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Primary Investigation of Barite-Weighted Water-Based Drilling Fluid Properties

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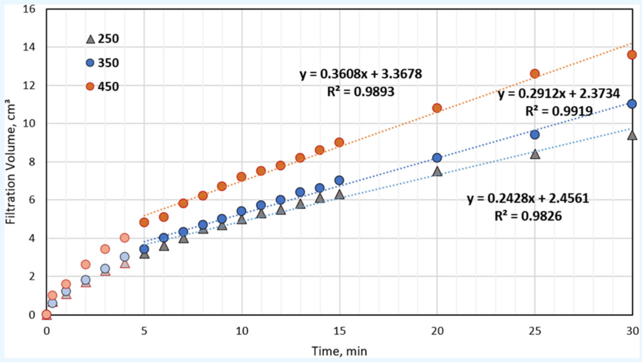

ABSTRACT: Drilling fluid is a critical component in drilling operation due to its various functions. It consists of many elements, and one of the main components is the weighting material which controls the mud density. The weighting material type and concentration have a significant impact on the drilling fluid properties. A common weighting material used in the oil and gas industry is barite. In this work, the impact of barite concentration on water-based drilling fluid was evaluated. The investigated drilling fluid properties are density, pH value, filtration behavior, and rheological parameters. An intense investigation was carried out to evaluate the impact of barite concentration on the filtration and filter cake sealing properties. The density and pH values were measured at room temperature, filtration test was performed at room temperature, and differential pressure was equal to 100 psi. The rheological parameters were determined after hot rolling for 16 h at a temperature of 250 °F. The results showed that both the density and pH value increased linearly with barite dosage. The filtration volume, filter cake thickness, and permeability increased with the incremental increase in barite dosage, and the exponential relationship was the best in describing the relation with barite concentration. However, the filter cake porosity had an inverse proportional relation with barite dosage. In the case of rheological properties, all the investigated properties including the plastic viscosity, yield point, ratio of yield point to plastic viscosity, and gel strength at two different times (i.e., 10 s and 10 min) increased in general as the barite concentration increased.

1. INTRODUCTION

Drilling fluid is considered as the blood in drilling operation, and it consists of many chemicals (e.g., weighting material, viscosifier, filtration agents, etc.) to perform several functions (e.g., controlling sub-surface pressure, cleaning the well, carrying the cuttings, etc.).[1,2] Weighting material addition to the drilling fluid enables the drilling operation to reach higher depths.[3] This is due to the fact that the one concern with the deeper wells is the high hydrostatic pressure column needed to prevent the kick from entering the well. The weighting material is simply a material with high specific gravity, which is used in the drilling fluid or cementing slurry to increase the density. There are several examples of weighting materials including ilmenite, hematite, barite, calcium carbonate, ferromagnetic magnetite, siderite, galena, anhydrous calcium sulfate, and so forth.[2,4−12] The criteria for choosing the weighting material include the availability, cost, removal process, compatibility with other components in the drilling fluid, formation type that will be drilled, and so forth. The most common weighting material is barite.[13]

Barite is a mineral with barium sulfate as the main component, and it deposits in many forms such as bedded-sedimentary/volcanic. Barium accounts for 59% of the barite weight used in ceramic, steel hardness, and other products. Barite has many applications in several industries such as plastic, rubbers, and so forth, but the drilling activity represents almost 90% of the total consumption of barite.[14,15] The high consumption percent when using the oil and gas as weighting materials is due to several reasons such as the abundance of barite compared to the other weighting material, relatively high specific gravity, low cost, relatively high solubility percent using chelating agents, and so forth.[16,17] Over the years, many researchers investigated barite from different standpoints, and Scharf and Watts (1984) investigated two weighting materials and compared their performance, namely, barite and micaceous hematite.[7] They compared them in oil-based mud with a density equal to 18 ppg. The results revealed that barite had lower filtration volume and lower rheological properties in

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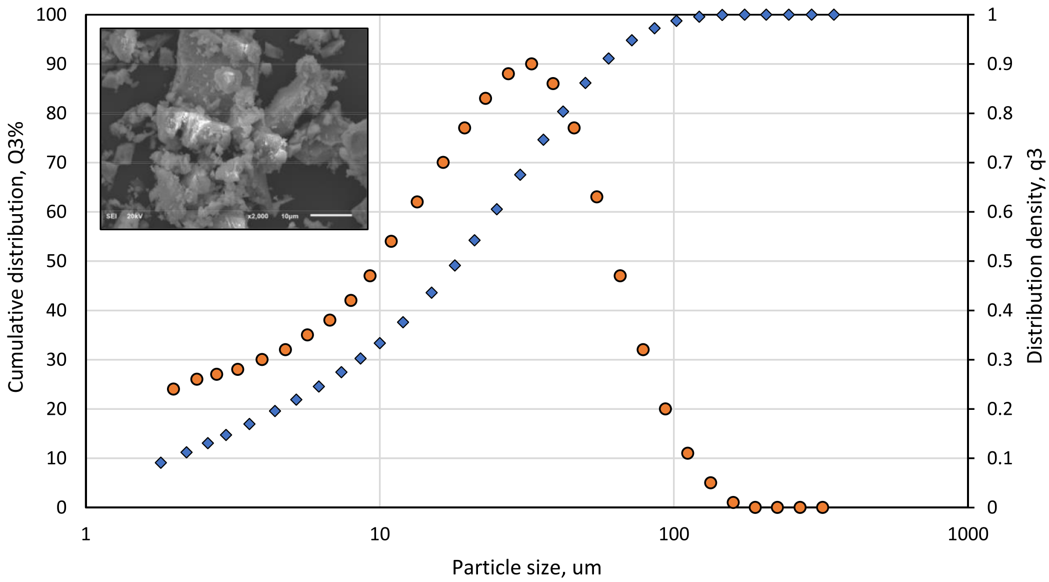

Figure 1. PSD and the scanning electron microscopy image of barite particles.

