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Evaluation of Using Fly Ash as a Weighing Material for Oil-Based Drilling Fluid

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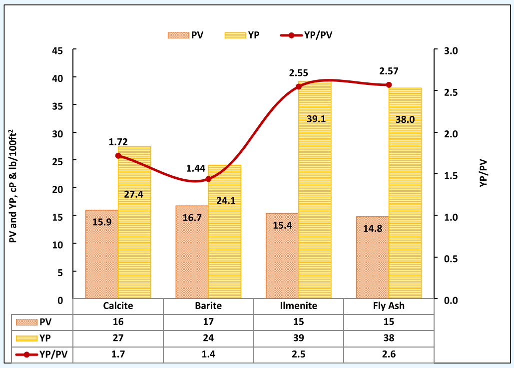
ABSTRACT: Innovation and sustainability are essential in the fast-changing oil and gas business. Fly ash, a byproduct of coal combustion in power plants and factories, has become a valuable resource in many industries, changing the concept of waste materials. Fly ash is essential to sustainable development and environmental care due to its unique qualities and multiple applications. In the drilling industry, a well-designed drilling fluid is essential and this requires the use of various additives that serve specific functions to achieve a successful borehole. This study investigates the use of fly ash as a weighing material in oil-based mud, with the intent to develop an economically acceptable drilling fluid system using industrial waste. The study compared fly ash to three commonly used weighing materials in the drilling industry: calcium carbonate ($CaCO_3$), barite ($BaSO_4$), and ilmenite ($FeTiO_3$). Drilling fluids were prepared using these weighing materials at various weights, and their properties (density, electrical stability, rheological features, and filtration properties) were measured using API-recommended methods. The rheology and filtration tests were conducted at elevated temperatures (350 °F). The results indicate that fly ash has the potential to be a useful weighing material in drilling operations. It can increase the fluid density up to 10 ppg without affecting the rheological properties at 350 °F. Additionally, the electrical stability of the drilling fluid was enhanced compared to the other used weighing materials. The addition of fly ash also improved rheological characteristics such as plastic viscosity, yield point, and gel strength without affecting HPHT filtration properties. The carrying capacity was improved by 53 and 86% over calcium carbonate and barite, respectively. Overall, the findings suggest that fly ash can be a viable alternative to other weighing materials in the recommended density range.



1. INTRODUCTION

Drilling mud is an essential part of any drilling operation and plays a vital role in ensuring the safety and efficiency of drilling.[1−3] The mud has several functions that must all be optimized to ensure safety and minimum hole problems.[4−6] Failure of the mud to meet its design functions can manage a huge loss in terms of materials and time and can also jeopardize the successful completion of the well and may even result in major problems such as stuck pipes, kicks, or blowouts.[7,8]

Water-based mud (WBM) is commonly employed, but it faces significant hurdles in hostile environments such as water-sensitive and high-pressure and high-temperature (HPHT) formations, while oil-based mud (OBM) has a technical advantage but economic and environmental issues.[9] As a consequence, the specific inverted emulsion mud is realistically introduced to support the higher technical standards and meet environmental laws, resulting in the integration of the practical benefits of both WBM and OBM.[10]

Because of the drilling fluid relationship to most drilling operational challenges, the drilling fluid selection and maintenance is vital in whole drilling operations.[11] The average cost of drilling fluid typically constitutes approximately 1/10 of the total cost of a drilling operation, making it a significant and tangible expense.[12] Moreover, the right drilling fluid selection and control of its properties have a significant impact on the entire well cost.[13,14] The additives required to produce and maintain fluid characteristics can be of extreme cost, especially for OBMs. Furthermore, the drilling-fluid characteristics have a substantial impact on the rotary bit penetration rate and operational delays caused by circulation loss, stopped drill pipe, caving shale, and other factors.[15] To avoid facing these problems either while drilling or after, the establishment of a drilling fluid system shall be optimized by providing the proper design for that system in terms of industry, economics, and environment.

It is necessary to add weighting materials to the drilling fluids for maintaining the mud density and managing the downhole

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pressures. These additives need to sustain the mud's desirable rheology and minimal solids-sagging propensity while giving it the required density.[8] There were extensive efforts to find an appropriate weighting agent to fit the needs of increased drilling activity. As a result, the usage of diverse weighing agents as alternatives to the dominating barite over the world is expanding.

