

DESIGN OF RESERVOIR FRIENDLY DRILLING FLUID FOR SHALE RESERVOIRS USING SYNTHESIZED ZINC OXIDE(ZnO)NANOPARTICLES

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Abstract

Numerous studies have explored how nanoparticles (NPs) affect the properties of drilling fluids, such as rheology, fluid loss control, and thermal and electrical conductivity. These studies consistently demonstrate that the addition of various NPs can enhance the rheological and filtration properties of drilling fluids across different temperature and pressure conditions. Such studies show that carefully designed drilling mud can be used for drilling the difficult unconventional resources such as Shale Reservoirs. In this study, for Shale Reservoir, a Water Base Drilling Mud (WBDM) were designed with ZnO NPs, that were synthesized in the laboratory using the sol-gel method with Zinc Nitrate Hexahydrate ($\text{Zn}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$) as a precursor. Base mud was prepared with 5 wt% Bentonite, 1 wt% XG, 1 wt% PAC-R; 0.5 wt% PAC-L, and 6 wt/v% KCl in 400mL deionized water. In the base mud, 0.05 wt%, 0.1 wt% & 0.15 wt% ZnO nanoparticles were thoroughly mixed and KOH was added to maintain the pH level at 9-10. Results show that the concentration of 0.1 wt% ZnO NPs in Base Mud is the optimum concentration and the mud can be used for Shale Reservoir, as the fluid loss was reduced. API Fluid loss was reduced by almost 18% with 0.1% ZnO addition.

Keywords: Drilling Mud; Filtration Properties; Rheological Properties; Shale Reservoir; ZnO Nanoparticle

Introduction

Drilling mud, a critical component of the oil and gas drilling process plays a pivotal role in ensuring the success, efficiency, and safety of drilling operations. Traditionally, drilling mud formulations have undergone continuous optimization to meet the increasingly complex challenges posed by diverse geological formations, high-pressure environments, and demanding drilling conditions. Nowadays, there is a need to exploit unconventional resources

(Shale Reservoir, Coal-bed Methane), especially with Shale Reservoirs, as traditional drilling mud causes a lot of problems, e.g. hole instability, and clay swelling. In recent years, the integration of nanoparticles into drilling mud formulations has emerged as a promising avenue for enhancing drilling mud performance and addressing such challenges.

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Over the past decade, nanotechnology has been developed to achieve better results in a number of sectors, including medicine (Emerich and Thanos, 2003; Zhang *et al.*, 2008), chemistry (Albrecht *et al.*, 2006; Whitesides, 2005), environment (Zhou and Keeling, 2013), material and surface treatment (Mamalis *et al.*, 2004), heavy industry and food processing (Rashidi and Khosravi-Darani, 2011; Siddiqui and Alrumman, 2021). Nanotechnology has presented encouraging prospects in the last few years for the development of problems pertaining to the petroleum industry, including improved oil recovery procedures, enhanced oil recovery, oil and gas exploration, well stimulation, drilling engineering, cementing operation, sensor development, and production operation (Abdo and Haneef, 2012; Alshubbar *et al.*, 2017; Fakoya and Shah, 2013; Perween *et al.*, 2018; Taha and Lee, 2015; Zhang *et al.*, 2015). Abdo and Haneef were among the pioneers to study nanotechnology in drilling mud, they analyze the use of Nanoparticles (NPs) in drilling mud for solving problems relating to pipe sticking and reducing fluid loss (Abdo and Haneef, 2012). Ahmed *et al.* found that the addition of 3 wt% concentrations of Iron oxide NPs can enhance Plastic Viscosity (PV), Yield Point (YP), and 10-sec Gel Strength (Gel₀) by 15, 3, and 12.5% respectively (Ahmed *et al.*, 2020). Ogolo *et al.* studied the effect of Aluminium oxide and Silicon oxide and found that they are good agents for Enhanced Oil Recovery (EOR) (Ogolo *et al.*, 2012). On the other hand, several researchers have studied the effect of ZnO NPs on drilling mud. Bayat and Shams studied the effect of various NPs namely TiO₂, SiO₂, and ZnO on rheological properties of Water Based Drilling Mud (WBDM) at two temperatures (25°C and 50°C). They concluded that ZnO NPs at both temperatures increase the PV and YP, however only at 50°C ZnO NPs reduce fluid loss (Bayat and Shams, 2019). Dejtardon *et al.* observed a decline in the rheological properties following the addition of ZnO NPs (Dejtardon *et al.*, 2019). Aftab *et al.* prepared a Zinc oxide-acrylamide composite and mix with drilling fluid to investigate its effect on fluid loss control and mud cake thickness. They discovered that the ideal concentrations of ZnO-Am composite for API LPLT and HPHT filter tests were 0.23 wt% and 0.3 wt%, respectively (Aftab *et al.*, 2016). Ahasan *et al.* investigated the impact of zinc oxide (ZnO) nanoparticles on WBDM in the absence of potassium chloride (KCl) at temperatures of 40°C and 80°C. He found that at both temperatures even without KCl, ZnO NPs increase rheological properties and reduces mud cake thickness (Ahasan *et al.*, 2022).

