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Study of the Impact of Water Droplets on the Rheological Behaviour of Water-in-Oil Invert Emulsion Fluids

Rabah Amara[1], Rezki Akkal[2]* and Ratiba Mitiche[3]

[1]Hydraulic Engineering, Water Sciences Laboratory, National Polytechnic School, Department of Hydraulic Engineering, El Harrach, Algiers, Algeria
[2]National Polytechnic School, Department of Mining Engineering, Algiers, Algeria; rezki.akkal@g.enp.edu.dz
[3]National Polytechnic School, Department of Civil Engineering, Algiers, Algeria

Abstract

The rheological properties and stability of Water-in-Oil (W/O) emulsions in drilling fluids are critical for improving drilling efficiency. This study investigates the effects of varying water-to-oil ratios (10/90, 15/85, 20/80, and 30/70) and organoclay concentrations (0.1%, 0.15%, 0.20%, 0.30%, 0.50%, and 0.75% (m/m)) on emulsion behavior. Viscosity measurements demonstrate consistent shear-thinning, typical of non-Newtonian fluids. Increasing water content enhances initial viscosity due to stronger interfacial interactions, with the 30/70 emulsion showing the highest value. Organoclay improves emulsion stabil- ity by limiting droplet coalescence and promoting uniform dispersion. At 0.30 wt.%, emulsions with low water content (10/90) exhibit resistance to phase separation. In contrast, high water emulsions (30/70) with low organoclay levels (0.10 wt.%) display larger droplet sizes, indicating weaker stabilization. Microscopic observations confirm that higher clay loadings yield finer, more uniformly dispersed droplets, strengthening emulsion integrity under shear. Shear-thinning behavior was observed in all systems, with elevated organoclay concentrations providing enhanced viscosity retention under shear. At 0.75 wt.%, emulsions maintained higher viscosities, improving cuttings sus- pension and flow control. This dual viscosity response high at low shear, low at high shear is advantageous for drilling performance. Overall, the results emphasize optimizing water-to-oil ratios and organoclay loadings to achieve stable, effective drilling fluids.

Major Findings: *The rheology and stability of water-in-oil drilling emulsions are governed by the combined effect of water-to-oil ratio and organoclay concentration. All systems exhibited shear-thinning non-Newtonian behavior, while organoclay concentrations ≥ 0.30 wt.% significantly improved droplet dispersion and resistance to phase separation. At 0.75 wt.% organoclay, emulsions showed the highest viscosity retention and structural stability, demonstrating its key role in designing high-performance drilling fluids.*

Keywords: *Drilling Fluids, Emulsion Stability, Organoclay, Rheology, Shear-Thinning, Water-in-Oil Emulsions*

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1.0 Introduction

As environmental regulations continue to evolve, significant research efforts are being directed toward understanding the chemistry, rheology, and formulation of drilling fluids[1]. Concurrently, advancements in the

*Author for correspondence

properties of drilling fluids, such as enhanced rheological stability under extreme temperatures and pressures, have facilitated the ability to drill at increasingly greater depths, driven by technological progress[2]. Organoclay (OC) serves as an effective rheological modifier in oil-based drilling fluids (OBM) at low loading levels (< 5 wt.%)[3,4]. These fluids typically comprise invert macroemulsions with a water-in-oil (W/O) composition containing more than 5% water. Despite environmental concerns, OBMs are frequently favored over water based drilling fluids to mitigate in- teractions with rock formations[5,6]. This preference is especially pronounced under extreme pressure and temperature conditions or when drilling in tight reservoirs characterized by low permeability and porosity[7,8]. Although environmental considerations advocate for the use of mineral or synthetic oils, diesel oil continues to be the predominant choice for the continuous oil phase in drilling operations, primarily due to its cost-effectiveness[9]. The incorporation of Organoclay (OC) at this stage facilitates the achievement of optimal fluid properties across various drilling phases[10,11]. OC enhances thixotropic behavior, enabling the rapid formation of a gel to retain suspended solids when shear ceases while ensuring low viscosity under shear conditions encountered during drilling[12]. Therefore, maintaining the rheological properties of OBMs across a broad temperature range and varying depths is essential. The inhibition of shale swelling during drilling operations requires Organoclay (OC) additives to minimize interfacial interactions between OBMs and formation rock. This is achieved through two key mechanisms: (1) development of optimal surface characteristics that modify interfacial behavior, and (2) formation of an impermeable filtration barrier along the wellbore wall. OBMs employ Organoclay (OC) in combination with interfacial surfactants to optimize emulsion stability. These formulations are supplemented with wellbore-strengthening additives including sodium silicate, Partially Hydrolyzed Polyacry-lamide (PHPA), Polyanionic Cellulose (PAC), and Polyalkylene Glycols (PAG/glycol) to enhance formation integrity during drilling operations. The synergistic action of these components addresses both fluid stability and borehole maintenance requirements[13,14]. The formulation of drilling fluids is inherently complex, with their rheological properties largely determined by the interactions among three primary components: oil, water, and organic compounds[1,15]. The physicochemical interactions within these systems are governed by multiple parameters, including aqueous phase droplet dimensions, dispersed phase volume fraction, and the spatial distribution of anisotropic Organoclay (OC) platelets suspended in the oil continuum[16]. The literature provides extensive analysis of direct Oil in Water (O/W) emulsions, with numerous reviews detailing their influence on rheological properties. Comprehensive evaluations of these systems generally examine four critical parameters: (1) the volumetric proportion between hydrophilic and hydrophobic phases, (2) the inclusion of supplementary surfactant compounds functioning as emulsion stabilizers, (3) the dimensional characteristics of dispersed droplets, and (4) the morphological changes of droplets under shear conditions[17,18]. Research has consistently shown that in simple emulsions, raising the dispersed phase volume fraction causes a shift from Newtonian flow (constant viscosity across shear rates) to non-Newtonian characteristics[19,20]. The observed non-Newtonian rheological response is characterized by a dramatic viscosity decrease, frequently exceeding multiple logarithmic scales, when applied shear stress surpasses a well-defined critical value termed the yield point[21]. The rheological properties of emulsions exhibit significant dependence on droplet size characteristics. A polydisperse size distribution typically results in reduced system viscosity, though this thinning effect diminishes for emulsions containing predominantly submicron droplets. Conversely, maintaining constant dispersed phase concentration while reducing mean droplet diameter produces concurrent increases in both viscous resistance and yield stress behavior[22,23]. The behavior of droplets plays a crucial role in viscosity variations during flow. When the shear rate exceeds a critical threshold, the emulsion exhibits non-Newtonian behavior, characterized by droplet deformation under flow, eventually leading to the breakup of oil/water droplets[18]. The presence of water in oil depends not only on water droplets but also on the dispersion characteristics of swelling inorganic clay minerals, particularly in comparison to Organoclay (OC) dispersions[24]. It is well established that parameters such as clay mineral concentration in water, aspect ratio, pH, and ionic strength play a

crucial role in determining mineral dispersion. These parameters modulate interfacial electrostatic forces, consequently altering the colloidal stability and spatial arrangement of clay particles in the solvent, leading to direct impacts on the system's viscous properties[25,26]. The present study employs rheology experiments to investigate the rheological correlation between a clay mineral and droplets in Water-in-Oil (W/O) drilling fluids. This investigation focuses on analyzing the shear-dependent viscosity characteristics of gas-oil emulsions containing 10% aqueous phase (v/v), stabilized by surfactant additives. The research specifically evaluates how the rheological properties are affected by two key parameters: (1) the degree of Organoclay (OC) particle dispersion within the continuous phase, and (2) variations in the dispersed water droplet size distribution. These investigations aim to determine how droplets impact the stability of these drilling fluids. Future work should assess long-term stability under high temperature and pressure, and explore synergistic effects with alternative additives to further enhance performance in complex wellbore conditions.

2.0 Materials and Methods

2.1 Preparation of Oil-in-Water (O/W) Emulsions

Oil-in-Water (O/W) emulsions with a fixed volumetric O/W ratio of 10:90 (v/v) and an emulsifier concentration of 1% by mass were prepared through a controlled dispersion pro- cess (Figure 1). A homogeneous mixture containing 0.2 g of Versamul and Versacoat (1:1 by weight) was uniformly dispersed in 18 mL of gasoil using continuous magnetic agitation. The surfactant concentration was maintained slightly above the Critical Micelle Concentration (CMC) to ensure effective emulsification[16]. Organoclay (OC) powder was gradually incorporated into the surfactant gasoil mixture by adding small increments while stirring continuously for 15 minutes. Subsequently, 2 mL of the aqueous phase was introduced dropwise via a syringe over a duration of 2 minutes to promote uniform dispersion. The emulsion was then subjected to continuous magnetic stirring for 4 hours, followed by homogenization using an Ultra-Turrax® disperser at 7200 rpm for 5 minutes. This procedure resulted in OC-loaded emulsions with OC mass fractions of 0.1%, 0.15%, 0.20%, 0.30%, 0.50%, and 0.75% (m/m)[16].

2.2 Stability Analysis

Emulsion stability in drilling fluids was assessed with a Turbiscan analyzer, an optical instrument that tracks dispersion changes in real time through vertical scanning. This technique relies on multiple light scattering to detect changes in the internal structure of the emulsion, including sedimentation, creaming, and coalescence. By analyzing the backscattering intensity over time, the degree of instability and potential separation phenomena were quantified. The measurements were

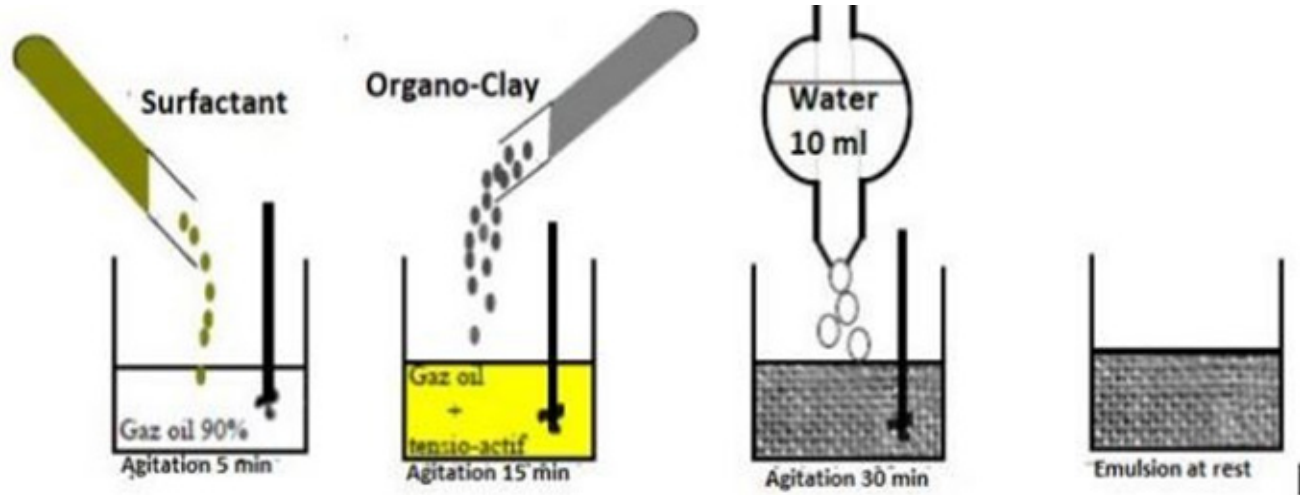


Figure 1. Experimental Procedure for Oil-in-Water (O/W) Emulsion Preparation[16].

conducted over an extended period to assess the long-term stability of the formulation. This approach ensured a comprehensive understanding of the emulsion behaviour under static conditions, which is crucial for drilling applications.