Barite is widely used and ecologically acceptable, and its specific gravity of 4.2−4.5 allows it to increase the mud density by up to 19 ppg. Furthermore, the softness of its particles does not harm the equipment. Despite its widespread use and beneficial characteristics, barite has several major related difficulties, including an increase in equivalent circulation density, removal challenges, and increased torque.[16,17]

Calcite (calcium carbonate) is found in nature as limestone. Its specific gravity ranges from 2.7 to 2.8 and is used to raise the mud weight to around 12 ppg. It is preferred over barite because it dissolves in acid, and its composed filter cake can be easily removed with hydrochloric acid. Nowadays, calcite is valued more for its acid solubility than for its density and it is employed mostly as a bridge material in drill-in, completion, and workover fluids.[18,19] Ilmenite, with a specific gravity of 4.5−5.1 and the ability to dissolve in acids, is employed in drilling fluids as an alternate weight agent. Because ilmenite has a harder hardness than barite, its particles are more abrasive. However, utilizing ilmenite with fine particle size helps to reduce abrasion and increase drilling fluid stability.[20−22]

Calcite and ilmenite are two examples of alternative weighing substances that have been employed successfully; nevertheless, as previously indicated, they show some drawbacks. As a result, there is a demand for affordable, readily accessible, and functionally superior alternatives to barite for use as a weighting agent.

Fly ash (FA) is a finely dispersed byproduct generated during the combustion of coal for energy production,[23,24] which is recognized as an environmental pollutant because of its compositional structure, which consists of organic pollutants, probable toxic minerals, and radioactive elements.[25−27] FA is a fine gray-colored powder having a specific gravity of 2.1−3.0. The annual production of coal ash throughout the world is predicted by about 600 million tons, and the FA with 500 million tons constitutes around 75−80% of this rate.[28] Moreover, the amount of waste fly ash released by thermal power plants has been increasing worldwide, and the disposal of a huge amount of fly ash has become a serious environmental problem.[29] From an economic point of view, private companies spend roughly 0.70$ per metric ton on fly ash disposal and control.[30] For that several studies have been carried out regarding the effective utilization of FA.

FA is used in the cement industry because it possesses pozzolanic properties and a bonding property that assists in controlling filtrate losses and ensuring well stability. FA is often used as a stabilizing ingredient in drilling fluid wastes to prevent groundwater pollution. It is also utilized as an ingredient in foam drilling fluid for deep-water offshore wells.[31−34]

FA can be considered the world's fifth-largest raw material resource.[28] Due to the environmental problems presented by fly ash, considerable research has been undertaken on the subject worldwide.[35,36] However, there are currently only a few studies in the literature to investigate the effect of fly ash on the rheological and filtration characteristics of drilling fluids.

Some experimental studies were performed on the effect of fly ash on drilling fluids. Most of these studies were of interest in WBM. Vikas and Rajat[37] experimented with FA as a filtration loss control additive without altering the rheological behavior of the drilling mud; however, there is little information on the functionalization of FA that can be used as a drilling fluid additive to regulate both viscosity and filtration loss. The impact of FA on WBM was also investigated in a study conducted by Özkan et al.[38] The findings revealed that a concentration of 6% (w/v) FA improved the plastic viscosity (PV), yield point (YP), and filtration properties. On the other hand, it was observed that the gel strength decreased as a result. Two different kinds of fly ash were studied in refs 35,39. The results showed that the use of brown coal fly ash (class F) was found to improve the rheological and filtration properties of the drilling fluid, and the rate of improvement was found to be greater than that of lignite fly ash (class C). Bentonite and barite drilling fluids with polymer were tested to see how they performed with respect to fly ash particles smaller than 63 μm.[40,41] The results showed that incasing fly ash particles have a positive enhancement in both the rheological and filtration properties of WBM.

From the literature, it can be inferred that all of the previous studies were conducted on water-based drilling fluids. None of them investigated the effect of FA on oil-based drilling fluid; therefore, in this study, FA was considered as a weighing material because it is highly produced and contains a variety of heavy metals and organic compounds. The study includes the results of density, electrical stability, rheological properties, and filtration properties, for four prepared OBMs that have the same composition with a change in the weighing material for each sample. Additionally, FA was used in OBMs at various concentrations (40, 182, and 300 lb/bbl) as a weighing material and density measurement and rheological properties were acquired to compare the effect of introducing various concentrations of FA into OBMs. Demonstrating the feasibility of recycling FA as a localized weighing material for drilling fluids converts it to a valuable commodity and decreases the demand for virgin materials, resulting in a low-cost, environmentally friendly alternative.