Due to problems like clay swelling with WBDM in Shale Reservoirs, many companies like to use Oil Based Drilling Mud (OBDM). However, they are expensive and not environmentally friendly. Waste management and cutting disposal become a hassle with OBDM. Therefore, there is a need to develop WBDM that works in Shale Reservoir without any problem with hole stability. For this, water invasion into the shale has to be minimal, as with water, the clay swells up, causing problems like formation damage and hole collapse. To reduce water invasion or fluid loss, low-permeable mud cake has to be formed on the surfaces of the hole. But in the case of shale, as the pore throats are small, normal drilling mud doesn't form an effective mud cake. Suri and Sharma showed that to form an effective mud cake, the particle size has to be less than the pore throat size (Suri and Sharma, 2004). So, with the addition of nanoparticles, drilling mud can plug tight Shale Reservoirs preventing water invasion (Jung *et al.*, 2013; Sayyadnejad *et al.*, 2008; Sensoy *et al.*, 2009).

Various NPs are used in the formulation of the Drilling Mud. Table 1 shows some types of NPs used in drilling mud formulation and their respective optimizations. ZnO NP is an abundant metal oxide second to iron and it is cost-effective, easy to synthesize and toxicity is low (Kalpana *et al.*, 2018). ZnO is found to be relatively less toxic compared to other Engineered NPs (Maurer-Jones *et al.*, 2013).

In this study, the effect of ZnO nanoparticles on WBDM, where KCl is used as an additive for clay stabilization, is analyzed for Shale Reservoirs. KCl was found to be effective for shale inhibition (O'Brien and Chenevert, 1973; Steiger and Leung, 1992); but higher concentrations lead to toxicity in aquatic environments. Thus, KCl concentration was kept at 6% for this study. First Rheological parameters and API filtrate loss for base mud were determined, and then the same for nanoparticle-enhanced muds were determined to compare the results. Furthermore, the ZnO nanoparticle is synthesized by a wet-chemical method, using Zn(NO₃)₂·6H₂O and NaOH, which is a cost-effective and simple method. In this study, the optimum conc. of ZnO was determined to be used for Shale Reservoirs. But, ZnO can also be synthesized by eco-friendly methods using Aloe Vera extract. Rasli *et al.* proposed a method for green synthesis of ZnO using Zinc Nitrate as a precursor and Aloe Vera extract (Rasli *et al.*, 2020). Thus, further research is needed towards the green synthesis of ZnO and its effect on WBDM.

Table 1. Nanoparticles used in Drilling Mud

NPs	Type of Mud	Size (nm)	Modifications	Conc. of NPs (wt%)	Authors
Fe ₂ O ₃	PHPA-WBM	40	Fluid loss control without drastic changes in rheology	0.1-3.0	(Ahmed <i>et al.</i> , 2020)
SiO ₂ ; ZnO; TiO ₂	Bentonite-WBM	20; 20; 20	Rheological Properties	0.01-0.5	(Bayat and Shams, 2019)
ZnO; CuO	Bentonite-WBM	50; 50	Rheological and Filtration Properties	0.1-1	(Dejtaradon <i>et al.</i> , 2019)
ZnO-Am composite	WBM	-	Rheology, Lubricity and Filtration	0.1-1	(Aftab <i>et al.</i> , 2016)
ZnO	Bentonite-WBM	27	Rheological and Filtration Properties	0.05-2	(Ahasan <i>et al.</i> , 2022)
Fe ₂ O ₃	Bentonite-WBM	3 & 30	Rheology and Filtration Control	0.5-5	(Jung <i>et al.</i> , 2011)
SiO ₂	Bentonite-WBM	12	Lubricity	0.001-0.2	(Ismail <i>et al.</i> , 2016)
ZnO	WBM	14-25	H ₂ S Removal	-	(Sayyadnejad <i>et al.</i> , 2008)
TiO ₂	Bentonite-WBM	20	Thermal Properties	0.1-0.3	(Sabbaghi <i>et al.</i> , 2015)
CuO	Bentonite-WBM	4	Rheology and Thermal Properties	-	(Saboori <i>et al.</i> , 2019)

Materials and Methods

Synthesis of ZnO Nanoparticles

A wet-chemical method was used to create ZnO nanoparticles using zinc nitrate and sodium hydroxide as precursors. An aqueous ethanol solution of (Zn(NO₃)₂·6H₂O) was created by steady stirring 7.437 grams of (Zn(NO₃)₂·6H₂O) in 50 mL ethanol with a magnetic stirrer for one hour, for complete zinc nitrate dissolution to get 0.5 M solution. Likewise, 0.9 M aqueous ethanol solution of sodium hydroxide (NaOH) was also made by dissolving 1.5392 grams of NaOH in 50 mL ethanol. The NaOH solution was then slowly added dropwise into the zinc nitrate solution for 2 hours while the solution was constantly stirred at high speed. After complete addition, the solution was stirred continuously for another 2 hours. The solution was allowed to settle overnight before removing the supernatant solution, centrifuged for 10 minutes, and the precipitates were collected. Deionized (DI) water and ethanol were used three times to clear the precipitates of any by-products. The precipitates were then dried in a Hot Air Oven at 60°C. Zn(OH)₂ was entirely transformed to ZnO after drying (Talam *et al.*, 2012).

