Improved Rheological Properties and Lubricity of Drilling Fluids at Extreme Temperatures and Pressures Using Graphene Oxide and Flowzan

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Summary

The use of graphene-based lubricants in water-based drilling fluids (WDFs) has emerged as a promising avenue for enhancing their tribological properties, particularly under high-temperature (HT) conditions, by incorporating inorganic-material-based additives. For this study, we used a green and adsorption-based approach to prepare highly-dispersed graphite for modification, utilizing a cationic surfactant. Our research demonstrated the effective dispersion of the prepared graphite in water, characterized by low sedimentation rates and small contact angles in distilled water. The concentration dosage of Flowzan® on graphite was determined to be 0.02 g/g. To assess the effectiveness of modified graphite as a lubricating additive in water-based drilling, we conducted rheological studies and measured viscosity coefficients. The results revealed a significant decrease in the viscosity coefficient of the drilling fluid by 68% at 300°F when incorporating 0.05% modified graphene. Furthermore, the study investigated the thickness of six WDFs under high-temperature, high-pressure (HTHP) conditions. The addition of 3% graphene expansion resulted in a notable reduction in the volume of HTHP liquid filtrate by up to 30% compared with the control. These experimental findings underscore the advantageous effects of nanoparticle addition on properties such as lubricity, rheology, fluid loss, and thermal stability, potentially revolutionizing the drilling process. In addition to evaluating the performance of modified graphite, we analyzed its primary, crystalline, and morphological properties using various techniques, including particle size tests, zeta potential tests, Fourier transform infrared (FTIR), powder X-ray diffraction (XRD), and scanning electron microscopy (SEM). These analyses elucidated the lubrication mechanism, demonstrating that graphite modification primarily occurred through physical adsorption without altering the crystal structure. These insights provide valuable guidance for the development of high-performance WDFs tailored to endure the challenges of drilling operations.

Introduction

The petroleum industry heavily relies on drilling fluids, which can be compared to blood in the human body (Du et al. 2019; Jie-nian 2001). A WDF, also known as mud, is a mixture of water, bentonite, a viscosity enhancer, fluid loss agents, and lubricants. Together, these components create a coarse-scattering colloidal suspension system, consisting of a liquid stage, a strong stage, and a substance stage (Jie-nian 2001; An et al. 2014). Drilling fluids play several significant roles and possess essential properties that make them crucial in drilling tasks. They are responsible for (1) removing debris from under the drill and transporting it to the surface; (2) building a thin, low-permeability filter cake that covers pores and other permeable openings; (3) maintaining the safety of the wellbore; (4) cooling and lubricating the drillstring and the bit; (5) transmitting information to the surface; and (6) reducing friction between the drillstring and the sides of the borehole. Initially, Einstein's model served as the basis for the formulas used to estimate the viscosity of nanofluids (Apaleke et al. 2012; Skalle 2012). Einstein (1906) proposed an intrinsic viscosity value of 2.5, but recent findings by Anoop et al. (2014) suggest that the intrinsic viscosity could go as high as 10.0. Further research is needed to understand how the solute affects the viscosity of nanofluids. Einstein introduced a model in 1906, and subsequent models have been developed by Batchelor (1956), Brinkman (1949), Krieger and Dougherty (1959), Nielsen et al. (2006), and Mooney (1940). Nonetheless, more research is required to fully understand this topic (Abdo and Haneef 2012).

Scientists have found that drilling fluids containing conventional WDF viscoelastic surfactants become unstable when exposed to HTs. To address this issue, they have proposed using nanometer-sized particles with advanced heat transfer properties that can function effectively in HPHT downhole conditions. These particles can help to close the nanopore throats of shales and immobilize the fluid's rheological behavior (Al-Bazali 2005; Amanullah et al. 2011). Drilling problems are the challenges that can arise during the drilling of a complex well. These challenges may occur when drilling deviated wells or when encountering different levels of hardness in shale or rock layers. These complications can lead to issues such as pipe blockage, shale swelling, or wellbore instability. The main cause of these problems is the limitations of conventional drilling fluids, which are unable to effectively meet the demands of modern drilling and production environments (Aftab et al. 2017; Amanullah and Al-Tahini 2009; Akpan et al. 2019). The use of water-based muds (WBMs) can increase wear rates in the wellbore. In contrast, oil-based muds and synthetic-based muds tend to have a lower coefficient of friction (COF) compared with WBMs, especially when there is contact between the formation and steel. However, oil-based muds and synthetic-based muds are limited due to their high cost and negative environmental impacts. It is important to note that drilling fluids can contaminate the cement and affect the integrity of the wellbore during the drilling process (Li and Radonjic 2019).

Various experts have demonstrated that using fluids containing nanoparticles significantly impacts the overall performance of the fluid being used (Aftab et al. 2016; Sensoy et al. 2009; Zakaria et al. 2012; Zoveidavianpoor and Samsuri 2016). Numerous experimental studies have explored the incorporation of nano-sized particles, including zinc oxide (ZnO) and copper oxide (CuO) nanoparticles, into

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drilling fluids to enhance their properties and performance. These nanoparticles offer unique advantages due to their small size, large surface area, and surface reactivity, which can impart desirable characteristics to drilling fluids (Urmi et al. 2022). Nanosilica can be effectively dispersed without using an ultrasonicator by simply adjusting the pH of the mud. This adjustment causes the nanosilica particles to repel each other on the surface (Katende et al. 2019).

Any nanoparticles that are intended to be used as additives in drilling fluids must be fully dispersed before being added to the fluid (Barroso et al. 2018; Addagalla et al. 2018). Because of their superior performance, nanoparticles are widely used in the formulation of drilling fluids, specifically WBM, to enhance the environmentally friendly and cost-effective nature of the fluid. This application aids in resolving challenges such as shale inhibition and fluid loss (Peter et al. 2019). Ferric oxide nanoparticles were found to improve filtration and mudcake porosity reduction in filter-cake properties (Mahmoud et al. 2017).

When drilling wells, WBM is used to help with the process. However, if the temperature and salinity levels increase, the effectiveness of WBM decreases. This is because the mud's rheology (flow behavior) and filtration capacity are negatively impacted by these changes. Drilling into salt formations or HT wells can be very challenging due to these factors (Raheem and Vipulanandan 2020). It is crucial to formulate the drilling fluid, or WBM, using the appropriate additives to maintain its properties as it penetrates deeper into the well. This will aid in efficiently moving and suspending the drilled cuttings, resisting salt contamination, and creating a filtration barrier with an appropriate filter cake. These details have been emphasized in studies such as that by Zhu et al. (2021). Indeed, achieving adequate dispersion of nanoparticles in drilling fluids, particularly under bottomhole conditions, presents significant challenges. Poor dispersion can lead to various issues such as borehole instability, formation damage, and reduced drilling efficiency. Several factors contribute to the challenges of nanoparticle dispersion, including changes in pH, salinity, and temperature of the base fluid, as well as the inherent properties of the nanoparticles themselves.

Nanoparticles smaller than 100 nm are often preferred in drilling mud design due to their reduced abrasive forces and lower kinetic energy impact. Smaller nanoparticles are more likely to disperse evenly throughout the drilling fluid, enhancing their effectiveness in achieving desired rheological and filtration properties without causing excessive wear on drilling equipment or formation surfaces (Boyou et al. 2019; Vipulanandan and Mohammed 2015). Using nanoparticles in mud design is considered safer for the environment compared with traditional mud. Typically, the concentration of nanoparticles added to drilling mud is low, around 1% (Aramendiz and Imqam 2019). Salt contamination in brine-based drilling muds can cause various issues, such as wellbore swelling, frictional loss, pipe sticking, formation collapse, and lost circulation. These issues can significantly affect the density, filtration characteristics, and rheology of drilling mud (Hirata et al. 2004; Gbadamosi et al. 2018). Graphene derivatives can act as a filter in oil-based drilling fluids due to their stability in an aqueous medium (Magzoub et al. 2019). Nanomud is a drilling fluid that contains mud additives in the nanoparticle size range of 1–100 nm (Salih and Bilgesu 2017). Due to the extremely small size of the particles, the ratio of surface area to volume is exceptionally high (Z.A. et al. 2019). Nanoparticles are often stronger and more reactive than non-nanoparticles (El-Diasty and Ragab 2013). These nanoparticles possess unique characteristics that make them highly sensitive and reactive agents, both chemically and physically. Due to their small size, they are effective bridging agents capable of plugging nano-sized pores. Consequently, they can prevent fluid loss, especially in shale formations, thereby avoiding wellbore instability (Sharma et al. 2012; Song et al. 2016).

The use of polymer beads in WBM enhances the efficiency of cuttings transportation by harnessing the buoyant force (Hakim et al. 2018). The contact angle between graphite and distilled water was measured before and after modification using a contact angle measuring instrument. The angle was calculated using the measurement method found in Perween et al. (2018). Graphene oxide (GO) remains stable in WDFs, unlike graphene which has dispersion challenges in an aqueous medium (Hemmati-Sarapardeh et al. 2018). Graphene is a single layer of graphite that possesses unique properties. This material has been the subject of extensive research lately (Kosynkin et al. 2012). Not many studies have been conducted on nanoparticles, specifically GO when used as the primary component of drilling mud. It is essential to examine their type, stability, and concentration, along with their size. These materials are susceptible to changes in pH, temperature, and ionic strength (Taha and Lee 2015). Graphene and its derivatives have indeed garnered considerable attention as nanoadditives in the research and development of drilling fluids. Graphene, characterized by its atom-thick, 2D conjugated structure, boasts exceptional properties such as high conductivity and a large surface area. These unique characteristics make graphene-based materials promising candidates for enhancing the performance of drilling fluids.

One area where graphene-based materials show promise is in controlling fluid loss in WDFs. Fluid loss control is a critical aspect of drilling operations, as it helps maintain wellbore stability and prevents formation damage. Studies have suggested that incorporating graphene-based additives into WDF formulations can positively impact fluid loss control mechanisms (He et al. 2021). By penetrating the microscopic pores of the downhole assemblies and creating a protective film on their surface, it can lubricate and extend the lifespan of a drill bit (Fagundes et al. 2018). Numerous studies have investigated the dimensions, composition, and density of graphene derivatives. However, there is still a need for further research to gain a better understanding of their behavior under various conditions.

It has been observed that drilling mud containing fewer suspended particles can increase penetration rates while also minimizing negative environmental impacts (Sun et al. 2021). There are four primary ways to create graphene, which are chemical vapor deposition, graphite exfoliation, epitaxial growth on silicon carbide, and GO chemical reduction. Among these techniques, chemical activation has been thoroughly studied because it offers significant advantages over other methods that require HTs, high vacuums, and expensive experimental setups (Tian 1995; Siddique et al. 2017).

Chemical activation is indeed a preferred method for converting waste materials and biomass into various forms of graphene due to several advantages it offers. First, chemical activation results in a well-defined micropore size distribution within the graphene structure. This ensures uniformity in pore sizes, which can be advantageous for specific applications such as adsorption and catalysis. Second, chemical activation typically yields high (Antonelou et al. 2018). Graphene nanoparticles (GNPs) tend to clump together due to a bond-like graphite interaction, making it challenging to disperse in water-based solutions (Motozuka et al. 2020). It is crucial to prevent graphene sheets from aggregating to maintain their separation. Steric or electrostatic repulsion can be utilized to achieve this objective (Medhekar et al. 2010). Chemical modification has the potential to significantly alter the properties of graphene (Muramatsu et al. 2014). The use of solvents aids in overcoming the dispersion of graphene in various applications, a limiting factor. Techniques such as layer-by-layer assembly, spin coating, and filtration are utilized to address this issue (Hussain et al. 2020).

Using graphene as an additive in WDF offers advantages such as thermal stability, lubricating properties, and reduced fluid loss (Romero-Anaya et al. 2014). Indeed, graphene can be effectively dispersed in certain organic solvents such as N-methyl pyrrolidone, dimethyl sulfoxide, and dimethylformamide. These solvents possess unique properties that enable them to interact favorably with graphene, leading to improved dispersion. Specifically, N-methyl pyrrolidone, dimethyl sulfoxide, and dimethylformamide exhibit high solubility and strong interactions with graphene sheets, facilitating their separation and dispersion. As a result, these solvents are commonly used in research and industrial applications to disperse graphene and graphene-based materials for various purposes, including coatings, composites, and electronic devices. By utilizing these organic solvents, researchers can achieve stable and homogeneous dispersions of graphene, enabling the exploration of its diverse properties and potential applications (Apaleke et al. 2012).

Achieving dispersion of graphene in common solvents typically requires extended sonication periods. This process involves subjecting the graphene material to ultrasonic energy for a prolonged duration to ensure its uniform distribution throughout the solvent. The sonication action helps break down agglomerates and promote the separation of graphene sheets, facilitating better dispersion. However, it is essential to note that the exact duration of sonication necessary may vary based on factors such as the type of solvent, the specific graphene material used, and the desired dispersion quality. While longer sonication times are often necessary for optimal dispersion, other techniques such as functionalization or the use of dispersing agents can also aid in achieving better dispersion with shorter sonication durations (Liu et al. 2011).

