples with high NaOH content (C and E). A diffuse ionic layer

and an EDL made up of exchangeable cations encircle the negatively charged basal surfaces of clay particles. When NaOH is added, the system's pH and ionic strength increase due to dissociation into  $\text{Na}^+$  and  $\text{OH}^-$  ions. While the high concentration of  $\text{Na}^+$  ions compresses the diffuse double layer and encourages charge neutralization at localized places, allowing closer particle approach, the  $\text{OH}^-$  ions boost the negative charge density at clay borders.

Stronger flocculation and particle aggregation result from this change in surface charge distribution, which strengthens edge-to-face and face-to-face connections. The higher plastic viscosity values observed for samples C and E are indicative of increased interparticle friction and flow resistance. These results are in line with previous research demonstrating that flocculated structures in water-based muds are intensified by alkalinity-driven alterations of electrochemical interactions, boosting PV.

In contrast, sample D, which also contained barite and lime in addition to NaOH, showed a lower PV than sample C, indicating that  $\text{Ca}^{2+}$  ions may have modulated the degree of aggregation by encouraging a more uniform particle network rather than uncontrolled clustering. Other rheological characteristics that are sensitive to the strength and structure of the particle network, like yield point and gel strength, also exhibit this effect: In comparison to dispersed systems,  $\text{Ca}^{2+}$  mediated

flocculation tends to increase yield stress and gel strength while limiting the extreme thickening observed under high NaOH alone. This improves stability and workability while preventing brittle or excessively rigid gels. Furthermore, the interpretation that  $\text{Ca}^{2+}$  ions help balance flocculation effects against particle dispersion to achieve desired flow behavior is supported by Samura et al., 2025 work that demonstrates how chemical interactions and gradual additive addition can effectively tailor rheological characteristics like yield point and gel strength in drilling fluids.

### Yield point

YP is a crucial rheological property of cement slurries, representing the stress required to initiate fluid movement. YP is affected by the type and concentration of ions in the fluid phase, the volume concentration of the mud solids, and their surface characteristics. If YP appears to be high, this could be a sign of strong attraction between the charged particles (Abduo et al. 2016 – Yunita et al. 2016 – Nasser et al. 2013). Figure 5 illustrates the yield point of the base mud and modified samples (A–F), showcasing the effects of sodium hydroxide, barite, calcium sulphate, and lime on cement rheology.

Base mud serves as a reference, representing the initial yield point (3 lb/100 ft<sup>2</sup>) without any modifications. From Figure 5, the YP of sample A increased significantly till it reached 13.5 lb/100 ft<sup>2</sup>. Due to the addition of NaOH, which promotes

particle flocculation, increasing interparticle attraction and fluid resistance (Caenn et al. 2017). As the weight of NaOH increased to 3 g and 5 g, showing a reduction in YP to 11 and 7.5 lb/100 ft<sup>2</sup>, respectively. The addition of NaOH reduces the yield point of cement primarily by dispersing flocculated particles through increased electrostatic repulsion at high pH, which alters the zeta potential and weakens interparticle forces (Banfill 2006). NaOH also accelerates early hydration, temporarily increasing fluidity by promoting the dissolution of aluminate and silicate phases, releasing free water and reducing initial yield stress (Banfill 2006).

The YP of sample B is recorded as 2 lb/100 ft<sup>2</sup> when contaminated with 3 g barite, 4 g calcium sulphate, and 7.5 ml lime. The lower YP suggests that barite and lime act as dispersants, reducing interparticle interactions (Ahmed et al., 2019). Moreover, when increasing the inorganic additive amount as in samples D and F, the YP is significantly reduced compared to sample B, indicating that higher barite and lime concentrations help disperse cement particles, reducing viscosity and flow resistance (Caenn et al. 2017; Nelson & Guillot 2006).