Characterization of ZnO nanoparticle

Formation of ZnO nanoparticles was analyzed with X-Ray Diffraction (XRD). XRD peaks were generated with an x-ray diffractometer (40kV/30mA). A scanning electron microscope (SEM) was used to analyze the morphology and structural properties of the ZnO sample. The size of the nanoparticles was also assessed using this approach. A Scanning Electron Microscope (SEM) works by scanning a focused beam of electrons over

a sample to create high-resolution images of its surface and gather information about its composition. Nanoparticles' size was further analyzed by Brookhaven 90Plus Particle Size Analyzer. It uses the scattering of light by particles to measure their effective size. This method is also known as DLS (Dynamic Light Scattering).

Preparation of Drilling Fluid Samples

A bentonite slurry was used to prepare mud samples. To make the slurry, 5 wt% bentonite was mixed with DI water. This slurry was used to make base mud by incorporating Xanthan Gum (XG) (1 wt%) as a viscosifier, Polyanionic Cellulose-R (PAC-R) (1 wt%) & Polyanionic Cellulose-L (PAC-L) (0.5 wt%) as a fluid loss reducer, and KCl (6 wt%) as a clay stabilizer. In the base mud, 0.05-0.15 wt% ZnO nanoparticles were added and its rheological and filtration properties were examined. pH of the mud was maintained at 9-10 with KOH. Table 2 shows different additives with the added amount.

Table 2. Drilling mud additives with quantity and main purpose

Additives	Amount	Main Purpose
Water	500 mL	Base Fluid
Bentonite	25 g	Viscosifier
Xanthan Gum	5 g	Viscosifier
PAC-R	5 g	Fluid loss reducer
PAC-L	2.5 g	Fluid loss reducer
KCl	30 g	Clay stabilizer
ZnO	0.25-0.75 g	Nanoparticle

Analysis of Drilling Fluid Properties

Rheological Properties

Drilling mud's cleaning properties are depended on its rheology. The better the rheological

characteristics better will be its performance. Rheology depends on the pressure, temperature, and solid content in the mud. Plastic viscosity is directly affected by solid content. For smooth hole cleaning, mud must have plastic viscosity in optimum range. Gel strength is also essential for holding cuttings in static conditions. Grace M3600 Viscometer was used to test the rheological properties of mud samples following the API standard test protocol (API RP 13B-1, 2023). The instrument operates based on the principle of applying varying shear rates using a motor-driven rotating assembly submerged in the sample. As the rotor rotates, it imparts motion to the sample, generating torque on the stator. This torque causes movement in the stator, which is then translated into readings. In essence, the movement of the rotor induces motion in the sample, enabling the measurement of rheological properties through the resulting torque on the stator. The dial reading is recorded by the viscometer and used to calculate rheological parameters such as plastic viscosity, apparent viscosity, and yield point. It can also determine mud gel strength.

Anton Paar Rheometer was used also to evaluate shear stress at various shear rates and measure viscosity with varying temperatures. A rheometer was used to analyze the shear-thinning characteristics of mud samples.

Filtration Properties

API Filter Press by Fann, Texas, USA used to analyze the filtration properties of mud samples. In the filtration testing process, the mud sample is contained within a cylindrical cup with a central opening, providing an area of 45.8 cm² for filtration. This assembly utilizes a 60 US mesh size mesh and 2.7-micron filter paper. To simulate real-world conditions, a pressure of 100 psi is applied to the top of the mud sample for a duration of 30 minutes at room temperature. The resulting filtered volume, known as API filter loss, serves as an indicator of the drilling mud's effectiveness in preventing water intrusion into the formation. Mud cake thickness was also measured.

Results and Discussion

XRD Analysis

Figure 1 shows the X-ray diffraction pattern of synthesized ZnO NPs. A pronounced line broadening of the XRD peaks suggests that the synthesized material contains particles in the nanoscale range (Soosen *et al.*, 2009). The peaks are located at 31.86°, 34.4°, 35.62°, 47.44°, 56.6°, 62.86°, 66.52°, 69.1°, corresponding to the planes

(100), (002), (101), (102), (110), (103), (200), (201) suggest hexagonal wurtzite structure of ZnO (Khoshhesab *et al.*, 2011; Talam *et al.*, 2012; Zhou *et al.*, 2007). It also corresponds to the characteristic peaks of ZnO as provided in the JCPDS Card Number: 36-1451 (Phuruangrat *et al.*, 2009). This pattern confirms no peaks of any impurity are present in the synthesized nanopowder.

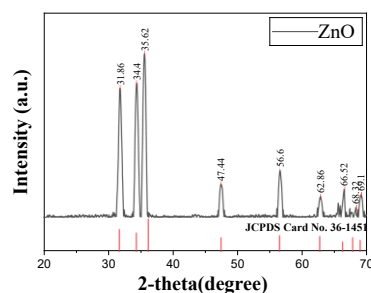


Figure 1. XRD pattern of synthesis ZnO NPs

SEM Analysis

Figure 2 represents the SEM picture of ZnO NPs at different magnifications. The images confirm the formation of ZnO. Most of the particle size was found to be below 100nm. They are mostly spherical with some amount of rough edges. ZnO NPs were found to be agglomerate resulting in larger particles. This may be due to their high surface area and surface energy (Srivastava *et al.*, 2013).