The study conducted by Sankar et al. (2017) delves into the production of superthin crumpled silk-veil-wave nanosheets with high surface area and porosity from carbonized brown rice husk through a process involving heating with KOH. This method leads to the creation of activated GNPs with remarkable properties. These activated GNPs possess an extensive surface area of 1225 m^2/g, ensuring enhanced reactivity and adsorption capacity. In addition, their high porosity enables efficient gas and liquid transport, making them valuable candidates for various applications, including energy storage, catalysis, and environmental remediation. The study sheds light on a novel approach for synthesizing activated GNPs from renewable biomass sources, offering insights into sustainable and scalable nanomaterial production methods (Guardia et al. 2011; Kuila et al. 2012).

GNPs are indeed regarded as the next generation of nanomaterials for the oil and gas industry, owing to their exceptional thermal and mechanical properties, high aspect ratios, and plate-like shapes. These characteristics make GNPs highly desirable for various applications within the oil and gas sector, including enhanced drilling fluid formulations, improved wellbore stability, and increased thermal conductivity in downhole environments. Compared with traditional additives, GNPs offer significant advantages, making them a promising choice for addressing the evolving challenges in oil and gas exploration and production (Kusrini et al. 2020).

The study conducted by Urie et al. (2018) revealed that GNPs exhibit greater effectiveness compared to silica nanoparticles when used in HT WBM filtration. This finding suggests that GNPs may offer superior filtration performance and thermal stability under elevated temperature conditions, making them a promising additive for enhancing the properties of WDFs in HT environments (Saner et al. 2020). Graphite is indeed a valuable mineral composed of carbon particles bonded by single covalent bonds, forming a stable hexagonal structure. These single covalent bonds are exceptionally strong and demand a significant amount of energy to break. However, at temperatures exceeding 600°C, graphite can undergo oxidation when exposed to oxygen from the air. This characteristic renders graphite an excellent material for serving as a barrier against HTs, making it highly suitable for various applications where thermal resistance is crucial (Shanker and Rani 2022).

In this paper, we present a new concept related to the properties of graphene when combined with Flowzan in drilling fluids. Our study highlights the multiple applications of graphene, especially in graphite composites. The material's unique features are derived from its conductive and permeable microstructure, which results from a synergistic effect between well-organized graphene particles and graphite. During drilling operations, WDFs can create high friction, leading to difficulties in various scenarios such as directional, horizontal, extended reach, cluster, and very deep wells. The primary lubricants used in this industry's drilling fluids are mineral oil and vegetable oil, both of which have the potential to harm the environment.

Reagents

The chemical components utilized in this study were sourced from Shiajizhuang Huabang Mineral Products Co., Ltd., situated in Qingdao, China. These components include the following:

- Clay bentonite, primarily based on montmorillonite and characterized by a particle size smaller than 2 μm, with a surface area of approximately 700–800 m^2/g.
- Graphene carbon nanomaterials, with a particle size of 20–30 nm, purity of 99%, density of 2270 kg/m^3, and thermal conductivity of 4000 W/mK.
- Barite powder, with a particle size of 100 μm and a molecular weight of 233.39 g/mol.
- Potassium chloride (KCl), with a molecular weight of 74.55 and a concentration of 500 μm.
- Polyanionic cellulose, exhibiting an average particle size of 2 μm, bulk density of 1.5 g/cm^3, purity of 99.99%, and specific gravity ranging from 1.5 to 1.6.
- Flowzan particles, possessing a size small enough to potentially enter human lungs, typically ranging between 0.4 μm and 0.7 μm.
- Polyacrylamide (PAM), a synthetic polymer characterized by a high molecular weight ranging from 1000 to 20×10^6 g/mol and a wide range of degrees of hydrolysis.
- Sodium hydroxide (NaOH), with a molecular weight of 39.997 g/mol, density of 2.13 g/cm^3, and boiling point of 1388°C.

Experimental Procedure

In the experiment, we aimed to assess the impact of graphene on lubrication in conjunction with Flowzan and other additives while adhering to API standard requirements. The results affirmed the potential application of graphene for solidifying oil wells. For the fluid drilling design, we used a mixture of 350 mL of natural water and synthesized materials including KCl, NaOH, polyanionic cellulose, polyhydrolytic PAM, barite, and graphene. Six samples were prepared, varying the weight of graphite from 0.5% to 3%. The procedure involved adding 14 g of bentonite and 2 g of potassium chloride, stirring the mixture for 4 minutes, followed by the addition of 0.14 g of NaOH and stirring for an additional 2 minutes. Subsequently, 0.2 g of Flowzan was introduced and stirred for 6 minutes, followed by the inclusion of 1.2 g of polyanionic cellulose and stirring for another 6 minutes. This was succeeded by the addition of 1.2 g of polyhydrolytic PAM and stirring for 10 minutes. Finally, after 30 minutes of stirring, 1.8 g of barite was added. The apparent viscosity (AV), plastic viscosity (PV), yield point (YP), and gel strength (GS) of the six drilling fluids were determined using the Fann Model 35 viscometer. The compositions of the drilling fluids are detailed in **Table 1**.

Component	Function	Type	Value
Water	Fluid base		350 mL
Bentonite	Drilling mud	Industrial grade	14 g

Table 1—Chemical composition of drilling fluids.

Component	Function	Type	Value
KCl	Density control	Analytical purity	2
NaOH	Hardness control	Analytical purity	0.14
Polyanionic cellulose	Additive	Analytical purity	1.2
Polyhydrolytic PAM	Additive	Industrial grade	1.2
Barite	Hardness control	Analytical purity	1.8
Flowzan	Hardness control	Analytical purity	0.2
Graphene powder	Lubrication	Industrial grade	0–5 to 3

Table 1 (continued)—Chemical composition of drilling fluids.

Results and Analysis

Infrared Spectroscopy. The graphene samples were ground before the test. During the test, the ground sample was mixed with KBr in a ratio of 1:200. The mixture was then placed into a tablet press and pressed into transparent flakes.

Contact Angle Measurement. The modification process of the graphene powder entailed pressing it into graphite flakes using a four-column press with a pressure of 20 MPa. Subsequently, the resulting flakes underwent testing for their contact angle using a measuring instrument to ascertain the optimal amount of Flowzan needed for the graphene. It was observed that the average contact angle between the graphite flakes and distilled water was determined to be 300°F. Furthermore, the contact angle for the graphite flakes treated with Flowzan exhibited a decrease on average compared with the untreated graphite samples (Samples 1–6.

Synthesis of Graphene. To create a blend of graphene powder, we used a substance precipitation procedure. The process began by dissolving 10 g of graphene in 150 mL of demineralized water. Subsequently, the mixture underwent scrubbing and washing with deionized water and ethanol to eliminate any excess base. The resulting material was then dried at 70°F for 3 hours in a hot air oven. Following the drying process, the material was crushed and subjected to calcination for 4 hours in a stifling heater at 300°F. Finally, the graphite powder content obtained was analyzed through powder XRD, and the residue was examined using SEM to verify that the desired outcome was achieved.

High-Pressure Rheology Measurement. The rheological and filtration properties of WBM affect its efficiency and performance in drilling operations. The thixotropic and shear-thinning properties also impact the WBM's performance (Parsamehr et al. 2019). PV is influenced by various factors such as the concentration, size, and shape of solid particles, along with the viscosity of the fluid phase. The fluid behavior at high rates is determined by the PV. Mechanical friction from the solid particles present in the drilling fluid produces PV, according to Urie et al. (2018). YP is the primary resistance between solid particles and electrochemical gravity. High YP in drilling fluid helps transfer cuttings from a wellbore but should not exceed a certain level that puts pressure on the pump when mud is stopped and resumed (Rafieefar et al. 2021). As a result of the nanoadditives in the fluid, the particles are more attracted to each other, which increases the YP of the fluid. Increasing the YP of a fluid has several positive effects, including improving its ability to clean drilling cuttings from wells, reducing drillstring sticking probability, and reducing the torque associated with the drillstring (Gang et al. 2019). It is YP that determines the ability of drilling fluid to remove drilling cuttings from beneath the drill bit to the surface through the annulus (Gang et al. 2019; Rana et al. 2020). The higher the YP is, the more effective the fluid is at carrying cuttings to the surface. This is because the higher the YP, the greater the potential energy it has, which allows it to overcome the friction from the walls of the wellbore and move the cuttings efficiently. As nanoparticle concentration was increased, YP improved, which means that cuttings removal from boreholes to the surface will be improved (Zhang et al. 2019). A Fann Model 35 viscometer was used to measure the consistency, plastic thickness, yield strength, and GS of drilling fluids. By taking dial readings at different speeds, we were able to determine the consistency, plastic thickness, yield strength, and GS of the fluid. In addition, we measured the GS at 10 seconds and 10 minutes with Plate Number 1. The following methods were used to determine the rheological properties of the drilling mud, including consistency (Condition 1), plastic thickness (Condition 2), and yield strength (Condition 3):

$$\mathrm{AV} = \frac{\theta 600}{2}, \tag{1}$$

$$\mathrm{PV} = \theta 600 - \theta 300, \tag{2}$$

$$\mathrm{YP} = \theta 030 - \mathrm{PV}, \tag{3}$$

where AV represents the clear viscosity, PV represents the plastic viscosity, and *YP* represents the yield point. The dial readings at 600 rev/min and 300 rev/min are denoted as $\theta 600$ and $\theta 300$, respectively.

Laser Particle-Size Measurement. The synthesized graphene was used in the laser particle sizing experiment to measure the size of bentonite particles in various drilling fluids that had been treated with a conditioning agent known as "Treatment." These estimations were utilized to decide the middle and ordinary molecule sizes of the bentonite particles. The review planned to notice the progressions in the molecule size of bentonite particles utilizing the information gathered from the analysis referenced above (Gang et al. 2019).

Zeta Potential Measurement. The zeta potential of the supernatant solutions was evaluated using a high-sensitivity Omni multiangle particle size and zeta potential analyzer. Changes in graphite's zeta potential were analyzed at various adsorbent concentrations. We used the electrophoretic light scattering method in our study to investigate the zeta potential of graphite. We measured the particle velocity under an electric field, and these data were used to calculate the zeta potential. Zeta potential tests were conducted on modified graphite to assess the efficacy of surface modifications. A notable alteration in the surface charge would indicate a successful modification. Suppose there is a significant change in zeta potential following modification. In that case, it suggests that the surface chemistry of graphite has been modified, potentially affecting its interactions in various environments and its stability in suspensions. This analytical approach provides valuable insights into the surface charge of the graphite particles and how it changes with varying concentrations of adsorbent. Such information is crucial for understanding the interaction between the adsorbent and the surrounding fluid, which can influence properties like dispersion stability and colloidal behavior (Benyounes et al. 2010; Yu 1985).

Synthesized Graphene XRD. Graphene plates are connected by an irregular lattice of hydrogen bonds, which are regulated by water molecules, oxygen-containing functional groups, as well as other xanthan gum (XG) and carboxymethyl cellulose low-viscosity (CMC LV) functional groups. The formation of the H-bond network plays a crucial role in defining the overall structure of solutions containing GOES. Molecular dynamics studies suggest that the characteristics of such solutions are primarily governed by the H-bond lattice, which encompasses both functional groups and water molecules present in the interlayer space (Park et al. 2008). It was observed that graphene plates have a strong tendency to form hydrogen bonds with other particles, including themselves. When combined with a smaller and stiffer particle like CMC LV, GO improved filter-cake formation better than larger particles like XG. The combination of GO and CMC LV resulted in considerably superior filtration characteristics. The individual platelets could join together, forming structures similar to jellyfish which could block the micropores. Although XG has a more significant impact on viscosity than CMC LV, CMC LV's ability to form jellyfish structures with GO platelets further reduces the filtrate volume (Livescu 2012). The mixed graphene was taken apart using a Bruker D8ADVAHCL X-pillar diffractometer (Berlin, Germany). The following qualities were present in the instrument: Cu target, clay X-beam tube, 40 Mama tube current, 40 kV tube voltage, 0.02 step size, and an output scope of 5−90° (2θ). The model was recognized as changed graphite, and the Bragg condition ($n\lambda = 2 \sin \theta$) was used to conclude the spatial difference in bentonite layers under different conditions. The powder of graphite was broken down for a change, as announced by William et al. (2021). XRD was utilized to notice the translucent capacitance of the orchestrated graphene. The deliberate diffraction designs are displayed in **Fig. 1**. It very well may be seen that the GNPs are situated principally on the c-pivot with a little (002) top. The trademark tops show up in the accompanying 2θ territories: ≈85, 43.23, as indicated by the Debye-Scherrer equation $D = K\lambda\beta \cos \theta$. Modifying processes may disrupt the well-organized layers of graphite, resulting in alterations in peak positions and intensities. Shifts in peak positions or changes in peak intensities in the XRD pattern suggest modifications in the graphite crystal structure. For instance, exfoliation or intercalation would cause the peaks to become broader and their intensity to decrease.

