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Rheological Properties and Emulsion Stability Performance of Invert Emulsion Drilling Fluid using Emulsifier Derived from Waste Cooking Oil

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This study investigates the rheological properties and emulsion stability of invert emulsion drilling fluids using emulsifiers derived from waste cooking oil (FA-WCO) compared to commercial emulsifiers (CPE) and stearic acid (FA-SA). The objective is to develop an environmentally friendly and cost-effective emulsifier for high-pressure, high-temperature (HPHT) drilling conditions. The research involved preparing oil-based mud (OBM) samples at varying oil-water ratios (70/30, 80/20, 90/10) and temperatures (250°F and 400°F) and analyzing their performance using different emulsifiers. The findings revealed that the FA-WCO emulsifier exhibited comparable rheological behavior and emulsion stability to the CPE, with an optimal performance at an 80/20 oil-water ratio and 250°F. The plastic viscosity and yield point of FA-WCO were similar to those of CPE, and the emulsion stability was also closely matched. Stearic acid (FA-SA) showed higher plastic viscosity, yield point and gel strength but struggled with thermal stability at temperature more than 250°F. The study concludes that emulsifiers derived from waste cooking oil offer a sustainable and effective alternative for drilling operations, reducing environmental impact and promoting the recycling of waste materials. The results recommend the adoption of FA-WCO as a viable emulsifier in the oil and gas industry, particularly for HPHT drilling applications.

1. Introduction

Oil and natural gas are the world's leading sources of energy, and the drilling process is a critical challenge due to its high costs, ecological, health, and safety implications (Osman et al., 2023). Drilling fluids, classified as water-based or oil-based, are essential for drilling operations due to their ability to solve certain undesirable properties of water-based muds (Pereira et al., 2022). Emulsifiers, fatty acid-derived chemicals, are used in oil-based mud or invert emulsion mud to reduce interfacial tension between water and oil, allowing a stable emulsion to develop(Ramasamy & Amanullah, 2019). The majority of commercially available emulsifiers are based on tall oil fatty acid (TOFA), which has high emulsion stability even in extreme settings (Ramasamy & Amanullah, 2019). The most common fatty acids in TOFA are stearic acid and palmitic acid. Severe downhole conditions in geothermal wells, such as high pressure and high temperature (HPHT), make drilling challenging (Mohamed et al., 2021). A special drilling mud formulation with strong heat stability and good rheological qualities is needed to perform drilling fluid functions in such circumstances. Due diligence should be taken to ensure the right drilling fluid is chosen, its parameters are optimized and tracked during the drilling process, and its performance is anticipated in downhole conditions. To establish a cost-effective and environmentally friendly mud composition, a new emulsifier will be developed from recycled waste cooking oil derived from used sunflower oil. By using an environmentally friendly emulsifier made from leftover cooking oil, this study highlights the significance of fluid rheology while analyzing the flow behavior of the inversion emulsion drilling fluid under HPHT settings.

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2. Methodology

2.1 Materials Preparation

The materials used for the invert emulsion mud preparation include Escaid (a base oil), a rheological modifier agent, a viscosifier or gelling agent, a fluid loss control agent, a pH control agent, and an emulsifier activator. Escaid aids in dissolving blended additives, while a viscosifier or gelling agent improves drilling fluid's ability to suspend cuttings and remove them from the wellbore. A pH control agent and emulsifier activator neutralize corrosive gases like CO_2 and H_2S. A brine made from calcium chloride salt and water acts as a reactive clay stabilizer, preventing shale from hydrating, expanding, and sloughing into the wellbore. Barite is an essential weighing agent. The primary additive used in this study is an emulsifier, with primary and secondary emulsifiers used for commercial oil-based mud. An emulsifier made from leftover cooking oil (waste sunflower oil) was used to create environmentally friendly OBM, producing fatty acids as an emulsifier. Stearic acid was used as a controlled sample for comparison purposes.