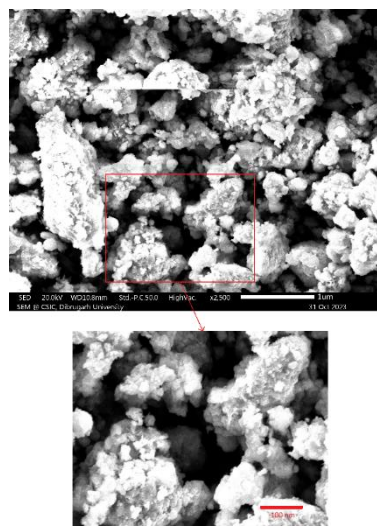


Figure 2. SEM pictures of ZnO NPs at different magnifications

Particle Size Analysis

Dynamic Light Scattering (DLS) technique was used to measure the effective size of NPs with

Brookhaven 90Plus Particle Size Analyzer. The effective size of NPs was found to be 98 nm with a Polydispersity of 0.304, which is in the nanoscale range. The lognormal distribution is shown in Figure 3. From the figure, it can be inferred that most of the particles are in the nanoscale range.

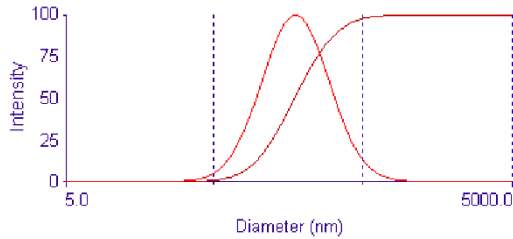


Figure 3. Lognormal Distribution of ZnO NPs

Rheological Experiments

Continuous monitoring of rheological parameters such as apparent viscosity, plastic viscosity, yield point, and gel strength is crucial for optimizing drilling mud performance. These parameters directly influence the mud's behavior during drilling operations. The equations (1)-(3), based on the Bingham Plastic Model, are employed to calculate the apparent viscosity (AV), plastic viscosity (PV), and yield point (YP) (Growcock and Harvey, 2004; Mahto and Sharma, 2004):

$$AV = 300 \times \frac{\theta}{N} \quad (1)$$

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

$$YP = \theta_{300} - PV \quad (3)$$

Where AV is apparent viscosity (cp); N is rotor speed (RPM); θ is the viscometer dial reading at N RPM ($^{\circ}$); PV is plastic viscosity (cp); YP is yield point (lbs/100ft²); θ_{600} is dial reading at 600 RPM; and θ_{300} is dial reading at 300 RPM. 10-sec gel strength (Gel0) and 10-min gel strength (Gel10) values are calculated from direct dial reading in lbs/100ft². The shear stress and shear rate can be calculated as per the following equations (4) and (5) (API RP 13B-1, 2023):

$$\text{Shear rate, sec}^{-1} = 1.7023 N \quad (4)$$

$$\text{Shear stress, lbs/100ft}^2 = 1.067 \theta \quad (5)$$

However, for more accurate results, shear stress vs shear rate graphs were plotted with Anton Paar Rheometer experiments.

The apparent viscosity of a fluid is defined as the ratio of shear stress to shear rate, a value that

remains constant for Newtonian fluids. However, drilling mud, being a non-Newtonian fluid, behaves differently. Its apparent viscosity is not fixed but varies with the applied shear rate. As the shear rate increases, the apparent viscosity of drilling mud decreases. In drilling mud, the plastic viscosity represents the resistance to flow posed by solid particles suspended within it. This viscosity directly influences the rate of penetration during drilling operations, a critical factor in determining the overall economics of the drilling process. Therefore, monitoring plastic viscosity becomes essential as it directly impacts drilling efficiency and cost-effectiveness. Plastic viscosity of less than 30 cp is desired for an effective rate of penetration during drilling (Khodja *et al.*, 2010). The yield point is an essential characteristic of drilling mud for carrying drilled cuttings out of the open hole under dynamic conditions. Too much yield point is not desirable as it directly increases the pumping pressure which will affect the cost. Previous studies show that a yield point in the range of 9-15 Pa or 18-31 lbs/100ft² is desired (Guo *et al.*, 2006). Gel strength affects the cutting holding capacity of mud in static conditions. As drilling mud has a shear-thinning property, its apparent viscosity decreases with increasing shear rate. Figures 4 and 5 show the comparison of the shear-thinning property of base mud with the muds with added NPs.

