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Investigation of mud density and weighting materials effect on drilling fluid filter cake properties and formation damage

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A B S T R A C T

Drilling fluid density/type is an important factor in drilling and production operations. Most of encountered problems during rotary drilling are related to drilling mud types and weights. This paper aims to investigate the effect of mud weight on filter cake properties and formation damage through two experimental approaches. In the first approach, seven water-based drilling fluid samples with same composition are prepared with different densities (9.0–12.0 lb/gal) and examined to select the optimum mud weight that has less damage. The second approach deals with investigating the possible effect of the different weighting materials ($BaSO_4$ and $CaCO_3$) on filter cake properties. High pressure/high temperature loss tests and Scanning Electron Microscopy (SEM) analyses were carried out on the filter cake (two selected samples).

Data analysis has revealed that mud weigh of 9.5 lb/gal has the less reduction in permeability of ceramic disk, among the seven used mud densities. Above 10.5 ppg the effect of the mud weight density on formation damage is stabilized at constant value. Fluids of $CaCO_3$-based weighting material, has less reduction in the porosity (9.14%) and permeability (25%) of the filter disk properties than the $BaSO_4$-based fluid. The produced filter cake porosity increases (from 0.735 to 0.859) with decreasing of fluid density in case of drilling samples of different densities. The filtration loss tests indicated that $CaCO_3$ filter cake porosity (0.52) is less than that of the $BaSO_4$ weighted material (0.814). The thickness of the filter cake of the $BaSO_4$-based fluid is large and can cause some problems.

The SEM analysis shows that some major elements do occur on the tested samples (Ca, Al, Si, and Ba), with dominance of Ca on the expense of Ba for the $CaCO_3$ fluid sample and vice versa. The less effect of 9.5 lb/gal mud sample is reflected in the well-produced inter-particle pore structure and relatively crystal size. A general recommendation is given to minimize the future utilization of Barium Sulfate as a drilling fluid.

1. Introduction

Drilling operations are based mainly on the type and composition of the drilling fluids that represent one fifth (15–18%) of the total cost of well petroleum drilling. The main functions of the drilling fluids are to carry out the rock cutting to surface, cooling and cleaning the bit, reducing friction, maintaining wellbore stability and preventing pore fluids from prematurely flowing into the wellbore. The complexity of the problems met in petroleum drilling has led to new emerging techniques for formulating appropriate fluids. Owing to the rapid development in the drilling industry these fluids went through major technological evolution, since the first operations performed in the United States (using a simple mixture of water and clays) to the complex mixtures of various specific organic and inorganic products that are now in use. In favorable cases, drilling fluids must comply with some important requirements, i.e. easy to use, not too expensive and environmentally friendly (Khodja et al., 2010).

In geological reservoirs, the fine solids that may encountered during drilling operation are mainly came from two principal sources; reservoir and drilling fluid additives. Generally, the formation damage originates in the poor performances of un-

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weighted solid-free fluids, giving low return permeability. Drilling fluids are originally designed in order to reduce the damage effect and to make sure that rotary drilling of subterranean formations is possible and economical. In addition, the drilling fluids are essentially designed to build a filter cake, which is basically intended to decrease filtrate loss to the formation, and to be thin and capable of holding the drilling fluid in the wellbore (Khodja et al., 2010; Watson et al., 2012; Rathnaweera et al., 2015).

The liquid phase of the drilling mud being forced into a permeable formation by differential pressure is referred to as the filtration process. For the solid particles to be filtered out, forming a filter cake, the fluid must undergo a higher pressure than the permeable medium. Three conditions must be present, i.e. a liquid or a liquid/solid slurry fluid and a permeable medium. The characteristics and in-situ properties of the enhanced filtration is very important in the design of drilling fluid formulation (Li, 1996; Argillier et al., 1997; Benna et al., 2001; Khodja et al., 2010; Blkoor and Fattah, 2013). Drilling fluid filtrates can lead to formation damage because of rock wettability changes, fines migration, drilling fluid solids plugging and formation water chemistry incompatibilities. Thus, one of the most critical functions of drilling fluids is to try to minimize the amount of fluid filtrate entering the hydrocarbon-bearing formation (Warren et al., 1993).

