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Research Article

Effect of Arenite, Calcareous, Argillaceous, and Ferruginous Sandstone Cuttings on Filter Cake and Drilling Fluid Properties in Horizontal Wells

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Fine, small-size, drilled cuttings, if not properly separated using mud conditioning equipment at the surface, are circulated with the drilling fluid from the surface to the bottom hole. These drilled cuttings have a significant effect on the drilling fluid properties and filter cake structure. During drilling long lateral sandstone formations, different cuttings with varied properties will be generated due to sandstone formations being heterogeneous and having different mineralogical compositions. Thus, the impact of these cuttings on the drilling fluid and filter cake properties will be different based on their mineralogy. In this paper, the effect of different sandstone formation cuttings, including arenite (quartz rich), calcareous (calcite rich), argillaceous (clay rich), and ferruginous (iron rich) sandstones, on the filter cake and drilling fluid properties was investigated. Cuttings of the mentioned sandstone formations were mixed with the drilling fluid to address the effect of these minerals on the filter cake thickness, porosity, and permeability. In addition, the effect of different sandstone formation cuttings on drilling fluid density and rheology, apparent viscosity (AV), plastic viscosity PV), and yield point (YP) was investigated. High-pressure high-temperature (HPHT) fluid loss test was conducted to form the filter cake. The core sample's petrophysical properties were determined using X-ray fluorescence (XRF) and X-ray diffraction (XRD) techniques and scanning electron microscopy (SEM). The results of this work indicated that all cutting types increased the rheological properties when added to the drilling fluid at the same loadings but the argillaceous sandstone (clay rich) has a dominant effect compared to the other types because the higher clay content enhanced the rheology. From the filter cake point of view, the ferruginous sandstone improved the filter cake sealing properties and reduced its thickness, while the argillaceous cuttings degraded the filter cake porosity and permeability and allowed the finer cuttings to penetrate deeply in the filter medium.

1. Introduction

During the drilling process, an impermeable layer called a filter cake is formed on the face of the drilled formation to minimize the filtration and solid invasion [1, 2]. There are several variables that affect filter cake properties, filtration volume, and invasion depth, such as drilling fluid additives, formation properties, and well conditions (temperature, pressure, and drill pipe rotation). The drilling fluid additives highly affect the filtration properties. Therefore, intensive research has been carried out to improve the characteristics of drilling fluid additives to minimize their adverse effect on drilled formations. Currently, nanomaterials have been introduced in the drilling fluid application for different functions. Silica and ferric oxide nanoparticles were introduced to stabilize the performance of drilling fluid and improve the filter cake properties [3–6]. Nanoclay, cellulose, and polymers were used to improve the rheological properties of drilling fluid [7–9]. On the other hand, the formation permeability and lithology play a great role on the cumulative mud filtrate loss [10, 11]. Thus, the filter cake buildup through either static or dynamic conditions was simulated to understand the filter cake properties [12–15].

Although drilling fluid is carefully designed through several comprehensive API tests [16–21], it is important to control drilling fluid properties during drilling operations to control the wellbore stability and prevent formation damage [22–29]. Many factors affect drilling fluid properties while drilling, including changing the particle size of additives during the fluid circulation, passing through high-temperature formations, and contaminating the drilled formation [28, 30–32]. The key factors that cause major changes in drilling fluid properties are changing the property of drilling fluid additives and/or introducing new solids to the drilling fluid during the drilling operation. Mainly, the source of the noncontrollable solids added to the drilling fluid during the drilling process is the drilled formation particles.

In practice, solid removal equipment is installed at the surface to control the sloid content generated during the drilling process and maintain the drilling fluid properties for efficient drilling operations. Solid removal units consist of shale shakers, sand traps, desanders, desilters, and centrifuges [33, 34]. Many factors affect the overall solid removal efficiency, such as total solid content, particle size, mud properties, and cleaning equipment design. Each piece of equipment is designed to remove solids with a specific particle size range, and combining them together will increase the sloid removal efficiency [35]. Particle size is a challenging factor in the solid removal process and drilling operation, and its effect becomes more serious as the particle size decreases [33]. The desander can remove particle sizes of 40 μm to 45 μm, while the desilter can remove particle sizes of 20 to 25 micron. From a practical point of view, it is not recommended to use desanders and desilters with oil-based drilling fluids because of their very wet solid discharge [33, 34].