general. Al-Awad and Al-Qasabi (2001) assessed the performance of Saudi barite as a weighting material and compared its performance with commercial barite.[18] They characterized the local barite using several techniques and tests such as flame test and chemical analysis. In addition, they tested the local barite from API requirement as a weighting material in comparison to commercial barite. Their results showed that the local barite can be utilized as a weighting material since it passed all the checklist components in comparison to the commercial barite and based on the economic feasibility study that they performed. Accordingly, they recommenced the use of the local barite. It can even be commercialized and used as a financial source for Saudi Arabia. Igwilo et al. (2019) studied the impact of the mud density of barite and calcium carbonate as weighting materials on hole cleaning and transport efficiency.[19] They varied the concentration of each weighting material, and the resulting mud density was around 8.7, 9.5, 9.9, 10.6, and 11 ppg. Their results displayed that calcium carbonate had better outcomes in comparison to barite in terms of transporting efficiency. On the other hand, barite outperforms calcium carbonate in term of the equivalent circulating density. Moreover, some researchers tried to use barite with alternative weighting materials in different percentages to improve their performance, Abdou et al. (2018) investigate the usage of ilmenite with barite in terms of the rheological and filtration properties.[20] They prepared three mud formulations where the weighting material in the first was barite, the second was ilmenite, and the third formulation consists of 50% barite and 50% ilmenite. The mud formulations (i.e., 8.7 and 18 ppg) were prepared in varied densities and then tested at different temperatures ranging from 76 to 180 °F. The outcomes of their study illustrated how the mix of barite/ilmenite was equal or better compared to the other formulations in terms of lower solid content and fluid loss which reflected positively on the formation damage. In terms of the rheological properties, the barite/ilmenite mix formulation gave a comparable result with the other formulations. In a similar manner, Basfar et al. (2019) evaluated the usage of ilmenite with barite to minimize the sagging problem in barite water-based drilling fluid.[21] They prepared five different mud formulations with mixed weighting materials of ilmenite/barite including 100/0, 25/75, 50/50, 75/25, and 0/100 as ratios. They examined several properties including the density, pH value, sag, filtration, and rheology. They found that 50/50 was able to enhance the drilling mud formulation under static and dynamic conditions. The rheological properties were improved, while the filtration results did not show any difference. Moreover, they also tested the mixture of barite with Micromax in inverted emulsion drilling fluids.[22] They tried different percentages of Micromax addition to the barite, and the best results were found at 30% of Micromax with 70% of barite. At this percentage, the barite sagging issue was solved under dynamic and static conditions. Moreover, this percentage increased the density and the yield point, maintained the gel strength, and decreased the plastic viscosity. The filtration and the filter cake properties were improved upon the Micromax addition. Bageri et al. (2021) evaluated the impact of different weighting materials on the drilling fluid properties.[23] They used barite, ilmenite, hematite, and Micromax as weighting materials, and the sandstone cores were used as a filtration medium. Their results showed that the ratio of large to small particle size of weighting materials (i.e., D_{90}/D_{10}) is an important factor to be considered, and they found several relations between the ratio and the drilling fluid properties.

In this work, barite, as a weighting material, was varied from a concentration perspective to evaluate its effect on the drilling fluid properties. The investigated drilling fluid properties are the viscosities, density, and pH value. Furthermore, the impact of barite concentration on the filtration and filter cake sealing properties was deeply investigated. The tests were conducted after aging the fluid in a hot rolling oven for 16 h at a temperature of 250 °F.

2. MATERIALS AND EXPERIMENTS

Barite used in this work is obtained from Baroid which has a specific gravity equal to 4.2. The particle size distribution (PSD) was evaluated for the barite particles using wet dispersion unit ANALY- SETTE 22 Nano Tec plus, and the PSD is shown in Figure 1. As can be seen in Figure 1, the largest barite particle has a size of almost 100 μm, while the

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smallest barite particle has a size of 1.8 μm. The particle diameter percentiles, namely, 10, 50, and 90% have diameters equal to 1.97, 18.52, and 57.75 μm, respectively. As shown in the scanning electron microscopy (SEM) image of the barite particle at a scale of 10 μm in the inset of Figure 1, it is difficult to identify a certain geometric shape for the particles, and they have an irregular shape. Moreover, SEM−electron-dispersive spectroscopy (SEM−EDS) is shown in Table 1. Barium sulfate showed the highest weight percentage which equals 40.37%, followed by oxygen and carbon with weight percentages equal to 28.48 and 14.77%, respectively. The remaining elements including silicon, sulfur, and boron represent collectively 16.38%.

Table 1. SEM-EDS for the Barite Particles

element	B	C	O	Si	S	Ba
wt %	3.79	14.77	28.48	4.69	7.9	40.37

The drilling formulation used in this work is presented in Table 2, and three mud formulations were prepared with the same components. The only difference between them is how much barite dosage was added. It consists of water as a continuous phase and a defoamer to minimize foam formation. Four salt types were used represented by soda ash, potassium hydroxide, potassium chloride, and calcium carbonate. Moreover, two viscosifiers were used, namely, xanthan gum and bentonite with two filtration agents utilized known as starch and natural polyanionic cellulosic polymer (i.e., PAC-R). Finally, barite is used as a weighting material to increase the density to the desired one.

Table 2. Drilling Fluid Formulation

unit	unit	mud-1 quantity	mud-2 quantity	mud-3 quantity
water	cm^3			
defoamer	g	0.08	0.08	0.08
soda ash	g	0.5	0.5	0.5
xanthan gum	g	0.5	0.5	0.5
bentonite	g	4	4	4
starch	g	6	6	6
PAC-R	g	1	1	1
potassium hydroxide	g	0.5	0.5	0.5
potassium chloride	g	20	20	20
calcium carbonate	g	5	5	5
barite	g	250	350	450

A suit of experiments was performed in this study to achieve the main objective, starting by measuring the density and pH using the mud balance and pH meter, respectively. Then, the rheological properties were measured after aging the sample for 16 h at a temperature of 250 °F and a pressure of 500 psi. The rheological properties were measured using a Grace viscometer at a temperature of 120 °F. The filtration test was performed using low-pressure low-temperature filter press manufactured by FANN, the drilling fluid was placed inside the cell, a pressure of 100 psi was applied on top of the drilling fluid, a filter paper was placed in the bottom side to form the filter cake, and filtration fluid is accumulated in a cylindrical tube.