Arthur and Peden (1988) discussed the fluid flow through the filter cakes. They stated that as suspended solids are deposited during cake filtration, liquid flows, as a result of the hydraulic pressure gradient, through the cake interstices. A cumulative drag force is therefore exerted on the solid particles as liquid moves towards the filter medium. The compressible filter cakes exhibit non-linear permeability and porosity profiles, with a maximum porosity at the cake surface and a minimum at the filter medium surface. Drilling mud can be described as thixotropic shear-thinning fluids with a yield stress (Coussot et al., 2004). The filtration control additives for water-based drilling fluids can be used to prevent leak-off of water from the drilling fluid to the formation. Organic polymers constitute by far the huge number of filtration-control additives (Plank and Gossen, 1991).

The knowledge of the filtration properties, along with microscopic structure and chemical composition of its associated filter cake are very important in the preparation of drilling fluid (Azizi et al., 1997; Amaefule et al., 1988; Loeber, 1992; Li, 1996; Argillier et al., 1997; Benna et al., 1999, 2001; Watson and Nelson, 2003; Shenglai et al., 2008; Elkatatny et al., 2011; Blkoor and Fattah, 2013).

Moreover, the increase of Barite in the drilling fluids has a bad effect on other well completions and logging processes. For example, it tends to attenuate the intensity of the emitted gamma rays from the different geological formations, especially those enriched by shale and clay minerals. This tends to give low count rate of the gamma rays and hence erroneous estimate of some important reservoir properties, such as shale volume, effective porosity, and fluid saturations (Schlumberger, 1986, 1991 and 1995; Lashin and Abd El-Naby, 2014; Lashin et al., 2011, 2016).

This study involves two main procedures; the first includes the preparation of seven samples of water-based drilling fluids that contains the same composition, but at different densities to select the optimum mud weight which has less damage. While the second, implies preparing of two water-based drilling fluids that attain the same composition but with different weighting materials, i.e., $BaSO_4$ and $CaCO_3$. It aims mainly to, 1) study the effect of drilling fluids on the filter cake properties, filtrate loss and formation damage, 2) study the characteristics of filter cake such as thickness, porosity and permeability, and 3) describe the mineralogy and the chemical composition of the filter cake.

2. Experimental work

The testing materials that are used in this experimental work are represented mainly by a water-based drilling fluid. Bentonite is used as viscosifier, while Barite and Calcium Carbonate are used as weighting materials. The porosity of ceramic disk is determined by using the saturated method (the difference in weight of the disk in dried and saturated conditions). The diameter (D) of the core sample is taken as 6.35 cm, while the length (L) is taken as 0.635 cm. The weights of the ceramic disk are found to be 38.40 g and 45.9 g for both of the dry and wet conditions, respectively. The porosity of ceramic disk is measured to be 37 vol %, assuming a fluid density (ρ_f) of 1.0 g/cm^3.

2.1. Drilling fluid preparation and properties

Water-based drilling mud most commonly consists of Bentonite, with some additives such as Barium Sulfate (Barite), Calcium Carbonate (Calcite). The performance of drilling fluid is influenced mainly by three main factors; i.e, drilling fluid density, drilling fluid viscosity and mud pH (Chilingarian and Vorabutr, 1981). Therefore, more attention for these factors should be paid while preparing the water-based fluid samples for experimental work. A standard of 1 g of material is added to a 350 ml laboratory barrel, to prepare the drilling fluid samples, which is equivalent to adding 1 pound of material to 1 barrel of fluid. Tables 1 and 2 demonstrate the composition of the drilling fluids that are used in this study.

Table 1 shows that a 24.5 g of Bentonite is added as viscosifier and filtration control material, while a 0.20 g of Caustic Soda is utilized as PH control material. Control materials weights of 0.40 g, 0.25 g and 1.0 g are used for each of the starch filtration (Poly–Sal), hardness (Soda Ash) and rheology (Xanthangum), respectively. Meanwhile, concentrations of 217.0 g and 305 g are used as weighting materials for both of the Barite and Calcium Carbonate (see, Table 2).