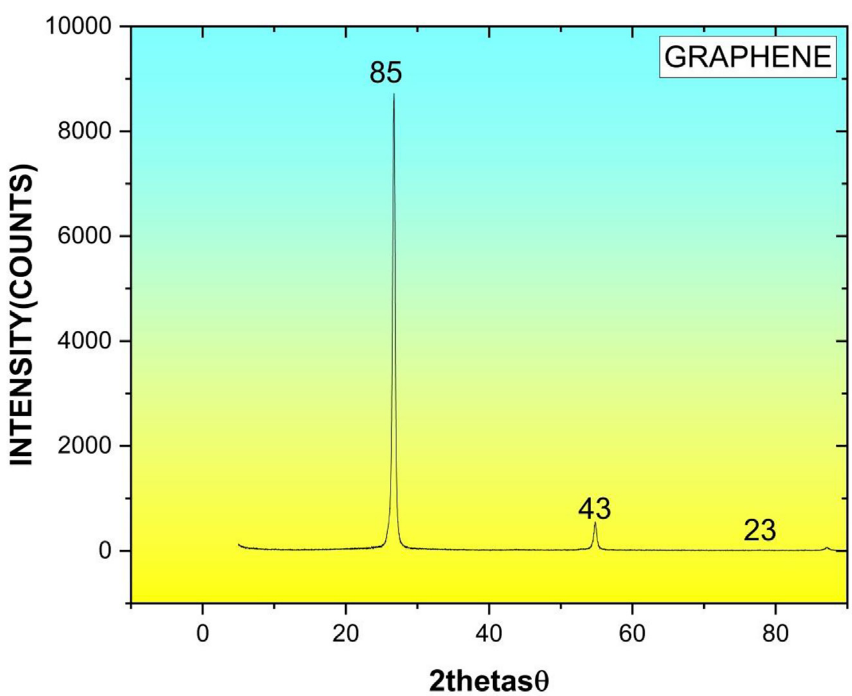

Fig. 1—XRD of graphene.

Synthesized Graphene SEM. The sample is bombarded with a focused electron beam, and the resulting secondary electrons are detected to form an image. SEM is used to observe the surface morphology of modified graphite, allowing for the visualization of changes in surface texture, particle shape, and size distribution. The SEM images provide a clear comparison between the surface structures before and after modification. For example, in the case of exfoliation, the SEM images would display more distinct and thinner layers compared with the unmodified graphite. These techniques contribute to a comprehensive understanding of the properties of modified graphite. Graphene composition and morphology were studied using SEM. **Fig. 2** shows a surface of compact clay soil with large, smooth, and homogeneous crystals with a grain size of less than 5 µm.

FTIR spectroscopy is a technique that utilizes an infrared absorption spectrum to provide information about the chemical bonds present in molecules. In this study, FTIR measurements were conducted using an IRTracer-100 FTIR SHIMAD 24 instrument. This technique allowed for the examination of the characteristics of graphite, as depicted in **Fig. 3**. Specifically, the FTIR analysis enabled the identification of various chemical bonds within the graphite sample. For instance, the metallic oxygen bond was assigned to the spectral region between 314 cm^{-1} and 600 cm^{-1}. This region corresponds to vibrations associated with metal-oxygen bonds present in the graphite

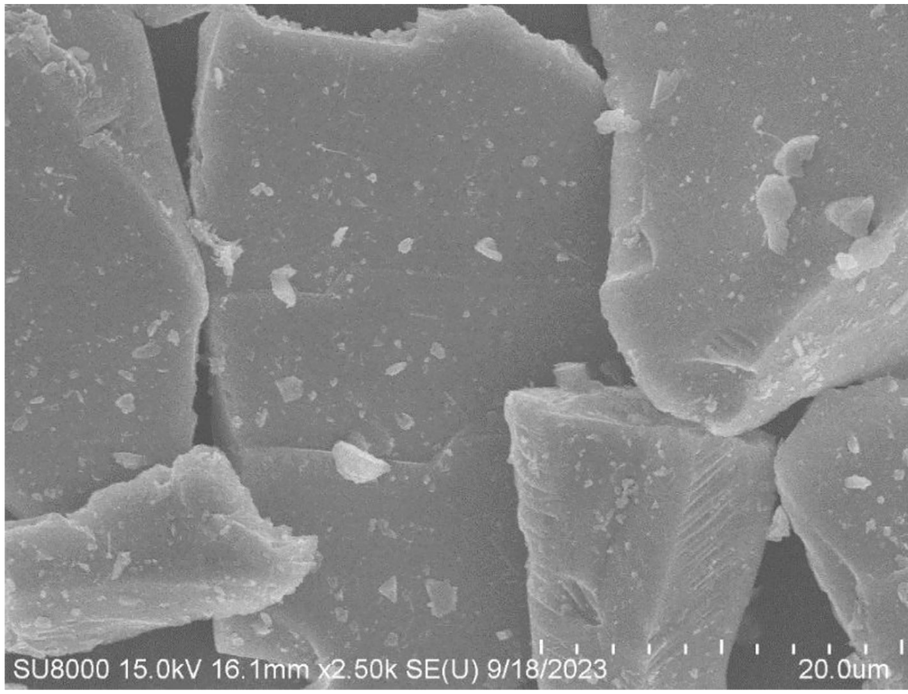

Fig. 2—SEM of graphene.

structure. Additionally, the bonding region was observed between 1400 cm^{-1} and 1123 cm^{-1}, representing vibrations related to various bonding interactions within the graphite material. The sample is subjected to infrared light, and the absorbed wavelengths are measured. Various functional groups can absorb specific frequencies of infrared light. The FTIR technique is used to verify the existence of particular functional groups that are introduced during the modification of graphite. For instance, if oxidation was used for the modification process, peaks corresponding to carbonyl (C = O) or hydroxyl (OH) groups should be observable. The emergence of new peaks or alterations in existing peaks in the FTIR spectrum after modification signposts the presence of new functional groups, thereby confirming the success of the chemical modification.

Investigation of Thermal and Electrical Conductivities. Tables 2 and 3 display the thermal and electrical conductivities data for six drilling mud formulations. The incorporation of graphite nanoparticles within a polymer matrix has notably enhanced the thermal stability of the drilling mud. The study encompassed five temperature levels, simulating downhole conditions, specifically a low-temperature range of 0–70°F, a moderate-temperature range of 70–120°F, an elevated-temperature range of 120–180°F, an HT range of 180–250°F, and an ultra-HT range of 250–300°F. These temperature ranges are representative of conditions encountered in wells during drilling operations (Anand et al. 2012; Liu et al. 2018; Qamar et al. 2019). Across all five temperature ranges, the lubrication efficiency of the composite remained acceptable. However, as temperatures increased, larger quantities of graphene were required to maintain this level of lubrication. Nevertheless, the graphite composite exhibited minimal changes in weight loss across various drilling mud conditions.

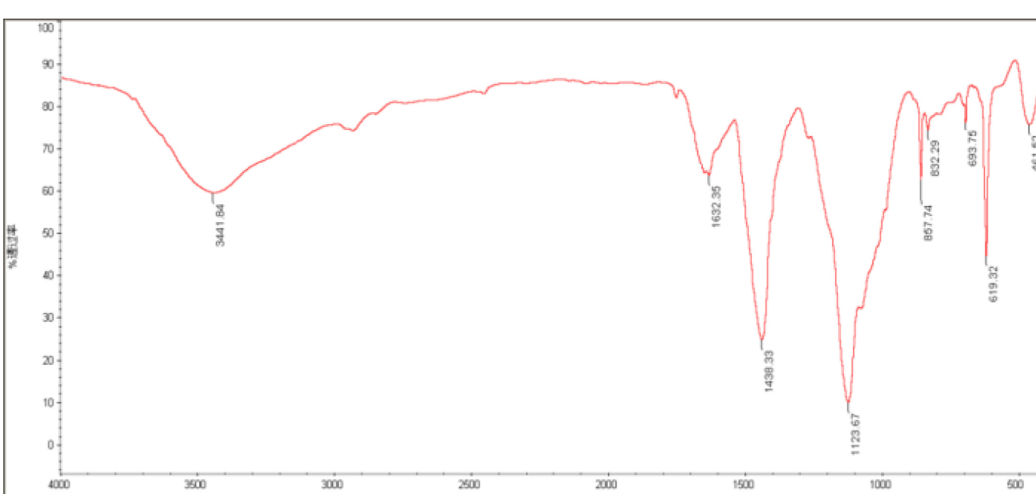

Fig. 3—FTIR spectroscopy of graphene.

Drillings Fluids	Thermal Conductivity (W/mK)b	% Age Intensification
Drilling Fluid A	0.372	–
Drilling Fluid B	0.417	12.1
Drilling Fluid C	0.441	18.55
Drilling Fluid D	0.46	23.66
Drilling Fluid E	0.476	27.96
Drilling Fluid F	0.503	35.22

Table 2—Thermal conductivities.

Drillings Fluids	**Electrical Conductivity (μS/cm)**	% Age Increase
Drilling Fluid A	276	–
Drilling Fluid B	302	9.42
Drilling Fluid C	326	18.12
Drilling Fluid D	350	26.81
Drilling Fluid E	398	44.2
Drilling Fluid F	403	46.01

Table 3—Electrical conductivities.

Thermogravimetric Examination. The thermogravimetric analysis (TGA) was conducted on two types of surfaces: GNP-RHC and GNP-TXT, to evaluate the percentage of oxygen-containing groups and to assess the thermal degradation of block copolymers. For GNP-RHC, the analysis revealed two distinct weight loss steps. The first step occurred in the temperature range of 65–120°C, attributed to a process such as moisture desorption or removal of physically adsorbed gases. The second weight loss step was observed in the range of 310–550°C, indicating thermal decomposition of the material. On the other hand, GNP-TXT exhibited a more gradual weight loss profile. At 300°C, GNP-TXT experienced only a 10% weight decrease, suggesting minimal degradation at this temperature. However, the modified GNP-TXT underwent significant weight loss, approximately 78%, up to 885°C. This substantial weight loss was attributed to the thermal degradation of dispersants used in the modification process. Overall, the TGA results provide valuable insights into the thermal stability and degradation behavior of the GNP surfaces, aiding in understanding their suitability for various applications (Wissing et al. 2004). The thermal stability of modified graphene is significantly enhanced compared with unmodified graphene when incorporated into the drilling fluid composition. The modified graphene experiences only a 6% weight loss at 70°F, whereas the unmodified graphene undergoes a much higher weight loss, approximately 73%, at 250°F. This can be seen in **Fig. 4**. This substantial difference in thermal stability highlights the effectiveness of the modification process in improving the graphene's resistance to HTs, making it a valuable additive for applications in drilling fluids where elevated temperatures are encountered.

Particle Size Measurement. Particle-size analysis is important for characterizing drilling fluid additives. The particle-size distribution affects the rheological properties, stability, and effectiveness of the fluid in controlling fluid loss and providing lubrication. Laser diffraction measures the angular change in the intensity of scattered light as it passes through a sample with dispersed particles. This method relies on the principle that smaller particles scatter light at wider angles than larger particles. The molecular shape of the samples was analyzed using a molecule size analyzer called laser diffraction. **Table 4** illustrates that the average particle size of modified graphite is larger than that of unmodified graphite. The average particle sizes for Samples 1–6 were 102.80 μm, 25.11 μm, 17.1 μm, 15.45 μm, 10.03 μm, and 22.03 μm, respectively. In contrast, the median particle size of modified graphite was larger than that of unmodified graphite, with values of 90.25 μm, 18.98 μm, 13.71 μm, 12.54 μm, 7.93 μm, and 18.68 μm for Samples 1–6, respectively. The addition of excessive amounts of Flowzan and potassium initially led to a decrease and then an increase in the average and median particle sizes of graphite. This indicates that an excessive amount of potassium causes aggregation of graphite, resulting in poor dispersion between the graphite particles.

Drilling Fluids	Average Particle Size (μm)	Median Particle Size (μm)
Drilling Fluid A	102.8	90.25
Drilling Fluid B	25.11	18.98
Drilling Fluid C	17.1	13.71
Drilling Fluid E	15.45	12.54
Drilling Fluid D	10.03	7.93
Drilling Fluid F	22.03	18.68

Table 4—Average and median particle sizes of graphene.

Zeta Potential Measurement. According to Ravichandran et al. (2014), zeta potential values above 30 mV indicate good dispersion and stability. Furthermore, zeta potential values above 60 mV suggest excellent long-term stability, while values around 20 mV indicate

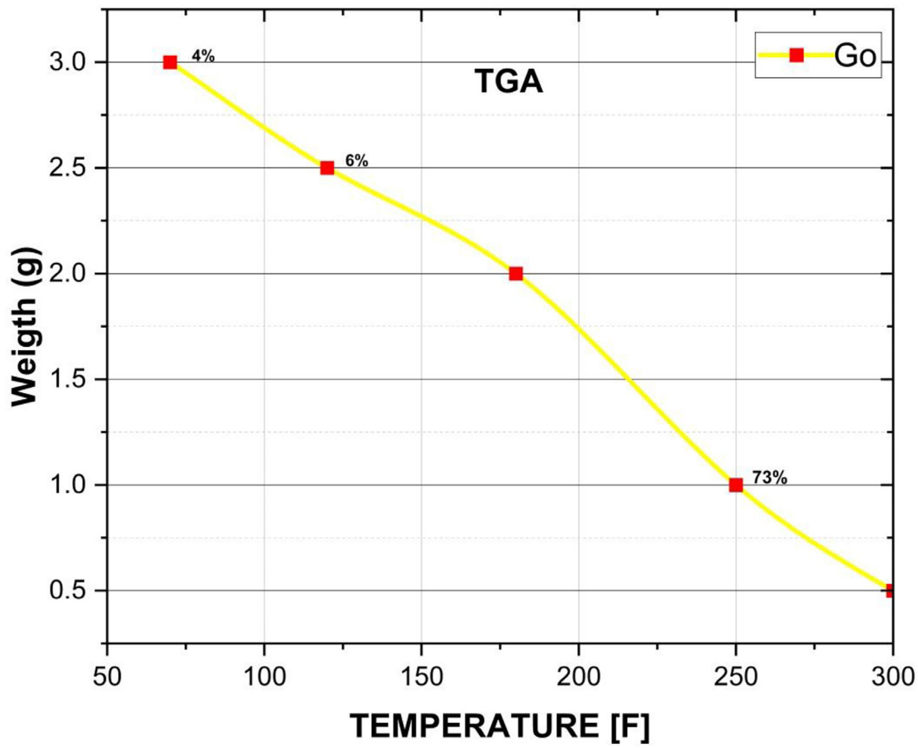

Fig. 4—TGA spectra for drilling fluids with graphene modified under HTPT.

good short-term stability (Honary and Zahir 2013). We used a high-sensitivity Omni multipoint particle size and zeta potential analyzer to measure the sample dispersion. We aimed to investigate the zeta potential of graphite before and after the addition of potassium. We observed that the zeta potential of the modified graphite increased from 8.65 mV to 30.77 mV, 35.05 mV, 40.86 mV, 50.25 mV, and 50.19 mV for Tests A through F, as indicated in **Table 5**. This rise in potential indicates that the adsorption of potassium and Flowzan has enhanced the stability of the suspension.