3. RESULTS AND DISCUSSION

As stated previously, the used barite has specific gravity equal to 4.2. Expectedly, the drilling mud density will have a probation relation with barite dosage. Figure 2 shows the relation between the dosage and the drilling density. Barite dosages of 250, 350, and 450 grams resulted in drilling mud density equal to 13.9, 15.6, and 17.5 ppg, respectively. Another important property is the drilling fluid pH, and it was evaluated as a function of the barite dosage. For the lowest barite dosage (250 g), the pH value was 11.04. As the barite concentration increased, the pH increased as well. It reached 11.35 and 11.41 for barite concertation equal to 350 and 450 g, respectively. The increase in pH value is due to the barite nature, and it becomes more alkaline as the barite concertation increases.

Moreover, additional properties that were impacted by the barite dosage are the filtration and the filter cake properties. The filtration behavior of three samples was investigated. As shown in Figure 3, higher filtration trends were obtained as the

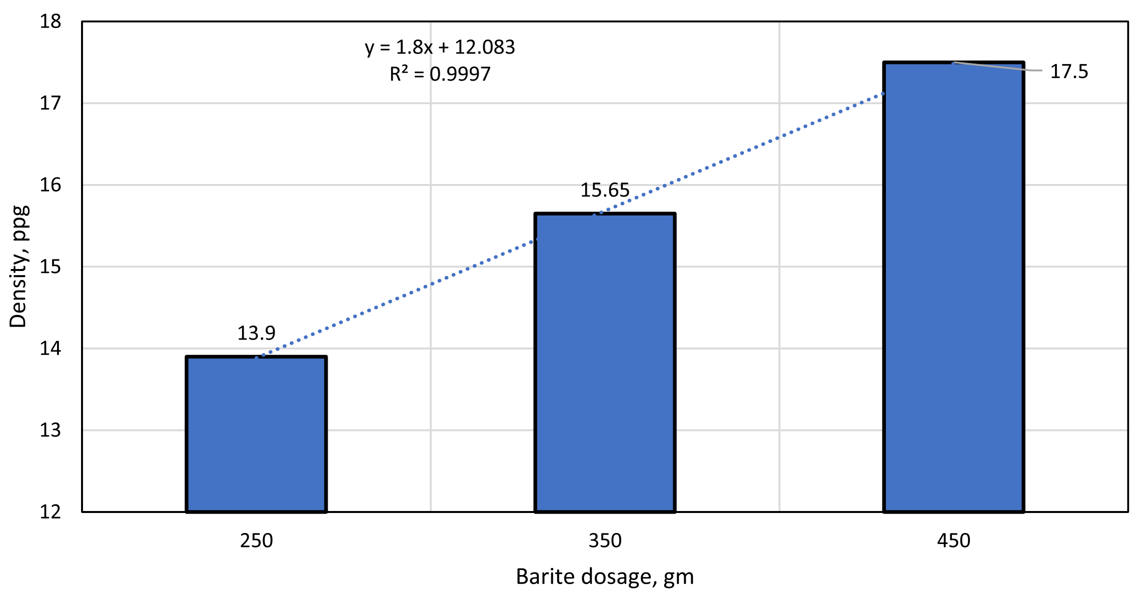

Figure 2. Density as a function of barite dosage.

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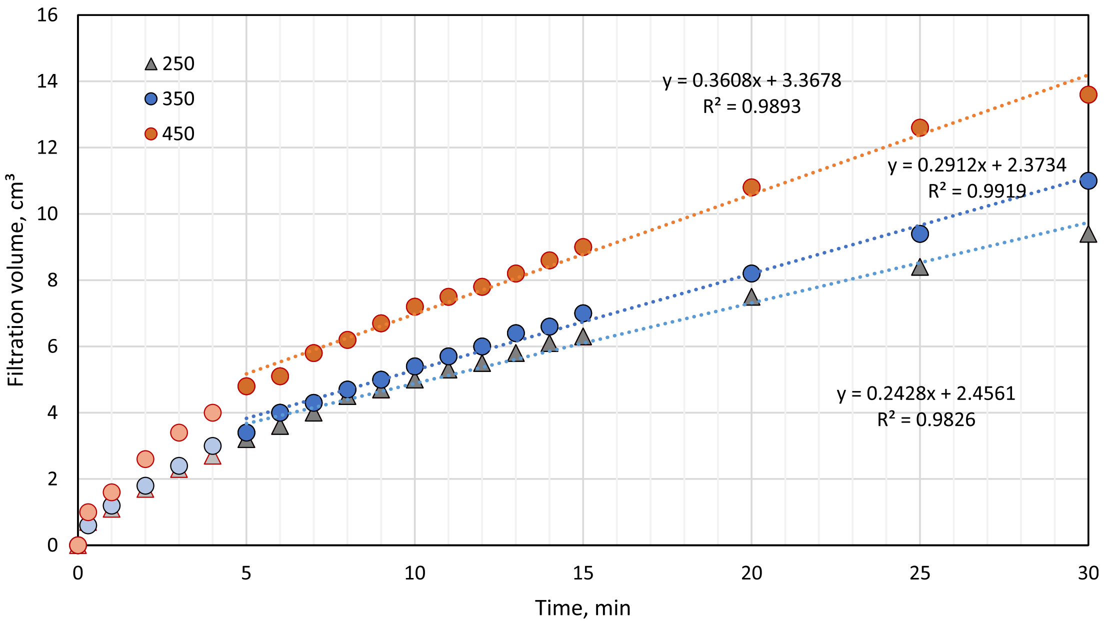

Figure 3. Filtration behavior as a function of three mud samples.