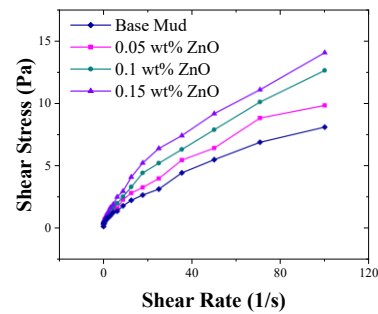


Figure 4. Shear Stress vs Shear rate curve for base mud and ZnO NPs muds

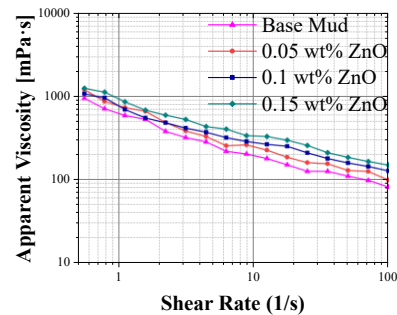


Figure 5. Apparent viscosity vs Shear rate curve for base mud and ZnO NPs muds

Rheological characteristics of mud samples were measured at 25°C. Plastic viscosity is found to be increased by approximately 11%, 46%, and 52% with the addition of 0.05 wt%, 0.1 wt%, and 0.15 wt% ZnO NPs respectively. Plastic viscosity is offered by the counteraction of solid and liquid mud suspension in dynamic conditions. Therefore, with the addition of NPs, mud's solid content changes, and a change in PV is observed. One study found that even with the addition of ZnO NPs PV remains stable due to positively charged ZnO NPs interacting with negatively charged bentonite plates and forming larger particles in the absence of KCl (Ahasan *et al.*, 2022). In this study, the presence of KCl allows positive potassium ions to attach to negatively charged bentonite plates by exchanging ions with sodium (Benyounes and Benmounah, 2016). Consequently, positively charged ZnO NPs may not form larger particles with bentonite as prominently as noted by Ahasan *et al.* (Guan *et al.*, 2020). Thus, PV is affected in such a drastic way as solid content increases. Yield Point, with the addition of 0.05 wt%, 0.1 wt%, and 0.15 wt% ZnO NPs, increased approximately by 32%, 100% and 120% respectively. Yield Point is mainly offered by positive and negative surface charged particles. As positively charged ZnO NPs are introduced into the mud, it reacts with negatively charged bentonite clay plates; this phenomenon contributes to viscosity as it resists flow (Ahasan *et al.*, 2022). As for gel strength, 10-sec gel strength (Gel0) increases by approx. 20%, 90%, and 100%, and 10-min gel strength (Gel10) increase by approx. 10%, 18% and 30% with addition of 0.05 wt%, 0.1 wt% and 0.15 wt% ZnO NPs respectively. Figure 6 shows a comparison of the rheological properties of NPs added mud with base mud.

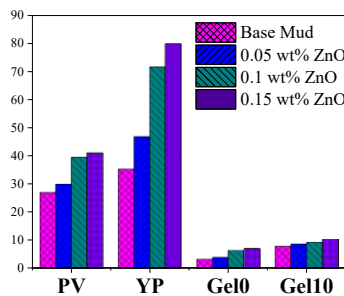


Figure 6. Bingham Plastic Rheological Parameters for base mud and ZnO NPs muds

Variation of Apparent viscosity with temperature was determined with the help of Anton Paar Rheometer at a shear rate of 50 sec⁻¹. All mud samples show a decrease in viscosity with an increase in temperature. This is mainly due to the

degradation of mud's additives with an increase in temperature (Craft and Exner, 1933; Makinde *et al.*, 2011). Figure 7 shows the variation of viscosity with temperature for all the mud samples.

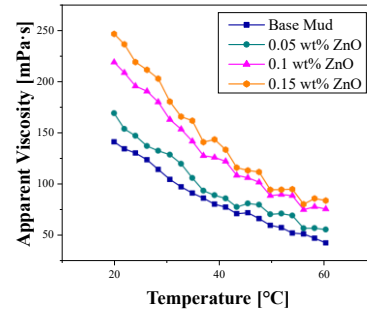


Figure 7. Apparent viscosity vs Temperature curve for base mud and ZnO NPs muds

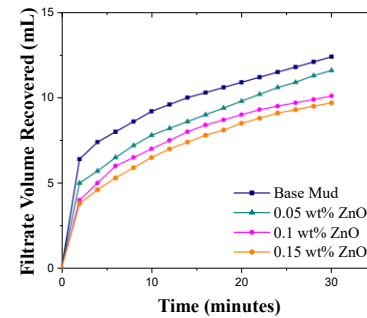


Figure 8. API Filtrate Loss for base mud and ZnO NPs muds

Filtration Experiments

API filtrate loss gives a measure of liquid invasion into wellbore formation due to pressure difference. Also, an impermeable layer called mud cake forms inside the wellbore walls, preventing further invasion of liquid. Thickness of this mud cake is essential, while a thicker mud cake may give more protection, it might also result in increased frictional pressure during subsequent operations. In contrast, a thin mud cake may not provide adequate protection against fluid infiltration and formation damage. Achieving an ideal mud cake thickness requires constant observation and adjustments to drilling parameters. Figure 8 compares the filtrate loss with respect to time for all the samples. The filtration test for base mud gives a filtrate loss of 12.4 mL for 30 minutes under 100 psi differential pressure. API filtrate loss for 0.05 wt%, 0.1 wt%, and 0.15 wt% ZnO added mud was found to be 11.6 mL, 10.1 mL, and 9.7 mL respectively under the same conditions. With 0.1 wt% NPs API filtrate loss was improved by 18%. This may be due to well-dispersed NPs in mud adding to an increase in solid content forming an impervious mud cake.

Mud cake thickness for Base mud was 2.4 mm. For 0.1% ZnO NPs-based mud was 1.7 mm. The mud cake formed is shown in Figure 9.