For long horizontal sections of the well, it has been reported that the sand content could reach 30% in the filter cake structure while drilling the sandstone is lateral with a 3000 ft. length [23]. The reported results showed that mixing the drilled sand particles with the drilling fluid while drilling had a significant impact on the drilling fluid properties [30, 36]. Furthermore, integrating high sand content with the circulated drilling fluid produced a thicker filter cake, degraded the sealing properties of the filter cake, and allowed the solids to invade into the formation [30, 37, 38]. This will reduce the productivity of the well and will require additional costs in order to stimulate the near-wellbore area. Lots of research was conducted to investigate the impact of drilling fluid properties on the wellbore stability, well integrity, and filter cake formation during the drilling operations [23–28, 36, 39].

The properties of the drilled solids contaminating the drilling fluid depend on the formation characteristics. Although, the properties of the drilled formation are based on the same clay type and amount of other contamination metals, no attention was paid on the effect of different sand types on drilling fluid and filter cake properties. For the sandstone, there are four common types—quartz arenite, ferruginous, calcareous, and argillaceous sandstones. Quartz arenite is a matrix-poor sandstone with more than 90% quartz [40]. Ferruginous sandstone is a sandstone with more than 15 percent of iron oxides (e.g., hematite). The iron oxides occur as pore-filling and grain-coating materials and stained rock with the reddish brown colour [41]. Calcareous sandstone is composed of more than 15 percent of carbonate minerals (e.g., calcite) as cementing materials. Argillaceous sandstone has significant amounts of clay minerals (e.g., kaolinite), which come from the dissolution of unstable detrital minerals such as feldspars.

In the past, a majority of the research focused on the drilled cutting rock type (i.e., sandstone and limestone), while studying the effect of different mineralogy of the same formation was not addressed. In order to address the knowledge gap, it is critically important to understand whether changing the mineralogy of the sandstone formation with a large percentage (about 30 wt.%) of calcite, clay, and iron will have major effect on filter cake porosity, sealing properties (permeability), and drilling fluid properties.

The main objective of this study is to address the effect of drilled cuttings of quartz arenite, calcareous, argillaceous, and ferruginous sandstone formations on filter cake and drilling fluid properties. The drilled cuttings were mixed with the drilling fluid in varying quantities (ranging from 15 to 30 wt.%) to study their impact on filter cake and drilling fluid properties.

2. Materials and Experiments

2.1. Rock Sample. Four types of the sandstone cores with varying mineralogy were used—quartz arenite, calcareous, argillaceous and ferruginous sandstone formations. The selected core samples were crushed to generate the drilled cuttings. From this point forward, we will refer to quartz arenite as sandstone (reference sample) and the others will be referred to as calcareous argillaceous and ferruginous.

The petrophysical properties (porosity and permeability) of the tested core samples were measured in the laboratory. The helium porosimeter was used to measure the porosity and grain density of the core samples. The gas permeabilities of the selected core samples were obtained using Hassler Core Holder Assembly.

The elemental and mineralogical composition of the cuttings were determined using X-ray fluorescence (XRF) and X-ray diffraction (XRD) techniques. The cuttings generated with the different sandstone core samples were mixed with the drilling fluid with two concentrations (15% and 30 wt.%).

2.2. Rock Sample Properties. The XRD and XRF results showed that the first core sample (the reference sample sandstone) consisted mainly of quartz (90 wt.%), whereas the amount of the quartz in the other three samples ranged between 65 and 70%. The remaining 25-30% constitutes other types of rock particles—either calcite (calcareous sandstone), clay (argillaceous sandstone), or iron (ferruginous sandstone). Figure 1 shows the difference in the mineralogy between the sandstone core samples used in the study. The detailed mineralogical composition using XRD and XRF results of the core samples is presented in Figures 2 and 3.

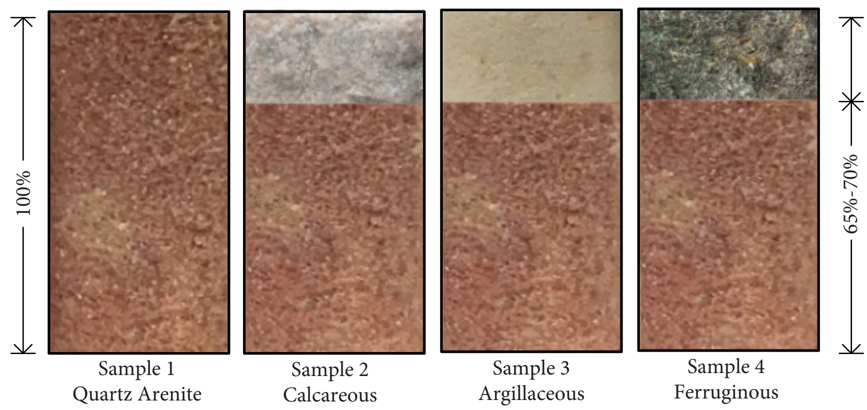


FIGURE 1: Diagram showing the difference in the mineralogy of the sandstone core samples for this work.