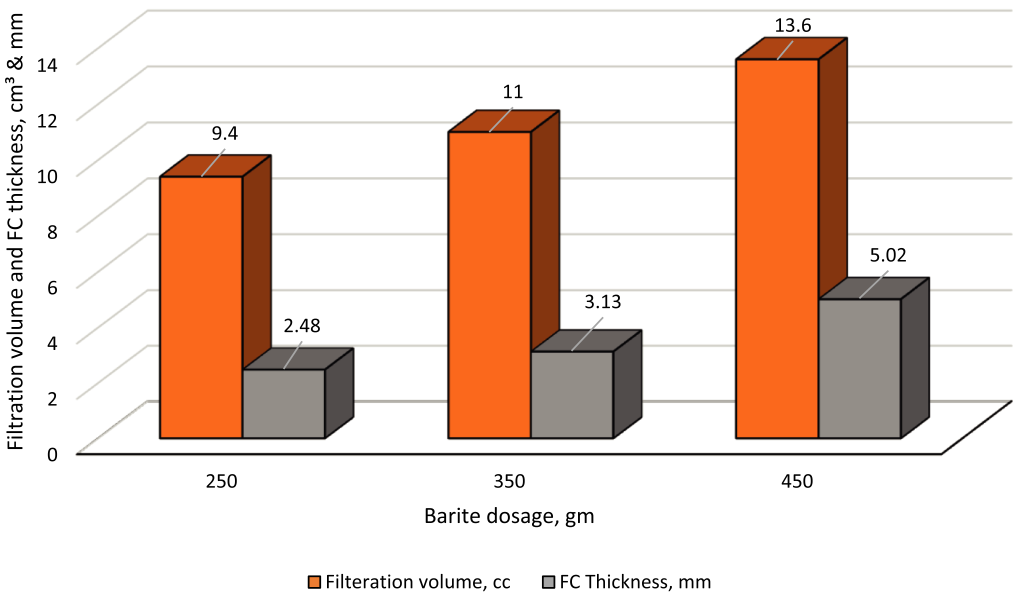

Figure 4. Filter cake thickness and filtration volume for three mud samples.

barite concentration increased. The period before 5 min showed the initial stage of the filter cake buildup. At this period, increasing the barite dosages showed a minor influence. However, the 450 dosage showed a higher buildup rate at this time. At further buildup time, after 5 min, there is a linear increase in the filtration volume for all the dosages until reaching the final filtration volume. Moreover, there was a clear separation in the filtration rate as illustrated by increasing the slope for each line. This indicated that the higher dosage of barite has a higher buildup rate. The buildup rate increased from 0.24 to 0.29 and then 0.34 cm^3/min as the dosage increased from 250 to 350 and then to 450 g. The final filtration volumes are 13.6, 11, and 9.4 cm^3 for 250, 350, and 450 g of barite, respectively, as shown in Figure 4. In addition, Figure 4 shows the filter cake thickness which equals 2.45, 3.13, and 5.02 mm for 250, 350, and 450 g of barite, respectively. As expected, higher dosage causes the formation of thicker filter cake due to the high content of barite particles. Furthermore, the linear region in Figure 3 can be utilized to determine the filter cake permeability based on the Lee model.[24] The permeability values for each barite dosage are shown in Figure 5. The permeability values are 3.22×10^{-2}, 4.88×10^{-2}, and 3.69×10^{-2} mD for 250, 350, and 450 g of barite, respectively. Filter cake porosity was determined using the gravimetric method that depends on the filter cake weight and volume.[25] As can be seen in Figure 4, the filter cake had porosity equal to 0.53, 0.37, and 0.21 for drilling mud with barite concentrations of 250, 350, and 450 g, respectively. It is tempting to find a simple correlation that relates the filtration and filter cake properties to the barite dosage. Hence, several correlations were investigated and found with admirable accuracy, as shown in Figure 6. The filter cake permeability

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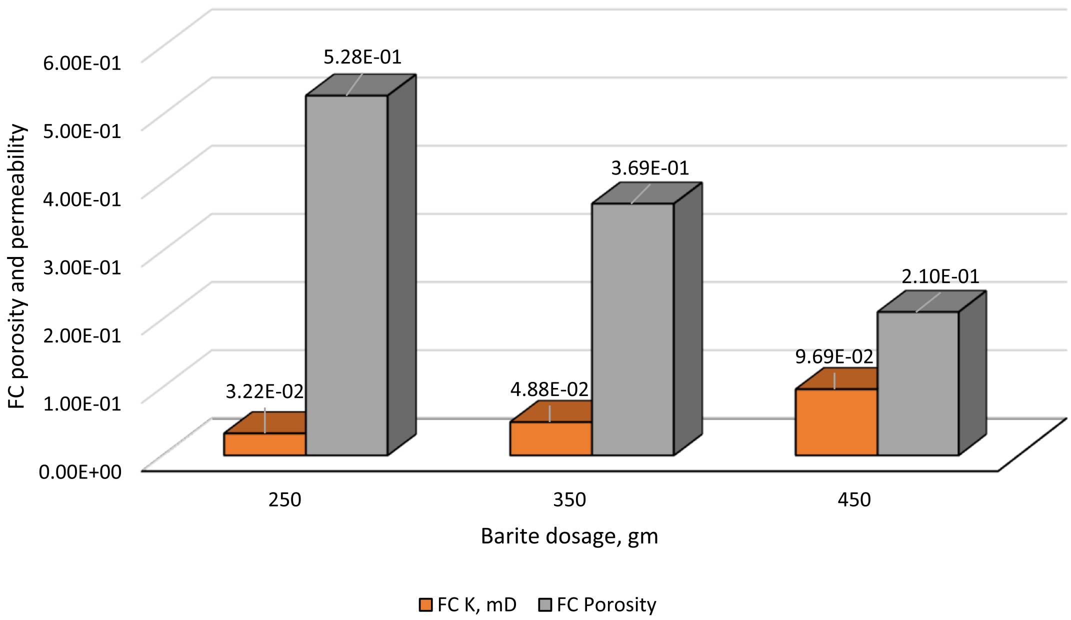

Figure 5. Porosity and the layer permeability of the filter cake for three mud samples.