Drilling Fluids	Zeta Potential Value (mV)
Drilling Fluid A	8.65
Drilling Fluid B	30.77
Drilling Fluid C	35.05
Drilling Fluid D	40.86
Drilling Fluid E	50.25
Drilling Fluid F	50.19

Table 5—Zeta potential value of drilling fluids.

Rheological Properties. Drilling mud with favorable shear-thinning properties is highly sought after in drilling operations as it facilitates easier pumping into the bottom of a wellbore. GO serves as an excellent component for modifying fluid flow behaviors owing to its exceptional properties. Additionally, even in the absence of GO, the XG/CMC LV suspension displayed a nearly shear-thinning property. This observation suggests that XG can serve as a potent viscosifier in drilling mud formulations. Therefore, the combination of GO and XG or the use of XG alone can contribute significantly to achieving the desired rheological properties essential for efficient drilling operations (Shanker and Rani 2022). As the concentration of GO increases from 0 wt% to 0.15 wt%, there is a steady increase in shear stress. For instance, at a high shear rate of 1,022 s^{-1}, the shear stresses of GO/XG/CMC LV-WDF with 0.0 wt%, 0.05 wt%, 0.1 wt%, and 0.15 wt% of GO are 13.24 Pa, 22.98 Pa, 24.61 Pa, and 27.58 Pa, respectively. This indicates that the shear stress in the presence of 0.15 wt% GO is double that of the absence of GO at a high shear rate. Rheological analysis confirmed that the rheological characteristics of GO/CMC LV/XG were positively influenced by the increase in GO concentration. The sheet-like shape of GO is well-known, and it was found that carboxyl and hydroxyl groups were present on the edges and planes of the GO sheets. These functional groups contribute to the interaction between GO sheets and the XG/CMC LV matrix, enhancing the rheological properties of the drilling fluid. As the concentration of GO increases, more interactions occur between the GO sheets and the fluid matrix, leading to an increase in shear stress and improved rheological behavior (Ahmed et al. 2020). A drilling fluid solution displaying thixotropic behavior experiences a reduction in viscosity as shear rates increase. Thixotropy refers to the property of certain fluids where the viscosity decreases under shear stress and returns to its original viscosity when the stress is removed. This behavior is advantageous in drilling operations as it allows the fluid to flow more easily under high shear conditions, such as during pumping, while still maintaining sufficient viscosity to suspend solids and carry cuttings when the shear stress is removed. Thixotropic drilling fluids provide efficient performance in wellbore operations by balancing fluid flowability and suspension properties (Bayat et al. 2018). Mohammadsalehi and Malekzadeh (2011) have observed that drilling fluid rheology and flow rate are the two primary factors that significantly impact the transport of cuttings. However, they also mentioned that managing these parameters in the field is relatively straightforward. Ogunrinde and Dosunmu (2012) further affirmed that the flow rate of the fluid is the most influential factor in the formation of the cuttings bed. **Fig. 5** illustrates plots of shear stress vs. shear rate under HTHP conditions. By analyzing the drilling fluid as a Herschel-Bulkley fluid model, the shear stress (τ) can be determined. The Herschel-Bulkley model describes the rheological behavior of fluids that exhibit both shear-thinning and yield stress properties. By fitting the experimental data from **Fig. 5** to the Herschel-Bulkley model, the yield stress can be determined, representing the pressure required to start flow in the drilling fluid under HTHP conditions.

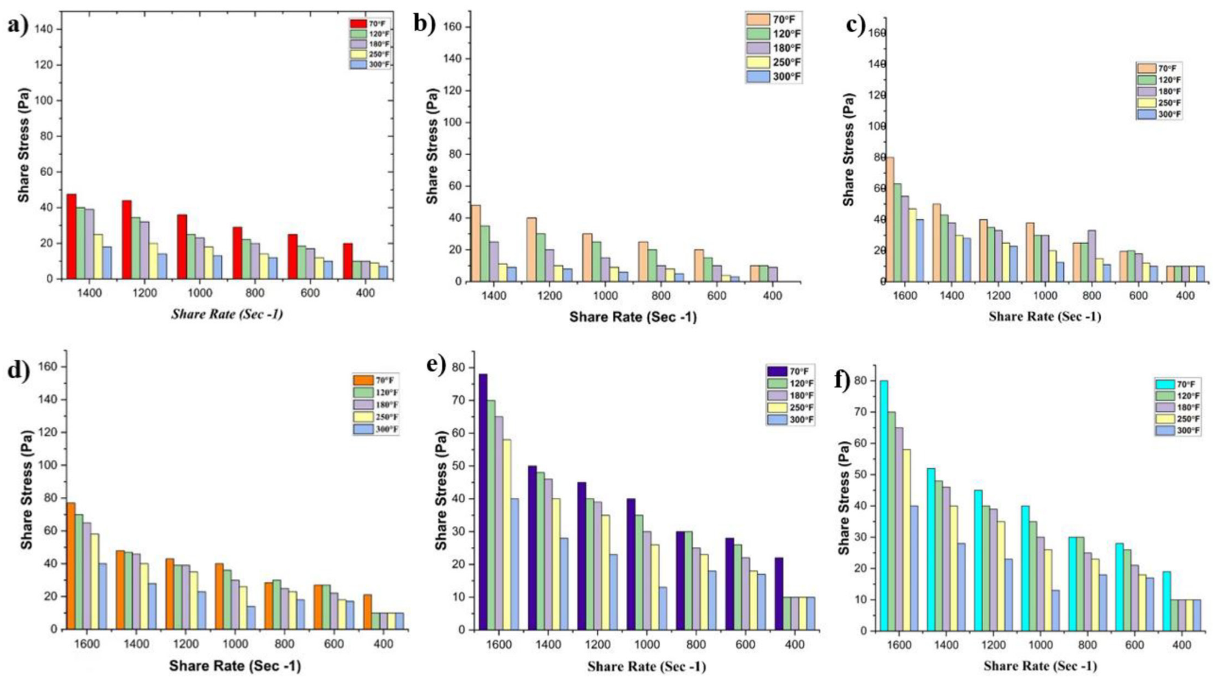

Fig. 5—Variations of shear stress vs. shear rate under HTPT.

Effect of Graphene on PV and YP. GS measurement is crucial for assessing a drilling fluid's ability to withstand the settling of solid particles and cuttings when fluid circulation ceases. When the fluid is at rest, solid particles suspended in the drilling mud demonstrate GS due to the electrochemical forces acting on them. Drilling fluid with higher GS typically exhibits higher viscosity and is more effective in resisting particle settling. Therefore, monitoring GS is essential for ensuring the stability and performance of drilling fluids during drilling operations (Akpan et al. 2020). In drilling operations, "low-flat gels" are preferred over "high-flat gels." Low-flat gels have a more desirable rheological profile because they require lower pumping pressures to break and resume fluid circulation compared with high-flat gels. When drilling mud forms a high-flat gel, it exhibits higher resistance to flow, leading to increased viscosity and GS. As a result, higher pumping pressures are required to break these gels and resume fluid circulation, which can increase the risk of issues such as stuck pipes during drilling operations. Therefore, drilling fluids with low-flat gels are favored as they offer better fluid circulation and help mitigate the risk of operational challenges associated with high viscosity and GS (Oseh et al. 2024). Indeed, the rheological and filtration properties of drilling fluids are influenced by several parameters, including the concentration of additives and fluid temperature. By carefully controlling these parameters and optimizing the formulation of drilling fluids, operators can ensure desirable rheological and filtration properties tailored to specific drilling conditions, ultimately enhancing drilling efficiency and minimizing operational challenges (Blkoor et al. 2023). When the temperature rises, it can cause the main chain of the polymeric molecule in the drilling fluid to break. This, in turn, leads to an increase in the amount of fluid that is lost as per API standards. Furthermore, an increase in temperature can also cause a decrease in the rheological properties of the drilling fluid (Hyne et al. 2014). The rheological behavior of drilling fluids is determined by crucial parameters such as mud density, PV, and YP. These parameters play an important role in maintaining formation pressure and improving wellbore stability. If the mud density is low, it can cause the wellbore to collapse due to rock shear failure, which is also known as wellbore breakout. Conversely, high mud density can lead to circulation loss, a decrease in penetration rate, and formation damage. The addition of nanoadditives to WDFs has almost no effect on the weight of mud (Ismail et al. 2016). Although all the PV values obtained when using nanosilica as an additive are within the recommended range, it is advisable to choose the mud sample with the lowest PV value. Lower PV values increase the rate of penetration, reduce energy consumption during mud circulation, improve cooling and lubrication for downhole equipment, and minimize mud loss. Selecting the mud sample with the lowest PV value helps avoid the risk of excessive equivalent circulation density and formation fractures (Salih and Bilgesu 2017; Parizad et al. 2018). A decrease in PV is observed once 0.5 ppb of nanosilica is added to the mud. This decrease is attributed to the nanosilica's capacity to disrupt gel formations among the mud particles (Boyou et al. 2019). Using nanosilica helps reduce the PV of mud, which is beneficial for drilling at both low and high mud weights. However, it should be noted that increasing the concentration of nanosilica to 1.0 ppb and 1.5 ppb leads to an increase in PV. This is because there is a higher presence of solid particles in the mud at these concentrations (Katende et al. 2019). PV refers to the resistance of drilling fluid to flow caused by mechanical friction. Two key factors that affect PV are the volume of solids present in the mud and the viscosity of the liquid in which they are suspended. Additionally, PV is influenced by the physical properties of the material, such as its size and concentration Fatihah Majid et al. (2019). When drilling for oil, it is important to use non-Newtonian

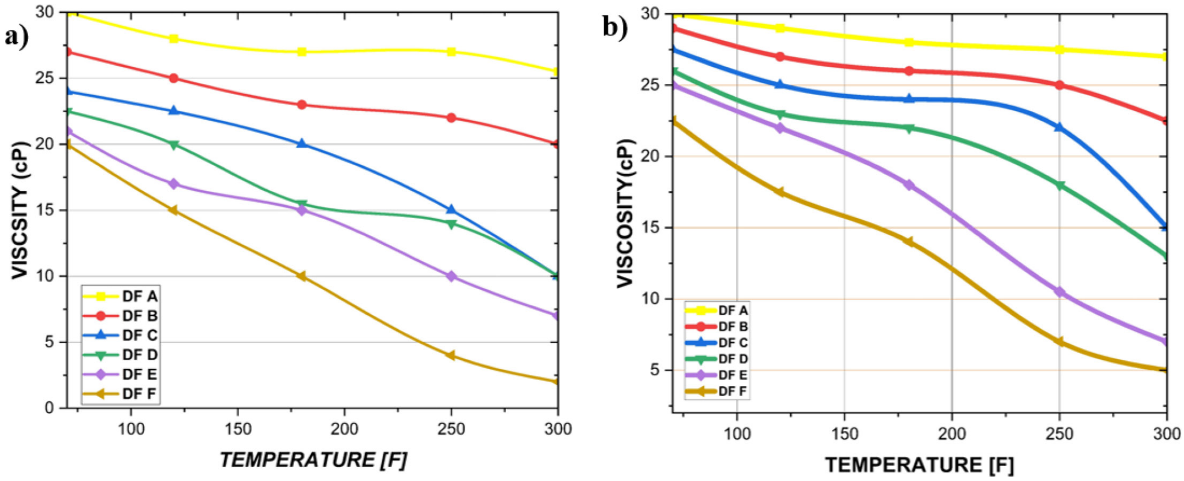

Fig. 6—(a) PV variations. (b) YP variations.