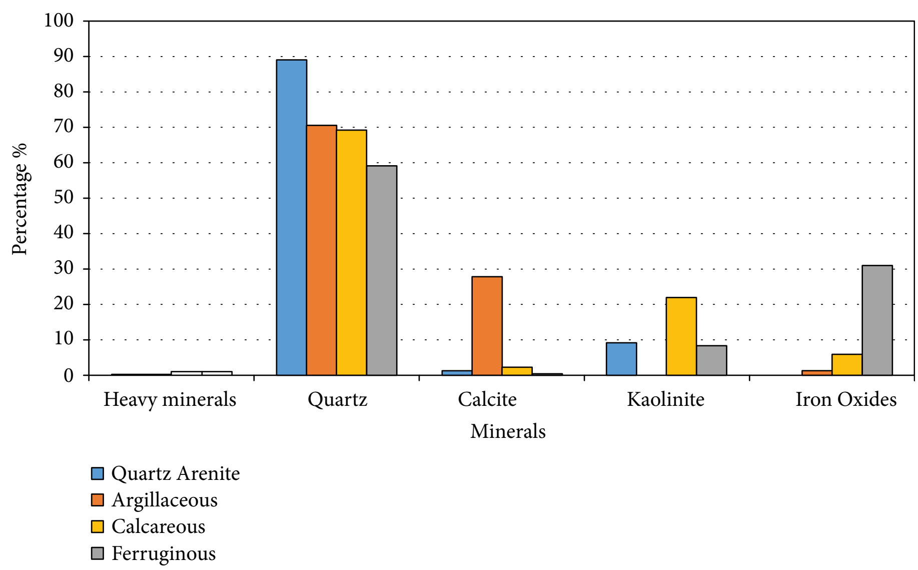


FIGURE 2: XRD results of the drilled cuttings (core samples).

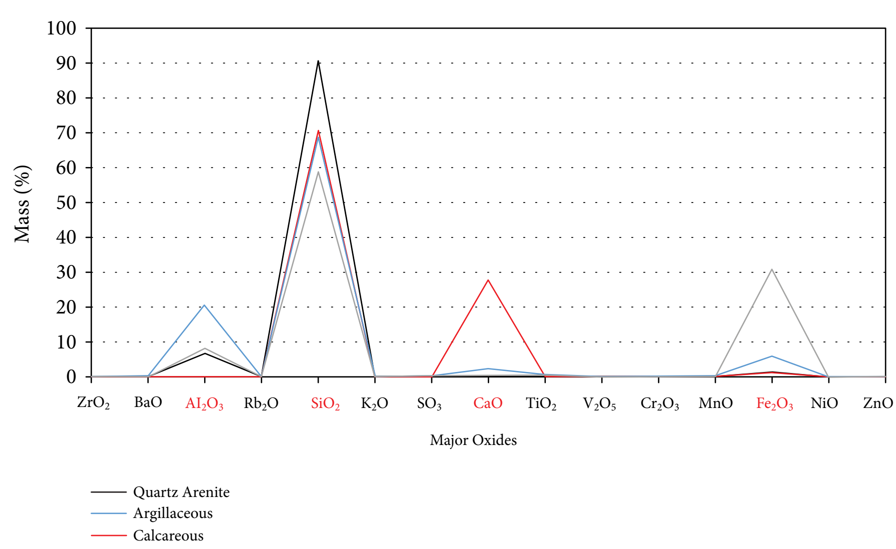
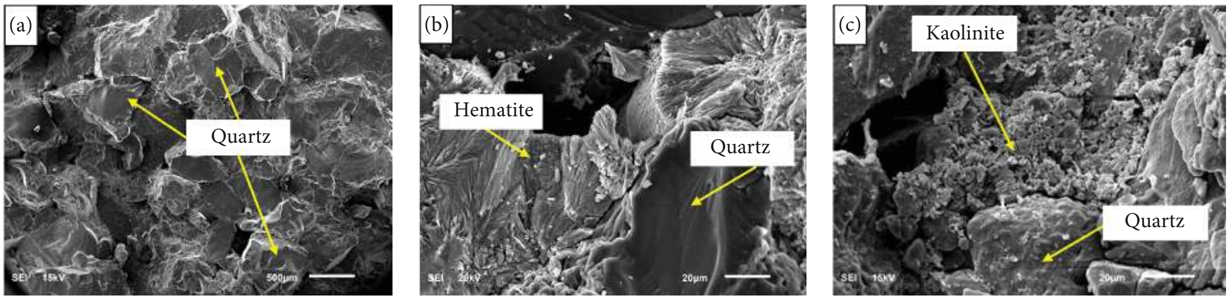


FIGURE 3: XRF results of the drilled cuttings (core samples).