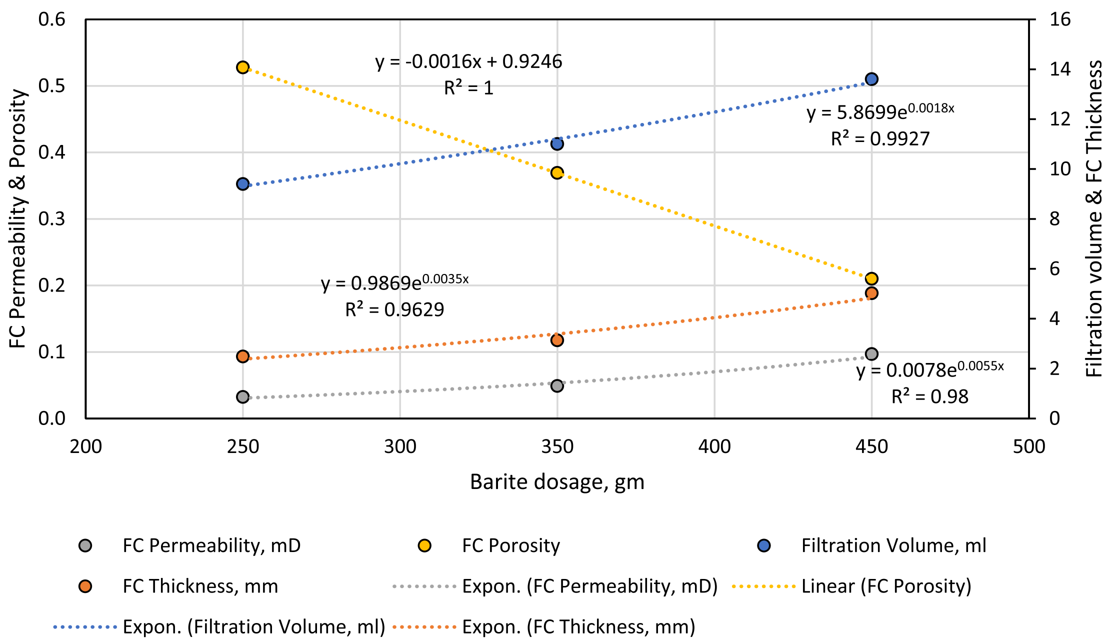

Figure 6. Relation between filter cake permeability, filter cake porosity, filter cake thickness, and filtration volume.

showed probational exponential relation with barite dosage as follows

$$k_{FC} = 0.0078\ e^{0.0055(\text{barite dosage})} \quad (1)$$

For the filter cake porosity, a linear relation was the best in describing the relation with the barite dosage with a correlation coefficient equal to unity. The filter cake porosity can be determined as a function of the barite dosage as follows

$$\phi_{FC} = -0.0016 \times (\text{barite dosage}) + 0.9246 \quad (2)$$

As the dosage increased, the porosity of the filter cake decreased, while the permeability increased. This can be justified as follows: the high dosage mud will have higher packing of barite particles which will reduce the spaces that exist in the filter cake. In the case of the filter cake permeability, the model has two crucial parameters, namely, the filtration rate and the filter cake thickness. Both increased with barite dosage, but the incremental increase in each one caused the filter cake permeability.

Moreover, an exponential relationship was found between the barite dosage and the filtration volume with a correlation coefficient equal to 0.99. The filtration volume can be predicted by the following correlation

$$\text{filtration volume} = 5.8699\ e^{0.0018\times\text{barite dosage}} \quad (3)$$

Similarly, the relation between the filter cake thickness and barite dosage has the exponential form with a correlation coefficient equal to 0.97. Using the barite dosage as the input, the filter cake thickness can be estimated as follows

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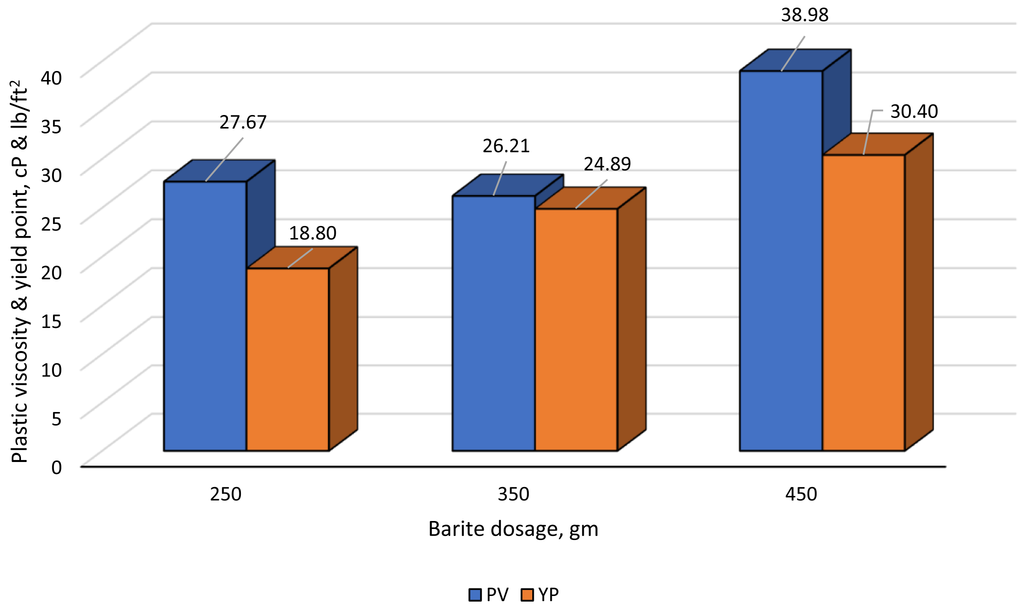

Figure 7. Rheology of the three mud samples after aging at 250 °F for 24 h.