2.3 Microstructural Characterization

An optical microscope equipped with a high-resolution camera was utilized to examine the microstructure of the emulsified drilling fluids. The study focused on characterizing water droplet size distribution in the oil continuum, as this parameter significantly influences the fluid's stability and functional properties. Images were captured at various magnifications, and droplet sizes were analyzed using image processing software to ensure accurate measurements. A uniform and fine droplet distribution is indicative of a well-stabilized emulsion, whereas larger or irregular droplets may suggest coalescence or phase separation. This microscopic analysis provided key insights into the correlation between emulsion structure and its rheological properties.

2.4 Rheological Characterization

The rheological properties of the drilling fluid emulsions were investigated using an advanced rotational rheometer equipped with a cone-and-plate geometry. Viscosity measurements were conducted under varying shear rates to characterize the non-Newtonian behaviour of the fluid, which is essential for predicting its flow performance under downhole conditions. This comprehensive rheological study allowed for the optimization of the formulation to ensure effective cuttings transport and wellbore stability.

3.0 Results and Discussion

3.1 Emulsion Stability

To evaluate the stability of various drilling mud formulations, a Turbiscan device was used to monitor changes in light transmission. As shown in Figure 2, the formulation consisting solely of water and diesel oil exhibited 100% light transmission. This phenomenon is attributed to the inherent transparency of both water and diesel oil. Water allows visible light to pass through with minimal attenuation, while diesel oil, being a clear liquid, also facilitates light transmission[27]. In the absence of opaque or scattering particles, light travels through the medium unimpeded, resulting in full transmission. This observation underscores the clarity and homogeneity of the water-diesel oil formulation, indicating its stability and the absence of dispersed phases or particles that could interfere with light transmission[28]. When surfactants are introduced into the Water-in-Oil emulsion (W-O-S), the light trans- mission rate decreases to 10%, compared to the 100% transmission observed in the water- in-diesel oil emulsion Figure 2. This reduction is attributed to the presence of surfactant molecules within the water phase. Surfactants, which lower the interfacial tension between water and oil, form a stabilizing layer around water droplets, known as micelles[29]. These micelles can scatter or absorb light, thereby reducing overall transmission. As light passes through the emulsion containing surfactants, it interacts with these micelles, leading to partial absorption and scattering[30]. In contrast, the water-in-diesel oil emulsion, which lacks surfactants, allows light to pass through unobstructed. Consequently, the addition of surfactants modifies the optical properties of the emulsion, resulting in decreased

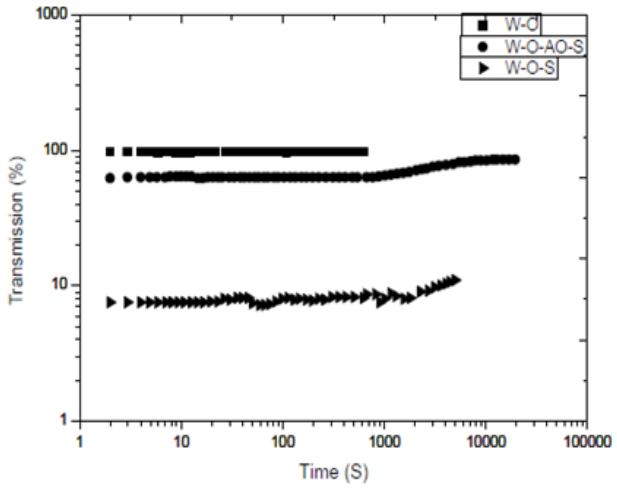


Figure 2. Transmission variation over time for the **(a)** formulation composed exclusively of water and diesel oil (W/O), **(b)** formulation composed of water, diesel and surfactant (W/O/S), and **(c)** formulation composed of water, diesel, organoclay and surfactant (W/O/S/OC).

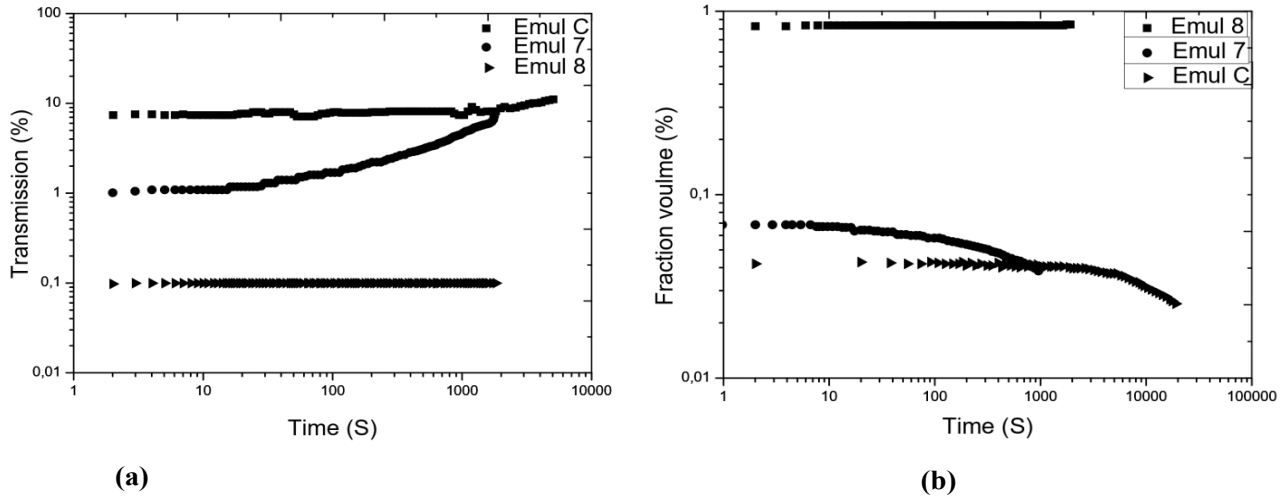


Figure 3. Comparative evolution of transmission and volume fraction in emulsions with 2% surfactant and varying organoclay levels (Emul 1%, Emul 2%, Emul 3%).

light transmission. The decrease in volume fraction over time in water-in-diesel oil emulsions stabilized with Surfactants and viscosified with organoclay can be attributed to the dynamic instability of the system[31]. Water droplets may undergo coalescence, where smaller droplets merge into larger ones, reducing their overall number and leading to a decline in volume fraction[32]. Additionally, the density difference between water and diesel oil can result in phase separation through creaming, where droplets rise to the surface, or sedimentation, where they settle at the bottom. Furthermore, organoclay particles dispersed within the emulsion can interact with water droplets, forming aggregates or flocs that are denser than individual droplets[33,34]. These flocs may settle or migrate within the emulsion, further contributing to the reduction in volume fraction over time.

Figure 3 presents the stability analysis of three water-in-diesel emulsions (Emul7, Emul8, and EmulC), evaluated through transmission (%) and volume fraction (%) measurements over time (Figures 3(a) and 3(b)). All formulations contained a constant surfactant concentration of 2%, while the organoclay content varied (2% for Emul7, 3% for Emul8, and 1% for EmulC). The transmission results reveal distinct stability behaviors: Emul7 (blue) exhibits a gradual increase in transmission over time, indicating progressive phase separation.

Separation. Emul8, which contains the highest organoclay concentration (3%), maintains a consistently low transmission, highlighting its superior stability and resistance to phase separation. The observed improvement in emulsion stability can be attributed to elevated rheological resistance resulting from greater organoclay loading, which effectively restricts droplet mobility and inhibits coalescence phenomena. These results are consistent with previous research by Akkal *et al.*[16] which established that elevated organoclay concentrations in emulsions enhance resistance to coalescence through two primary mechanisms : (1) augmentation of continuous phase viscosity, and (2) modification of particle surface wettability characteristics[35]. Conversely, EmulC (gray), with only 1% organoclay, exhibits a More pronounced increase in transmission, indicating a higher degree of instability. The lower organoclay concentration in EmulC likely resulted in insufficient viscosity to stabilize the emulsion effectively[36]. The fraction volume plot (Figure 3 (b) further confirms these trends, showing a significant decline for Emul7 and EmulC, attributed to droplet coalescence or sedimentation, while Emul8, with the highest organoclay concentration, remains stable over time. The improved stability of Emul8 is likely due to the enhanced thickening and structuring effects of the higher organoclay content, which increases viscosity and reduces droplet mobility[37,38]. These results