A wide range of Barite densities (23.50–217 g) is used along with a base fluid concentration of 325.5 ml of distilled water (Table 1). However, the quantity of Barite that is needed as a weighting agent can be given using the following formula:

$$\text{Weighting Agent} = \frac{1490(W_2 - W_1)}{35 - W_2} \tag{1}$$

where, W_1 is the initial weight (ppg) and W_2 is the final required weight (ppg).

2.1.1. Drilling fluid density and rheological properties

To study the effect of drilling fluids on the filter cake properties, filtrate loss and formation damage, the fluid density is the first parameter to consider. The stability of a drilling fluid is generally guaranteed by its homogeneity after a long aging period. Mud weigh/density is measured by using a mud balance device to select such weight that has less damage on ceramic disk. Barite ($BaSO_4$) is one of the most common drilling fluids in hydrocarbon industry and then comes Calcite ($CaCO_3$), to less extent. In the first approach of study seven samples of the drilling fluids are prepared and Barite is added gradually to increase the mud density. The amount of added Barite ranges between 23.50 and 217.0 g (Table 3). In the second approach of study, both of the $CaCO_3$ and $BaSO_4$ are used as weighting materials and added for the first and seconded water-based samples at 12.0 ppg, respectively.

The Model 900 Viscometer is used to measure the rheological properties of the drilling fluids. It is a true Couette coaxial cylinder rotational viscometer, which employs a transducer to measure the induced angle of rotation of the bob by a fluid sample. The test fluid

Table 1
Formulation of drilling fluids & Seven samples of water-based drilling fluids at different densities.

Product	Per Lab. bbl (350 ml)						
	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Sample 7
Water	325.5 ml	325.5 ml	325.5 ml	325.5 ml	325.5 ml	325.5 ml	325.5 ml
Bentonite	24.5 g	24.5 g	24.5 g	24.5 g	24.5 g	24.5 g	24.5 g
Barite	23.5 g	34.0 g	52.0 g	83.5 g	114 g	147 g	217 g
Caustic Soda	0.20 g	0.20 g	0.20 g	0.20 g	0.20 g	0.20 g	0.20 g
Soda Ash	0.25 g	0.25 g	0.25 g	0.25 g	0.25 g	0.25 g	0.25 g
Poly – SAL	0.40 g	0.40 g	0.40 g	0.40 g	0.40 g	0.40 g	0.40 g

Table 2
Formulation of drilling fluids & Water-based drilling fluids having the same composition but with different weighting materials.

Product	Function	Per Lab. bbl (350 ml)	
		Sample 1 $CaCO_3$	Sample 2 $BaSO_4$
Water	Based liquid	325.5 ml	325.5 ml
Bentonite	Viscosifier & filtration control	24.5 g	24.5 g
Calcium carbonate $CaCO_3$	Adjust mud density	305.0 g	–
Barite $BaSO_4$	Adjust mud density	–	217.0 g
Caustic Soda	Ph control	0.20 g	0.20 g
Soda Ash	Hardness control	0.25 g	0.25 g
Poly - SAL	filtration control	0.40 g	0.40 g
XC-Polymer	Rheology control	1.0 g	1.0 g

Table 3
Drilling fluid density (samples with different densities).

Fluid reference	Density of drilling fluid lb/gal	Amount of barite ($BaSO_4$) g
Sample 1	9.0	23.5
Sample 2	9.2	34.0
Sample 3	9.5	52.0
Sample 4	10	83.5
Sample 5	10.5	114
Sample 6	11	147
Sample 7	12	217

is contained in the annular space, or shear gap, between the rotor and the bob, which is attached to a shaft with a biasing spring (OFITE, 2015). All types of viscosities (apparent μ_a, plastic μ_p and effective μ_e) are measured in addition to the yield point (Y_P) and gel strength (Gel). The following equations are utilized:

$$\text{Apparent Viscosity}(\mu_a),\ \text{cp} = \frac{\varnothing_{600}}{2} \tag{2}$$

$$\text{Plastic Viscosity}(\mu_p),\ \text{cp} = \varnothing_{600} - \varnothing_{300} \tag{3}$$

$$\text{Effective Viscosity}(\mu_e),\ \text{cp} = \frac{300 \times \varnothing}{\omega}, \tag{4}$$

$$\text{Yield Point}(Y_P), \left(\text{lb}/100\text{ft}^2\right) = \varnothing_{300} - \mu_p \tag{5}$$

$$\text{Shear Stress}(\tau),\ \text{lb}/100\text{ft}^2 = 1.065 * \phi \tag{6}$$

$$\text{Shear Rate}(\gamma), \text{sec}^{-1} = 1.7023 * \omega \tag{7}$$

where, ϕ is the dial reading, lb/100 ft^2 and ω is the rotor speed, rpm.

Tables 4 and 5 summarize the measured rheological properties with respect to the different utilized drilling fluids.

2.2. Filtration properties (filter cake & filter disk)

Filtration refers to the liquid phase of the drilling mud being forced into a permeable formation by differential pressure. During this process, the solid particles are filtered out, forming a filter cake (Khodja et al., 2010). In the current work, the filtration properties are investigated using a standard High Pressure-High Temperature (HPHT) filter press device. The fluid is subjected to a high temperature (212 °F) and high differential pressure (200 psi) and the volume of filtrate is measured in a 30-min period. A high temperature density meter (DMA 4500) is used to measure the density of the filtrate at different temperature ranges (Figs. 3 and 4), while a Brookfield viscometer is utilized to measure the filtrate viscosity (Figs. 5 and 6).

2.2.1. Filter cake porosity and permeability

Dewan and Chenevert (2001) method is mainly utilized to measure the porosity of the filter cake of the drilling fluids. A sensitive balance of 0.01 g is used to measure the dry and wet weights of the ceramic disk (fluid loss). After the fluid loss, the filter cake is directly removed from the cell and the total weight (wet) of both the ceramic disk and filter cake is measured. The net wet weight of the filter cake is measured by subtracting the weight of wet ceramic disk. Then the cake is dried at 200 °F (24 h) and the dry weight of both of the ceramic disk and filter cake is measured. Finally, the net dry weight of the filter cake is measured by subtracting the weight of dry filter cake.

On the other hand, the methodology of Li et al. (2005) is used to measure the permeability of filter cake, which is based on liquid flow through the formed cake (Darcy's Law). A relation is generated between the cumulative filtrate volume and time (slope q/A is equal to flow rate, m^3/m^2 s). The method implies measuring the media resistance K_m (water flow through filter media test), the cake and media thicknesses (L_c and L_m), and the pressure drop across filter media (Δp_m). Finally the permeability of filter cake (K_c) can be determined using the following equation:

Table 4
Rheological properties of drilling fluids (seven samples).

Fluid reference	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Sample 7
Plastic Viscosity (cp)	36	26	36	36	37	35	40
Apparent Viscosity (cp)	48.5	36	51	50.5	51	50	62.5
Yield Point (lb/100 ft^2)	25	20	30	29	28	30	45
Gel @ 10 s (lb/100 ft^2)	7.5	6	9	8.8	10	11	17
Gel @ 10 min (lb/100 ft^2)	13.5	11	11.5	12.7	21	23	29
θ_{600}	97	72	102	101	102	100	125
θ_{300}	61	46	66	65	65	65	85
θ_{200}	49	33	52	52	53	52	71
θ_{100}	32	21	34	35	34	34	48
θ_6	9	6	10	10	13	15.8	21
θ_3	8	5	8.5	8	11	14	19

Table 5
Rheological properties (different weighting materials).