### Gel strength

Figure 6 shows gel strength results at 10 seconds and 10 minutes with different amounts of cement and additives. The results of gel strength shown in Figure 6 reflect the effect of sodium

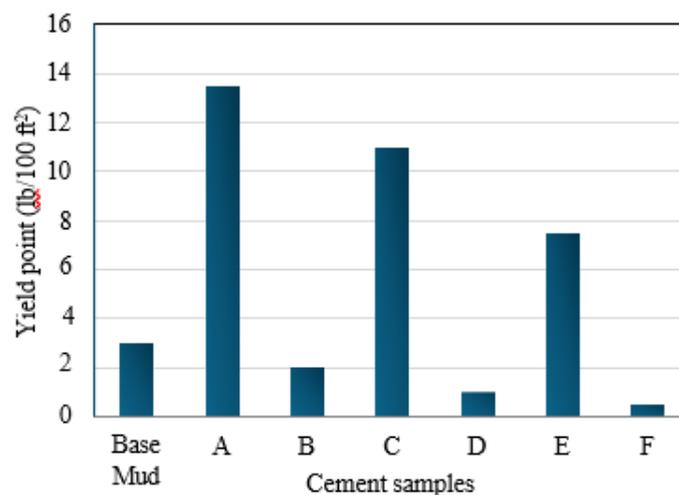


Figure 5. WBM Yield point results for various cement samples and additive concentrations.

hydroxide concentration on cement slurry crystallization at rest. Gel strength is an important aspect that prevents sedimentation and ensures proper zonal isolation during well cementing (Nelson & Guillot 2006). In sample A we find the base mud to have a low gel strength meaning minimal structural buildup. In sample A we find to have a large increase of gel strength especially at 10 minutes suggesting that NaOH has enhanced flocculation which resulted in stronger interparticle interactions (Caenn et al., 2017). Sample C has moderate gel strength with a balance of dispersion and flocculation and is consistent with observations that optimal NaOH concentration enhances slurry stability without over-thickening (Ahmed et al., 2019). Sample E is the least among the modified samples to achieve gel strength and indicates that higher levels of NaOH can be a dispersant that minimizes the capacity to gel (Gupta & Gupta 2019). These results put great significance on optimizing the concentration of NaOH in order to achieve the required gel strength to enhance wellbore stability and successful cement placement. Furthermore, Figure 6 shows the non-newtonian gel strength of various additives, e.g., sodium hydroxide, barite, calcium sulphate, and lime at different concentrations and the impact on the cement slurry's capacity to acquire structure over time. It can be described that sample A has shown the higher gel strength (30 lb/100 ft<sup>2</sup> after 10 minutes) as explained referred to earlier. Samples B, D and F that contain barite, calcium sulphate and lime showed a lower gel

strength than sample A indicating that these inorganic additives could minimize excessive gelation caused by an increased slurry density alter the interparticle forces (Ahmed et al., 2019). This indicates that NaOH and other additives have a considerable effect on the gel structure since the base mud has the minimum gel strength. Samples D and F, with higher barite and lime concentrations, exhibit moderate gel strength, demonstrating a controlled balance between gelation and fluidity, which is desirable for cement placement and long-term stability (Gupta & Gupta 2019). These results underscore the need for optimized additive concentrations to achieve an ideal gel strength profile for cementing applications.

**Fluid loss**

Figure 7 shows the fluid loss results at 25°C that increasing NaOH concentration in WBM significantly affects the fluid retention. The base mud (without NaOH) shows the lowest fluid loss over time, maintaining better filtration control. However, with the addition of 1, 3, and 5 g NaOH, fluid loss progressively increases, with 5 g NaOH exhibiting the highest loss (≈ 40 ml at around 6 minutes). This trend suggests that higher NaOH concentrations reduce the mud's ability to retain water, likely due to increased dispersion of clay particles and breakdown of the mud cake structure, leading to higher permeability (Caenn et al. 2017). While mild NaOH concentrations (e.g., 1 g) can slightly enhance mud stability, excessive NaOH

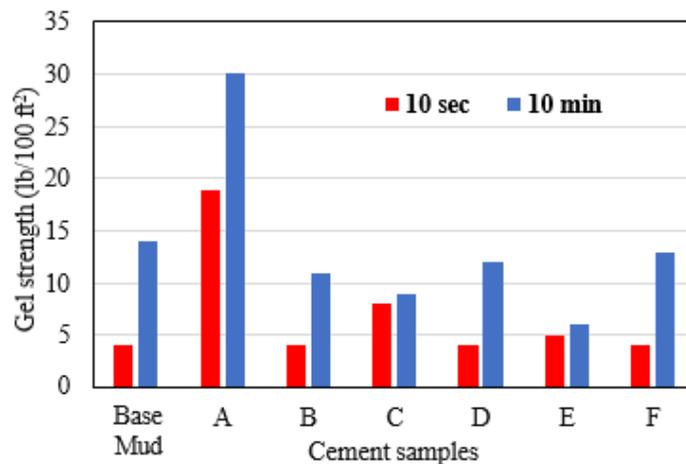


Figure 6. Gel strength of WBM with diverse cement concentrations and different quantities of inorganic additives.