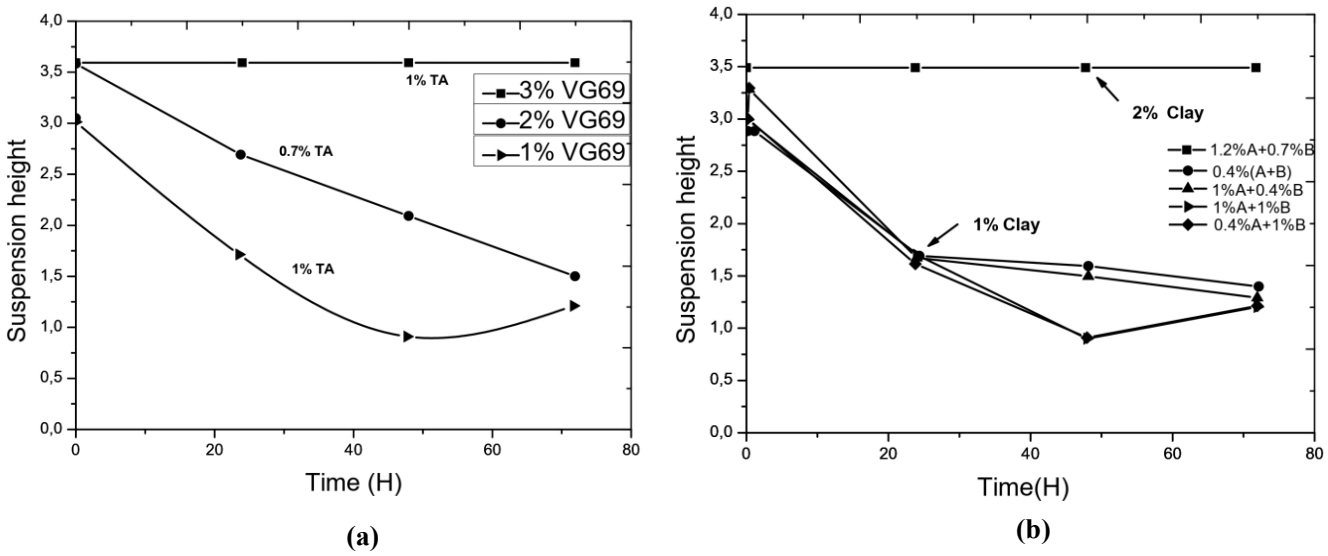


Figure 4. Effect of **(a)** VG69 Organoclay and **(b)** Surfactant on the Temporal Stability of Suspensions[16].

highlight the crucial role of both surfactant concentration and organoclay content in stabilizing water-in-diesel emulsions and preventing phase separation over time.

The results in Figure 4 indicate that VG69 organoclay markedly improves the temporal stability of suspensions compared to surfactant (TA) or Argile alone. At 2% VG69, the suspension height remains nearly unchanged over time, reflecting strong resistance to sedimentation. In contrast, systems containing only surfactant or organoclay show a progressive decline in suspension height, with more pronounced sedimentation at higher concentrations. Notably, with 3% organoclay, the suspension remains stable even in the presence of 1% surfactant, confirming the superior stabilizing effect of organoclay.

The Figure 5 presents microscopic images of four Water-in-Oil (W/O) emulsions with varying Water-to-Oil ratios (W/O) while maintaining a constant 75% clay concentration. The images highlight differences in droplet size and distribution, which are influenced by the water content in the emulsion. In Figure 5 (a) 10/90 W/O, the small and densely packed droplets suggest a more stable emulsion with efficient surfactant coverage, preventing Droplet coalescence. As the water content increases in Figure 5 (b) 15/85 W/O, larger droplets begin to appear, indicating the onset of coalescence. In Figure 5 (c) 20/80 W/O, the droplet size distribution becomes broader, and the presence of larger droplets suggests reduced emulsion stability. The microstructural evolution shown in Figure 5 (d) for the 30/70 W/O emulsion demonstrates progressive droplet coalescence, resulting in markedly enlarged aqueous domains and increased phase heterogeneity. This analysis highlights the critical role of the water-to-oil ratio in influencing droplet stability. Higher water fractions tend to promote droplet coalescence, likely due to increased interactions between dispersed water droplets, ultimately compromising the stability of the emulsion[39,40]. However, the presence of 75% clay appears to stabilize smaller droplets, as seen in images (a) and (b), suggesting that clay particles act as stabilizers, reducing coalescence at lower water fractions[41,42].

The Figure 6 illustrates the stability of Oil-in-Water (O/W) emulsions formulated with different concentrations of organoclay (1%, 2%, and 3%). In image (a), the emulsion with 1% organoclay shows visible phase separation, indicating low stability. Image (b) demonstrates better dispersion at 2% clay, though slight sedimentation is observed. In image (c), the emulsion with 3% organoclay appears more homogeneous and stable, with reduced phase separation. The increased clay concentration enhances stability due to improved interfacial adsorption and viscosity enhancement. However, excessive clay may lead to flocculation or

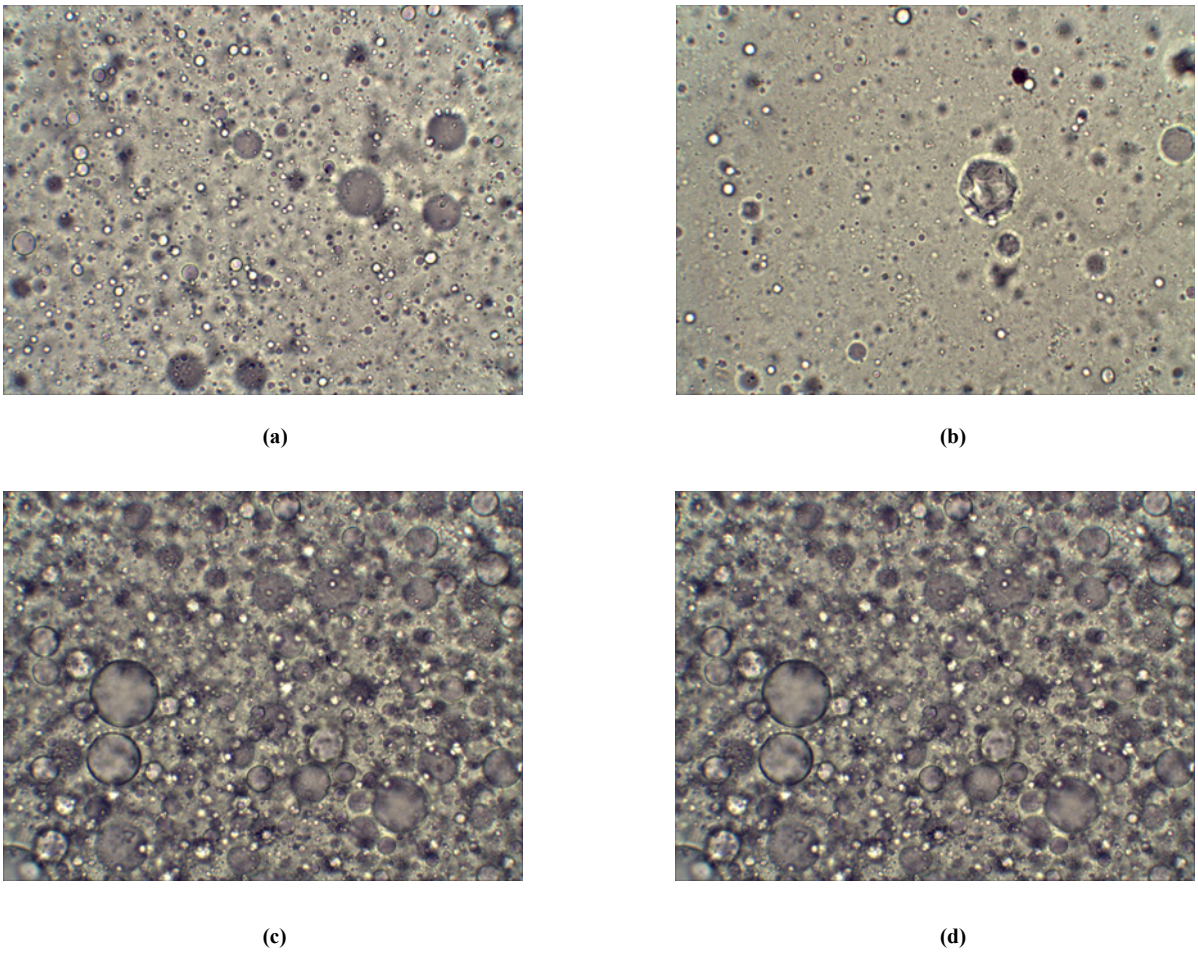
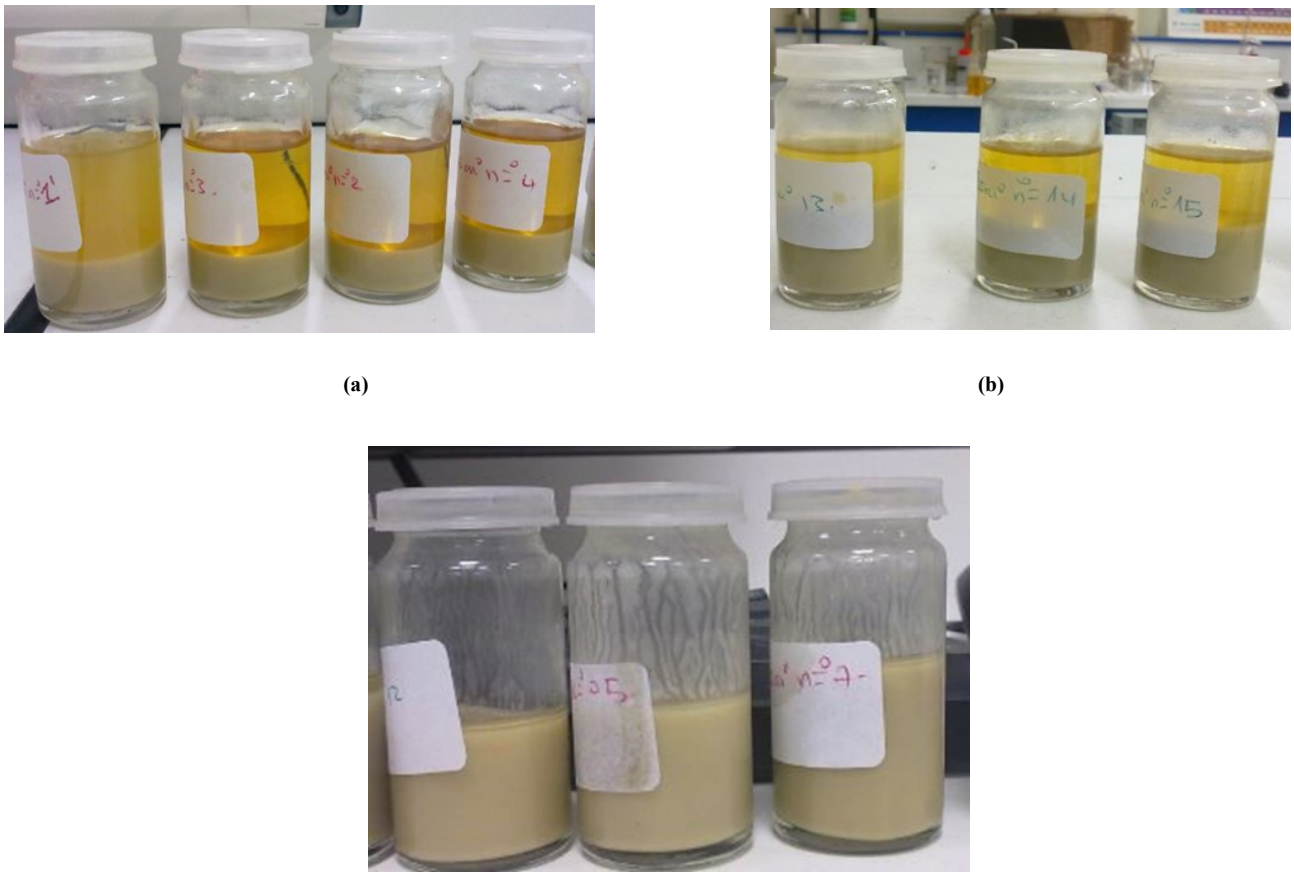