Fluid reference	Sample 1 $CaCO_3$	Sample 2 $BaSO_4$
Plastic Viscosity (cp)	97	52
Apparent Viscosity (cp)	168	76
Yield Point (lb/100 ft^2)	142	48
Gel Strength @ 10 s (lb/100 ft^2)	45	19.5
Gel Strength @ 10 min (lb/100 ft^2)	67	32
θ_{600}	336	152
θ_{300}	239	100
θ_{200}	195	83
θ_{100}	137	60
θ_6	53	26
θ_3	48	24

$$q = K_c \frac{\Delta P_c}{\mu L_c} \quad (8)$$

where K_c is the filter cake permeability, m^2, q is the filtrate rate, m^3/m^2-s, Lm is the thickness of filter medium, m, Lc is the thickness of filter cake, m, μ is the filtrated fluid viscosity, Pa.s, Δp_c is the pressure drop across the filter cake.

2.2.2. Filter disk permeability& reduction in permeability

Lambert (1981) developed a unique methodology for measuring the change in permeability of the ceramic disk. Mathematically, the form is:

Table 6
Thickness of filter cake h_c of different densities samples.

Fluid reference	Thickness of ceramic disk mm	Thickness of ceramic disk + mud cake mm	Thickness of mud cake mm	Thickness of mud cake $^1/_{32}$ in
Sample 1	6.35	10.005	3.655	2.90
Sample 2	6.35	10.04	3.69	2.93
Sample 3	6.35	10.15	3.80	3.02
Sample 4	6.35	10.10	3.75	2.98
Sample 5	6.35	10.30	3.95	3.14
Sample 6	6.35	10.27	3.92	3.11
Sample 7	6.35	10.65	4.30	3.41

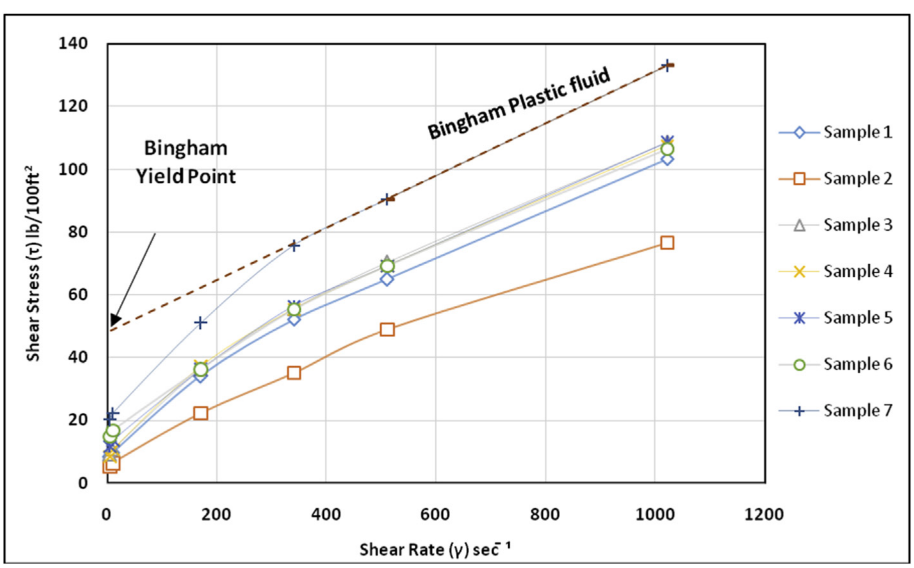

Fig. 1. Shear rate vs. shear stress (samples with different densities).