(a) (b) (c)

Figure 4: SEM photomicrographs showing (a) quartz arenite sandstone (quartz-rich sandstone), (b) ferruginous sandstone, (c) argillaceous sandstone.

Furthermore, the argillaceous and ferruginous drilled cutting particle samples were identified using scanning electron microscopy (SEM), as shown in Figure 4.

The porosity of the sandstone and argillaceous core samples (samples 1 and 3) was 28% and 17%, respectively. The other two samples, calcareous and ferruginous, displayed low porosity values of 8.5% and 2.3, respectively. The permeability measurements showed that the calcareous, argillaceous, and ferruginous sandstones displayed low permeability values, 1.3 mD, 0.67 mD, and 0.28 mD, respectively, while the first sample (sandstone) permeability was 329.5 mD.

2.3. Drilling Fluid Properties. The density and rheology of the drilling fluid was measured after adding different cutting types with different percentages (15% and 30%) using mud balance and a Fann viscometer. The cuttings generated from drilling operations vary in size from large, medium, fine, and ultrafine particles. Table 1 shows the particle size of the solids that can be separated with solid removal equipment [33]. This study focuses on the fine particles that cannot be removed with the main solid removal equipment, less than 20 μm. Therefore, the rock samples were crushed to fine powder and then sieved to make sure that only fine particles will be used.

Calcite-weighted water-based drilling fluid was used in this study. The composition of the drilling fluid is listed in Table 2. The primary properties of the base drilling fluid such as density, apparent viscosity (AV), plastic viscosity (PV), and yield point (YP) are shown in Table 3.

2.4. HPHT Fluid Loss Test. The filter cake was formed using HPHT fluid loss test. The static test was conducted at 300 psi differential pressure and 90°F. The filter cake was formed on the face of the ceramic disk. The 50 μm ceramic disk was used as a filter medium. Drilling fluid consisting of a cutting concentration of 30% was used to form the filter cake. The thickness of the ceramic disk was 6.35 mm.

Filter cake porosity ($\varnothing_c$) was determined using the equation presented by Dewan and Chenevert [42]:

$$\varnothing_c = \frac{\alpha}{\alpha + \left(\rho_f / \rho_g\right)}, \quad (1)$$

where ρ_f and ρ_g are the fluid and the grain densities, respectively, and α is measured using the following equation [42]:

$$\alpha = \frac{\text{net wet weight of the filter cake}}{\text{net dry weight of the filter cake}} - 1. \quad (2)$$

The weight of the filter cake over the saturated ceramic disk was recorded. After this step, the disk with the filter cake was placed in the oven for 24 hrs, at 100°C in order to evaporate the water [23]. The dry weight of the filter cake was recorded after this step.

The permeability of the formed filter cake (K_c) was calculated using Khatib [43] correlation for the water-based $CaCO_3$ mud:

$$K_c = 112.7\, e^{-8.8(1-\varnothing_c)}. \quad (3)$$

2.5. Solubility Test. Solubility experiments were conducted to investigate the effect of the drilled cuttings (of different sandstone formations) on the filter cake removal efficiency. One gram of the solids was added to 50 mL of GLDA (20 wt.%) at a pH of 4 [23]. Solids contain 70 wt.% weighting material (calcite) and 30 wt.% drilled cuttings. The experiments were performed at 100°C under static conditions for 24 hours.

3. Results and Discussion

3.1. Effect of Cutting Content on Drilling Fluid Properties. The cuttings generated with the different core samples were mixed with the drilling fluid with concentrations of 15% and 30 wt.%. This range of the cutting content was observed as the maximum amount of sand content that may contaminate the drilling fluid while drilling long horizontal sections [12, 23]. The effect of different sandstone cutting content (quartz arenite, calcareous, argillaceous, and ferruginous) on drilling fluid density was not significant. The drilling fluid density of the base fluid was 10.5 ppg, while the density of the drilling fluid mixed with sandstone cuttings was in the range 10.5 to 11 ppg. This is due to the similarity in the weighting agent density ($CaCO_3$ = 2.71 gm/cc) and the density of the mixed sand contents—quartz arenite (2.64 gm/cc), calcareous (2.69 gm/cc), argillaceous (2.68 gm/cc), and ferruginous (2.84 gm/cc).

Table 1: Solid removal by type of equipment.