2. MATERIALS AND EXPERIMENTAL WORK

2.1. Materials Characterization. HELOS particle size analysis is used to measure the particle sizes of all weighting materials, including barite. The PSD of fly ash in Figure 1 resembles that of barite with mean sizes (D_{50}) of 16.2 and 18 μm, respectively. However, ilmenite and calcite have different PSDs that are smaller and larger than those of fly ash.

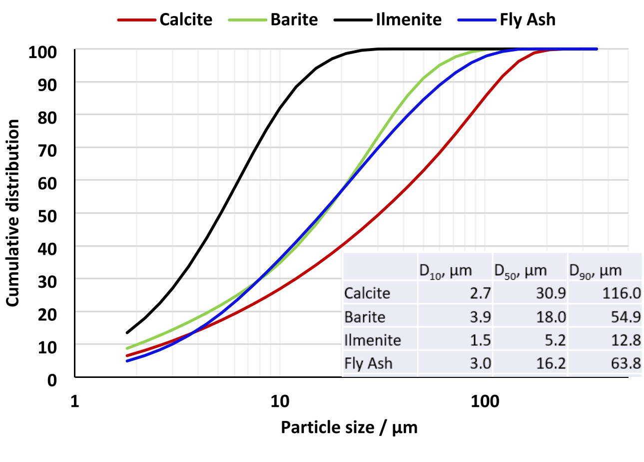

Figure 1. Particle size distribution of the used weighting materials

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ACS Omega 2023, 8, 38045−38052

The composition of the fly ash as shown in Table 1 used in this investigation was determined using X-ray fluorescence (XRF) techniques. The primary constituents were found to be Si (52%), Al (26%), Fe (12%), K (4%), and K (3%). However, the composition of calcite was found to consist solely of Ca (84%) while barite consisted mainly of Ba (69%) and S (20%) and ilmenite consisted of Fe (56%) and Ti (37%) with trace amounts of impurities.

Table 1. Composition of the Used Weighting Materials

component	calcite	barite	ilmenite	fly ash
Si	6	5	3	52
Al	8	5	3	26
Fe	2	0	56	12
K	0	1	0	5
Ti	0	0	37	3
Ca	84	0	0	2
Ba	0	69	0	0
S	0	20	0	0

A scanning electron microscope (SEM) was utilized to conduct an analysis of the morphology and particle shapes of calcite, barite, ilmenite, and fly ash. To prepare the samples, a small quantity of weighting material particles was affixed to conductive tape, which was then coated with a layer of gold metal. The micromorphology of barite and calcite exhibited notable agglomeration as depicted in Figure 2, while fly ash particles were uniform and spherical without any corners.

2.2. Fluid Preparation. The prepared invert emulsion mud with an oil/water ratio (OWR) of 75/25 for this study was mixed using a three-speed mud mixer, with diesel as the continuous phase and $CaCl_2$ brine as a discontinuous phase. Additives were sequentially added and mixed, starting with the primary and secondary emulsifiers, followed by lime for enhanced emulsion alkalinity. To prevent fluid filtrate invasion, Duratone is used as a fluid loss control additive. GELTONE was utilized as a viscosifier to maintain the drilling fluid's rheology. The used additives were provided by a drilling fluid services