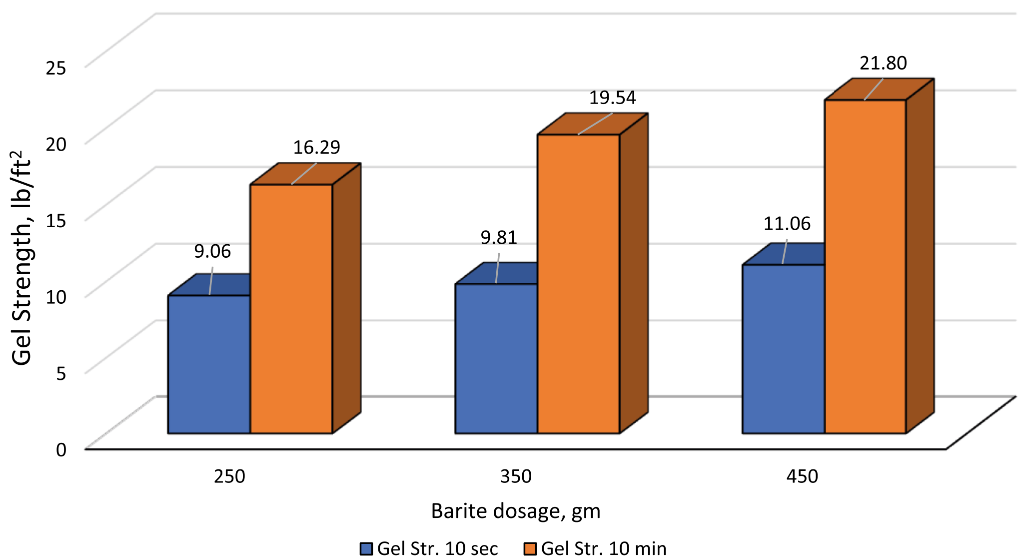

Figure 8. Gel strengths of the three mud samples after aging at 250 °F for 24 h.

$$Th_{FC} = 0.9869\ e^{0.0035 \times \text{barite dosage}} \quad (4)$$

The barite dosage has an impact as well on the rheological properties. Mao et al. (2020) emphasized how the dense packing in high- and ultra-density water-based drilling fluid can impact the rheological and filtration properties.[26] Therefore, it was crucial to assess the impact of the dosage on the rheological properties including the plastic viscosity, yield point, and gel strength at 10 s and 10 min. Figure 7 shows the plastic viscosity and yield point as a function of the barite dosage, while Figure 8 shows gel strength results at two different times as barite concentration increased. The plastic viscosity showed a clear change when the barite dosage increased from 250 to 350 g but a clearer increase as the barite dosage reached 450 g (i.e., PV increased from 26.21 to 38.98 cP). The yield point change with barite dosage is more noticeable, and it increased from 18.8 lb/ft^2 at 250 g of barite to 24.89 lb/ft^2 at 350 g of barite. Similarly, it reached 30.4 lb/ft^2 as the barite concentration increased to 450 g. For the gel strength, there was a small variation as the barite dosage increased especially at 10 s. The value increased from 9.06 to 11.06 lb/ft^2 when the barite concentration increased from 250 to 450 g. The 10 s gel strength values were not influenced as the barite dosage increased from 250 to 350 g. Likewise, the 10 min gel strength increased as the barite dosage, but it remains in the acceptable range.[27] Moreover, the ratio of the yield point to the plastic viscosity (YP/PV) was plotted, as shown in Figure 9. The ratio provided an index for assessing the carrying capacity of the drilling fluid, where a ratio equal to or more than 0.75 is recommended.[28] In this work, the dosage of barite equal to 250 g was out of the acceptable range, while the other two dosages, namely, 350 and 450 g, had ratios that equal 0.95 and 0.75, respectively. It was tempting to see the relations between the different rheological properties that were just mentioned with barite concentration, which is shown in Figure 10. Noticeably, there was no clear trend for both the plastic

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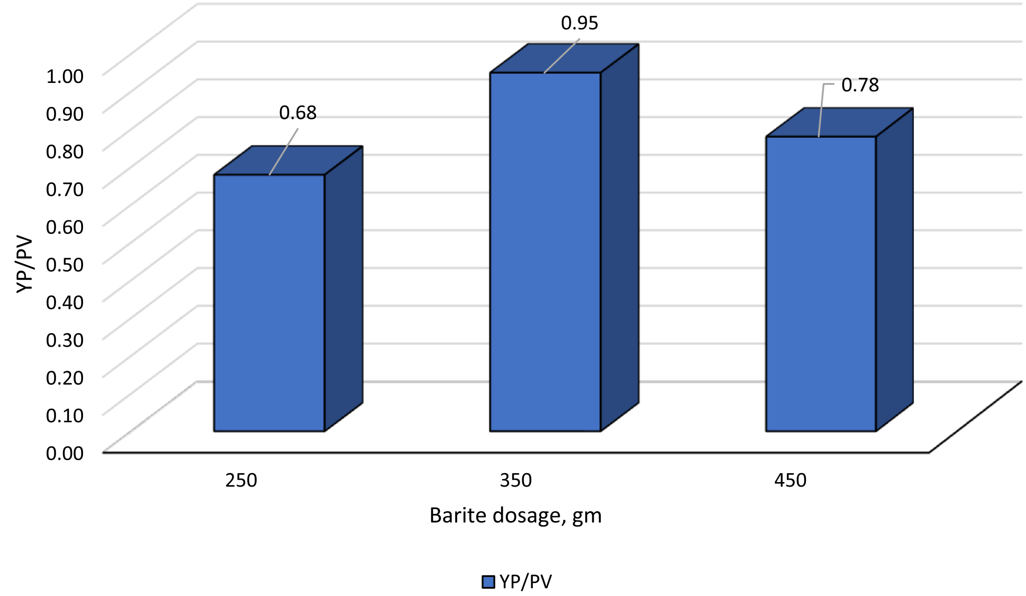

Figure 9. Ratio of yield point to the plastic viscosity.