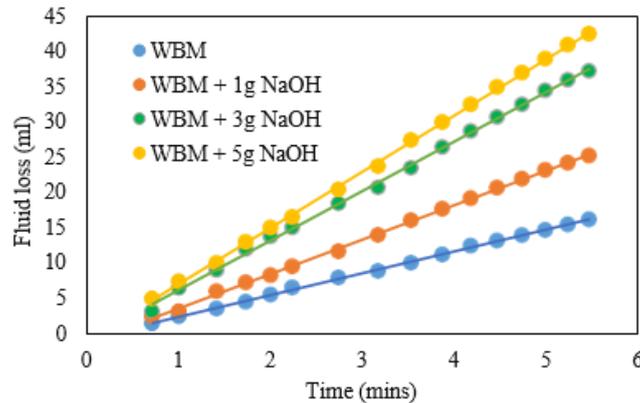


Figure 7. WBM fluid loss verses time at various NaOH concentrations

weakens the hydration and flocculation of clay particles, causing a less effective filter cake and higher filtration rates (Darley & Gray 1988). These findings align with past research indicating that alkaline additives impact the electrochemical balance in drilling fluids, influencing fluid retention properties (OFI Testing Equipment, Inc. 2017– Schlumberger 2023 – Gamal et al. 2019 – Borah & Das 2022). Optimizing NaOH concentration is crucial to control filtration loss while maintaining the desired mud rheology for effective drilling operations. Ionic interactions that change the clay electrical double layer in water-based muds cause an increase in fluid loss as the NaOH concentration increases. Dissociation of NaOH releases  $\text{Na}^+$  and  $\text{OH}^-$  ions, increasing pH and ionic strength. At low doses, this promotes limited clay hydration and stability, but at higher dosages, it causes excessive dispersion of clay particles. Excess  $\text{Na}^+$  ions break flocculated structures, leading to a thinner and more permeable mud cake. Elevated  $\text{OH}^-$  levels enhance negative surface charge density and reduce edge-to-face attractions. As a result, filtration loss gradually rises with NaOH dose, emphasizing the necessity of optimizing alkalinity in water-based mud systems to balance electrochemical stability, filter cake integrity, and efficient fluid loss control.

## CONCLUSION

This study evaluated how some physical characteristics of WBM were affected by cement contamination. The mud system was supplemented with varying quantities of 1 g, 3 g, and 5 g of NaOH and different quantities of inorganic

components, including lime, barite and calcium sulphate. Presentation of NaOH significantly increases pH of mud (alkalinity), but its effect is moderated when combined with barite, calcium sulphate, and lime. Barite plays a crucial role in maintaining or increasing density.

As NaOH concentration increases, increasing  $\text{OH}^-$  and  $\text{Na}^+$  ion levels progressively disrupt the electrochemical balance of the mud system, potentially leading to over-flocculation, excessive viscosity, decreased filter cake structure, and increased fluid loss. These reactions mimic alkaline overtreatment or alkaline infiltration scenarios that could arise during field operations. Barite is effective in reducing plastic viscosity, ensuring better cement placement and pumping efficiency. Furthermore, NaOH increases cement yield point, flocculation and thickening, while barite and lime improve flow properties. A balance between additives is crucial for optimal rheological properties in cementing and drilling operations to ensure proper fluid placement and well stability.

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**GLOSSARY OF TERMS AND SYMBOLS**

<b>Terms &amp; Symbols</b>	<b>Definition</b>	<b>Unit</b>
WBM	Water-based mud is a drilling fluid made of water, bentonite, and heavy minerals to which additional weight is added.	-
HPHT	High pressure and high temperature indicator of a solution's	-
pH	Acidity or alkalinity	-
$\rho$	Density is mass of a unit volume of a material substance	ppg/or lb/ft <sup>3</sup>
Plastic viscosity	The fluid's resistance to flow in bores	C <sub>P</sub>
Yield point	The stress level at which a material starts to undergo plastic deformation	-
Gel Strength	A colloidal dispersion's resistance to shear is a measure of its capacity to form and hold a gel	lb/100 ft <sup>2</sup>
Fluid loss	The escape of liquid part of a drilling mud into permeable formations	ml/30 minutes

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