Figure 5. Stability of Oil-in-Water (O/W) Formulations Enhanced by Clays and Surfactant. **(a)** Emulsion with 10/90 W/O and 75% clay. **(b)** Emulsion with 15/85 W/O and 75% clay. **(c)** Emulsion with 20/80 W/O and 75% clay. **(d)** Emulsion with 30/70 W/O and 75% clay.

gelation. The figure suggests that an optimal clay concentration is crucial for maintaining emulsion stability in drilling fluid applications. All emulsions were prepared across the concentration range (01-075 % m/m), with the optimal Organoclay (OC) quantity of 3g (0.30% m/m) identified from the stability of the different formulation.

3.2 Rheology of W/O Emulsions

Drilling fluids are complex systems whose rheological properties depend on the interactions between their main constituents, such as water, oil, and emulsifiers. These interactions govern key parameters, including viscosity and yield stress, which determine the fluid's performance in drilling operations. Pure emulsions and clay dispersions are known to exhibit shear thinning behavior, and the rheology of drilling fluids is therefore inherently non-Newtonian. Traditionally, three models have been used to describe drilling fluid rheology: the Newtonian model (reference case), the Bingham plastic model (for yield-stress fluids), and the power law model (for shear-dependent viscosity). While the power law model is useful at low shear rates, it loses accuracy at higher shear conditions. The Herschel–Bulkley model provides a more comprehensive description by combining yield stress with shear-thinning or shear-thickening behavior. It is expressed as:



(a) **(b)** **(c)**

Figure 6. Stability of O/W formulations stabilized by clays and surfactant. **(a)** Emulsion with 1% organoclay. **(b)** Emulsion with 2% organoclay. **(c)** Emulsion with 3% organoclay[16].

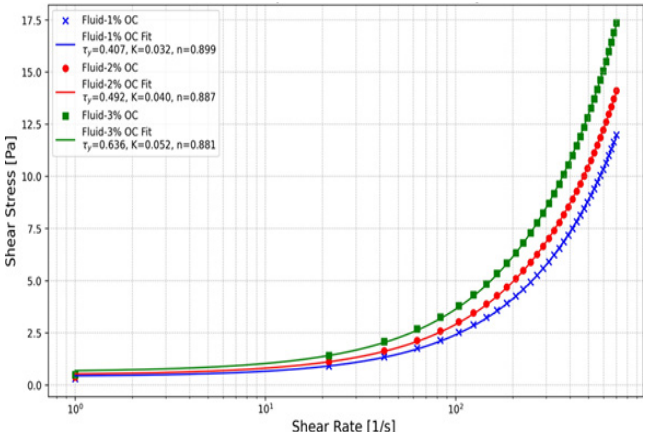


Figure 7. Shear stress–shear sate behavior of organoclay based Fluids at different Concentrations fitted with the Herschel–Bulkley model.

$$\tau = \tau_0 + K\dot{\gamma}^n,$$

Where τ is the shear stress (Pa), τ_0 the yield stress (Pa), $\dot{\gamma}$ the shear rate (s^{-1}), K the consistency index (Pa $\cdot s^n$), and n the flow behavior index. Values of $n < 1$ indicate shear-thinning, while $n > 1$ indicate shear-thickening behavior. The three investigated fluids were analyzed using this model. Fluid 1, with the lowest τ_0 and K, flows more readily and is suitable for low-pressure drilling conditions. Fluid 2 exhibited intermediate rheological parameters, reflecting a balance between flowability and carrying capacity. Fluid 3 showed the highest yield stress and consistency, indicating strong resistance to flow and higher viscosity, which are advantageous in high-pressure wells requiring efficient cuttings transport. All fluids had $n < 1$, confirming shear-thinning behavior. Fluid 1, with

the lowest *n*, demonstrated greater viscosity reduction under shear, favoring pumping efficiency, whereas Fluid 3 maintained higher viscosity at shear, ensuring better borehole cleaning. Thus, the selection of these fluids can be optimized according to drilling conditions, balancing pumpability and cuttings suspension.

3.3 Clay Effect on the w/o Emulsion

To explore how clay affects water-in-oil emulsions, various mixtures were created using different amounts of organophilic clay VG69, ranging from 0.1 to 0.75 grams, as depicted in Figure 8 (a). The results show that at low shear rates and higher concentrations of clay, there is an increase in shear stress, indicating the emergence of a distinct yield stress for each clay fraction[43]. This effect becomes more stable, particularly at the highest fraction of organoclay (0.75g), suggesting the formation of a yield point[16]. Organophilic clays are known to modify the rheology of a system by increasing the internal resistance to flow in water-in-oil emulsions[4,36]. As the concentration of clay increases, the interaction between clay particles becomes more significant, leading to an increase in the viscosity of the emulsion[44,45]. In addition, at higher concentrations, clay particles tend to form a network-like structure within the emulsion. This structure is responsible for the increased shear stress observed at low shear rates. The clay particles are dispersed throughout the emulsion, creating a matrix that resists flow until a certain stress (yield stress) is applied[46,47]. Figure 8(b) presents the variation of apparent viscosity of clay-loaded water in oil emulsions as a function of shear rate. The main issue addressed here is the thixotropic behavior of clay-containing drilling fluids, which strongly influences their rheological performance during Drilling operations. At rest or under very low shear, clay particles form a three-dimensional network that maintains a high viscosity, reflecting their inherent thixotropic nature[48]. When the fluid is subjected to continuous shear, as occurs in drilling, this network progressively breaks down, leading to a reduction in viscosity. Once shearing stops, the network tends to rebuild; however, repeated or sustained shear may hinder complete reconstruction, resulting in a viscosity plateau instead of full recovery. As illustrated in Figure 8(b), the apparent viscosity systematically decreases with increasing shear rate, confirming the shear-thinning behavior of these emulsions. Moreover, at a fixed shear rate, the viscosity increases with the volumetric fraction of clay, indicating the reinforcing role of clay particles in strengthening

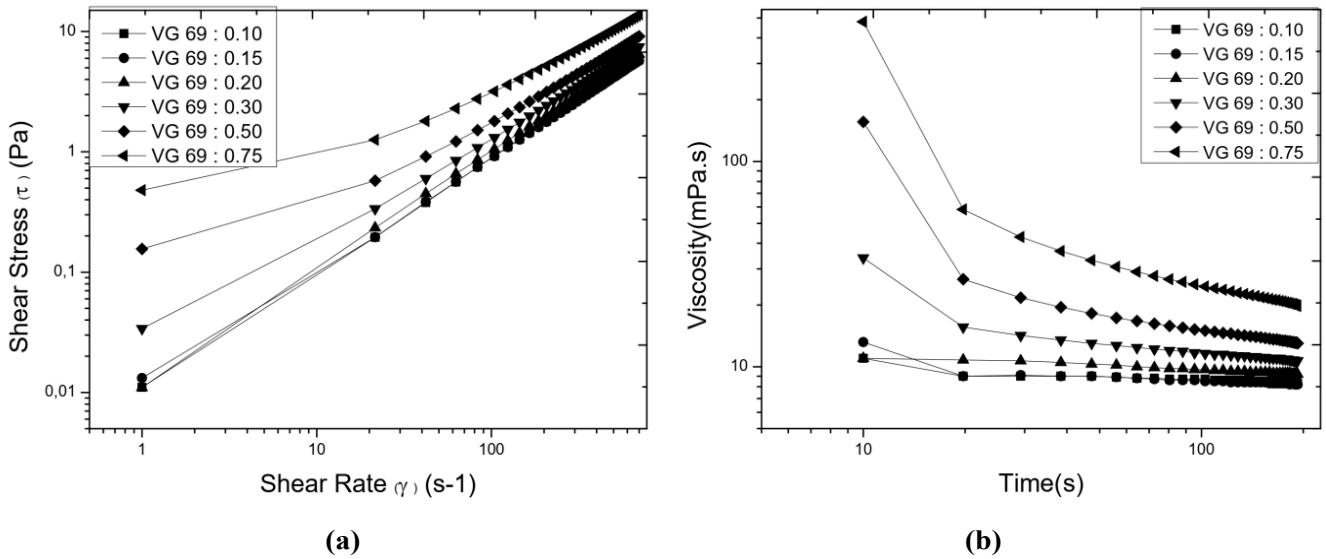
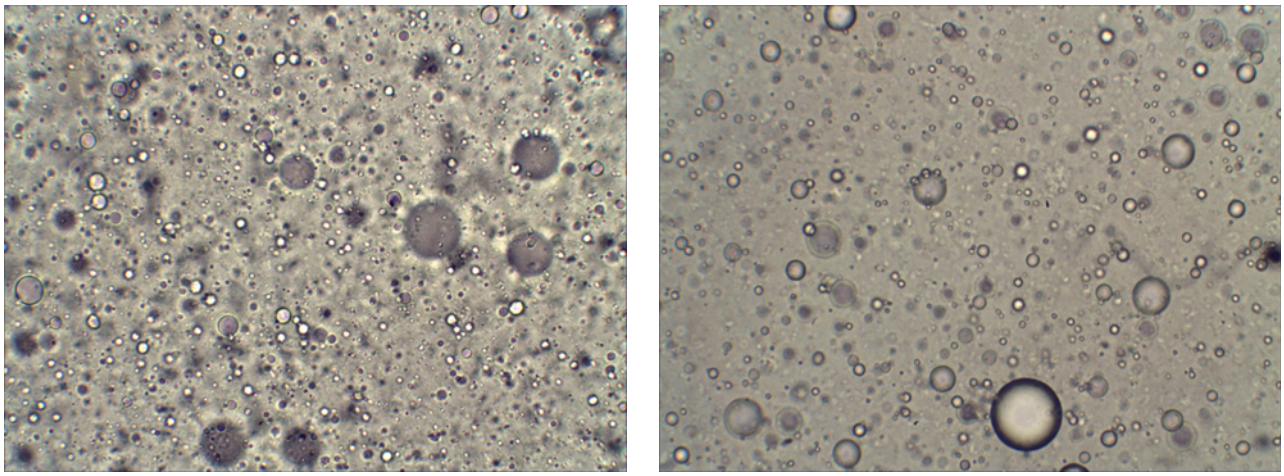


Figure 8. Effects of clay concentration variations on the flow behavior of 10/90 Water-in-Oil (W/O) drilling fluids.