2.2 Mud Formulation

The American Petroleum Institute Standard 13B-2: Recommended Practice for Testing Oil-Based Drilling Fluid was followed while preparing the mud sample (API, 2023). The additives were to be combined in the sequence while the oil-based mud components were being mixed with a Hamilton Beach mixer. One mud lab barrel produced 350 mL of mud after 60 minutes of mixing. The lab barrel contained 152.78 g of base oil (Escaid), 6.00 g of primary emulsifier, and 4.00 g of secondary emulsifier and a 70/30 oil-water ratio. The mixture was then swirled for 5 minutes. Then, 2.00 g of rheological modifying agent was added, and the mixture was stirred for 2 minutes. Next, 0.5 g of viscosifier, 5.00 g of fluid loss agent, and 10.00 g of lime were added to the mixture, in that order. To manufacture brine, 80.80 g of water and 28.87 g of calcium chloride were mixed and stirred for 15 minutes. Finally, 215.22 g of weighing agent was added into the slurry. The entire mud formulation process was completed by preparing oil-based mud (OBM) at various oil-water ratios (70/30, 80/20, and 90/10) and various primary emulsifiers i.e., commercial primary emulsifier (CPE), fatty acids derived emulsifier from waste cooking oil (FA-WCO) and stearic acid-fatty acid emulsifier (FA-SA).

2.3 Mud Testing

After completing the mud mixing process, the mud sample was tested for density using a mud balance. Then, the sample was transferred into a thermo cup and heated to 120°F for rheology determination. While being stirred at 600 rpm with a viscometer, the dial reading was stabilized at each speed before recording readings at 600, 300, 200, 100, 6, and 3 rpm. After obtaining the 3-rpm dial reading, the sample was mixed for 30 seconds at 600 rpm before taking the 10-second gel reading at 3 rpm after a 10-second rest. The sample was then restirred for 30 seconds at 600 rpm and left undisturbed for 10 minutes to maintain a temperature of 120°F. The 10-minute gel reading at 3 rpm was taken after the rest and the test was repeated twice for accuracy. After each test, the bob and rotor were cleaned for further use. The rheology test was also conducted after the mud had been hot rolled for 16 hours. The following rheology characteristics were determined: plastic viscosity-PV (cP), yield point-YP (lb/100ft^2), gel strength 10-seconds-GS-10s (lb/100ft^2), gel strength 10-minutes-GS-10m (lb/100ft^2), and YP/PV ratio. Plastic Viscosity (PV) and Yield Point (YP) were calculated using Eq(1) and Eq(2).

$$Plastic\ Viscosity\ (PV) = \theta_{600} - \theta_{300} \quad (1)$$

$$Yield\ Point\ (YP) = \theta_{300} - PV \quad (2)$$

The rolling aging test involves preheating an oven to specific temperatures (250°F and 400°F), stirring the sample for 5 minutes, and then placing it in an aging cell. The aging cell was then placed in the oven and rolled for 16 hours. After 16 hours, the oven was turned off, and the aging cell was placed in a water bath to cool down the sample. The sample was then transferred back into the mud cup, cleaned, and dried. The pH test involves placing an electrode in the mud sample and recording the reading. The electrode was then rinsed with distilled water for future use. The mud's Electrical Stability (ES) test involves filling a thermocup with the sample and stirring it with an ES probe until the temperature is uniform at 120°F. The voltage ramp test was then conducted until the reading becomes steady, indicating the mud's Electrical Stability (ES) (API, 2023)