Equipment	Particle size (μm)
Shale shaker	>74
Mud cleaner	>74
Desander	>45
Desilter	>20-25
Centrifuge	<8

Table 2: Drilling fluid formulation.

Component	Description	Units	Function
Water	308	cc	Base
Defoamer	0.08	g	Antifoam agent
XC polymer	1.5	g	Viscosifier
Starch	6	g	Loss circulation control
KCl	80	g	Clay stabilizer
KOH	0.3	g	pH adjustment
Sodium sulfide	0.25	g	Oxygen scavenger
$CaCO_3$ (MED)	80	g	Weighting material

Table 3: Drilling fluid properties.

Property	Value	Units
Apparent viscosity (AV)	24.1	cP
Plastic viscosity (PV)	15.1	cP
Yield point (YP)	18	lb/100 ft^2
Gel strength (GS) (10 sec)	13	lb/100 ft^2
Gel strength (GS) (10 min)	14	lb/100 ft^2
Density	10.3	ppg
pH	10.5	—

Increasing the concentration of the cutting content resulted in a noticeable increase in the drilling fluid viscosity. Particularly, as shown in Figure 5, the results demonstrate that the apparent viscosity of the drilling fluid consisting of 15 wt.% of argillaceous was the highest compared to the reference samples (quartz arenite-based drilling fluid) and the other two samples, calcareous- and ferruginous-based drilling fluids. Similar observations for the drilling fluid mixed with argillaceous sandstone cuttings were demonstrated for the other rheological parameters (plastic viscosity, yield point) in Figures 6 and 7. On the other hand, there was a minor variation in the drilling fluid gel strength (10 min and 10 sec) for all drilling fluids, as seen in Figure 8.

Based on the results obtained by this study, the experimental data of AV and PV show linear fitting of the drilling fluid AV and PV across the sand contents of the four different sandstone cuttings as shown in Figures 5 and 6, respectively. This finding is in agreement with the linear relationship reported for invert emulsion drilling fluid viscosity as a function of the sand content [36].

The highly rich clay cutting (argillaceous) drilling fluid showed the highest apparent viscosity compared to other drilling fluids (Figure 5). This can be attributed to the high clay content of the drilled cuttings mixed with the drilling fluid and enhanced drilling fluid rheology. This behavior of the argillaceous cutting confirmed the use of clay particles as viscosifier additives. In the same range, the 30 wt.% cutting content for the other two samples, calcareous and ferruginous, shows higher AV (Figure 5), PV (Figure 6), YP (Figure 7), and GS (Figure 8) values than that of the quartz arenite.

These results demonstrate that the drilled formation mineralogical composition has a strong impact on the drilling fluid rheological properties and this may affect the drilling operations. Drilling and mud engineers on the wellsite have to monitor the drilling fluid properties regularly and adjust these properties due to the contamination of the drilled formation cuttings.

3.2. Effect of Cutting Content on Filter Cake Properties. The filter cake thickness was measured at the end of the fluid loss test. To ensure accuracy, the measurement was conducted through different points [14]. An average of these values was taken as the final value of the filter cake thickness, as presented in Figure 9. The experimental data shows that the thickness of the filter cake for the base mud was around 2.9 mm. The results established that adding the same amounts of drilled cuttings of quartz arenite, calcareous, argillaceous, and ferruginous sandstone formations does not have the same effect on the filter cake thickness. As shown in Figure 9, it is clearly observed that there is a minor increase in the filter cake thickness by adding the quartz arenite. Calcareous sandstone also produced a thicker filter cake, while the ferruginous and argillaceous sandstones formed a very thin filter cake at the same test conditions.

The results of filter cake porosity and permeability are presented in Figure 10. In order to gain a deeper understanding of the effect on filter cake structure, both results for the thickness and permeability were linked together. For the quartz arenite sandstone, the sealing properties of the filter cake were not affected by mixing this type of cutting with the drilling fluid (i.e., mostly the filter cake porosity and permeability have the same values of the base drilling filter cake with a slight increase). Thus, the rate of building the filter cake mostly will be the same. The slight increment in the filter cake thickness formed by arenite sandstone can be attributed to the slight increment in the filter cake permeability of this sample, Figure 10.

On the other hand, the calcite-rich sandstone particles (calcareous) produced a thicker filter cake compared to the other drilling fluids. This can be attributed to the bad bridging of the calcite particles when mixed with the drilling fluid. This is very crucial while drilling calcite-rich sandstone formations, and care should be taken by adjusting the drilling fluid composition to eliminate the formation of a thick mud cake.