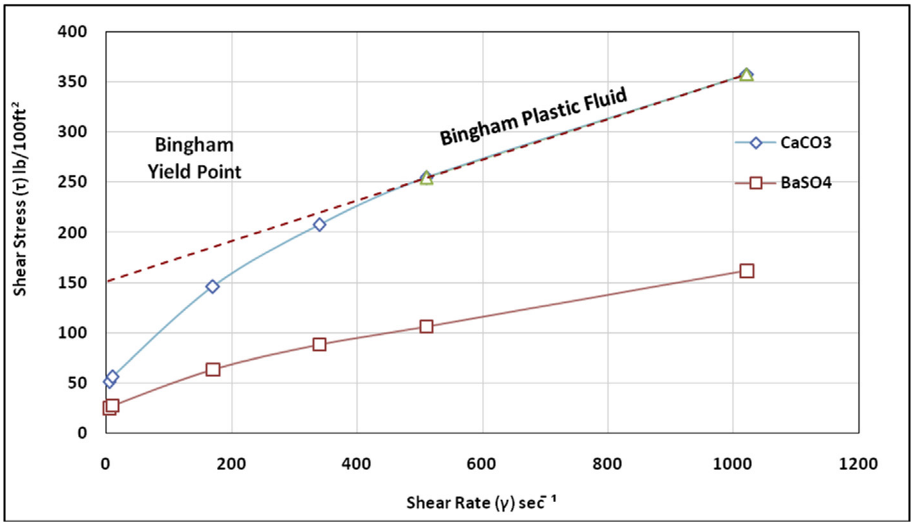

Fig. 2. Shear rate vs. shear stress (samples with different weighting materials).

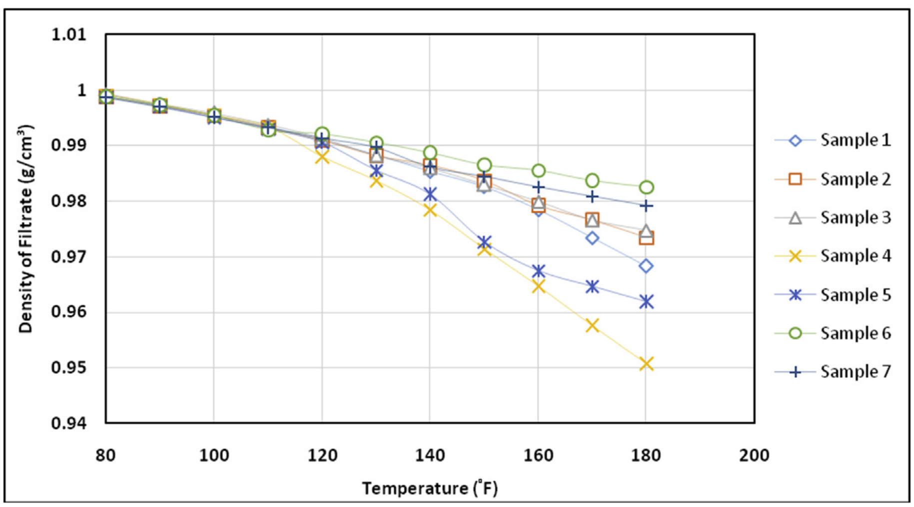

Fig. 3. Change of filtrate fluid density with temperature (Samples with different densities).

$$K_{final} = K_{initial}\left(\frac{\varnothing_{final}}{\varnothing_{initial}}\right)^3 \quad (9)$$

where, k_{final} is the permeability of ceramic disk after filtration process, mD, $k_{initial}$ is the initial permeability of ceramic disk, mD, $\phi_{initial}$ is the initial porosity of ceramic disk, fr, and ϕ_{final} is the final porosity of ceramic disk after filtration process, fr.

Generally, the formation damage is directly apparent to originate in the poor performances of un-weighted (without solid) fluids, giving low return permeability (Khodja et al., 2010). By taking the ratio of the final permeability of the ceramic disk (k_{final}) to the initial permeability of the ceramic disk ($k_{initial}$), the damage ratio can be determined.

2.3. Scanning electron microscopy (SEM) analysis

Scanning electron microscopy (SEM) performs high magnifications, so it generates high-resolution images and precisely measures very small features and objects. It uses a focused beam of high-energy electrons to generate a variety of signals at the surface of solid specimen. The signals generated during SEM analysis produce a two-dimensional image and reveal information about the sample including, external morphology (texture), chemical composition and orientation of materials making up the sample (Plank and Gossen, 1991). In the current work, the scanning electron microscope is used to study the structure and the morphology of the static filter cake formed for water-based drilling fluid, as well as investigating the effect of the different mud additives in the filter cake (Chenevert and Huycke, 1991; Blkoor and Fattah, 2013). Two selected samples are used mainly in this part of study, i.e. sample 3 among the seven samples of different densities and sample 1 with $CaCO_3$ weighting material.