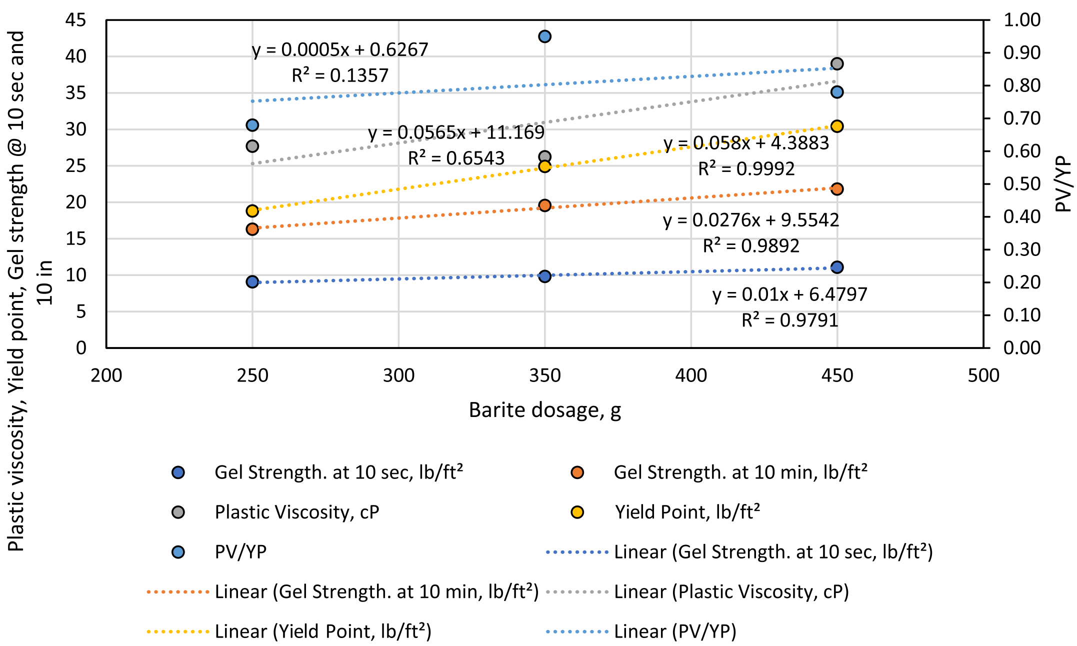

Figure 10. Relation between the barite dosage and the rheological properties.

viscosity and YP/PV ratio. The remaining properties, on the hand, showed a good relationship with the barite dosage. The yield point linear relationship with barite dosage showed a coefficient of determination equal to 0.999, and it has the following form

$$\text{YP} = 0.058 \times (\text{barite dosage}) + 4.3883 \quad (5)$$

Moreover, gel strength at 10 s and 10 min showed a good linear relationship with barite dosage, with their determination coefficient was equal to 0.979 and 0.989, respectively. They have the following forms

$$\text{gel strength}_{10\text{s}} = 0.01 \times (\text{barite dosage}) + 9.5524 \quad (6)$$

$$\text{gel strength}_{10\text{ min}} = 0.0276 \times (\text{barite dosage}) + 6.4797 \quad (7)$$

4. CONCLUSIONS

Barite is one of the most common weighting materials used in the oil and gas industry. It is utilized mainly to increase the drilling fluid density. In this work, three barite dosages were varied in consistent drilling formulation to assess the dosage impact on the drilling fluid properties. The findings of this work can be summarized as follows:

1. The filtration volume, filter cake thickness, and filter cake permeability increased as the barite dosage increased, and they showed an excellent relationship with barite concentration where the lowest determination coefficient was equal to 0.969. On the other hand, the filter cake porosity has an inverse proportional relationship with barite dosage. These can be attributed

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to the packing of the filter cake caused by the barite dosage.

2. The rheological parameters were increased as the barite dosage increased, and they showed a good linear relation with barite concentration.
3. The barite dosage showed a linear relation with water-based mud density, 100 g/cm^3 increase in barite dosage was able to increase the density by almost 1.7 ppg.

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Author Contributions

The manuscript was written through the contributions of all authors. All authors have approved the final version of the manuscript

Notes

The authors declare no competing financial interest.

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■ REFERENCES

(1) Hossain, M. E.; Al-Majed, A. A.*Fundamentals of Sustainable Drilling Engineering*; John Wiley & Sons, 2015.

(2) Caenn, R.; Darley, H. C. H.; Gray, G. R.*Composition and Properties of Drilling and Completion Fluids*, 7th ed.; Gulf Professional, 2016.

(3) Barrett, M. L. DRILLING MUD: A 20TH CENTURY HISTORY. *Oil-Industry History* **2011**, *12*, 161–168.

(4) Al-bagoury, M.; Steele, C. D.A New, Alternative Weight Material for Drilling Fluids. IADC/SPE 151331 Paper Presented at the 2012 IADC/SPE Drilling Conference and Exhibition. *IADC/SPE 151331 Pap. Present. 2012 IADC/SPE Drill. Conf. Exhib.*, 2012, No. March, 6–8.

(5) Haaland, E.; Pettersen, G.; Tuntland, O.*Testing of Iron Oxides as Weight Materials for Drilling Muds*; SPE, 1976.

(6) Walker, C. O. Alternative Weighting Material. *J. Pet. Technol.* **1983**, *35*, 2158–2164.

(7) Scharf, A. D.; Watts, R. D.Itabirite: An Alternative Weighting Material for Heavy Oil-Base Muds. *Proc. - SPE Annu. Tech. Conf. Exhib.*, 1984.

(8) Murtaza, M.; Tariq, Z.; Mahmoud, M.; Kamal, M. S.; Al-Shehri, D. Anhydrite (Calcium Sulfate) Mineral as a Novel Weighting Material in Drilling Fluids. *J. Energy Resour. Technol. Trans. ASME* **2021**, *143*, 023002.