(a) **(b)**

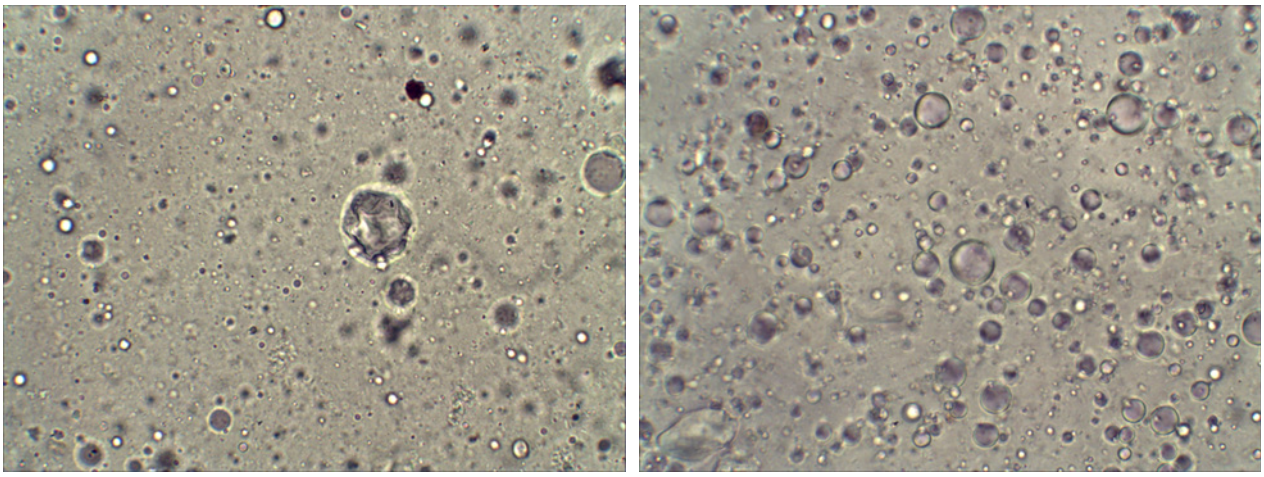
Figure 9. Microscopic analysis of 10/90 W/O emulsions stabilized with different organoclay concentrations: **(a)** microstructure with 0.75 wt% organoclay and **(b)** microstructure with 0.30 wt% organoclay.

the emulsion structure[49]. This rheological response highlights the dual function of clay: providing stability at rest while enabling flowability under shear, a balance that is crucial for effective drilling fluid performance.

The Figure 9 compares water-in-oil emulsions (10/90) stabilized with 0.75% and 0.30% organoclay, highlighting the impact of stabilizer concentration on emulsion stability. In the emulsion with 0.75% organoclay, the droplet size distribution is finer and more uniform, indicating enhanced stabilization due to stronger interfacial adsorption and increased viscosity, which restricts droplet movement and prevents coalescence[35,50]. In contrast, the emulsion with 0.30% organoclay exhibits larger and more polydisperse droplets, suggesting weaker stabilization and a higher tendency for coalescence. The experimental results indicate that progressive addition of organoclay significantly enhances emulsion stabilization through two primary mechanisms: (1) strengthening of interfacial films between phases, and (2) inhibition of droplet coalescence phenomena. These stabilizing effects are particularly valuable for petroleum engineering applications, where maintaining emulsion integrity is essential for both drilling fluid performance and enhanced oil recovery operations[51].

Figure 10 presents the microstructural features of 15/85 Water-in-Oil (W/O) emulsions stabilized with two organoclay concentrations (0.30 and 0.75 wt%). Compared with the 10/90 emulsions, the 15/85 system displays a higher droplet density and greater polydispersity, highlighting the influence of increasing the dispersed phase fraction on droplet interactions. As the aqueous phase fraction rises from 10% to 15%, the emulsion exhibits intensified droplet collisions, which promote coalescence and reduce overall stability[52,53]. At lower organoclay loading (0.30 wt%), the droplets are larger and partial coalescence is visible, reflecting weaker interfacial reinforcement. Conversely, at 0.75 wt% organoclay, the droplets appear finer and more uniformly distributed, indicating a stronger stabilizing effect due to improved adsorption of clay platelets at the interface and the formation of a viscoelastic network. Overall, the comparison demonstrates that the higher dispersed phase content in the 15/85 emulsions reduces inherent stability relative to 10/90 systems, making the role of organoclay concentration even more critical for maintaining droplet dispersion and preventing aggregation.

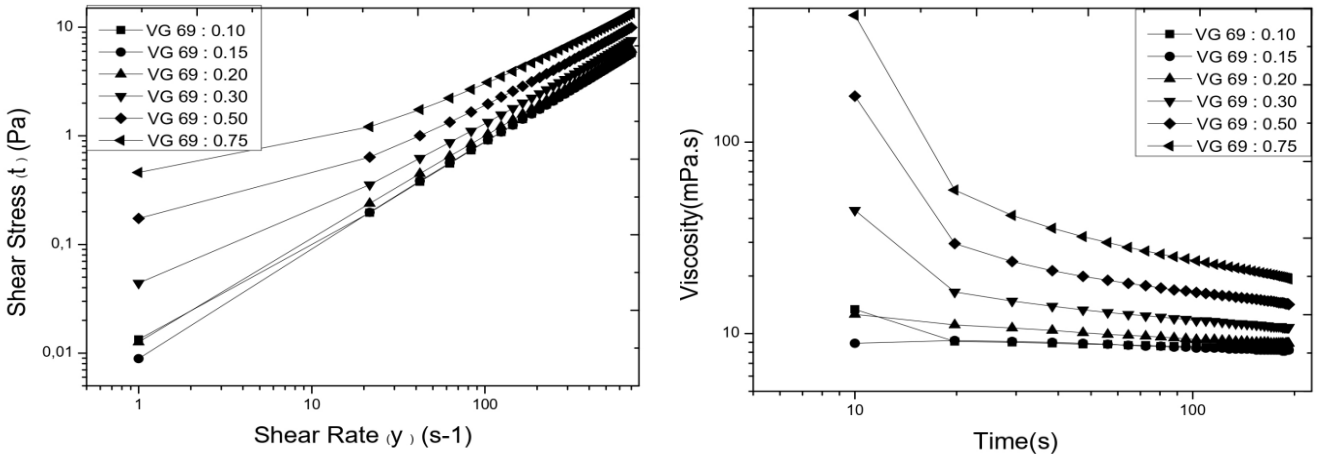
The Figure 11 and Figure 12 illustrate the impact of organoclay concentration on the rheological and



(a) **(b)**

Figure 10. Influence of organoclay concentration on 15/85 water-in-oil (W/O) emulsion drilling fluids: **(a)** microstructure with 0.75 wt% organoclay and **(b)** microstructure with 0.30 wt% organoclay, highlighting the corresponding flow behavior.

viscoelastic properties of W/O drilling fluids with water-to-oil ratios of 15/85 and 20/80. In both systems, shear stress increases with shear rate, confirming a shear-thinning response typical of non-Newtonian emulsions. The curves show that higher organoclay contents (≥ 0.30 wt. %) significantly raise viscosity and resistance to deformation, while lower Concentrations provide weaker reinforcement. Time-dependent tests reveal that viscosity diminishes under constant shear, but the decline is less pronounced at elevated organoclay levels, indicating improved structural stability. Notably, emulsions with 20/80 ratios display Higher viscosity retention compared to 15/85 systems, reflecting the influence of higher water content on network formation. Overall, the data highlight



(a) **(b)**

Figure 11. Rheological modification of 15/85 W/O drilling fluids through controlled organ- oclay incorporation.

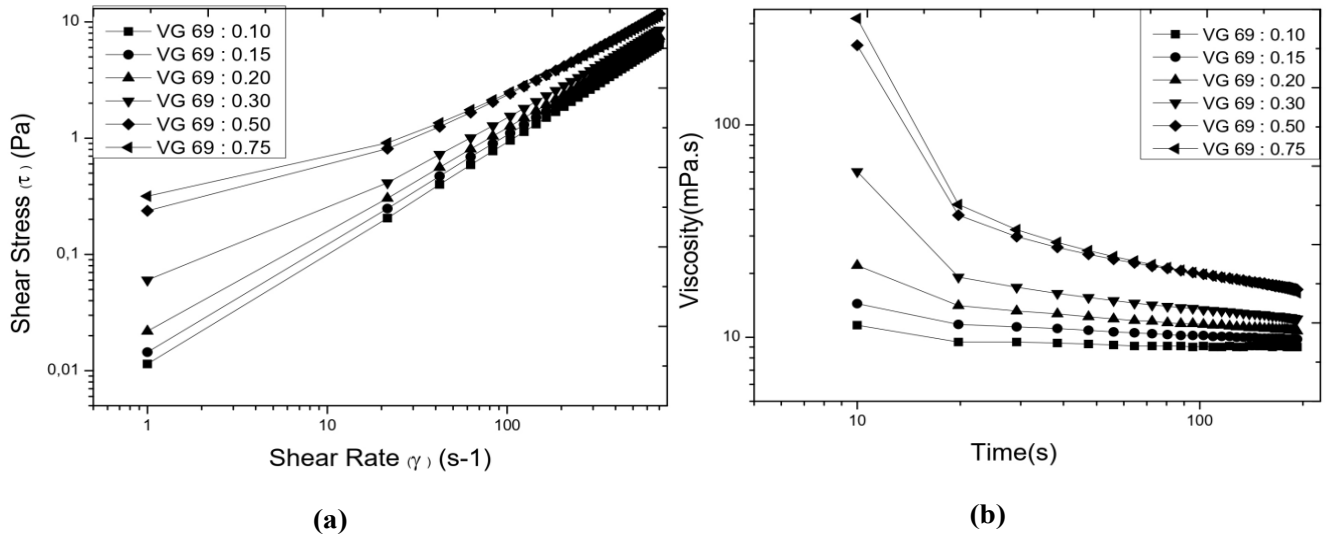


Figure 12. Organoclay concentration effects on viscoelastic properties of 20/80 W/O drilling muds.