fluids that can keep drill cuttings suspended in the wellbore and prevent issues like differential sticking. To measure the effectiveness of these fluids, we use the YP parameter. As the size of the solid additive particles decreases, the YP increases, which leads to better attraction forces between solid particles. This enhances the drill-cuttings carrying capacity and cleans the wellbore effectively (Ikram et al. 2021). Ensuring that the yield strength (YP) of drilling fluids is appropriate is crucial for supporting the conveyance of abrasive fluids and facilitating the removal of drill cuttings from beneath the drill to the surface through the annulus. By carefully controlling the yield strength of drilling fluids and optimizing other rheological properties, engineers can ensure that the fluid is capable of effectively conveying abrasive fluids and removing drill cuttings, thereby enhancing drilling efficiency and minimizing operational challenges (Hafshejani et al. 2016). The observation that at a concentration of just 0.5 wt% of nanoparticles, there is only a small 6.25% decrease in YP is significant. Despite this decrease, the resulting YP value remains within an acceptable range. This outcome is attributed to the positive surface charge of iron oxide nanoparticles in the aqueous state. The positive surface charge of the nanoparticles can contribute to maintaining the stability and performance of the drilling fluid. This charge may facilitate interactions between the nanoparticles and other components of the drilling fluid, helping to maintain or even enhance certain rheological properties such as YP. Therefore, even at relatively low concentrations, nanoparticles can still exert a beneficial effect on the rheological behavior of drilling fluids, contributing to their overall performance and suitability for drilling operations (Ismail et al. 2020). YP is a crucial factor in ensuring that fluids enter through the stream system, flowing from the lower part of the opening to the surface. A high YP is generally necessary for this purpose. If there is a lack of YP, it can adversely affect the transport efficiency and cause a transition from laminar to fierce streams. The use of nanoparticles can increase YP, but a high concentration of gas bubbles in the fluids can reduce the PV. Researchers are currently conducting further studies on this topic (Barry et al. 2015). Generally, increasing the concentration of nanosilica decreases the 10-second GS of the WBM. This is because the use of nanosilica allows for the formation of a more delicate gel (Salih and Bilgesu 2017). A good GS is always required as it helps maintain the necessary circulation pressure to restart drilling operations (Ismail et al. 2016; Anoop et al. 2019; Vryzas et al. 2019). The impact of different nanoparticle concentrations on the GS of graphite at 10 seconds is shown in **Figs. 6 and 7** and **Tables 6 through 9**. Interestingly, it has been found that even with a small amount of nanoparticles, adding 0.3 ppb of nanocomposite can have a negative impact on GS. This finding highlights the sensitivity of GS to nanoparticle concentrations and underscores the importance of carefully optimizing nanoparticle dosages in drilling fluid formulations. While nanoparticles can offer several benefits to drilling fluids, including improved rheological properties and thermal stability, excessive concentrations may adversely affect certain fluid properties such as GS. Therefore, it is crucial for drilling engineers to conduct thorough evaluations and trials to determine the optimal

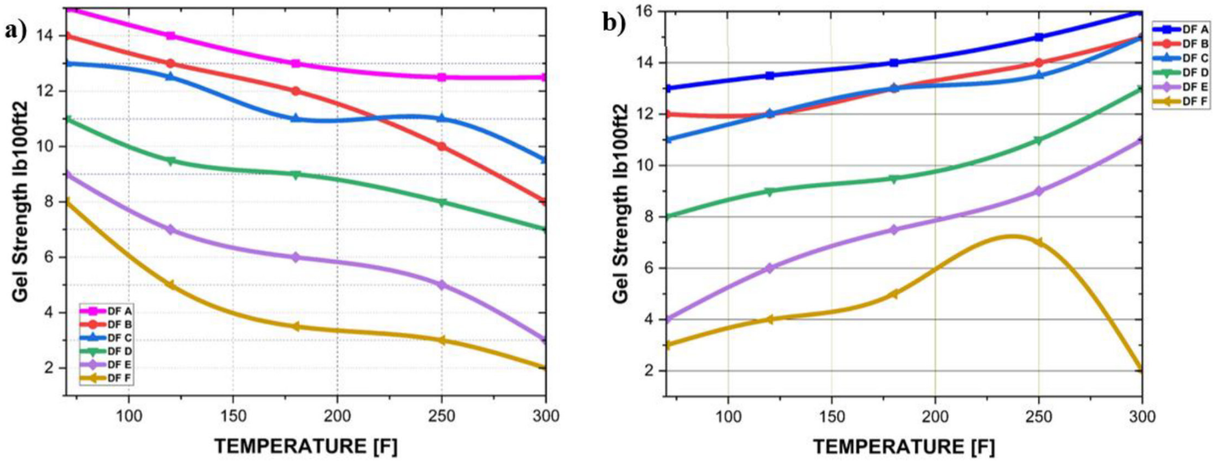

Fig. 7—(a) 10-second GS of drilling fluids. (b) 10-second GS of WBM.

Drilling Fluids	At 70°F	At 120°F	At 180°F	At 250°F	At 300°F
Drilling Fluid A	30	27.5	27	26.5	24.5
Drilling Fluid B	27	25	23	22	20
Drilling Fluid C	23.5	21.5	19	15	10
Drilling Fluid D	22.5	20	15.5	14	10
Drilling Fluid E	21	17	15	10	7.5
Drilling Fluid F	19	15	10	4	1.5

Table 6—PV variation under temperature, GO, and Flowzan.

Drilling Fluids	At 70°F	At 120°F	At 180°F	At 250°F	At 300°F
Drilling Fluid A	30	29	28	27.5	26.5
Drilling Fluid B	28.5	27	26	25	22.5
Drilling Fluid C	26.5	24.5	24	22	15
Drilling Fluid D	25.5	23	22	18	13.5
Drilling Fluid E	25	22	18	10.5	7
Drilling Fluid F	22.5	15	14	7	6

Table 7—YP variations under temperature, GO, and Flowzan.

concentrations of nanoparticles. This allows for a balance between the desired enhancements in fluid performance and the maintenance of critical properties, such as GS. By doing so, drilling operations can proceed smoothly.

Loss of Filtering. Wellbore plugging, formation expansion, and wellbore instability and collapse can all be caused by fluid outflow into the formation. Differential pressure adhesion, caused by cake buildup on the wellbore wall, increases the risk of drilling tool damage (Sun et al. 2020). To prevent drilling fluid from escaping and entering a formation, nanoparticles can be used to obstruct the pore space (Ahmed et al. 2020). **Fig. 8** illustrates the behavior of fluid loss in graphene-WBM; Drilling Fluid A, which contained 0.5% graphene, produced 13.5 mL of filtrate in the 30-minute API filtration test. In contrast, after incorporating 3% graphene in Drilling Fluid F, the volume of fluid loss was reduced to 4.3 mL. This substantial reduction in filtrate liquid is a result of the graphene's significant presence, which effectively blocks the pore space of the filter paper. The addition of 1 g of Fe_2O_3 nanoparticles resulted in a decrease in the filter losses of lignosulfonate-WBM to 8.6 mL. The use of 1 g of Fe_2O_3 nanoparticles can effectively reduce fluid loss in the base mud. Furthermore, Fe_2O_3 nanoparticles prove to be a superior option for minimizing fluid loss. These results support the consistent discovery made by Cheraghian (2021).

Lubricity Improvements. During drilling operations, heat and friction are generated at the bit and the drillstring/wellbore interface. The rotation of the drillstring can also create torque and drag due to friction between the wellbore and the drillstring. Lubricating the drillstring is one of the main functions of drilling fluid. To determine the COF, it is necessary to evaluate the level of traction between the two objects (Ismail et al. 2016). The lubricity of the drilling mud is a critical property that must be carefully controlled during mud formulation. This is because the mud plays a vital role in lubricating the drillstring throughout the drilling operation (Aston et al. 1998; Wu and Hareland 2012). The COF is defined as the ratio of the frictional forces between two bodies that are in contact with each other (Ismail et al. 2016; Quigley et al. 2016; Skalle et al. 2010; Samuel 2010). The extreme pressure oil coefficient of a new WDF is influenced by the presence of graphite, which decreases after 16 hours of aging at 300°F. Moreover, as the amount of graphene increases, the oil coefficient decreases proportionally. Specifically, when the graphite content reaches 3%, the extreme pressure grease coefficient of the freshwater-based drilling fluid can decrease by up to 92.4%. This indicates that incorporating graphite nanoparticles, particularly with potassium polymer, can enhance the efficiency of the drilling fluid component. To evaluate the extreme pressure oil coefficient, experiments were

Drilling Fluids	At 70°F	At 120°F	At 180°F	At 250°F	At 300°F
Drilling Fluid A	15	14	13	12.5	12.5
Drilling Fluid B	14.5	13	12	10	8
Drilling Fluid C	13	12.5	11	11	9.5
Drilling Fluid D	11	9.5	8	8	7
Drilling Fluid E	8.5	7	6	5	3
Drilling Fluid F	7	5	3.5	3	1.5

Table 8—10-second GS variations under temperature, GO, and Flowzan.

T (°F) Drilling fluids	70° F	120° F	180° F	250° F	300° F
Drilling fluid A	14	13.5	14	15	16
Drilling fluid B	12	12	13	14	15
Drilling fluid C	11	12	13	12.5	15
Drilling fluid D	8	9	9.5	11	13
Drilling fluid E	4	6	8	9	11
Drilling fluid F	2.5	4	5	7	3

Table 9—10-Minute gel strength under temperature and GO and Flowzan.

conducted using a Model 212 extreme pressure analyzer. The lubricity of the drilling mud samples depends solely on the concentration of nanosilica, while temperature does not have an impact on it. Nanosilica can increase the mud's lubricity by forming a type of boundary lubrication through physisorption (Alshubbar et al. 2017; Al-saba et al. 2018). The COF was adjusted through a metal-on-metal review, simulating the interaction between the drillstring and the drilling. Before testing the mud samples, the equipment underwent calibration with deionized water. The lubricity coefficient was then determined using Eqs. 4 and 5. This experimental setup allowed for a precise assessment of the lubricating properties of the drilling fluid under extreme conditions, providing valuable insights into its performance and effectiveness in drilling operations. According to **Fig. 9**, the COF values obtained are 0.428, 0.375, 0.342, 0.321, 0.319, and 0.268. The use of nanoparticles reduces the COF by creating a slippery layer between the drillstring and the borehole.

$$\text{Correction Factor} = \frac{\text{Standard Meter Reading for Deionized Water}}{\text{Meter Reading Obtained in Deionozed Water Calibration}}, \tag{4}$$

$$\text{Lubricity Coefficient } = \frac{\text{Meter Reading Correction Factor}}{\text{100 Pounds}}. \tag{5}$$

Characterization of Filter Cake. A filter cake or mudcake forms at the wellbore when the filtrate is lost from the wellbore into the permeable zone. Excessive filtration loss can damage the formation. Therefore, it is important for any mud formulation to create a thin, strong, and impermeable filter cake during filtration. This helps prevent further contamination of the formation due to filtrate loss and avoids pipe blockage caused by an uneven or excessively thick mudcake (Ismail and Paramasivam 2016). It is well-known that the introduction of fluids into a formation can lead to swelling, which can cause issues with the collapse of the wellbore. Furthermore, the filter cake that forms on the wall of the borehole can increase the risks of pipe sticking and damage to the wellbore (Blkoor and Ka 2013; Mao et al. 2015). The rate of filtration tends to decrease as the fluid viscosity increases, primarily due to the characteristics of the filter

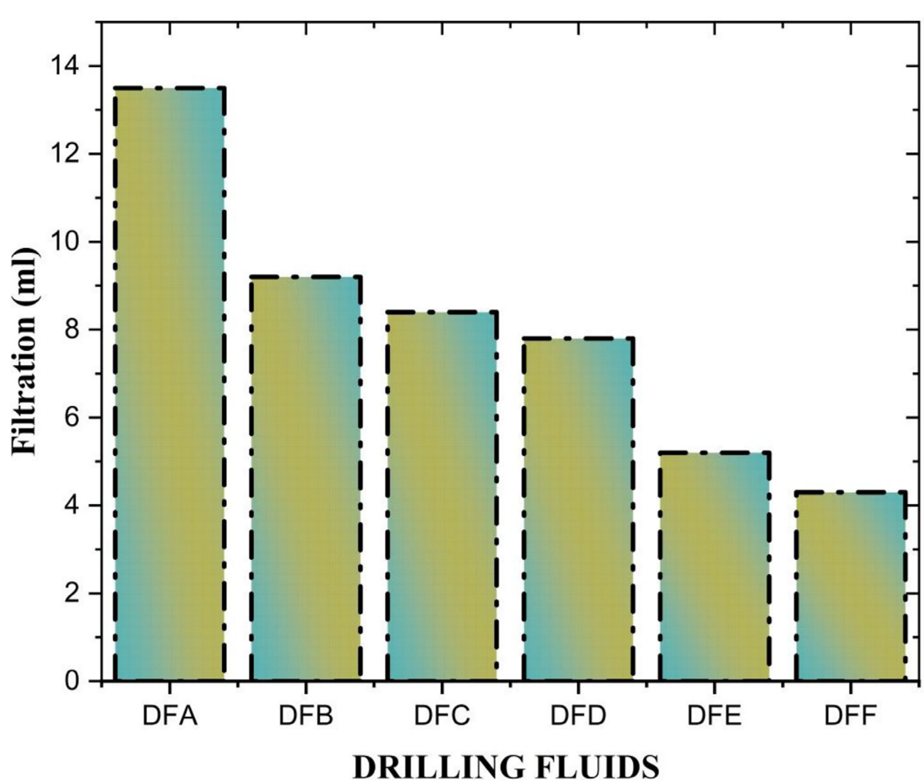

Fig. 8—Concentration of graphene affects the filtrate volume (mL).