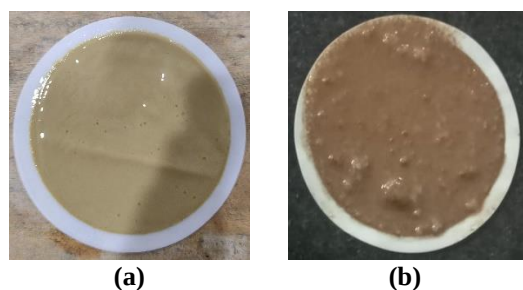


Figure 9. (a) Mud cake for base mud; (b) Mud cake for 0.1 wt% ZnO NPs added mud (Optimum concentration)

Conclusions

In this study, the effect of ZnO NPs on the rheological and filtration properties of WBDM was studied with laboratory-prepared ZnO NPs with the sol-gel method. The following points were observed:

1. Nanoparticles can greatly modify drilling muds to make them suitable for Shale Reservoirs.
2. The optimum amount for ZnO NPs was found to be 0.1 wt%, as 0.05 wt% didn't make much of a difference. The sample with 0.15 wt% ZnO NPs shows good results, but it comes with the setback of cost and almost the same results can be achieved with the sample with 0.1 wt% ZnO NPs but with lower cost.
3. The nano-based drilling muds exhibited slightly reduced fluid loss compared to the base mud. API Fluid loss is reduced by almost 18% with 0.1% ZnO addition. Reduced fluid loss indicates that ZnO nanoparticles can contribute to better sealing and mud cake formation, potentially preventing formation damage.

It's important to note that the studies were conducted under specific temperature and pressure conditions, and the effects of ZnO nanoparticles on drilling fluids may vary under different operational scenarios. Further research and field testing would be necessary to fully assess the practical applications and potential cost-effectiveness of incorporating ZnO nanoparticles into drilling fluids.

The introduction of ZnO nanoparticles to water-based drilling fluids, as demonstrated in these studies, holds promise for improving the overall performance of drilling operations. By enhancing

rheological properties, and fluid loss control, the use of nanoparticles in drilling fluids could lead to more efficient and cost-effective drilling processes. However, ongoing research and practical field applications are needed to confirm these findings and optimize the use of nanoparticles in the oil and gas industry.

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Nomenclatures

API	American Petroleum Institute
AV	Apparent Viscosity
DI Water	Deionized Water
ft	Foot
Gel ₀	10-sec Gel Strength
Gel ₁₀	10-min Gel Strength
HPHT	High Pressure and High Temperature
KCl	Potassium Chloride
KOH	Potassium Hydroxide
lbs	Pounds
LPLT	Low Pressure and Low Temperature
min	Minute
mL	Millilitre
NaOH	Sodium Hydroxide
nm	Nanometre
NPs	Nanoparticles
OBDM	Oil-Based Drilling Mud
PAC-L	Polyanionic Cellulose-Low Viscosity
PAC-R	Polyanionic Cellulose-Regular Viscosity
PV	Plastic Viscosity
sec	Second
SEM	Scanning Electron Microscopy
WBDM	Water Based Drilling Mud
wt	Weight
XG	Xanthan Gum
XRD	X-Ray Diffraction
YP	Yield Point
Zn(NO ₃) ₂	Zinc Nitrate
ZnO	Zinc Oxide