3. Results and Discussion

3.1 Effects of Different Oil-Water Ratio and Temperature on Rheological Performance of Invert Emulsion Mud

The experiment compared the performance of invert emulsion mud at different oil-water ratios (70/30, 80/20, 90/10) and temperatures (250°F and 400°F) to determine the optimum oil-water ratio and temperature for comparison with other primary emulsifiers. The results showed that the plastic viscosity (PV) of invert emulsion mud decreases with increasing oil-water ratio, as the percentage of water in the mixture reduces (Błaż et al., 2021). The overall plastic viscosity for 400°F is higher than 250°F which shows an improved emulsion of the mud in all samples. The plastic viscosity and yield point of invert emulsion mud increase at higher temperatures due to the impact on emulsion stability, affecting the fluid's rheological properties and performance (Peace, 2017). The YP decreases with temperature for 70/30 oil-water ratio but increases for 80/20 and 90/10 due to clay platelet swelling, which increases inter-particle links, causing a decrease in YP (Tchameni et al., 2018). However, the PV and YP of invert emulsion mud increase at higher temperatures due to enhanced intermolecular interactions among constituents, ensuring better suspension and stability during drilling operations (Tiwari et al., 2020). The gel strength of invert emulsion mud generally increases as the oil-to-water ratio increases, but this relationship is not uniform and may change depending on the exact composition of the oil-based mud (Palaoro et al., 2022). Some base oils tend to grow in viscosity and gel strength as the temperature rises, while others exhibit reverse behavior (Alkalbani et al., 2023). As shown on the right side of Figure 1, a 100% stacked column chart depicts columns as wholes, with segments indicating the proportions of subcategories within them. It shows the percentage of the total that each subcategory accounts for, with the total always being 100% for different series. The chart shows that the 80/20 mud maintained consistent rheology stability at both HPHT systems (250°F and 400°F). Thus, the optimal oil-to-water ratio of 80/20 was chosen for two reasons. On the one hand, mud rheology remained stable at an 80/20 ratio even at 400°F, while the percentage of PV remained constant (18%) in both HPHT systems. On the other hand, increasing the oil content influences the cost of drilling mud.