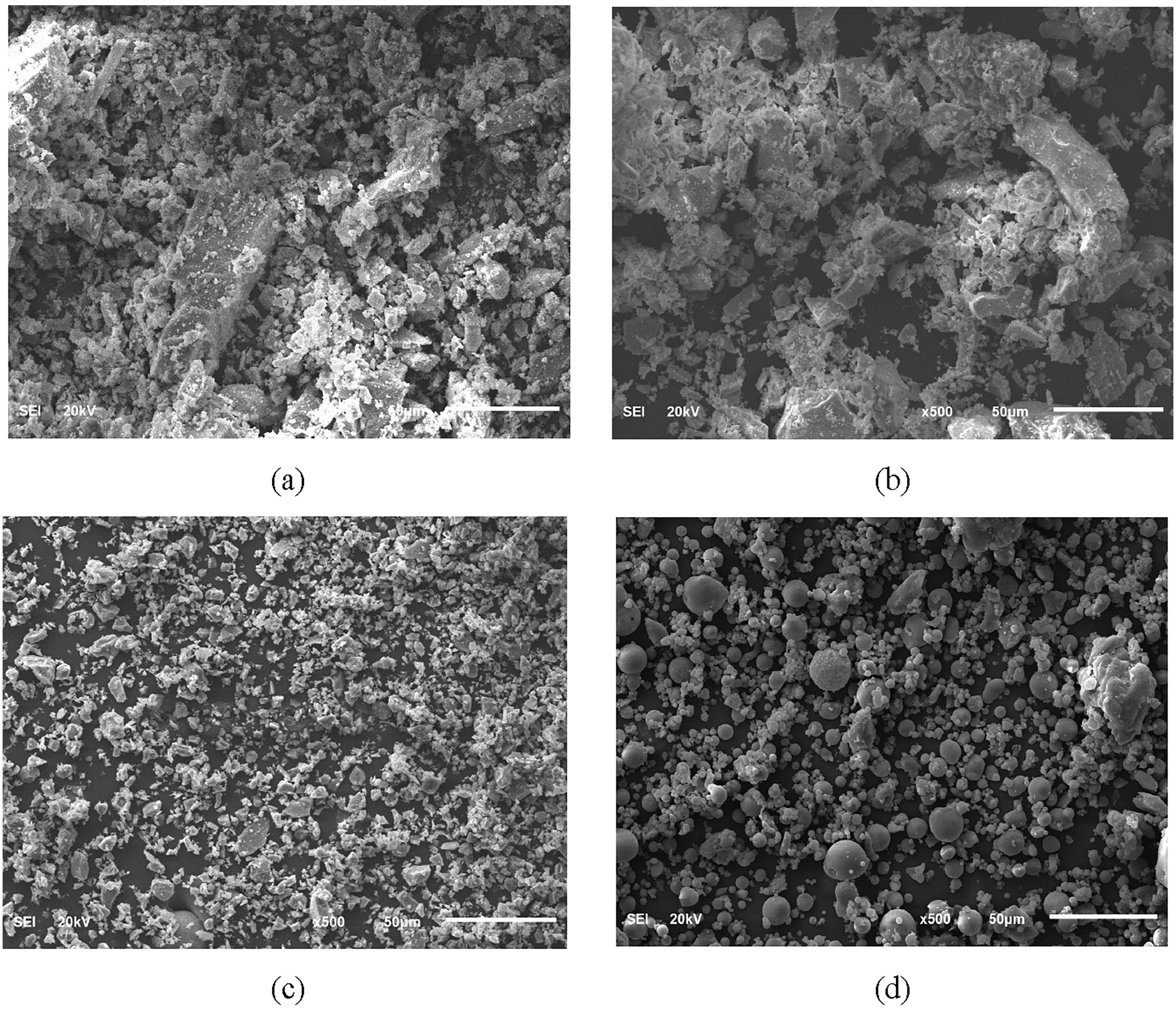

Figure 2. Micromorphology of particles: (a) calcite, (b) barite, (c) ilmenite, and (d) fly ash.

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ACS Omega 2023, 8, 38045−38052

provider in the middle east. The composition and quantity of the additives are listed in Table 2.

Table 2. Drilling Fluid Formula (8.6 ppg)

additive	fluid#1	fluid#2	fluid#3	fluid#4
diesel (continuous phase)	210 mL	210 mL	210 mL	210 mL
INVERMUL (primary emulsifier)	6 g	6 g	6 g	6 g
EZ-MUL (secondary emulsifier)	3 g	3 g	3 g	3 g
lime (alkalinity controller)	8 g	8 g	8 g	8 g
water (dispersed phase)	59.5 mL	59.5 mL	59.5 mL	59.5 mL
$CaCl_2$ (shale stabilizer)	44 g	44 g	44 g	44 g
GELTONE II (viscosity controller)	9 g	9 g	9 g	9 g
Duratone HT (fluid loss controller)	8 g	8 g	8 g	8 g
calcite (weighting agents)	30 g			
barite (weighting agents)		24 g		
ilmenite (weighting agents)			22 g	
fly ash (weighting agents)				40 g

2.3. Rheological Properties. A FANN viscometer is used to measure various rheological properties of a mud sample, including PV, YP, 10 s (10 s GS), 10 min (10 m GS), and 30 min gel strength (30 m GS). This equipment was operated by shearing the fluid in the annular space between the rotor and the bob. The reading of the bob was specified by dial deflection readings at various shear rates ranging from 3 to 600 rpm. The Bingham plastic flow model was used to determine the values of PV and YP, and the gel strengths were determined from the dial reading at 3 rpm after the static duration. These tests were conducted before and after the hot rolling at temperature of 350 °F.