References

- Abdo, J., and Haneef, M.D. (2012). Nano-enhanced drilling fluids: Pioneering approach to overcome uncompromising drilling problems. *Journal of Energy Resources Technology*, 134(1):014501. <https://doi.org/10.1115/1.4005244>
- Aftab, A., Ismail, A.R., Khokhar, S., and Ibupoto, Z.H. (2016). Novel zinc oxide nanoparticles deposited acrylamide composite used for enhancing the performance of water-based drilling fluids at elevated temperature conditions. *Journal of Petroleum Science and Engineering*, 146:1142-1157. <https://doi.org/10.1016/j.petrol.2016.08.014>
- Ahasan, M.H., Alahi Alvi, M.F., Ahmed, N., and Alam, M.S. (2022). An investigation of the effects of synthesized zinc oxide nanoparticles on the properties of water-based drilling fluid. *Petroleum Research*, 7(1):131-137. <https://doi.org/10.1016/j.ptlrs.2021.08.003>
- Ahmed, N., Alam, M.S., and Salam, M.A. (2020). Experimental analysis of drilling fluid prepared by mixing iron (III) oxide nanoparticles with a KCl-Glycol-PHPA polymer-based mud used in drilling operation. *Journal of Petroleum Exploration and Production Technology*, 10(8):3389-3397. <https://doi.org/10.1007/s13202-020-00933-1>
- Albrecht, M.A., Evans, C.W., and Raston, C.L. (2006). Green chemistry and the health implications of nanoparticles. *Green Chemistry*, 8(5):417-432. <https://doi.org/10.1039/b517131h>
- Alshubbar, G.D., Coryell, T.N., Atashnezhad, A., Akhtarmanesh, S., and Hareland, G. (2017). The effect of barite nanoparticles on the friction coefficient and rheology of water-based mud. 51st US Rock Mechanics/Geomechanics Symposium, 1:474-480.
- American Petroleum Institute. (2023). Field testing water-based drilling fluids (API RP 13B-1).
- Bayat, A.E., and Shams, R. (2019). Appraising the impacts of SiO₂, ZnO and TiO₂ nanoparticles on rheological properties and shale inhibition of water-based drilling muds. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 581:123792. <https://doi.org/10.1016/j.colsurfa.2019.123792>
- Benyounes, K., and Benmounah, A. (2016). Rheological and electrokinetic characterization of bentonite particles in aqueous phase in presence of KCl. *Particulate Science and Technology*, 34(1):39-44. <https://doi.org/10.1080/02726351.2015.1042563>
- Craft, B.C., and Exner, J.D. (1933). Effects of temperature on the viscosity of some Gulf Coast drilling muds. *Transactions of the AIME*, 103(01):112-115. <https://doi.org/10.2118/933112-G>
- Dejtaradon, P., Hamidi, H., Chuks, M.H., Wilkinson, D., and Rafati, R. (2019). Impact of ZnO and CuO nanoparticles on the rheological and filtration properties of water-based drilling fluid. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 570:354-367. <https://doi.org/10.1016/j.colsurfa.2019.03.050>
- Emerich, D.F., and Thanos, C.G. (2003). Nanotechnology and medicine. *Expert Opinion on Biological Therapy*, 3(4):655-663. <https://doi.org/10.1517/14712598.3.4.655>
- Fakoya, M.F., and Shah, S.N. (2013). Rheological properties of surfactant-based and polymeric nano-fluids. *Society of Petroleum Engineers - Coiled Tubing and Well Intervention Conference and Exhibition*, p. 321-337. <https://doi.org/10.2118/163921-MS>
- Growcock, F., and Harvey, T. (2004). Drilling fluids. In *Drilling Fluids Processing Handbook* (pp. 15-68). Elsevier. <https://doi.org/10.1016/B978-075067775-2/50003-2>
- Guan, O.S., Gholami, R., Raza, A., Rabiei, M., Fakhari, N., Rasouli, V., and Nabinezhad, O. (2020). A nanoparticle-based approach to improve filtration control of water-based muds under high pressure high temperature conditions. *Petroleum*, 6(1):43-52. <https://doi.org/10.1016/j.petlm.2018.10.006>
- Guo, J., Yan, J., Fan, W., and Zhang, H. (2006). Applications of strongly inhibitive silicate-based drilling fluids in troublesome shale formations in Sudan. *Journal of Petroleum Science and Engineering*, 50(3-4):195-203. <https://doi.org/10.1016/j.petrol.2005.12.006>
- Ismail, A.R., Aftab, A., Ibupoto, Z.H., and Zolkifile, N. (2016). The novel approach for the enhancement of rheological properties of water-based drilling fluids by using multi-walled carbon nanotube, nanosilica and glass beads. *Journal of Petroleum Science and Engineering*, 139:264-275. <https://doi.org/10.1016/j.petrol.2016.01.036>
- Jung, C.M., Zhang, R., Chenevert, M., and Sharma, M. (2013). High-performance water-based mud using nanoparticles for shale reservoirs. *Unconventional Resources Technology Conference*, Denver, Colorado, 12-14 August 2013, p. 1038-1044. <https://doi.org/10.1190/urtec2013-106>
- Jung, Y., Barry, M., Lee, J.-K., Tran, P., Soong, Y., Martello, D., and Chyu, M. (2011). Effect of nanoparticle-additives on the rheological properties of clay-based fluids at high temperature and high pressure. *AADE National Technical Conference and Exhibition*, p. 1-4.
- Kalpana, V.N., Kataru, B.A.S., Sravani, N., Vigneshwari, T., Panneerselvam, A., and Devi Rajeswari, V. (2018). Biosynthesis of zinc oxide nanoparticles using culture filtrates of *Aspergillus niger*: Antimicrobial textiles and dye degradation studies. *OpenNano*, 3:48-55. <https://doi.org/10.1016/j.onano.2018.06.001>
- Khodja, M., Canselier, J.P., Bergaya, F., Fourar, K., Khodja, M., Cohaut, N., and Benmounah, A. (2010). Shale problems and water-based drilling fluid optimisation in the Hassi Messaoud Algerian oil field. *Applied Clay Science*, 49(4):383-393. <https://doi.org/10.1016/j.clay.2010.06.008>
- Khosshesab, Z.M., Sarfaraz, M., and Asadabad, M.A. (2011). Preparation of ZnO nanostructures by chemical precipitation method. *Synthesis and Reactivity in Inorganic, Metal-Organic and Nano-Metal Chemistry*, 41(7):814-819. <https://doi.org/10.1080/15533174.2011.591308>
- Mahto, V., and Sharma, V.P. (2004). Rheological study of a water-based oil well drilling fluid. *Journal of Petroleum Science and Engineering*, 45(1-2):123-128. <https://doi.org/10.1016/j.petrol.2004.03.008>
- Makinde, F.A., Adejumo, A.D., Ako, C.T., and Efeovbokhan, V.E. (2011). Modelling the effects of temperature and aging time on the rheological properties of drilling fluids. *Petroleum and Coal*, 53(3):167-182.
- Mamalis, A.G., Vogtländer, L.O.G., and Markopoulos, A. (2004). Nanotechnology and nanostructured materials: Trends in carbon nanotubes. *Precision Engineering*, 28(1):16-30. <https://doi.org/10.1016/j.precisioneng.2002.11.002>
- Maurer-Jones, M.A., Gunsolus, I.L., Murphy, C.J., and Haynes, C.L. (2013). Toxicity of engineered nanoparticles in the environment. *Analytical Chemistry*, 85(6):3036-3049. <https://doi.org/10.1021/ac303636s>
- O'Brien, D.E., and Chenevert, M.E. (1973). Stabilizing sensitive shales with inhibited, potassium-based drilling fluids. *Journal of Petroleum Technology*, 25(9):1089-1100. <https://doi.org/10.2118/4232-PA>
- Ogolo, N.A., Olafuyi, O.A., and Onyekonwu, M.O. (2012). Enhanced oil recovery using nanoparticles. *SPE Saudi Arabia Section Technical Symposium and Exhibition 2012*, p. 276-284. <https://doi.org/10.2118/160847-MS>
- Perween, S., Beg, M., Shankar, R., Sharma, S., and Ranjan, A. (2018). Effect of zinc titanate nanoparticles on rheological and filtration properties of water-based drilling fluids.