(9) Alfa, K. A.; Harkouss, R.; Khatib, J. Siderite As a Weighting Material in Drilling Mud. *BAU J. - Sci. Technol.* **2019**, *1*, 1–10.

(10) Al Jaber, J.; Bageri, B. S.; Gamal, H.; Elkatatny, S. The Role of Drilled Formation in Filter Cake Properties Utilizing Different Weighting Materials. *ACS Omega* **2021**, *6*, 24039.

(11) Almutawa, W.; Ahmed, A.; Basfar, S.; Elkatatny, S.; Haidary, S.; Zitha, P. Investigation of Magnetite-Based Invert Emulsion Mud at High Pressure High Temperature. *Arab. J. Geosci.* **2021**, *14*, 1–8.

(12) Gross, H. Intensive Weighting of Petrolewn Drilling Muds with Galena. *Trans. AIME* **1937**, *127*, 263–273.

(13) Fjogstad, A.; Saasen, A.; Hagen, R.; Tanche-Larsen, P. B.; Ree, R.; Melgren, H.; Rostad, E.; Hoset, H.Field Trial of Alternative Weight Material with Improved Occupational Hygiene and Environmental Performance. *Int. Conf. Heal. Saf. Environ. Oil Gas Explor. Prod.*, 2000.

(14) Bruton, J. R.; Bacho, J.; Newcaster, J. A.The Future of Drilling-Grade Barite Weight Material - A Case for a Substitute Specification. *Proc. - SPE Annu. Tech. Conf. Exhib.*, 2006; Vol. *6*, pp 4140–4146.

(15) Johnson, C. A.; Piatak, N. M.; Miller, M. M.Barite (Barium) Chapter D. *Critical Mineral Resources of the United States—Economic and Environmental Geology and Prospects for Future Supply*, 2017.

(16) Elkatatny, S. M.; Nasr-El-Din, H. A.; Al-Bagouryv, M.Evaluation of Micronized Ilmenite as Weighting Material in Water-Based Drilling Fluids for HPHT Applications. *Soc. Pet. Eng.—Kuwait Int. Pet. Conf. Exhib. 2012, KIPCE 2012 People Innov. Technol. to Unleash Challenging Hydrocarb. Resour.* **2012**; Vol. 2 (Tran 2007), pp 944–959.

(17) Ba geri, B. S.; Mahmoud, M.; Abdulraheem, A.; Al-Mutairi, S. H.; Elkatatny, S. M.; Shawabkeh, R. A. Single Stage Filter Cake Removal of Barite Weighted Water Based Drilling Fluid. *J. Pet. Sci. Eng.* **2017**, *149*, 476–484.

(18) Al-Awad, M. N. J.; Al-Qasabi, A. O. Characterization and Testing of Saudi Barite for Potential Use in Drilling Operations. *J. King Saud Univ. Eng. Sci.* **2001**, *13*, 287–298.

(19) Igwilo, K. C.; Okoro, E. E.; Ohia, P. N.; Adenubi, S. A.; Okoli, N.; Adebayo, T. Effect of Mud Weight on Hole Cleaning During Oil and Gas Drilling Operations Effective Drilling Approach. *Open Pet. Eng. J.* **2019**, *12*, 14–22.

(20) Abdou, M. I.; Al-Sabagh, A. M.; Ahmed, H. E. S.; Fadl, A. M. Impact of Barite and Ilmenite Mixture on Enhancing the Drilling Mud Weight. *Egypt. J. Pet.* **2018**, *27*, 955–967.

(21) Basfar, S.; Mohamed, A.; Elkatatny, S.; Al-Majed, A. A Combined Barite-Ilmenite Weighting Material to Prevent Barite Sag in Water-Based Drilling Fluid. *Materials* **2019**, *12*, 1945.

(22) Basfar, S.; Mohamed, A.; Elkatatny, S. Barite–Micromax Mixture, an Enhanced Weighting Agent for the Elimination of Barite Sag in Invert Emulsion Drilling Fluids. *J. Pet. Explor. Prod. Technol.* **2020**, *10*, 2427–2435.

(23) Bageri, B. S.; Gamal, H.; Elkatatny, S.; Patil, S. Effect of Different Weighting Agents on Drilling Fluids and Filter Cake Properties in Sandstone Formations. *ACS Omega* **2021**, *6*, 16176–16186.

(24) Ba Geri, B. S.; Al-Mutairi, S. H.; Mahmoud, M. A.Different Techniques for Characterizing the Filter Cake. *Society of Petroleum Engineers—SPE Middle East Unconventional Gas Conference and Exhibition 2013, UGAS 2013—Unconventional and Tight Gas: Bridging the Gaps for Sustainable Economic Development*; Society of Petroleum Engineers, 2013; pp 104–116.

(25) Bageri, B. S.; Adebayo, A. R.; Al Jaberi, J.; Patil, S.; Salin, R. B. Evaluating Drilling Fluid Infiltration in Porous Media – Comparing NMR, Gravimetric, and X-Ray CT Scan Methods. *J. Pet. Sci. Eng.* **2021**, *198*, 108242.

(26) Mao, H.; Yang, Y.; Zhang, H.; Zheng, J.; Zhong, Y. Conceptual Design and Methodology for Rheological Control of Water-Based

Drilling Fluids in Ultra-High Temperature and Ultra-High Pressure Drilling Applications. *J. Pet. Sci. Eng.* **2020**, *188*, 106884.
(27) Katende, A.; Boyou, N. V.; Ismail, I.; Chung, D. Z.; Sagala, F.; Hussein, N.; Ismail, M. S. Improving the Performance of Oil Based Mud and Water Based Mud in a High Temperature Hole Using Nanosilica Nanoparticles. *Colloids Surf., A* **2019**, *577*, 645−673.
(28) Luo, Z.; Wang, L.; Pei, J.; Yu, P.; Xia, B. A Novel Star-Shaped Copolymer as a Rheology Modifier in Water-Based Drilling Fluids. *J. Pet. Sci. Eng.* **2018**, *168*, 98−106.

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