2.4. Electrical Stability. To evaluate the emulsion and oil-wetting characteristics of mud samples, the electrical stability (ES) test was conducted under ambient conditions. This test involves applying a sinusoidal alternating voltage to a pair of electrodes that are immersed in the OBM samples. The voltage is gradually increased to measure the ES, which helps to assess the stability of the emulsion and the extent to which the mud sample is oil wetted.

2.5. HPHT Filtration Test. The HPHT filtration properties of drilling and completion fluids were evaluated under simulated downhole conditions using an HPHT filter press. The prepared drilling fluid samples were analyzed to determine their filtration properties, which were measured as a function of the fly ash present. To perform the test, an HPHT filter press cell was used, applying a pressure of 500 psi and a temperature of 350 °F for 30 min. The filtrate volume was recorded at different time intervals, and the thickness of the resulting filter cake was measured using digital vernier calipers.

3. RESULTS AND DISCUSSION

3.1. Density and ES. Different weighing materials and their effects on the density and ES of 8.6 ppg of OBM samples are shown in Figure 3. All the OBM samples exhibit ES values exceeding 500 V, indicating stable emulsion systems, as recommended by the industry guidelines.[42] The results also show that the fly ash weighing material has the highest ES, which implies that it improves the OBM emulsion system.

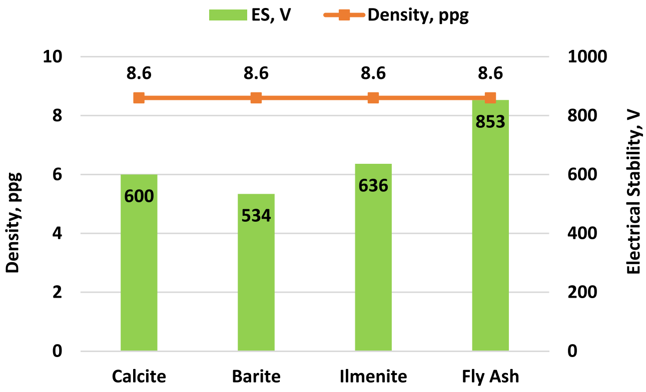

Figure 3. Density and ES of drilling fluids at ambient conditions

3.2. Rheological Properties. The viscosity and gel strength of oil-based drilling fluids are essential for their ability to carry cutting and weighing agent particles. However, the rheological properties of these fluids are affected not only by the properties of organoclays but also by the quantity and type of weighting materials. The rheological properties of oil-based drilling fluids prepared with FA and different weighting materials are shown in Figure 4. The rheology of drilling fluids is often evaluated by using the Bingham plastic flow model. The Bingham plastic flow model is a mathematical model that describes the behavior of fluids that exhibit both viscous and elastic properties. The PV and YP of drilling fluids are important rheological properties because they can be used to predict how the fluid will flow under different conditions. Figure 4 shows that the four prepared drilling fluids were divided into two clusters. Calcite- and barite-weighted drilling fluid exhibited higher PV and lower YP (i.e., 15.9 cP/27.4 lb/100 ft^2 and 16.7 cP/24.1 lb/100 ft^2), respectively, while ilmenite and fly ash had a little pit lower PV and much higher YP (i.e., 15.4 cP/39.1 lb/100 ft^2 and 14.8 cP/38.0 lb/100 ft^2) respectively. The reduction of PV is related to the shape and particle size of weighting materials.[43,44] Fly ash had a particle size distribution similar to barite but gave better rheology. This is attributed to the spherical shape of the particles of fly ash. The presence of a spherical shape facilitated particle sliding, leading to reduced friction among the particles compared to the sharp bulk of barite. Also, ilmenite and FA provided a higher YP/PV ratio, which indicates a better carrying capacity.

The gel strength (GS) is proportional to the mud's capacity to hold drill cutting and mud solids under static circumstances when mud circulation is stopped. It is a measurement of intraparticle electrochemical interactions in drilling fluid under nonflow conditions, which is critical because the drilling mud must be able to suspend drill cuttings while also maintaining a stable wellbore and conveying the cuttings to the surface. To decrease the generally excessive circulation pressure necessary to resume drilling mud flow and avoid cutting slumping, an optimal GS value is always required. Figure 5 shows the GS of different weighting materials of oil-based drilling fluids. It can be seen that FA has a better ability to suspend the cuttings, since it strengthens the gel structure due to the increase in electrostatic interactions over the other weighting materials. 10 and 30 min yield the same value of FA, which means no extra pump pressure is required to initiate the flow of drilling fluid.