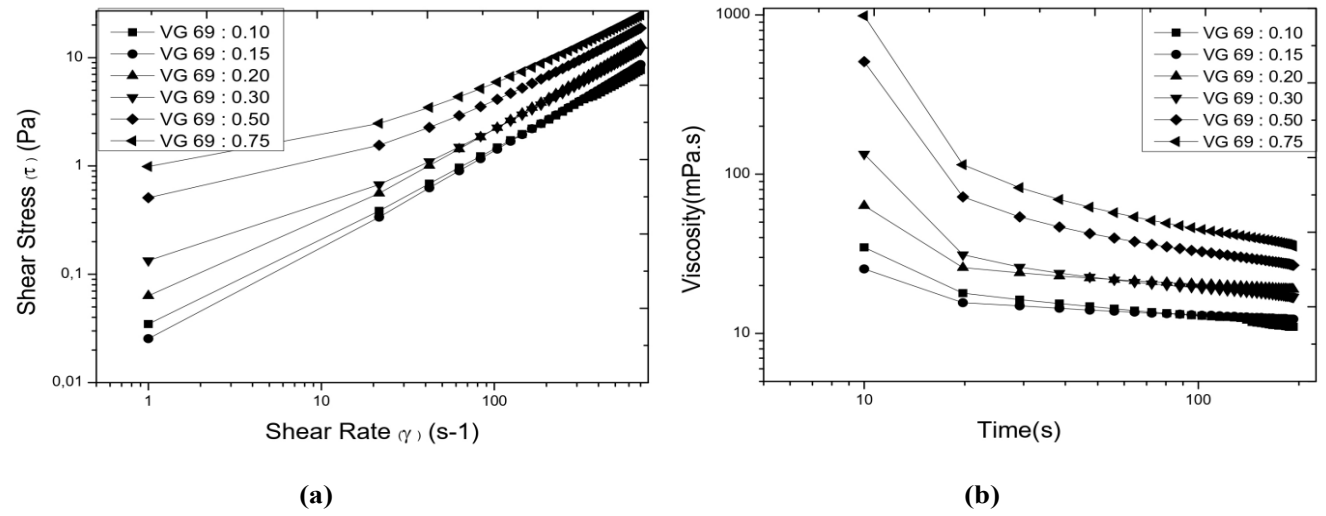


Figure 13. Rheological response of 30/70 W/O drilling fluids to different organoclay concentrations.

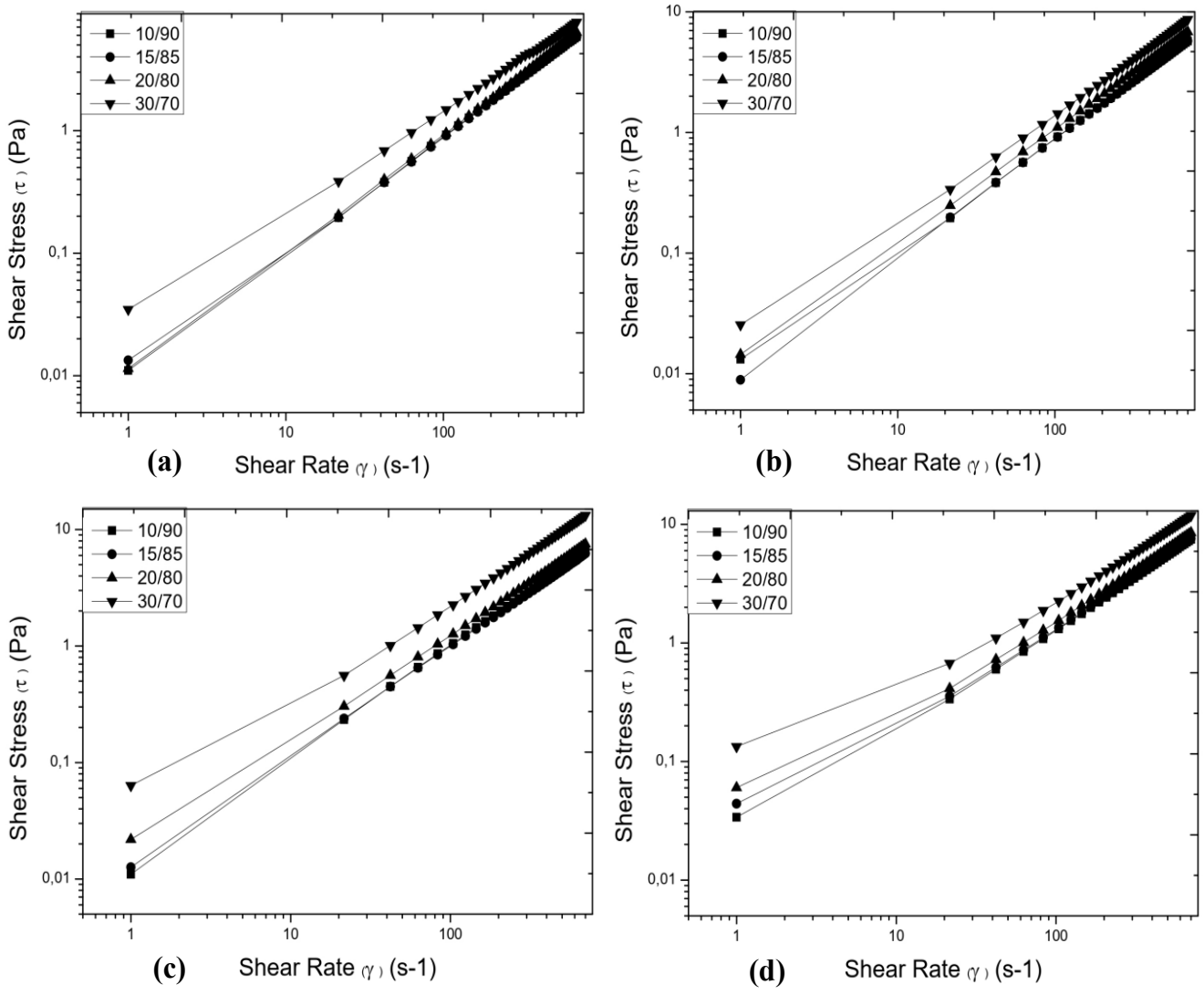
that optimizing organoclay concentration enhances droplet stabilization, viscosity maintenance, and fluid integrity under shear, which are essential for drilling efficiency.

From the Figure 13, the rheological profiles of the 30/70 W/O drilling fluids reveal a pronounced shear thinning response, with shear stress increasing nonlinearly with shear rate for all organoclay concentrations. At low shear rates, fluids with higher organoclay contents (≥ 0.30 wt. %) exhibit significantly greater stress values, indicating stronger network formation and resistance to deformation. The time dependent viscosity curves further confirm this stabilization effect, as higher clay loadings sustain elevated viscosities for longer durations, while low concentrations (0.10–0.15 wt.%) show rapid viscosity decay and weaker structural integrity. Overall, the results demonstrate that organoclay plays a pivotal role in enhancing both viscosity retention and droplet

dispersion in high-water emulsions, ensuring more stable and controllable drilling fluid behavior under shear.

3.4 Effect of Water-to-Oil Ratio on Rheological Properties

Figure 14 present the rheograms of Water-in-Oil (W/O) emulsions formulated with varying aqueous phase ratios (10/90, 15/85, 20/80, and 30/70) and different organoclay concentrations (0.10%, 0.15%, 0.20%, 0.30%, 0.50%, and 0.75%). The results demonstrate that the rheological response is strongly governed by both the water content and the organoclay loading. At lower water fractions (10/90 and 15/85), the emulsions display higher viscosities and more pronounced non-Newtonian behavior (Figure 14 (a)-(b)). This response can be attributed to the stability of the dispersed phase and the structuring effect of organoclay platelets within the continuous oil medium[3,54]. Conversely, as the water fraction increases (20/80 and 30/70), the emulsions exhibit reduced viscosity and a tendency toward phase inversion (Figure 14 (c)-(d)), indicating a weakening of the internal network[55]. The concentration of organoclay further modulates the rheological profile. At higher concentrations (0.50% and 0.75%, Figure 14 (e)-(f)), the emulsions show a substantial increase in yield stress and shear thinning behavior, reflecting the reinforcing role of organoclay in building a gel-like network within the oil phase. This effect is particularly pronounced in the



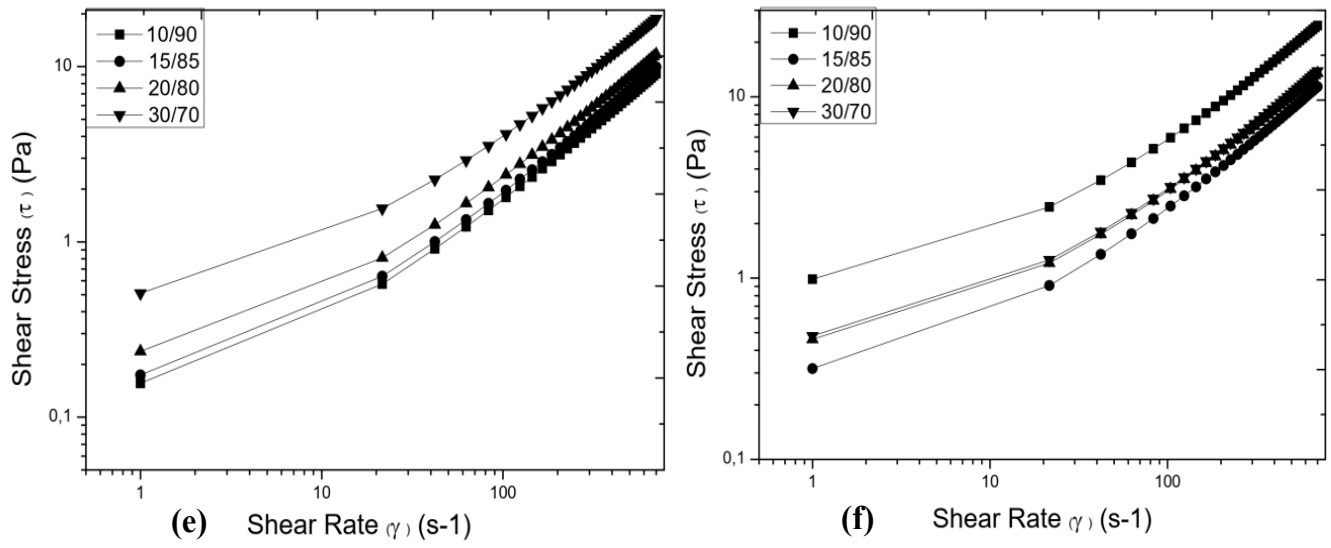


Figure 14. Effect of organoclay concentration (0.10–0.75% w/w) on the rheological behavior of Water-in-Oil drilling fluids with different water to oil ratios (10/90, 15/85, 20/80, and 30/70).