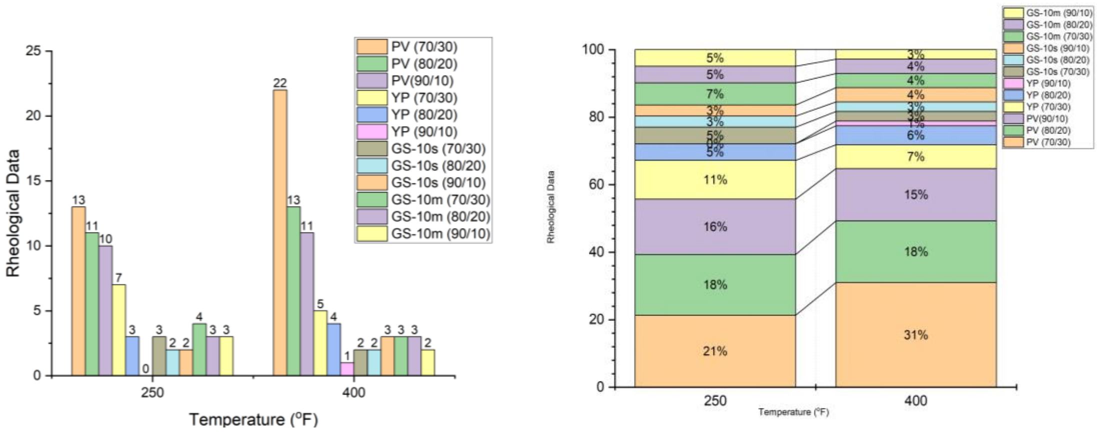

Figure 1: Rheological performance of invert emulsion mud at 250°F and 400°F

3.2 Effects of Different Oil-Water Ratio and Temperature on Emulsion Stability of Invert Emulsion Mud

An emulsion is formed in an invert emulsion mud when oil droplets are distributed in water and stabilised by emulsifiers. The emulsion stability is a measure of how well these oil droplets remain dispersed and do not agglomerate or separate (Azizi et al., 2020). When the oil-water ratio in an oil-based mud is increased, more oil is introduced into the system in comparison to water. As a result, raising the oil-water ratio improves emulsion stability in invert emulsion muds (Nechaeva & Kuznetsova, 2023). This result is consistent with Figure 2, which indicates that emulsion stability increases with increasing oil-water ratio. This is because as more oil is present, the emulsion becomes oilier and the water phase becomes more dispersed. Higher oil concentration increases emulsion stabilisation, resulting in greater stability. In general, the emulsion stability of oil-based muds decreases as temperatures rise. This is because when temperatures rise, the molecular mobility of the emulsion components increases, resulting in more severe thermal agitation (Hatam et al., 2023). The increased energy disrupts the stabilising bonds between the oil and water phases, as well as the emulsifying agents. As a result, the emulsion becomes less stable, which increases the likelihood of oil and water separation. However, the situation is reversed in terms of temperature. According to Figure 2, emulsion stability increases with temperature, which contradicts the preceding assumption. This issue could occur as a result of using an effective commercial emulsifier to keep drilling fluids stable during high-temperature drilling operations. Fayad et al. (2021) found that having a good emulsifier improves emulsion stability even at high temperatures, as stated in the research paper. However, a 70/30 mud system exhibits emulsion instability at 250°F. Katende et al. (2019) concluded that ES values greater than 400 V indicate that the emulsion system is stable. The obtained emulsion stability was 365V, which is less than the required limit (400V), indicating that the proposed mud formulation's 70/30 oil to water ratio is not optimal for HPHT settings.

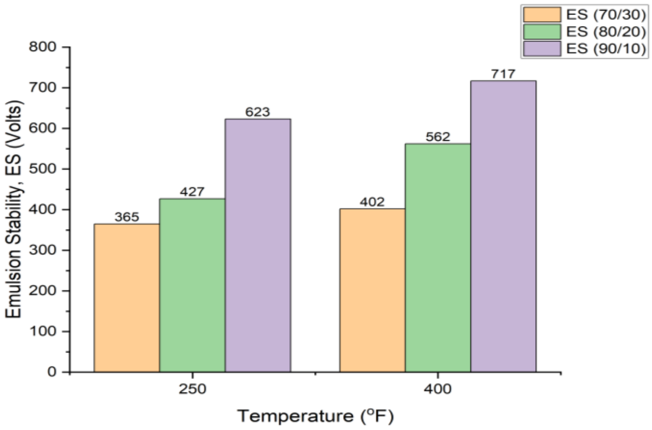

Figure 2: Comparison of Emulsion Stability of invert emulsion mud at different Oil-Water Ratio & Temperature

3.3 Effects of Different Primary Emulsifiers on Rheological Properties and Emulsion Stability of Invert Emulsion Mud

The experiment compared primary emulsifiers at an ideal oil-water ratio of 80/20 and a temperature of 250°F as shown in Figure 3. Stearic acid fatty acid (FA-SA) has the highest PV and YP, measuring 15cP and 7 lb/100ft^2. Its thixotropic qualities enable it to function as a thickening agent, raising the YP of invert emulsion mud. When coupled with emulsifiers or rheology modifiers, a synergistic effect can occur, increasing the rheological qualities of oil-based muds. The PV and YP of the invert emulsion mud with derived waste cooking oil emulsifier (FA-WCO) were substantially equal to those of commercial emulsifier (CPE), demonstrating that the FA-WCO is effective and promising in terms of product consistency and quality. FA-SA has a higher gel strength than FA-WCO or CPE emulsifiers, which is most likely related to its capacity to thicken. A drilling fluid's shear thinning is typically defined by the yield point-to-plastic viscosity ratio. A good shear thinning behaviour indicates that the mud has a high internal force at low shear rates but a low internal force at high rates (Ettehadi et al., 2022). The YP/PV ratio thus indicates the ability of mud to keep drilled cuttings from sagging at the bottom of a wellbore (Kania et al., 2021). Figure 3 shows that the YP/PV ratio of FA-WCO was higher than that of CPE but slightly lower than that of FA-SA, indicating that FA-WCO is comparable to CPE and FA-SA and capable of preventing sagging. Furthermore, the resulting FA-WCO emulsion stability was 412V, which is comparable to the CPE mud's 427V, indicating good emulsion stability. This lends support to the hypothesis that generated waste cooking oil could be a more sustainable and environmentally friendly method in the oil and gas industries. On the other hands, the controlled mud sample with FA-SA emulsifier was not stable and decomposed at high temperatures (more than 250°F), reducing its chemical structure and its efficiency as an emulsifier (Li et al., 2023). The thermal degradation process causes the breakdown of stearic acid molecules, resulting in the loss of their ability to stabilise emulsions. This decomposition can cause the oil and water phases of the drilling fluid to separate, diminishing the emulsion's efficacy and potentially posing operational issues in drilling operations requiring high temperature stability (Arain et al., 2022). The CPE or FA-WCO emulsifiers have more complex molecular structures or additional stabilising components, allowing them to withstand higher temperatures without breaking down, making them better suited to high-pressure, high-temperature (HPHT) drilling.