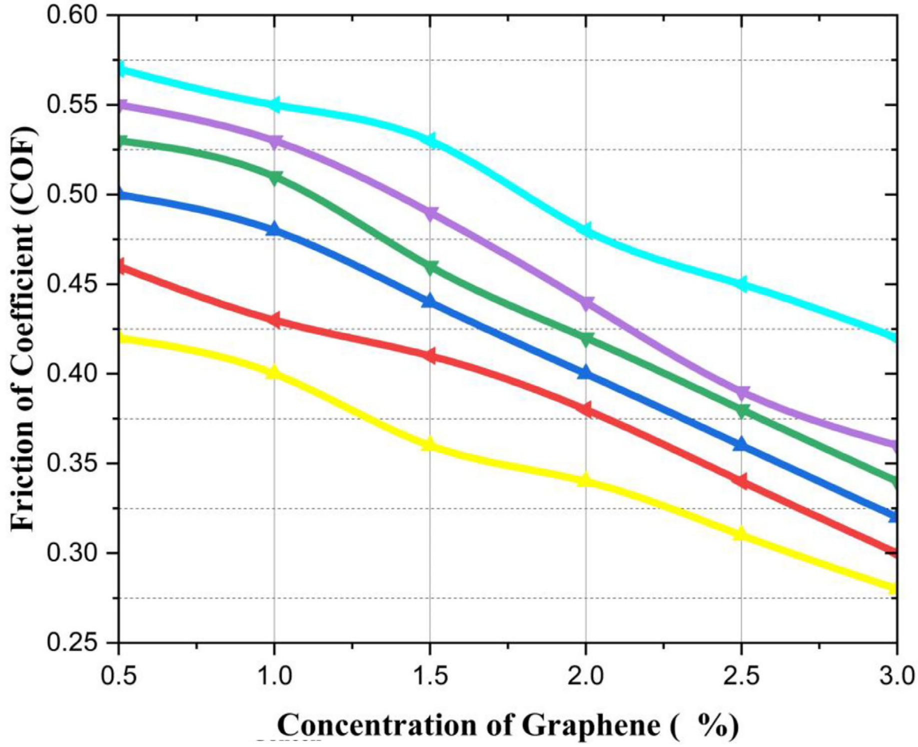

Fig. 9—COF of samples.

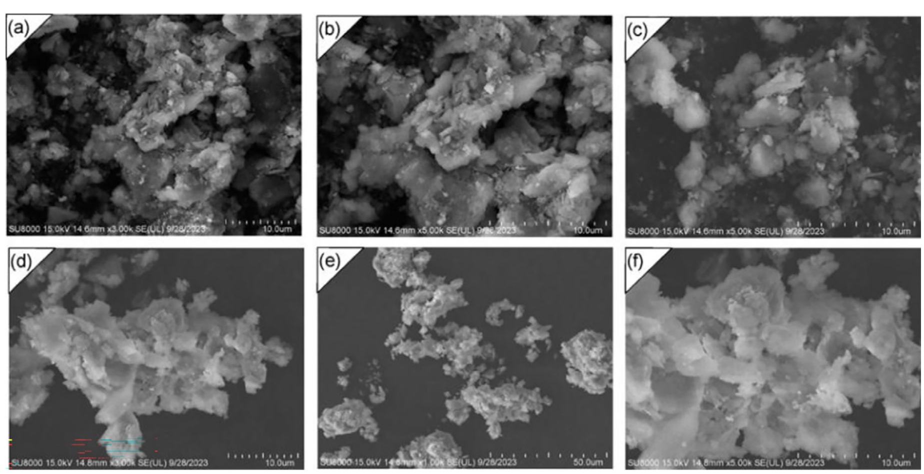

Fig. 10—Surface morphology of dried filter cake by SEM.

cake formed during the filtration process. When a drilling fluid passes through a permeable formation or filter medium, it forms a filter cake on the surface. This filter cake acts as a barrier, preventing further fluid loss and the passage of solid particles into the formation. However, the formation of a thicker and more viscous filter cake can impede fluid flow through the filter medium, reducing the rate of filtration. Higher fluid viscosity results in the formation of a denser and more impermeable filter cake, which offers greater resistance to fluid flow. As a result, the rate at which the fluid passes through the filter medium decreases, leading to a slower filtration rate. Therefore, maintaining optimal fluid viscosity is crucial in drilling operations to balance the need for effective filtration with the requirements for fluid mobility and wellbore stability (Bülichen and Plank 2012). The research study utilized SEM and XRD methods to examine the structure and morphology of six distinct filter cakes. Cross-sectional SEM images of the filter cakes are presented in **Figs. 10 and 11**. The study aimed to investigate the influence of various mud additives, including Flowzan, NaOH, graphite nanoparticles, and bentonite, on the static filter cake formed during a fluid loss in WBM. The findings revealed that the filtration cake formed from bentonite, which served as the base mud, exhibited a dense, smooth, and cohesive surface with a small particle size averaging 5 µm. This information provides valuable insights into how different mud additives impact the formation and characteristics of filtration cakes. Understanding the effects of mud additives on filter-cake formation is crucial for optimizing drilling fluid formulations and enhancing wellbore stability. By analyzing the structure and properties of filtration cakes, researchers can develop strategies to improve drilling fluid performance and mitigate fluid loss issues during drilling operations.

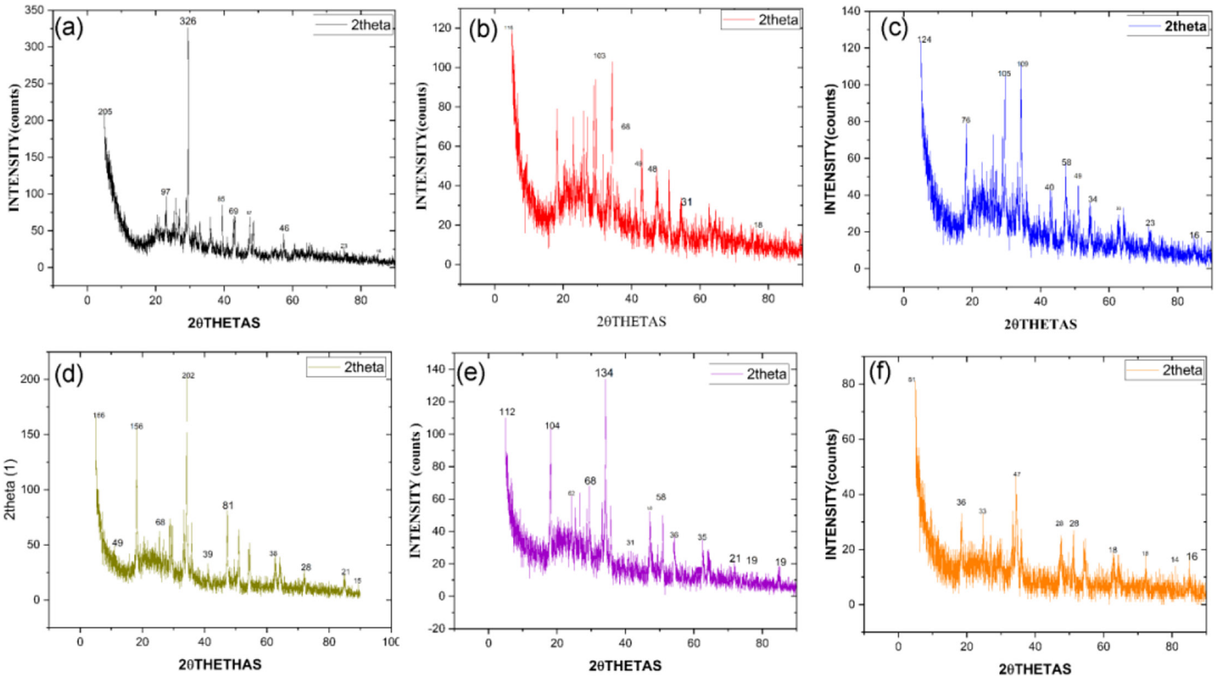

Fig. 11—XRD of filter cakes.

Conclusion

The experimental findings suggest that the addition of modified graphite has a significant positive impact on the performance of WDFs, particularly at HTs. At 300°F, the density coefficient notably decreases with the concentration of modified graphite reaching 3% in the drilling fluid. Additionally, the AV and plastic consistency of the freshwater-based drilling fluid decrease with increasing temperature, indicating the lubricating effects of the processed graphite under these conditions. Graphene plays a consistent role in forming a compact filter cake with low-solid materials, enhancing the fluid's oil capacity. The absorption of potassium and Flowzan contributes to spreading out double layers of electrical scattering, mitigating repulsiveness between particles, and improving the dispersal of graphite in the fluid or drilling fluid, thus enhancing its oil capacity. The large surface area of graphene plates necessitates additional liquid phases to wet their surfaces, efficiently increasing PV and carrying capacity. When graphene is combined with polyanionic cellulose, it influences the filter cake's microstructure, forming a tree-root-like morphology that effectively blocks micropores. Furthermore, the presence of polyhydrolytic PAM significantly affects filtration characteristics, while combining graphene with NaOH serves as an effective viscosifier, with bentonite acting as a filtration control agent. The combination of polyanionic cellulose and potassium chloride in a graphene WDF leads to improved rheological characteristics and filtration performance. However, the presence of GO in the filter-cake solution could alter its microstructure due to hydrogen bonding among oxygen-containing functional groups. The density of functional groups directly influences the strength of this hydrogen bonding. Uniform dispersion of GO plates is crucial to avoid discontinuities that could compromise the barrier against water infiltration, leading to micropore development in the mudcake structure. However, higher concentrations of GO plates result in a more robust tree-root structure, reducing the formation of micropores and decreasing fluid loss.

References

Abdo, J. and Haneef, M. D. 2012. Nano-Enhanced Drilling Fluids: Pioneering Approach to Overcome Uncompromising Drilling Problems. *J Energy Resour Technol* **134** (1): 014501. https://doi.org/10.1115/1.4005244.

Addagalla, A., Maley, I., Moroni, L. et al. 2018. Nano-Technology Based Bridging System Helps Drilling Success in Highly Depleted Mature Fields. Paper presented at the Abu Dhabi International Petroleum Exhibition & Conference, Abu Dhabi, UAE, 12−15 November. https://doi.org/10.2118/193153-MS.

Aftab, A., Ismail, A. R., Khokhar, S. et al. 2016. Novel Zinc Oxide Nanoparticles Deposited Acrylamide Composite Used for Enhancing the Performance of Water-Based Drilling Fluids at Elevated Temperature Conditions. *J Pet Sci Eng* **146**: 1142–1157. https://doi.org/10.1016/j.petrol.2016.08.014.

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. *J Petrol Explor Prod Technol* **10** (8): 3389–3397. https://doi.org/10.1007/s13202-020-00933-1.

Akpan, E. U., Enyi, G. C., Nasr, G. et al. 2019. Water-Based Drilling Fluids for High-Temperature Applications and Water-Sensitive and Dispersible Shale Formations. *J Pet Sci Eng* **175**: 1028–1038. https://doi.org/10.1016/j.petrol.2019.01.002.

Akpan, E. U., Enyi, G. C., and Nasr, G. G. 2020. Enhancing the Performance of Xanthan Gum in Water-Based Mud Systems Using an Environmentally Friendly Biopolymer. *J Petrol Explor Prod Technol* **10** (5): 1933–1948. https://doi.org/10.1007/s13202-020-00837-0.

AlBajalan, A. R. and Haias, H. K. 2021. Evaluation of the Performance of Conventional Water-Based Mud Characteristics by Applying Zinc Oxide and Silica Dioxide Nanoparticle Materials for a Selected Well in the Kurdistan/Iraq Oil Field. *Adv Mater Sci Eng* **2021** (1): 4376366. https://doi.org/10.1155/2021/4376366.

Al-Bazali, T. M. 2005. *Experimental Study of the Membrane Behavior of Shale during Interaction with Water-Based and Oil-Based Muds*. PhD thesis, The University of Texas at Austin, Austin, Texas, USA. https://doi.org/10.2118/100735-MS.

Al-saba, M. T., Al Fadhli, A. ., Marafi, A. . et al. 2018. Application of Nanoparticles in Improving Rheological Properties of Water Based Drilling Fluids. Paper presented at the SPE Kingdom of Saudi Arabia Annual Technical Symposium and Exhibition, Dammam, Saudi Arabia, 23−26 April. https://doi.org/10.2118/192239-MS.

Alshubbar, G. D., Coryell, T. N., Atashnezhad, A. et al. 2017. The Effect of Barite Nanoparticles on the Friction Coefficient and Rheology of Water-Based Mud. Paper presented at the ARMA US Rock Mechanics/Geomechanics Symposium, San Francisco, California, USA, 25−28 June.

Amanullah, M. and Al-Tahini, A. M. 2009. Nano-Technology - Its Significance in Smart Fluid Development for Oil and Gas Field Application. Paper presented at the SPE Saudi Arabia Section Technical Symposium, Al-Khobar, Saudi Arabia, 9−11 May. https://doi.org/10.2118/126102-MS.

Amanullah, M., AlArfaj, M. K., and Al-abdullatif, Z. A. 2011. Preliminary Test Results of Nano-Based Drilling Fluids for Oil and Gas Field Application. Paper presented at the SPE/IADC Drilling Conference and Exhibition, Amsterdam, The Netherlands,1−3 March. https://doi.org/10.2118/139534-MS.

Anand, S., Paxson, A. T., Dhiman, R. et al. 2012. Enhanced Condensation on Lubricant-Impregnated Nanotextured Surfaces. *ACS Nano* **6** (11): 10122–10129. https://doi.org/10.1021/nn303867y.