3.3. Effects of Fly Ash on HPHT Filtration Properties. The filtration properties of the samples were examined using the HPHT filter press under an operating pressure of 500 psi and

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ACS Omega 2023, 8, 38045−38052

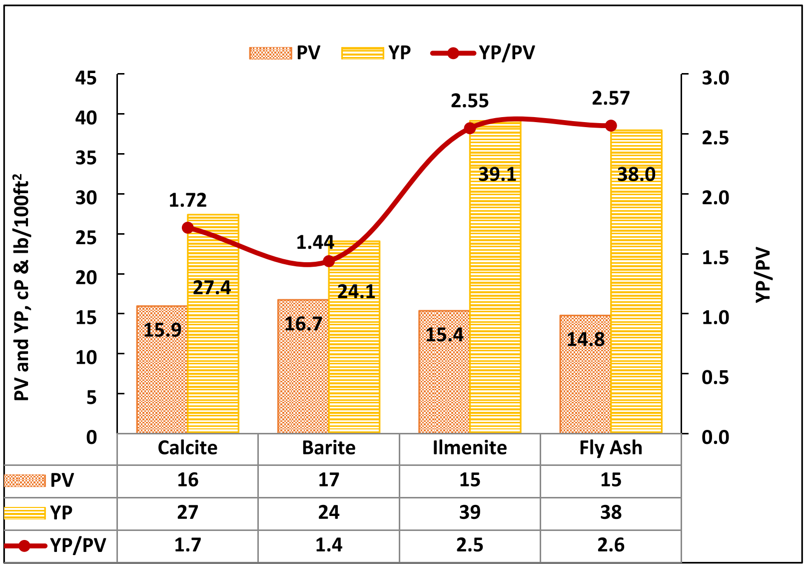

Figure 4. Plastic viscosity and yield point of drilling fluids at 350 °F.

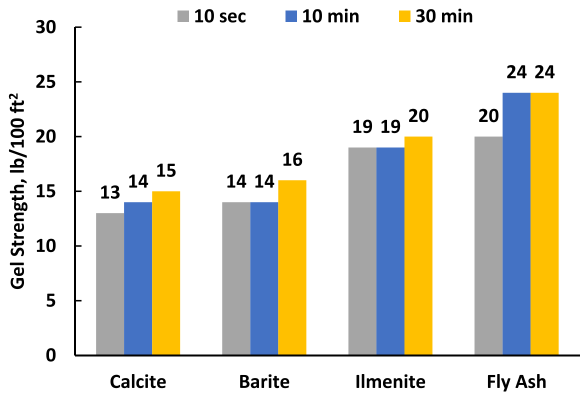

Figure 5. Gel strength of drilling fluids at 350 °F.

350 °F. The addition of FA to oil-based fluids as shown in Figure 6 slightly increased fluid loss by 10 and 4% over calcite and ilmenite, respectively, especially in the absence of bridging agents. However, FA has yielded the same fluid loss of barite as 9.6 cm^3 in the oil-based drilling fluid but still within operation range (i.e., less than 10 cm^3 after 30 min).[45] In conclusion, the characteristics of fly ash particles, combined with enhancements

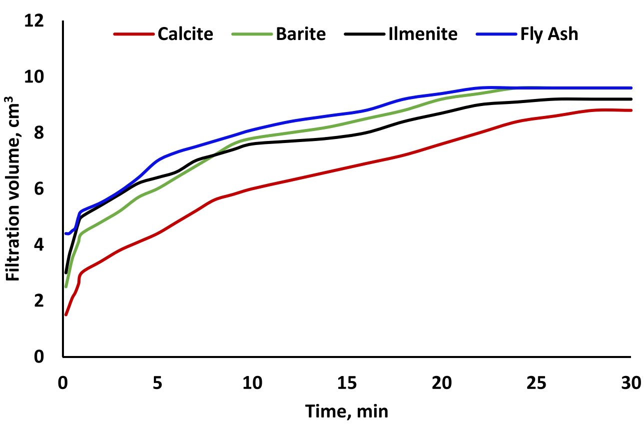

Figure 6. Filtration volume vs filtration time for various weighing agents

in rheological properties, have resulted in a rapid plugging mechanism and a reduction in the level of solid invasion.