For the argillaceous-based drilling fluid, although the filter cake thickness was lower than the thickness of the filter cake formed by the base drilling fluid, the sealing properties of the formed filter cake were poor. The highest filter cake permeability was observed for this type of cutting. Consequently, the fine particles still find a way to invade the filter

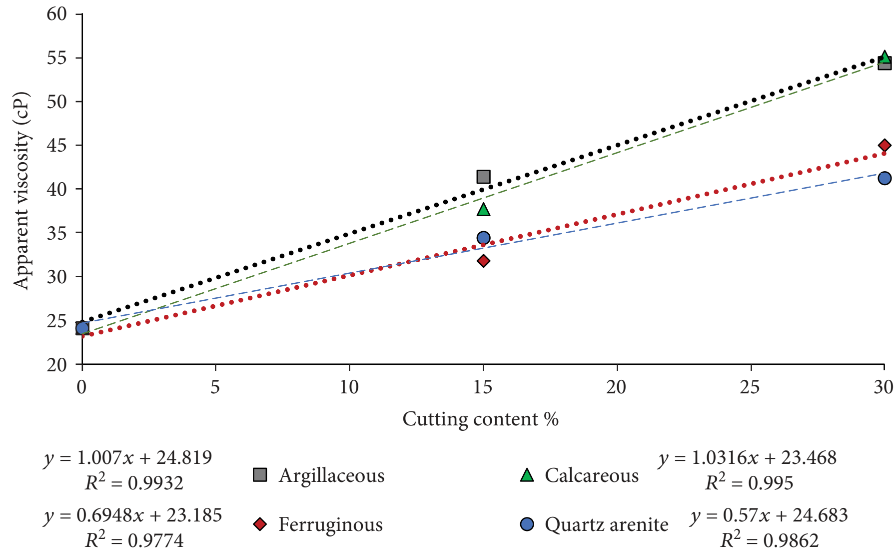


Figure 5: Drilling fluid apparent viscosity.

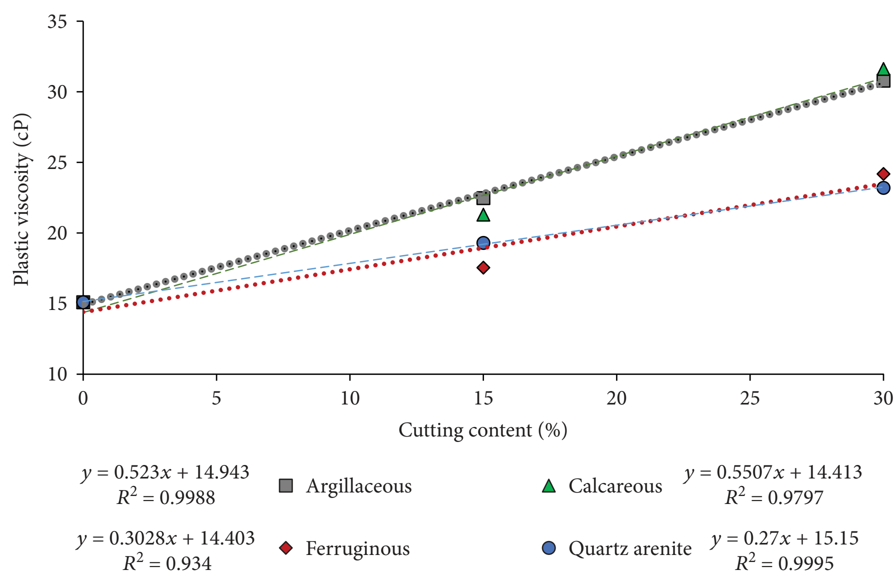


Figure 6: Drilling fluid plastic viscosity.

medium. Therefore, it is not just a matter of reducing the filter cake thickness; emphasis must be placed on providing good sealing properties as well. The high amount of solid invasion was confirmed by taking the weight of the ceramic disc of this sample after removing the filter cake and comparing it with the original weight of the ceramic disc before the filter cake was deposited.

Finally, for the ferruginous sandstone, the results show that there is an improvement in the filter cake permeability but the thickness was too small compared to the other samples. Typically, if the filter cake permeability is low, the filtration rate will be reduced, which will minimize the solid precipitation and invasion. This observation confirmed that the ferric oxide can deposit a filter cake with better characteristics. Several studies were conducted to evaluate the effect of ferric oxide nanoparticles on the sealing properties of filter cake [4, 15, 44–47]. It was proved that ferric oxide particles effectively improve the sealing properties of the filter cake and form a thin, non-erodible filter cake with low permeability and filtrate invasion into the formation. This is attributed to the high positive charge (+39.5 to 45 mV at 78°F) of ferric oxide particles, which indicates a high potential stability in suspension, thus leading to better particle dispersion and filter cake structure [47].