- Journal of Petroleum Science and Engineering, 170:844-857. <https://doi.org/10.1016/j.petrol.2018.07.006>
- Phuruangrat, A., Thongtem, T., and Thongtem, S. (2009). Microwave-assisted synthesis of ZnO nanostructure flowers. *Materials Letters*, 63(13-14):1224-1226. <https://doi.org/10.1016/j.matlet.2009.02.049>
- Rashidi, L., and Khosravi-Darani, K. (2011). The applications of nanotechnology in the food industry. *Critical Reviews in Food Science and Nutrition*, 51(8):723-730. <https://doi.org/10.1080/10408391003785417>
- Rasli, N.I., Basri, H., and Harun, Z. (2020). Zinc oxide from aloe vera extract: Two-level factorial screening of biosynthesis parameters. *Heliyon*, 6(1):e03156. <https://doi.org/10.1016/j.heliyon.2020.e03156>
- Sabbaghi, S., Saboori, R., and Barahoei, M. (2015). Enhanced heat transfer of drilling fluid with titania nanofluid. *Research and Reviews Journal of Engineering and Technology*, 4:12-17.
- Saboori, R., Sabbaghi, S., and Kalantariasl, A. (2019). Improvement of rheological, filtration, and thermal conductivity of bentonite drilling fluid using copper oxide/polyacrylamide nanocomposite. *Powder Technology*, 353:257-266. <https://doi.org/10.1016/j.powtec.2019.05.038>
- Sayyadnejad, M.A., Ghaffarian, H.R., and Saeidi, M. (2008). Removal of hydrogen sulfide by zinc oxide nanoparticles in drilling fluid. *International Journal of Environmental Science & Technology*, 5(4):565-569. <https://doi.org/10.1007/BF03326054>
- Sensoy, T., Chenevert, M.E., and Sharma, M.M. (2009). Minimizing water invasion in shale using nanoparticles. SPE Annual Technical Conference and Exhibition, 4:2143-2158. <https://doi.org/10.2118/124429-MS>
- Siddiqui, S., and Alrumman, S.A. (2021). Influence of nanoparticles on food: An analytical assessment. *Journal of King Saud University - Science*, 33(6):101530. <https://doi.org/10.1016/j.jksus.2021.101530>
- Soosen, M.S., Bose, L., and George, K. (2009). Optical properties of ZnO nanoparticles. *Optical Materials*, 16(1):57-65.
- Srivastava, V., Gusain, D., and Sharma, Y.C. (2013). Synthesis, characterization, and application of zinc oxide nanoparticles (n-ZnO). *Ceramics International*, 39(8):9803-9808. <https://doi.org/10.1016/j.ceramint.2013.04.110>
- Steiger, R.P., and Leung, P.K. (1992). Quantitative determination of the mechanical properties of shales. *SPE Drilling Engineering*, 7(3):181-185. <https://doi.org/10.2118/18024-PA>
- Suri, A., and Sharma, M.M. (2004). Strategies for sizing particles in drilling and completion fluids. *SPE Journal*, 9(1):13-23. <https://doi.org/10.2118/87676-PA>
- Taha, N.M., and Lee, S. (2015, December 6). Nano graphene application improving drilling fluids performance. International Petroleum Technology Conference. <https://doi.org/10.2523/iptc-18539-ms>
- Talam, S., Karumuri, S.R., and Gunnam, N. (2012). Synthesis, characterization, and spectroscopic properties of ZnO nanoparticles. *ISRN Nanotechnology*, p. 1-6. <https://doi.org/10.5402/2012/372505>
- Whitesides, G.M. (2005). Nanoscience, nanotechnology, and chemistry. *Small*, 1(2):172-179. <https://doi.org/10.1002/smll.200400130>
- Zhang, J., Li, L., Wang, S., Wang, J., Yang, H., Zhao, Z., Zhu, J., and Zhang, Z. (2015). Novel micro and nano particle-based drilling fluids: Pioneering approach to overcome the borehole instability problem in shale formations. Society of Petroleum Engineers - SPE Asia Pacific Unconventional Resources Conference and Exhibition. <https://doi.org/10.2118/176991-MS>
- Zhang, L., Gu, F., Chan, J., Wang, A., Langer, R., and Farokhzad, O. (2008). Nanoparticles in medicine: Therapeutic applications and developments. *Clinical Pharmacology & Therapeutics*, 83(5):761-769. <https://doi.org/10.1038/sj.clpt.6100400>
- Zhou, C.H., and Keeling, J. (2013). Fundamental and applied research on clay minerals: From climate and environment to nanotechnology. *Applied Clay Science*, 74:3-9. <https://doi.org/10.1016/j.clay.2013.02.013>
- Zhou, J., Zhao, F., Wang, Y., Zhang, Y., and Yang, L. (2007). Size-controlled synthesis of ZnO nanoparticles and their photoluminescence properties. *Journal of Luminescence*, 122-123(1-2):195-197. <https://doi.org/10.1016/j.jlumin.2006.01.089>