Another factor to study HPHT filtration is the thickness of the mud cake. Mud cake is an important part of drilling operations since it prevents drilling fluid invasion into drilled formations. The results in Figure 7 showed that FA as a weighting material maintain the thickness of mud cakes to 3.67 mm. The deposition of a thin mud cake by FA is a noteworthy factor in mitigating issues associated with mud cake, such as pipe sticking. The thinner of the mud cake is attributed to the small size and high dispersion of the FA particles, which effectively fill the minuscule surface pores due to their good dispersion.

3.4. Effect of Increasing Mud Density on Rheological Properties. As can be observed from Figure 8a, increasing the OBM over 10 ppg had a big effect on PV and YP. The difference in the patterns between the 8.6, 10, and 11 ppg of the OBM samples was confirmed by the shear stress vs shear rate curves (Figure 8b). This is due to the difference in the solid content at each mud weight. The 8.6 ppg OBM sample had a lower solid content, which made it lower PV and YP. The addition of FA to the 10 ppg OBM sample increased the strength of the mud, but the 11 ppg OBM sample cannot be used due to high PV and YP requiring more pumping pressure, which may cause surge and swap issues (Figure 8).[45]

Figure 9 shows the 10 s, 10 min, and 30 min GSs of 8.6, 10, and 11 ppg of OBM samples after aging, respectively. The recommended specification for the 10 min GS is that it should be less than or equal to 35 lb/100 ft^2 for both high-temperature and low-temperature conditions. The results showed that the GS of the OBM samples increased with an increasing FA concentration. This means that the more FA there is, the stronger the mud strength. Notably, the observed increase of the GSs over the range of FA contents could be due to the strengthening of the gel structure and the increase in electrostatic interactions within the mud upon FA addition. Although FA enhanced the GS of the drilling fluid, 11 ppg of FA OBM became very thick and yielded higher GS. The resulting pressure spikes will be quite high. The utilization of FA to increase mud density greater than 10 ppg was considered impractical, due to its specific gravity of 2.16 g/cm^3, which

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ACS Omega 2023, 8, 38045−38052

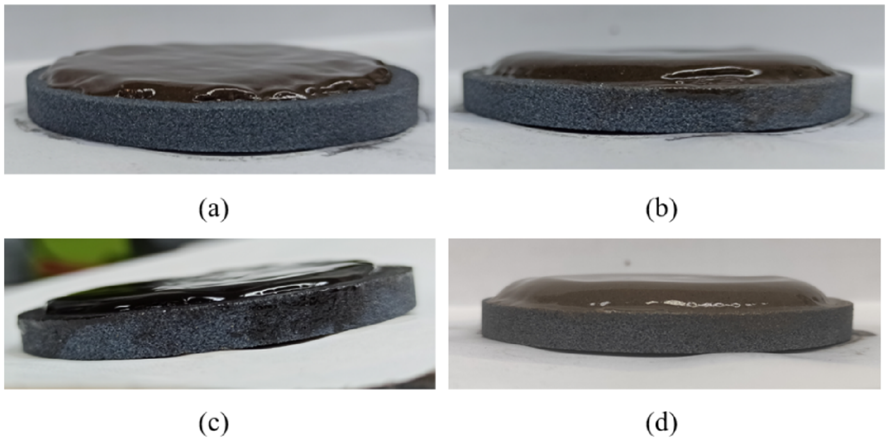

Figure 7. Filter cake thickness: (a) calcite, 2.46 mm; (b) barite, 3.12 mm; (c) ilmenite, 2.79 mm; (d) FA, 3.67 mm.