3. Results and discussion

3.1. Characteristics of drilling fluids

Table 3 shows that fluid density range of 9.0–12.0 Ib/gal corresponding to Barite amount range of 23.50–217 g is utilized for the seven drilling fluid samples. The different measured rheological properties of the seven drilling fluid and the two weighting

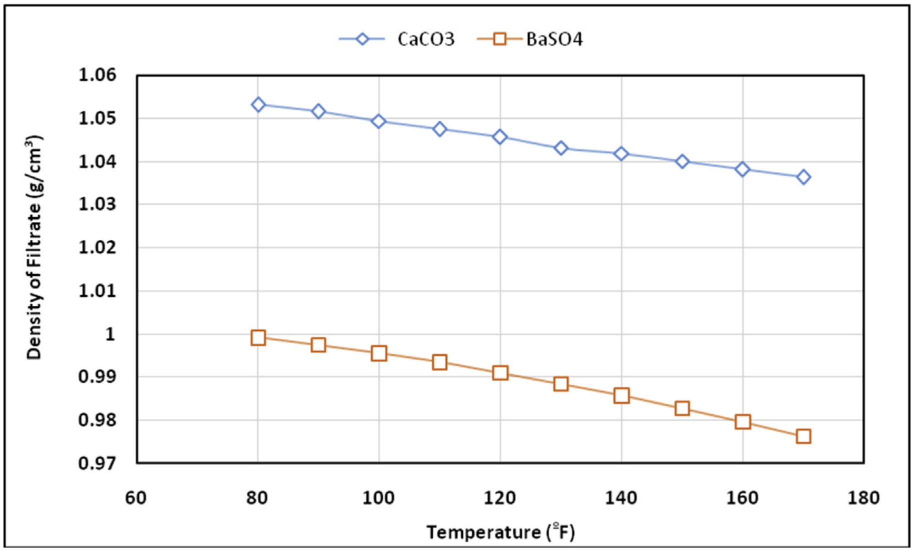

Fig. 4. Change of filtrate fluid density with temperature (samples with different weighting materials).

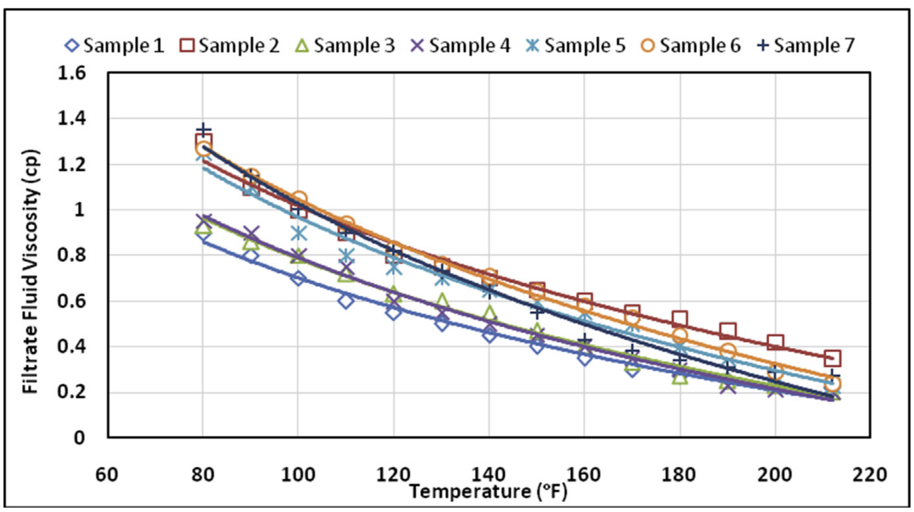

Fig. 5. Change in filtrate viscosity with temperature (Samples with different densities).