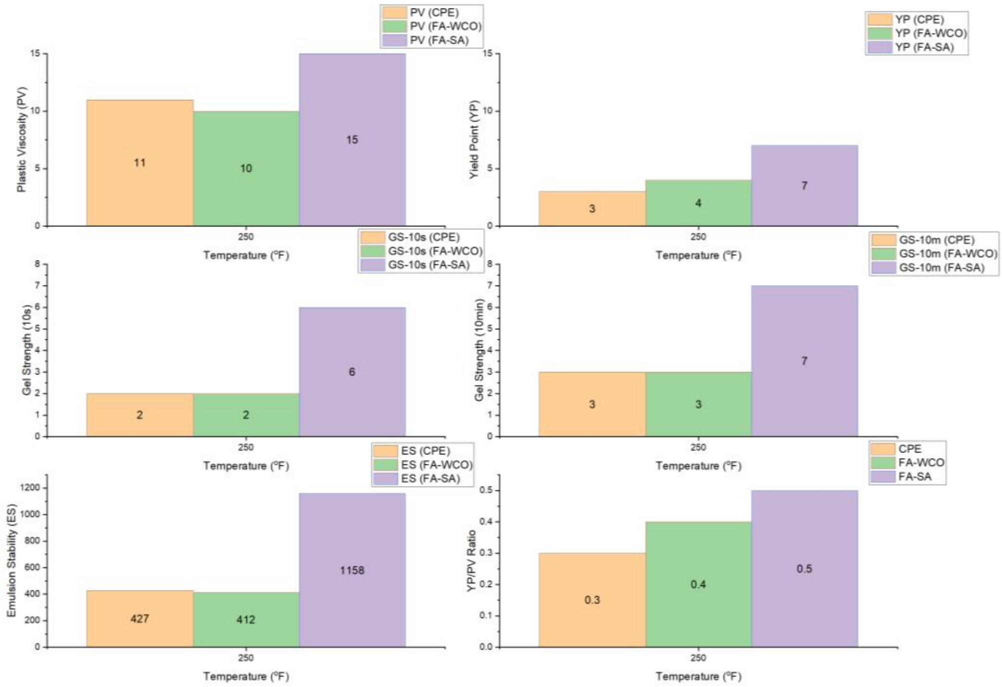

Figure 3: Comparison of Rheological Properties and Emulsion Stability Performance of invert emulsion mud at different types of primary emulsifiers i.e Commercial Primary Emulsifier (CPE), Fatty Acids-Derived Waste Cooking Oil Emulsifier (FA-WCO) and Pure Fatty Acid- Stearic Acid (FA-SA) at 250°F.

4. Conclusions

The study successfully developed an environmentally friendly invert emulsion drilling fluid using emulsifiers derived from waste cooking oil (FA-WCO) and evaluated its rheological properties and emulsion stability under various conditions. The FA-WCO emulsifier exhibited comparable performance to commercial emulsifiers, particularly at an 80/20 oil-water ratio and 250°F, demonstrating similar plastic viscosity, yield point, and emulsion stability. The findings suggest that FA-WCO is a viable and sustainable alternative for high-pressure, high-temperature drilling applications, offering the added benefit of reducing environmental impact through the recycling of waste materials.

Nomenclature

Θ_{600} – Viscometer dial reading at 600 rpm
Θ_{300} – Viscometer dial reading at 300 rpm

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