10/90 and 15/85 systems, where the dispersed droplets interact more effectively with the clay platelets, leading to enhanced structural rigidity[16,56]. Furthermore, for a given shear rate, the shear stress values are consistently higher in emulsions with lower water content. This finding suggests that reduced aqueous phase volume promotes stronger droplet organoclay interactions and a more cohesive internal structure[57]. These results highlight the synergistic influence of water fraction and organoclay concentration on the rheological performance of W/O drilling fluids. The observed increase in yield stress and shear stress with increasing organoclay content underscores the potential of these systems to improve suspension capacity and cuttings transport efficiency, making them particularly suitable for deep and highly deviated drilling operations[58].

3.5 Effect of Water in Oil Ratio on the Viscosity

The provided Figure 15 demonstrate the rheological behavior of Water-in-Oil (W/O) drilling fluids under varying organoclay concentrations (0.10%, 0.15%, 0.20%, and 0.75%) and water- to-oil ratios (10/90, 15/85, 20/80, and 30/70), with viscosity measurements recorded over time. Across all concentrations, the fluids exhibit shear-thinning behavior, characterized by a decrease in viscosity under continuous shear stress, which is typical of non-Newtonian fluids[58,59]. Higher water content increases initial viscosity due to greater interfacial tension and a more complex fluid structure, while higher clay concentrations enhance viscosity by contributing to internal friction and structural integrity[60,61]. The rheological behavior of W/O drilling fluids is strongly dependent on organoclay concentration. At low loading (0.10 wt.%), the 30/70 water-to-oil system shows high initial viscosity and pronounced shear- thinning, reflecting a weakly structured network easily disrupted by shear. In contrast, at 0.75 wt.% organoclay, the same system exhibits reduced shear-thinning and much higher steady-state viscosity, indicative of a robust three-dimensional network stabilized by strong inter-particle interactions. Intermediate concentrations (0.15–0.20 wt.%) represent a gradual transition, with progressive increases in viscosity and structural integrity. These trends arise from the combined effects of interfacial tension, droplet–particle interactions, and clay particle associations that collectively generate yield-stress behavior. Overall, organoclay concentration governs the shift from near-Newtonian to structured non-Newtonian rheology, underscoring its critical role in optimizing drilling fluid stability

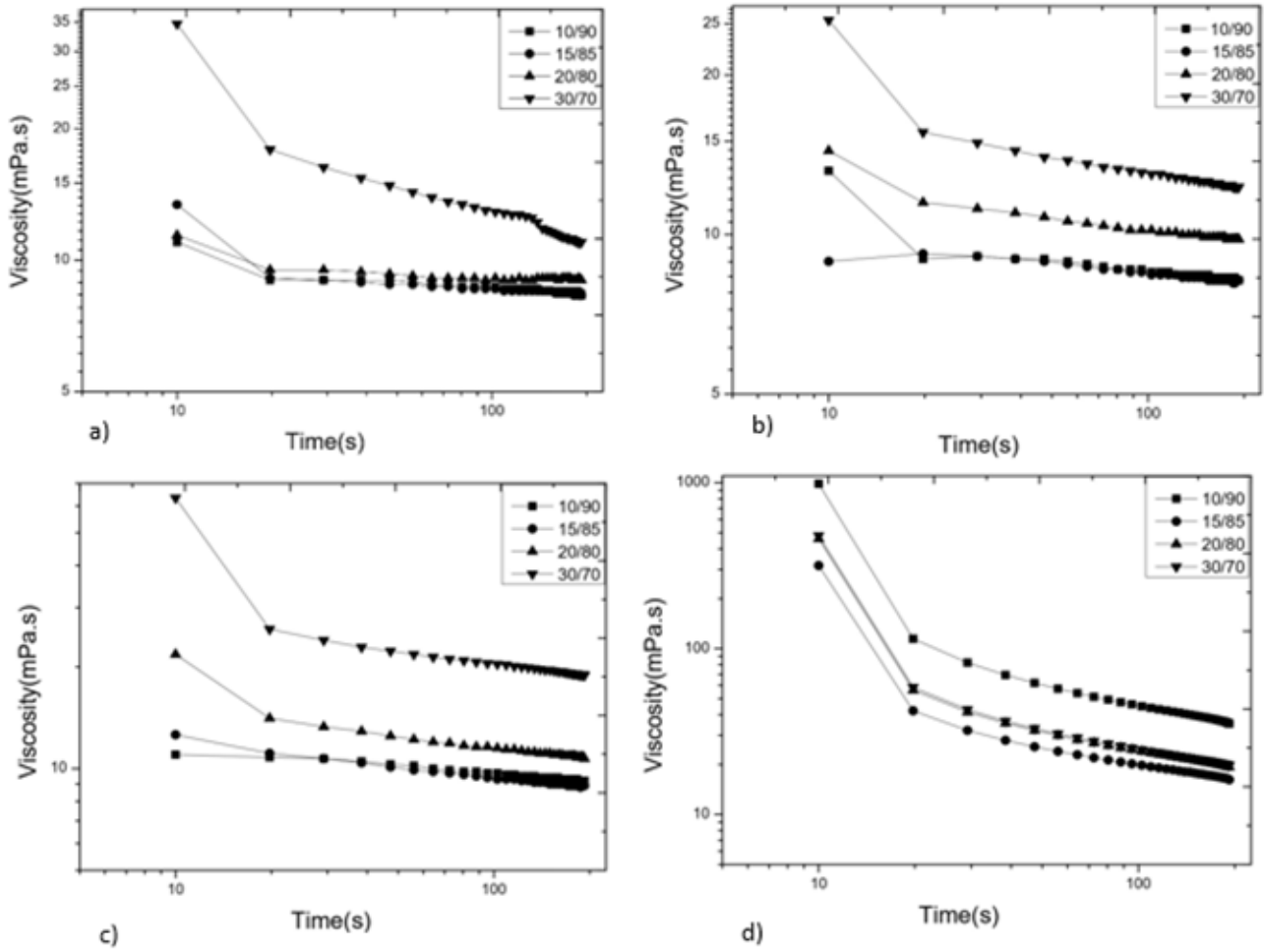


Figure 15. Viscosity profiles of Water-in-Oil (W/O) drilling fluids as a function of shear rate at varying organoclay concentrations: **(a)** 0.10 wt%, **(b)** 0.15 wt%, **(c)** 0.20 wt%, and **(d)** 0.75 wt%.

and performance. Overall, both water-to-oil ratio and organoclay concentration play critical roles in determining the viscosity and stability of W/O drilling fluids, underscoring their importance in optimizing formulations for specific drilling conditions[56].

The microscopic images presented in Figure 16 illustrate the microstructural evolution of Water in-Oil (W/O) emulsions stabilized with varying concentrations of organoclay (0.10% and 0.30%) and different water fractions (10/90 and 30/70). The images reveal a strong dependence of droplet dispersion and emulsion stability on both the organoclay concentration and the water content. In images (a) and (b), corresponding to 10/90 emulsions, increasing the organoclay concentration from 0.10% to 0.30% leads to a more uniform and finer droplet distribution, indicating enhanced emulsion stability due to the formation of a structured network by organoclay platelets within the continuous oil phase. The enhanced stability arises from organoclay particles adsorbing at the interfacial boundary between aque- ous and oil phases, effectively minimizing droplet merging and preventing demulsification. Conversely, image (d), representing a 30/70 emulsion with 0.10% organoclay, exhibits larger, Less evenly distributed droplets, suggesting a weaker interfacial stabilization and a tendency towards phase inversion. The pronounced increase in droplet size and coalescence in this sample implies that at higher water fractions, the organoclay concentration may be insufficient to maintain a stable