An, Z., Ningde, J., Lusheng, Z. et al. 2014. Liquid Holdup Measurement in Horizontal Oil–Water Two-Phase Flow by Using Concave Capacitance Sensor. *Measurement (Lond)* **49**: 153–163. https://doi.org/10.1016/j.measurement.2013.11.036.

Anoop, K., Sadr, R., Yrac, R. et al. 2019. Rheology of a Colloidal Suspension of Carbon Nanotube Particles in a Water-Based Drilling Fluid. *Powder Technol* **342**: 585–593. https://doi.org/10.1016/j.powtec.2018.10.016.

Antonelou, A., Benekou, V., Dracopoulos, V. et al. 2018. Laser-Induced Transformation of Graphitic Materials to Two-Dimensional Graphene-like Structures at Ambient Conditions. *Nanotechnology* **29** (38). https://doi.org/10.1088/1361-6528/aacf85.

Apaleke, A. S., Al-Majed, A., and Hossain, M. E. 2012. Drilling Fluid: State of The Art and Future Trend. Paper presented at the North Africa Technical Conference and Exhibition, Cairo, Egypt, 20−22 February. https://doi.org/10.2118/149555-MS.

Aramendiz, J. and Imqam, A. 2019. Water-Based Drilling Fluid Formulation Using Silica and Graphene Nanoparticles for Unconventional Shale Applications. *J Pet Sci Eng* **179**: 742–749. https://doi.org/10.1016/j.petrol.2019.04.085.

Aston, M. S., Hearn, P. J., and McGhee, G. 1998. Techniques for Solving Torque and Drag Problems in Today's Drilling Environment. Paper presented at the SPE Annual Technical Conference and Exhibition, New Orleans, Louisiana, USA, 27−30 September. https://doi.org/10.2523/48939-MS.

Azimi Dijvejin, Z., Ghaffarkhah, A., Sadeghnejad, S. et al. 2019. Effect of Silica Nanoparticle Size on the Mechanical Strength and Wellbore Plugging Performance of SPAM/Chromium (III) Acetate Nanocomposite Gels. *Polym J* **51** (7): 693–707. https://doi.org/10.1038/s41428-019-0178-3.

Barroso, A. L., Marcelino, C. P., Leal, A. B. et al. 2018. New Generation Nano Technology Drilling Fluids Application Associated to Geomechanic Best Practices: Field Trial Record in Bahia - Brazil. Paper presented at the Offshore Technology Conference, Houston, Texas, USA, 30 April−3 May. https://doi.org/10.4043/28731-MS.

Barry, M. M., Jung, Y., Lee, J.-K. et al. 2015. Fluid Filtration and Rheological Properties of Nanoparticle Additive and Intercalated Clay Hybrid Bentonite Drilling Fluids. *J Pet Sci Eng* **127**: 338–346. https://doi.org/10.1016/j.petrol.2015.01.012.

Batchelor, G. K. 1956. On Steady Laminar Flow with Closed Streamlines at Large Reynolds Number. *J Fluid Mech* **1** (2): 177–190. https://doi.org/10.1017/S0022112056000123.

Bayat, A. E., Jalalat Moghanloo, P., Piroozian, A. et al. 2018. Experimental Investigation of Rheological and Filtration Properties of Water-Based Drilling Fluids in Presence of Various Nanoparticles. *Colloids Surf A: Physicochem Eng Aspects* **555**: 256–263. https://doi.org/10.1016/j.colsurfa.2018.07.001.

Benyounes, K., Mellak, A., and Benchabane, A. 2010. The Effect of Carboxymethylcellulose and Xanthan on the Rheology of Bentonite Suspensions. *Energy Sources Part A Recovery, Utilization, and Environmental Effects* **32** (17): 1634–1643. https://doi.org/10.1080/15567030902842244.

Blkoor, S. O. and Ka, F. 2013. The Influence of XC-Polymer on Drilling Fluid Filter Cake Properties and Formation Damage. *J Pet Environ Biotechnol* **04** (5). https://doi.org/10.4172/2157-7463.1000157.

Boyou, N. V., Ismail, I., Wan Sulaiman, W. R. et al. 2019. Experimental Investigation of Hole Cleaning in Directional Drilling by Using Nano-Enhanced Water-Based Drilling Fluids. *J Pet Sci Eng* **176**: 220–231. https://doi.org/10.1016/j.petrol.2019.01.063.

Brinkman, H. C. 1949. A Calculation of the Viscous Force Exerted by A Flowing Fluid on A Dense Swarm of Particles. *Appl Sci Res* **1** (1): 27–34. https://doi.org/10.1007/BF02120313.

Bülichen, D. and Plank, J. 2012. The Role of Colloidal Polymer Is Associated with the Effectiveness of Hydroxyethyl Cellulose as a Fluid Loss Control Additive in Oil Well Cement. *J Appl Polym Sci* **126** (S1): E25–E34. https://doi.org/10.1002/app.36529.

Cheraghian, G. 2021. Nanoparticles in Drilling Fluid: A Review of the State-of-the-Art. *J Mater Res Technol* **13**: 737–753. https://doi.org/10.1016/j.jmrt.2021.04.089.

Du, W.-C., Wang, X.-Y., Liu, M. et al. 2019. Synthesis and Performance of AM/SSS/THDAB as Clay Hydration Dispersion Inhibitor. *Polímeros* **29** (4). https://doi.org/10.1590/0104-1428.06519.

Einstein, A. 1906. Doc. 34 On The Theory of Light Production and Light Absorption. *J Ann Phys*: 199–206. https://doi.org/10.1002/andp.19063250613.

El-Diasty, A. I. and Ragab, A. M. 2013. Applications of Nanotechnology in the Oil & Gas Industry: Latest Trends Worldwide & Future Challenges in Egypt. Paper presented at the North Africa Technical Conference and Exhibition, Cairo, Egypt, 15−17 April. https://doi.org/10.2118/164716-MS.

Elkatatny, S. M., Mahmoud, M. A., and Nasr-El-Din, H. A. 2012. Characterization of Filter Cake Generated by Water-Based Drilling Fluids Using CT Scan. *SPE Drill & Compl* **27** (2): 282–293. https://doi.org/10.2118/144098-PA.

Ezeakacha, C. P. and Salehi, S. 2019. Experimental and Statistical Investigation of Drilling Fluid Loss in Porous Media: Part 2 (Fractures). *J Nat Gas Sci Eng* **65**: 257–266. https://doi.org/10.1016/j.jngse.2019.03.007.

Fagundes, F. M., Santos, N. B. C., Damasceno, J. J. R. et al. 2018. Study on the Stability of a Shear-Thinning Suspension Used in Oil Well Drilling. *Oil & Gas Sci Technol - Rev IFP Energ Nouv* **73**: 10. https://doi.org/10.2516/ogst/2018007.

Fatihah Majid, N. F., Katende, A., Ismail, I. et al. 2019. A Comprehensive Investigation on the Performance of Durian Rind as a Lost Circulation Material in Water Based Drilling Mud. *Petrol* **5** (3): 285–294. https://doi.org/10.1016/j.petlm.2018.10.004.

Gang, C., Gao, L., Sun, Y. et al. 2019. A Green Shale Inhibitor Developed from Lignin Sulfonate and the Mechanism Study. *J Biobased Mat Bioenergy* **13** (6): 778–783. https://doi.org/10.1166/jbmb.2019.1908.

Gbadamosi, A. O., Junin, R., Manan, M. A. et al. 2018. Recent Advances and Prospects in Polymeric Nanofluids Application for Enhanced Oil Recovery. *J Ind Eng Chem* **66**: 1–19. https://doi.org/10.1016/j.jiec.2018.05.020.

Guardia, L., Fernández-Merino, M. J., Paredes, J. I. et al. 2011. High-Throughput Production of Pristine Graphene in an Aqueous Dispersion Assisted by Non-Ionic Surfactants. *Carbon* **49** (5): 1653–1662. https://doi.org/10.1016/j.carbon.2010.12.049.

Hafshejani, K. S., Moslemizadeh, A., and Shahbazi, K. 2016. A Novel Bio-Based Deflocculant for Bentonite Drilling Mud. *Appl Clay Sci* **127–128**: 23–34. https://doi.org/10.1016/j.clay.2016.03.037.

Hakim, H., Katende, A., Sagala, F. et al. 2018. Performance of Polyethylene and Polypropylene Beads towards Drill Cuttings Transportation in Horizontal Wellbore. *J Pet Sci Eng* **165**: 962–969. https://doi.org/10.1016/j.petrol.2018.01.075.

Hemmati-Sarapardeh, A., Varamesh, A., Husein, M. M. et al. 2018. On the Evaluation of the Viscosity of Nanofluid Systems: Modeling and Data Assessment. *Renew Sustain Energy Rev* **81**: 313–329. https://doi.org/10.1016/j.rser.2017.07.049.

Hirata, M., Gotou, T., Horiuchi, S. et al. 2004. Thin-Film Particles of Graphite Oxide 1:High-Yield Synthesis and Flexibility of the Particles. *Carbon* **42** (14): 2929–2937. https://doi.org/10.1016/S0008-6223(04)00444-0.