It was found that the drilled cuttings reduced the solubility by 25-30% when compared with the clean fluid. Consequently, the process of filter cake removal in the presence of drilled cuttings becomes more difficult as shown in Table 4. The results of this section confirmed the same observation reported in the previous study [23].

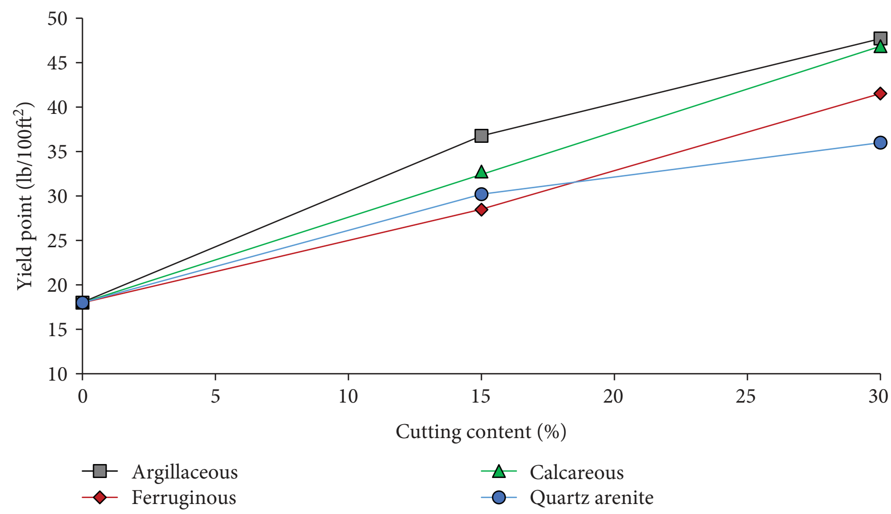


Figure 7: Drilling fluid yield strength.

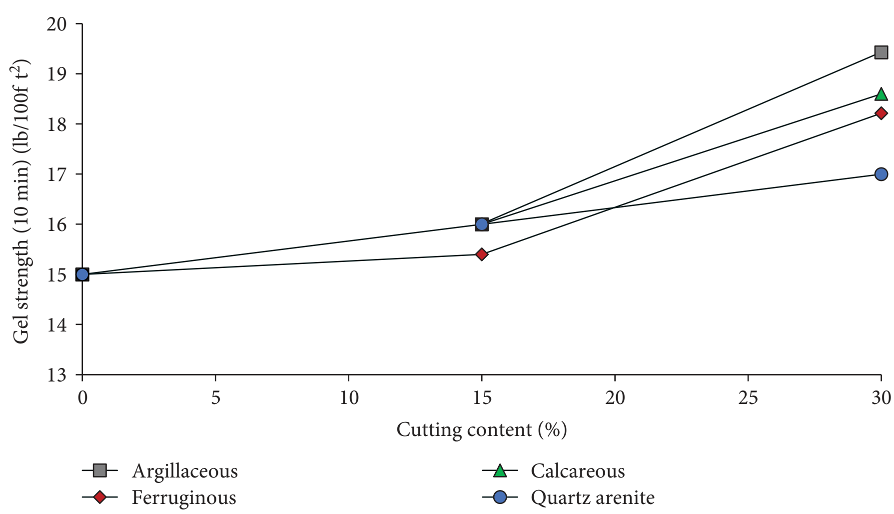


Figure 8: Drilling fluid gel strength (10 min).

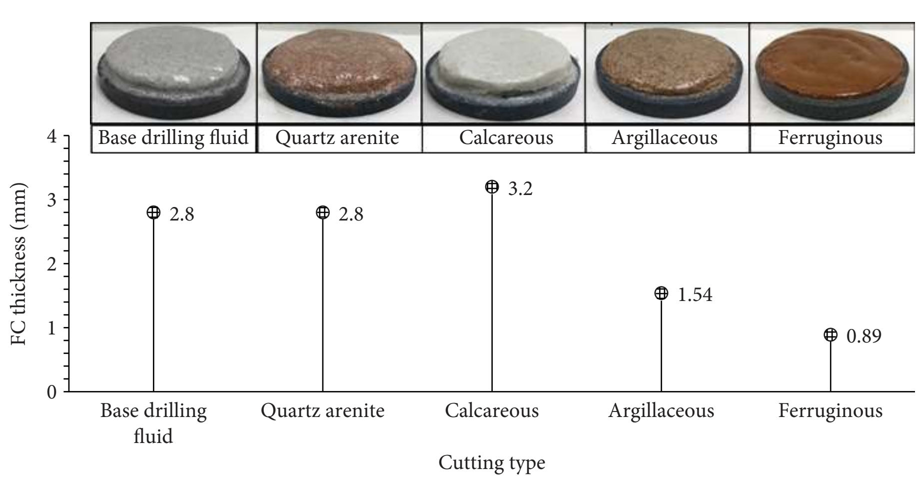


Figure 9: Filter cake thickness of different cutting types.