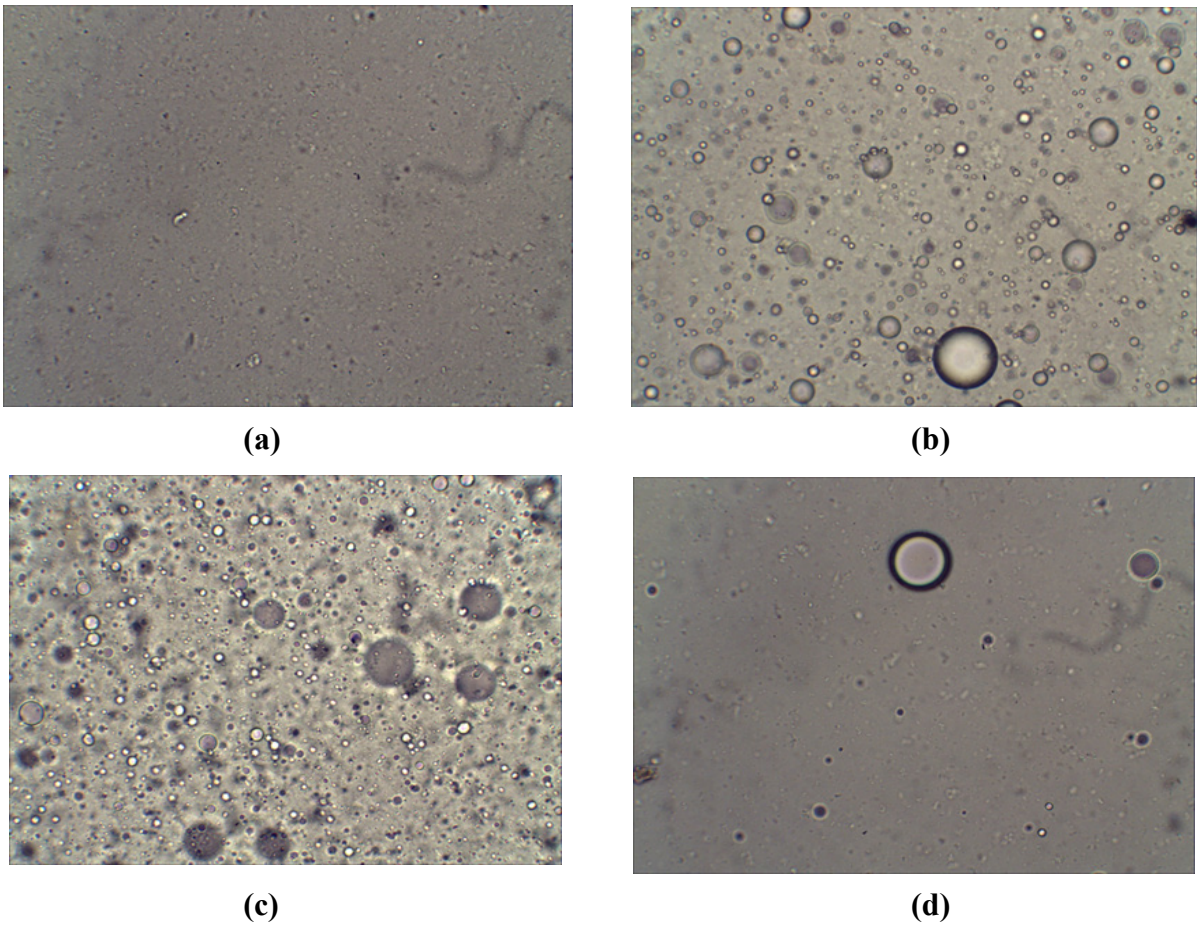


Figure 16. Optical microscopy images of Water-in-Oil (W/O) drilling fluid emulsions illustrating the combined effects of organoclay concentration (0.10 and 0.30 wt%) and water-to-oil ratio (10/90 and 30/70) on droplet size distribution and emulsion stability.

dispersed phase. The comparative analysis of these emulsions highlights the critical role of organoclay concentration in controlling the viscoelastic properties and interfacial stability of W/O emulsions. These findings are consistent with previous studies on nanoparticle-enhanced drilling fluids which demonstrated that increasing solid-phase content significantly enhances emulsion stability and rheological performance[45].

When examining the viscosity–shear rate profiles (Figure 17), drilling fluids containing organophilic clays at concentrations above 0.30% exhibit marked viscosifying effects, char- acterized by low initial viscosity values that progressively decrease with shear rate, demon- strating typical shear-thinning behavior. At low shear rates, the three-dimensional network formed by clay platelets resists deformation, leading to elevated viscosities due to strong particle–oil interactions[62,63]. As shear rate increases, this network is gradually disrupted, with clay platelets aligning in the flow direction, thereby reducing internal resistance and lowering viscosity. Such rheological behavior is advantageous in drilling operations, since high viscosities at rest facilitate cuttings suspension, whereas shear-thinning under dynamic conditions enhances pumpability. The influence of organophilic clay concentration is particularly significant: loadings exceeding 0.30% reinforce structural networking, resulting in stronger resistance at low shear rates but allowing progressive fluidization under applied Stress[32]. Additionally, the Water-to-Oil (W/O) ratio exerts a critical effect on rheology. When the ratio surpasses 15/85,

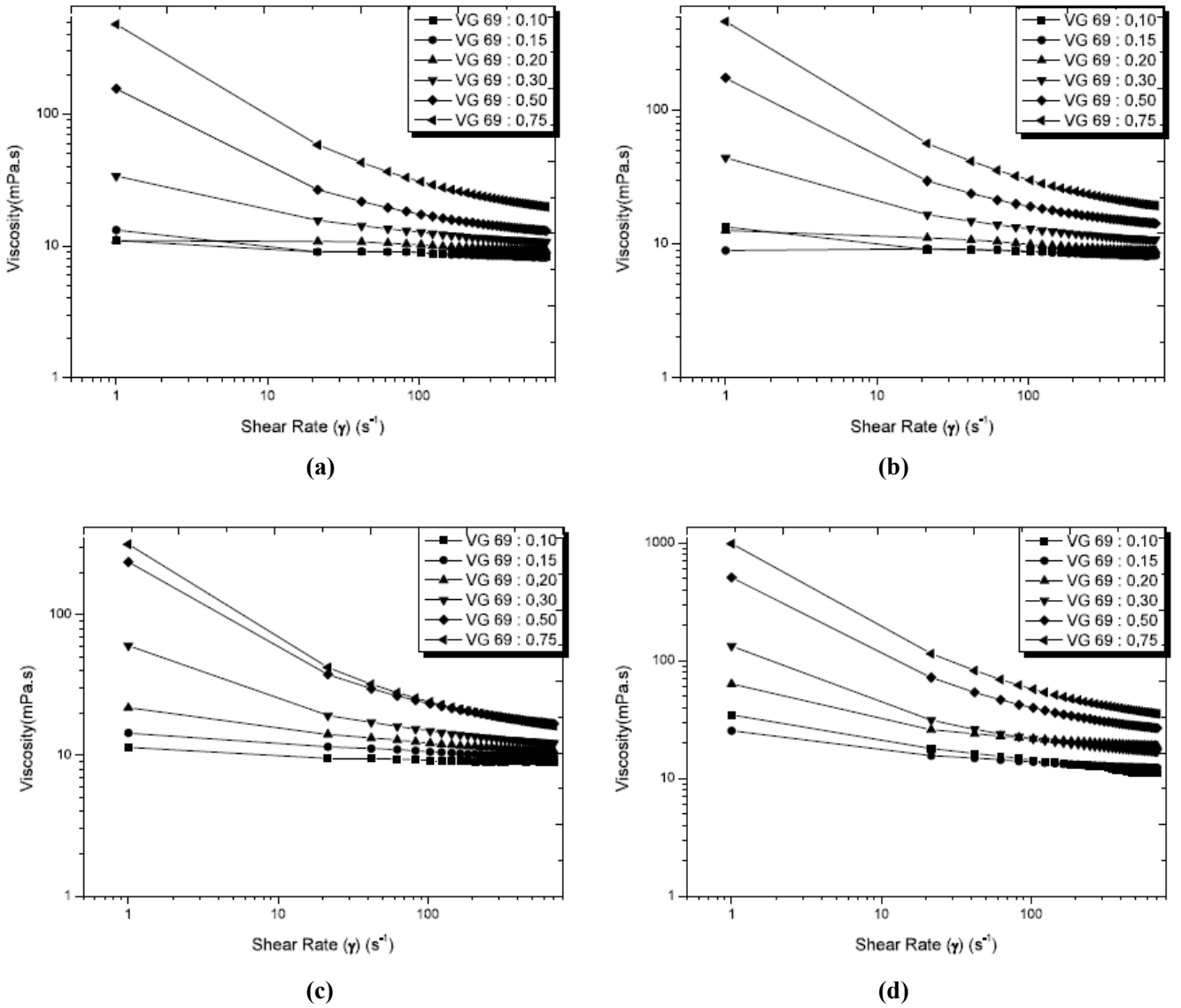


Figure 17. Viscosity–time profiles of water-in-oil (W/O) drilling fluids at different organoclay concentrations: **(a)** 0.10 wt%, **(b)** 0.15 wt%, **(c)** 0.20 wt%, and **(d)** 0.75 wt%, highlighting their rheological behavior under varying shear conditions.

viscosities rise markedly at low shear rates, reflecting in- tensified droplet–particle interactions. At ratios beyond 20/80, even relatively low clay con- centrations (0.10–0.15% VG69) contribute to a substantial viscosity increase, as dispersed water droplets act synergistically with clays to strengthen the internal microstructure. This phenomenon is most evident under low shear, where applied stress is insufficient to disrupt water–clay associations, leading to a rigid internal framework that impedes flow. Therefore, both organophilic clay concentration and W/O ratio play interdependent roles in defining fluid rheology, highlighting the need for an optimized balance that ensures cuttings suspension at low shear rates while maintaining efficient circulation at high shear rates.

4.0 Conclusion

This study demonstrates that the rheology and stability of water-in-oil drilling fluids are jointly controlled by

water-to-oil ratio and organoclay concentration. All systems exhibited shear-thinning, non-Newtonian behavior, confirming that the dispersed aqueous phase and solids generate structurally complex emulsions suitable for drilling applications. The baseline viscosity was strongly influenced by water fraction, with the 30/70 system showing the highest low-shear viscosity, although excessive water content increased the risk of coalescence without sufficient organoclay reinforcement. Organoclay emerged as the decisive structuring agent. At low loading (0.10 wt%), stabilization was limited, but incremental additions improved dispersion relative to clay-free systems. Concentrations of ≥0.30 wt% significantly enhanced droplet refinement, yield stress, and viscosity control, while 0.75 wt% induced three-dimensional particle networks that imparted strong gel-like behavior and superior stability across all formulations. Herschel–Bulkley modeling confirmed a direct correlation between organoclay content, yield stress, and consistency index, underscoring its dual role in modifying both interfacial interactions and bulk rheology. Overall, the interplay between aqueous fraction and organoclay loading dictates whether emulsions evolve into weakly structured fluids or robust, stable gels capable of meeting the demands of modern drilling. These insights establish concentration-dependent rheological transitions as a key design principle for next-generation drilling fluids. Future work should extend these findings under high temperature and pressure and assess the synergistic effects of organoclay with other additives to ensure field-ready stability under extreme drilling conditions.

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6.0 Data Availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request. Raw experimental data related to rheological measurements, emulsion stability tests, and microscopic observations have been archived. All analytical procedures and instruments used are described in the Materials and Methods section. The processed data presented in tables and figures are included within the article. No public repository was used for data deposition.

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Author Contribution

The first author (Doctorant) was responsible for the experimental work, including sample preparation, laboratory analysis, data processing, and interpretation of the results. The second author (Encadrant) supervised the research design, ensured the scientific and methodological accuracy, and provided guidance throughout the study. Both authors contributed to the writing of the manuscript, its critical revision, and the final approval of the submitted version. The first author prepared the figures and tables, while the second author provided scientific direction and validation of the results. The third author contributed to the review of the manuscript, provided additional scientific input, and participated in the validation of the results.

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