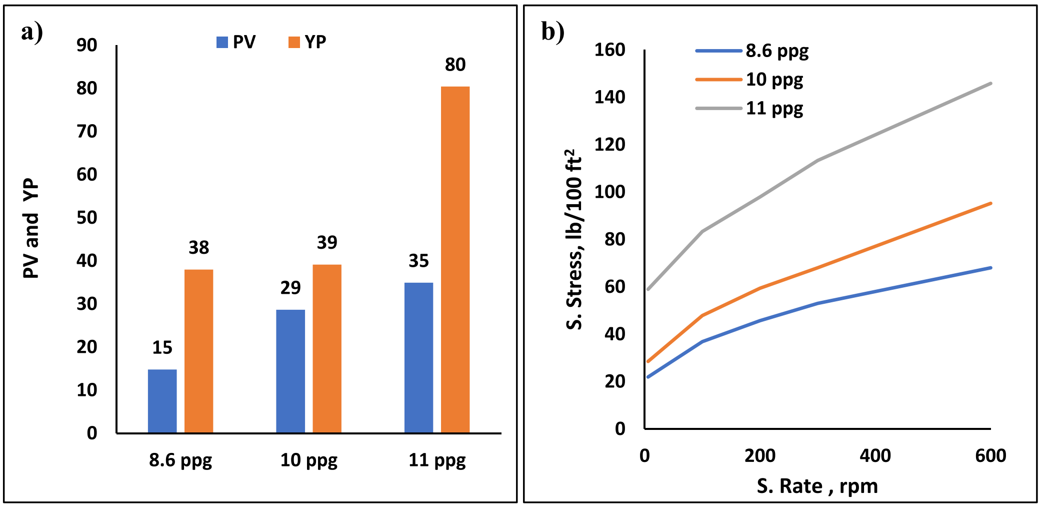

Figure 8. (a) PV and YP and (b) shear stress vs shear rate curves of FA at different densities.

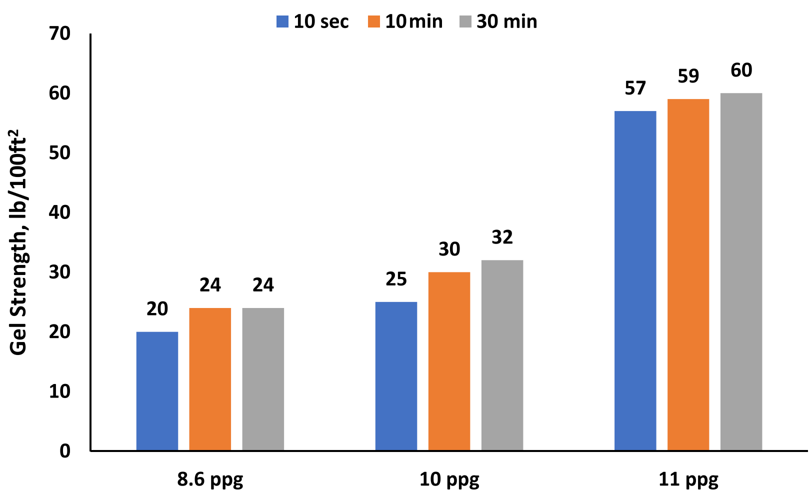

Figure 9. Gel strength of FA at different densities.

required high amounts of FA that contributed to destroying the rheological properties.

The obtained experimental results of this study proved the feasibility of using fly ash as a weighting agent, and its addition to the OBM improved the drilling fluid technical characteristics, since it improved the mud's emulsion stability, rheological properties, carrying, and suspension capacities, with a competent filtration performance. Besides, recycling fly ash as a localized weighting agent transfers it into a useful commodity and reduces the need for virgin materials, which provides an inexpensive alternative that has environmental benefits.

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ACS Omega 2023, 8, 38045−38052

However, using fly ash to obtain a mud weight over 10 ppg is not recommended.

4. CONCLUSIONS

This study investigated the impact of fly ash on drilling fluid properties, including density, ES, rheology, and filtration, across a range of concentrations (40, 182, and 288 lb/bbl). The following conclusions can be drawn from the experimental findings:

- Adding FA had a reasonable positive effect on ES. The ES of FA increased by 34% compared to the highest weighting agent (ilmenite), which indicates that the water phase would be well emulsified in the continuous-phase diesel.
- FA significantly improved the rheological properties, reducing PV compared to calcite by 6% and barite by 11%, while enhancing YP and GS over all used weighting materials leading to an improvement in the ability of the drilling mud to suspend the solid particles.
- In HPHT filtration, fly ash OBM showed filtration qualities like those of other OBMs, such as a comparable filtrate volume and filter cake thickness.
- Since the specific gravity of fly ash is less than that of other utilized materials, increasing mud density over 10 ppg requires substantially higher solids contents, which had a negative impact on the rheological properties.

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Author Contributions

Conceptualization, S.E. and S.B.; methodology, S.B. and M.A.-H.; formal analysis, S.B., M.A.-H., and A.A.; investigation, S.B. and M.A.-H.; data curation, S.E.; writing—original draft preparation, S.B. and M.A.-H.; writing—review and editing, A.A. and S.E.; supervision, S.E. All authors have read and agreed to the published version of the manuscript.

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Notes

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NOMENCLATURE

FA: fly ash
OBM: oil-based mud
WBM: water-based mud
PV: plastic viscosity
YP: yield point
GS: gel strength
HPHT: high-pressure high-temperature
ES: electrical stability
ppg: bound per gallon

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