Honary, S. and Zahir, F. 2013. Effect of Zeta Potential on the Properties of Nano-Drug Delivery Systems - A Review (Part 1). *Trop J Pharm Res* **12** (2): 4314. https://doi.org/10.4314/tjpr.v12i2.19.
Hussain, A., Mehdi, S. M., Abbas, N. et al. 2020. Synthesis of Graphene from Solid Carbon Sources: A Focused Review. *Mat Chem Phys* **248**: 122924. https://doi.org/10.1016/j.matchemphys.2020.122924.
Hyne, N. J. 2014. *Dictionary of Petroleum Exploration, Drilling & Production*. Tulsa, Oklahoma, USA: PennWell Corp..
Ikram, R., Mohamed Jan, B., Abdul Qadir, M. et al. 2021. Recent Advances in Chitin and Chitosan/Graphene-Based Bio-Nanocomposites for Energetic Applications. *Polymers (Basel*) **13** (19). https://doi.org/10.3390/polym13193266.
Ismail, A. R., Aftab, A., Ibupoto, Z. H. et al. 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. *J Pet Sci Eng* **139**: 264–275. https://doi.org/10.1016/j.petrol.2016.01.036.
Ismail, A. R., Mohd Norddin, M. N. A., Latefi, N. A. S. et al. 2020. Evaluation of a Naturally Derived Tannin Extracts Biopolymer Additive in Drilling Muds for High-Temperature Well Applications. *J Petrol Explor Prod Technol* **10** (2): 623–639. https://doi.org/10.1007/s13202-019-0717-7.
Ismail, A. and Paramasivam, R. 2016. Nanomaterial Additive in Oil-Based Mud for High-Temperature Condition. *Y Petro*: 39–52.
Jie-nian, Y. 2001. *Drilling Fluid Technology*. Dongying, Shandong: University of Petroleum Press.
Katende, A., Boyou, N. V., Ismail, I. et al. 2019. Improving the Performance of Oil Based Mud and Water Based Mud in a High Temperature Hole Using Nanosilica Nanoparticles. *Colloids Surf A: Physicochem Eng Aspects* **577**: 645–673. https://doi.org/10.1016/j.colsurfa.2019.05.088.
Kosynkin, D. V., Ceriotti, G., Wilson, K. C. et al. 2012. Graphene Oxide as a High-Performance Fluid-Loss-Control Additive in Water-Based Drilling Fluids. *ACS Appl Mater Interfaces* **4** (1): 222–227. https://doi.org/10.1021/am2012799.
Krieger, I. M. and Dougherty, T. J. 1959. A Mechanism for Non-Newtonian Flow in Suspensions of Rigid Spheres. *Trans Soc Rheol* **3** (1): 137–152. https://doi.org/10.1122/1.548848.
Kuila, T., Bose, S., Mishra, A. K. et al. 2012. Chemical Functionalization of Graphene and Its Applications. *Prog Mater Sci* **57** (7): 1061–1105. https://doi.org/10.1016/j.pmatsci.2012.03.002.
Kusrini, E., Oktavianto, F., Usman, A. et al. 2020. Synthesis, Characterization, and Performance of Graphene Oxide and Phosphorylated Graphene Oxide as Additive in Water-Based Drilling Fluids. *Appl Surf Sci* **506**. https://doi.org/10.1016/j.apsusc.2019.145005.
Li, Y. and Radonjic, M. 2019. Microstructural Comparison of the Impact of Drilling Fluids Contamination and Casing Corrosion on Wellbore Cement Barriers. Paper presented at the 53rd U.S. Rock Mechanics/Geomechanics Symposium, New York City, New York, USA, 23−26 June.
Liu, X., He, X., Lin, Y. et al. 2021. Enhanced Adhesion Strength and Solid Lubricity of Graphite like Amorphous Carbon Films by Hydrogen Implantation. *Surf Coatings Technol* **412**: 127013. https://doi.org/10.1016/j.surfcoat.2021.127013.
Liu, L., Kumar, S. B., Ouyang, Y. et al. 2011. Performance Limits of Monolayer Transition Metal Dichalcogenide Transistors. *IEEE Trans Electron Devices* **58** (9): 3042–3047. https://doi.org/10.1109/TED.2011.2159221.
Liu, F., Yang, D., Liu, Y. et al. 2018. Improving Dispersive Property, Biocompatibility and Targeting Gene Transfection of Graphene Oxide by Covalent Attachment of Polyamidoamine Dendrimer and Glycyrrhetinic Acid. *Colloids Surf B Biointerfaces* **171**: 622–628. https://doi.org/10.1016/j.colsurfb.2018.07.067.
Livescu, S. 2012. Mathematical Modeling of Thixotropic Drilling Mud and Crude Oil Flow in Wells and Pipelines—A Review. *J Pet Sci Eng* **98–99**: 174–184. https://doi.org/10.1016/j.petrol.2012.04.026.
Magzoub, M., Mahmoud, M., Nasser, M. et al. 2019. Thermochemical Upgrading of Calcium Bentonite for Drilling Fluid Applications. *J Energy Resour Technol* **141** (4): 042902. https://doi.org/10.1115/1.4041843.
Mao, H., Qiu, Z., Shen, Z. et al. 2015. Hydrophobic Associated Polymer Based Silica Nanoparticles Composite with Core–Shell Structure as a Filtrate Reducer for Drilling Fluid at Utra-High Temperature. *J Pet Sci Eng* **129**: 1–14. https://doi.org/10.1016/j.petrol.2015.03.003.
Medhekar, N. V., Ramasubramaniam, A., Ruoff, R. S. et al. 2010. Hydrogen Bond Networks in Graphene Oxide Composite Paper: Structure and Mechanical Properties. *ACS Nano* **4** (4): 2300–2306. https://doi.org/10.1021/nn901934u.
Mme, U. and Skalle, P. 2012. Effects of Mud Properties, Hole Size, Drill String Tripping Speed, and Configurations on Swab and Surge Pressure Magnitude during Drilling Operations. *Int J Pet Sci Technol*: 143–153.
Mohammadsalehi, M. and Malekzadeh, N. 2011. Application of New Hole Cleaning Optimization Method within All Ranges of Hole Inclinations. Paper presented at the International Petroleum Technology Conference, Bangkok, Thailand,15−17 November. https://doi.org/10.2523/IPTC-14154-MS.
Mooney, M. 1940. The Viscosity of a Concentrated Suspension of Spherical Particles. *J Colloid Sci* **6** (2): 162–170.
Motozuka, S., Sato, H., Muramatsu, Y. et al. 2020. Interfacial Effect between Graphite and Iron Substrate on Basal Plane Orientation and Lubricity of Graphite. *Tribol Int* **151**: 106455. https://doi.org/10.1016/j.triboint.2020.106455.
Muramatsu, H., Kim, Y. A., Yang, K.-S. et al. 2014. Rice Husk-Derived Graphene with Nano-Sized Domains and Clean Edges. *Small* **10** (14): 2766–2770. https://doi.org/10.1002/smll.201400017.
Nielsen, J. K., Rasmussen, H. K., Hassager, O. et al. 2006. Elongational Viscosity of Monodisperse and Bidisperse Polystyrene Melts. *J Rheol (N Y N Y)* **50** (4): 453–476. https://doi.org/10.1122/1.2206711.
Ogunrinde, J. O. and Dosunmu, A. 2012. Hydraulics Optimization For Efficient Hole Cleaning in Deviated and Horizontal Wells. Paper presented at the Nigeria Annual International Conference and Exhibition, Lagos, Nigeria, 6−8 August. https://doi.org/10.2118/162970-MS.
Oseh, J. O., Norddin, M. N. A. M., Ismail, I. et al. 2024. Sodium Dodecyl Sulphate-Treated Nanohydroxyapatite as an Efficient Shale Stabilizer for Water-Based Drilling Fluids. *Arab J Chem* **17** (6): 105760. https://doi.org/10.1016/j.arabjc.2024.105760.
Parizad, A., Shahbazi, K., and Tanha, A. A. 2018. SiO2 Nanoparticle and KCl Salt Effects on Filtration and Thixotropical Behavior of Polymeric Water Based Drilling Fluid: With Zeta Potential and Size Analysis. *Results Phys* **9**: 1656–1665. https://doi.org/10.1016/j.rinp.2018.04.037.
Park, S., Lee, K.-S., Bozoklu, G. et al. 2008. Graphene Oxide Papers Modified by Divalent Ions-Enhancing Mechanical Properties via Chemical Cross-Linking. *ACS Nano* **2** (3): 572–578. https://doi.org/10.1021/nn700349a.
Perween, S., Beg, M., Shankar, R. et al. 2018. Effect of Zinc Titanate Nanoparticles on Rheological and Filtration Properties of Water Based Drilling Fluids. *J Pet Sci Eng* **170**: 844–857. https://doi.org/10.1016/j.petrol.2018.07.006.
Qamar, S., Yasin, S., Ramzan, N. et al. 2019. Preparation of Stable Dispersion of Graphene Using Copolymers: Dispersity and Aromaticity Analysis. *Soft Mater* **17** (2): 190–202. https://doi.org/10.1080/1539445X.2019.1583673.
Quigley, M. C. 1989. Advanced Technology for Laboratory Measurements of Drilling Fluid Friction Coefficient. Paper presented at the SPE Annual Technical Conference and Exhibition, San Antonio, Texas, USA, 8−11 October. https://doi.org/10.2118/19537-MS.
Rafieefar, A., Sharif, F., Hashemi, A. et al. 2021. Rheological Behavior and Filtration of Water-Based Drilling Fluids Containing Graphene Oxide: Experimental Measurement, Mechanistic Understanding, and Modeling. *ACS Omega* **6** (44): 29905–29920. https://doi.org/10.1021/acsomega.1c04398.
Raheem, A. M. and Vipulanandan, C. 2020. Salt Contamination and Temperature Impacts on the Rheological and Electrical Resistivity Behaviors of Water Based Drilling Mud. *Energy Sources Part A Recovery Utilization Environmental Effects* **42** (3): 344–364. https://doi.org/10.1080/15567036.2019.1587080.

Rana, A., Arfaj, M. K., Yami, A. S. et al. 2020. Cetyltrimethylammonium Modified Graphene as a Clean Swelling Inhibitor in Water-Based Oil-Well Drilling Mud. *J Environ Chem Eng* **8** (4): 103802. https://doi.org/10.1016/j.jece.2020.103802.
Ravichandran, K., Palaniraj, R., Saw, N. M. M. T. et al. 2014. Effects of Different Encapsulation Agents and Drying Process on Stability of Betalains Extract. *J Food Sci Technol* **51** (9): 2216–2221. https://doi.org/10.1007/s13197-012-0728-6.
Romero-Anaya, A. J., Ouzzine, M., Lillo-Ródenas, M. A. et al. 2014. Spherical Carbons: Synthesis, Characterization and Activation Processes. *Carbon N Y* **68**: 296–307. https://doi.org/10.1016/j.carbon.2013.11.006.
Salih, A. H. and Bilgesu, H. 2017. Investigation of Rheological and Filtration Properties of Water-Based Drilling Fluids Using Various Anionic Nanoparticles. Paper presented at the SPE Western Regional Meeting, Bakersfield, California, USA, 23−27 April. https://doi.org/10.2118/185638-MS.
Samuel, R. 2010. Friction Factors: What Are They for Torque, Drag, Vibration, Bottom Hole Assembly and Transient Surge/Swab Analyses? Paper presented at the IADC/SPE Drilling Conference and Exhibition, New Orleans, Louisiana, USA, 2−4 February. https://doi.org/10.2118/128059-MS.
Saner, B., Okyay, F., and Yürüm, Y. 2010. Utilization of Multiple Graphene Layers in Fuel Cells. 1. An Improved Technique for the Exfoliation of Graphene-Based Nanosheets from Graphite. *Fuel (Lond)* **89** (8): 1903–1910. https://doi.org/10.1016/j.fuel.2010.03.036.
Sensoy, T., Chenevert, M. E., and Sharma, M. M. 2009. Minimizing Water Invasion in Shale Using Nanoparticles. Paper presented at the SPE Annual Technical Conference and Exhibition, New Orleans, Louisiana, 4−7 October. https://doi.org/10.2118/124429-MS.
Shanker, U. and Rani, M. 2022. *Liquid and Crystal Nanomaterials for Water Pollutants Remediation*. Boca Raton, Florida, USA: CRC Press.
Sharma, M. M., Zhang, R., Chenevert, M. E. et al. 2012. A New Family of Nanoparticle-Based Drilling Fluids, Society of Petroleum Engineers. Paper presented at the SPE Annual Technical Conference and Exhibition, San Antonio, Texas, USA, 8−10 October. https://doi.org/10.2118/160045-MS.
Siddique, S., Kwoffie, L., Addae-Afoakwa, K. et al. 2017. Oil Based Drilling Fluid Waste: An Overview on Environmentally Persistent Pollutants. *IOP Conf Ser Mater Sci Eng* **195** (1): 012008. https://doi.org/10.1088/1757-899X/195/1/012008.
Skalle, P. 2011. *Drilling Fluid Engineering*. Copenhagen, Denmark: Bookboon.
Song, K., Wu, Q., Li, M.-C. et al. 2016. Performance of Low Solid Bentonite Drilling Fluids Modified by Cellulose Nanoparticles. *J Nat Gas Sci Eng* **34**: 1403–1411. https://doi.org/10.1016/j.jngse.2016.08.036.
Sun, J., Chang, X., Lv, K. et al. 2020. Salt-Responsive Zwitterionic Copolymer as Tackifier in Brine Drilling Fluids. *J Mol Liq* **319**: 114345. https://doi.org/10.1016/j.molliq.2020.114345.
Sun, J., Chang, X., Lv, K. et al. 2021. Environmentally Friendly and Salt-Responsive Polymer Brush Based on Lignin Nanoparticle as Fluid-Loss Additive in Water-Based Drilling Fluids. *Colloids Surf A: Physicochem Eng Aspects* **621**: 126482. https://doi.org/10.1016/j.colsurfa.2021.126482.
Taha, N. M. and Lee, S. 2015. Nano Graphene Application Improving Drilling Fluids Performance. Paper presented at the International Petroleum Technology Conference, Doha, Qatar, 6−9 December. https://doi.org/10.2523/IPTC-18539-MS.
Tian, J. 1995. The Effect of Graphite Crystal Structure and Graphite Intercalation Compounds on Friction Properties. *New Carbon Mater* **33**: 54–58.
Urie, R., Ghosh, D., Ridha, I. et al. 2018. Inorganic Nanomaterials for Soft Tissue Repair and Regeneration. *Annu Rev Biomed Eng* **20** (1): 353–374. https://doi.org/10.1146/annurev-bioeng-071516-044457.
Urmi, W. T., Rahman, M. M., Kadirgama, K. et al. 2022. A Comprehensive Review on Thermal Conductivity and Viscosity of Nanofluids. *ARFMTS* **91** (2): 15–40. https://doi.org/10.37934/arfmts.91.2.1540.
Vipulanandan, C. and Mohammed, A. 2015. Smart Cement Modified with Iron Oxide Nanoparticles to Enhance the Piezoresistive Behavior and Compressive Strength for Oil Well Applications. *Smart Mater Struct* **24** (12): 125020. https://doi.org/10.1088/0964-1726/24/12/125020.
Vryzas, Z., Nalbandian, L., Zaspalis, V. T. et al. 2019. How Different Nanoparticles Affect the Rheological Properties of Aqueous Wyoming Sodium Bentonite Suspensions. *J Pet Sci Eng* **173**: 941–954. https://doi.org/10.1016/j.petrol.2018.10.099.
William, J. K. M., Gupta, P., and Sangwai, J. S. 2021. Interaction of Lubricants on the Rheological and Filtration Loss Properties of Water-Based Drilling Fluids. *Petrol Sci Technol* **39** (7–8): 235–248.
Wissing, S. A., Kayser, O., and Müller, R. H. 2004. Solid Lipid Nanoparticles for Parenteral Drug Delivery. *Adv Drug Deliv Rev* **56** (9): 1257–1272. https://doi.org/10.1016/j.addr.2003.12.002.
Wu, A. and Hareland, G. 2012. Calculation of Friction Coefficient and Downhole Weight on a Bit with Finite Element Analysis of Drill String. Paper presented at the 46th U.S. Rock Mechanics/Geomechanics Symposium, Chicago, Illinois, USA, 24−27 June.
Yu, X. Z. 1985. The Application of Solid Lubricants-Graphite Powder in Well Completion Operations. *Pet Drill Prod Technol* **9**: 38.
Zakaria, M. F., Husein, M., and Hareland, G. 2012. Novel Nanoparticle-Based Drilling Fluid with Improved Characteristics. Paper presented at the SPE International Oilfield Nanotechnology Conference and Exhibition, Noordwijk, The Netherlands, 12−14 June. https://doi.org/10.2118/156992-MS.
Zhang, R., Gao, L., Duan, W. et al. 2019. The Application of Ferric Chloride-Lignin Sulfonate as Shale Inhibitor in Water-Based Drilling Fluid. *Molecules* **24** (23). https://doi.org/10.3390/molecules24234331.
Zhu, M., Wang, J., Holloway, B. C. et al. 2007. A Mechanism for Carbon Nanosheet Formation. *Carbon N Y* **45** (11): 2229–2234. https://doi.org/10.1016/j.carbon.2007.06.017.
Zoveidavianpoor, M. and Samsuri, A. 2016. The Use of Nano-Sized Tapioca Starch as a Natural Water-Soluble Polymer for Filtration Control in Water-Based Drilling Muds. *J Nat Gas Sci Eng* **34**: 832–840. https://doi.org/10.1016/j.jngse.2016.07.048.