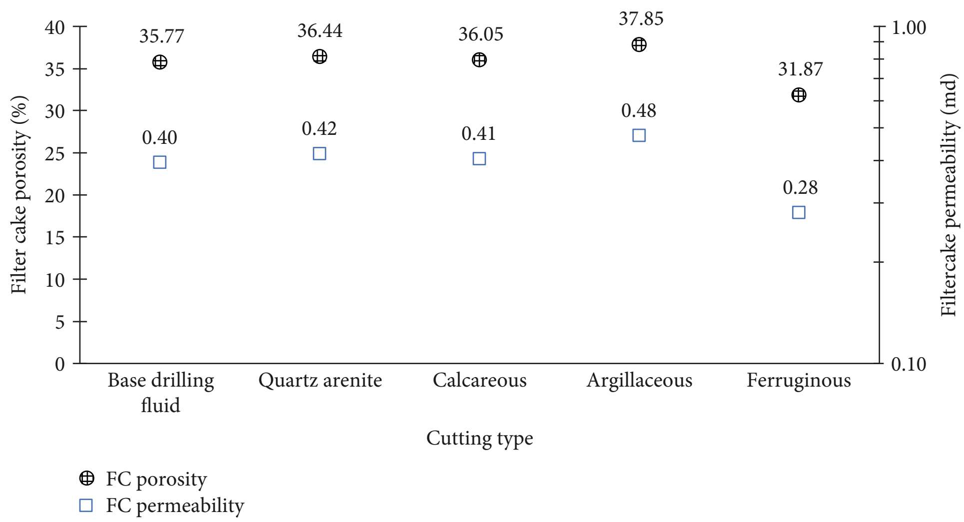


Figure 10: Filter cake porosity and permeability.

Table 4: Solubility for different types of sandstone cuttings.

Experiment no.	Solid description Weighting material (calcite)	Cutting particles	Total solids weight (gm)	Solvent	Solubility (%)
1	1 gm	0 gm	1 gm	GLDA 20 wt.% low pH (pH = 4) at 100°C	92.45
2	0.7 gm	0.3 gm quartz arenite	1 gm		64.60
3	0.7 gm	0.3 gm calcareous	1 gm		68.76
4	0.7 gm	0.3 gm argillaceous	1 gm		66.35
5	0.7 gm	0.3 gm ferruginous	1 gm		65.32

4. Conclusions

This experimental study was conducted to address the effect of drilled cuttings of quartz arenite, calcareous, argillaceous, and ferruginous sandstone concentration on filter cake and drilling fluid properties. This work was conducted using two cutting concentrations (15 and 30 wt.% of the drilling fluid) to investigate the effect of sand-cutting mineralogy on the drilling fluid and filter cake properties. Based on the obtained results, the following conclusions are drawn:

(1) As the quartz arenite, calcareous, argillaceous, and ferruginous sandstone formation cutting contents increased in the drilling fluid, the rheological properties (AV, PV, YP, and gel strength) increased

(2) For cutting concentrations lower than 15%, the results showed that the argillaceous-based drilling fluid viscosity was the highest compared to those of the other drilling fluid types. Ferruginous sandstone drilled cuttings improved the yield point plastic viscosity ratio. YP/PV ratio increased from 1.2 (based fluid) to 1.58

(3) For high cutting concentrations, 30 wt.%, argillaceous and calcareous had the highest drilling fluid viscosity. Ferruginous-based drilling fluid reported the lowest increase in plastic viscosity as compared with other formulations

(4) Calcareous- and arenite-based drilling fluids produced higher filter cake thickness compared to ferruginous- and argillaceous-based drilling fluids

(5) Ferruginous sandstone drilled cuttings produced the ideal filter cake. The based drilling fluid filter cake thickness was reduced by 66% after adding 30% of ferruginous sandstone. In addition, the filter cake permeability was reduced by 25%.

(6) Finally, increasing the argillaceous cutting content in the filter cake increased the permeability of the filter cake and allowed the solid particles of the filter cake to invade the formation more deeply

Data Availability

The data used to support the findings of this paper are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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