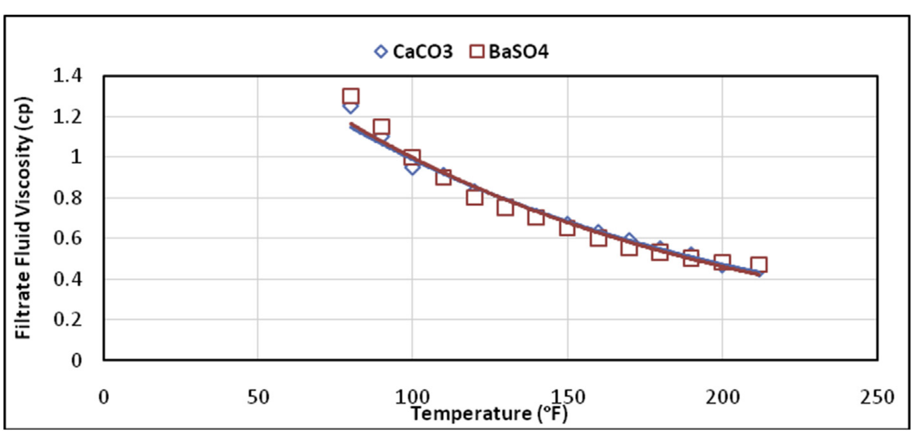

Fig. 6. Change in filtrate viscosity with temperature ($CaCO_3$ & $BaSO_4$).

samples are shown in Tables 4 and 5

Looking precisely to the measured values, it is observed that the rheological properties of drilling fluids with different densities exhibit a narrow range of variations (Table 4). In general, an increase in values with increasing the density is indicated. Meanwhile for samples with different weighting materials, the first water-based drilling fluid ($CaCO_3$-based sample at 12.0 ppg) shows higher rheological properties values than the second sample mainly occupied by $BaSO_4$. For example, the measured plastic and apparent viscosities of the Calcite sample are nearly double in range as compared to the Barite sample (Table 5).

Figs. 1 and 2 show the relationship between the measured share rate and shear stress (of non-Newtonian fluids). The plots illustrate that the shear stress of the seven water-based drilling fluid samples increases with increasing the added Barite fluid density. A general trend of the Bingham plastic fluid line is found cutting the vertical axis at a yield point of 50 b/100 ft^2 (Fig. 1). Meanwhile, fluid samples that are treated with two different weighting materials (i.e., $BaSO_4$ and $CaCO_3$) exhibit much higher shear stress for Calcite weighted martial than that of the Barite sample. A Bingham yield point is found at 150 b/100 ft^2 (Fig. 2).

3.2. Static HPHT test

The density of filtrate is measured by using high temperature density meter (DMA 4500), at a wide temperature range of 80–220 °F, as shown in Figs. 3 and 4. Generally speaking, the density of mud filtrate decreases gradually with increasing the temperature. The meaningful obvious decrease in density is begun to happen at a temperature range above 120 °F. Very important to notice that, samples with Barite density of 83.5 and 114 g (samples 4 and 5) exhibit much more decrease in filtrate density than other samples. Meanwhile, samples with more Barite density of 147 and 217 g (samples 6 and 7) exhibit the minimum response with temperature. It shows low decreasing range from 1.0 to 0.984 g/cm^3 in the density of the mud filtrate. Other low Barite density samples (samples 2–4) show intermediate response (Fig. 3).

For the second part of the experimental work, a wide range of decreasing of the filtrate density is observed between both of the weighted samples of Barite and Calcite (Fig. 4). With increasing temperature, meaningful decreasing ranges of the density of the filtrate, in the order of 1.052–1.036 g/cm^3 and 1.0–0.976 g/cm^3, are recorded for both of the weighted samples of the Calcite and Barite, respectively.

The measured filtrate viscosity values that are enhanced using a Brookfield viscometer at different temperatures are plotted in Figs. 5 and 6. With the exception of sample 2, the drilling fluid samples with low Barite density show much more decrease in filtrate fluid viscosity with temperature than other samples with high density (Fig. 5). On the other hand, no obvious change is observed in the behavior of the viscosity of the fluid filtrate with temperature, for both of the Calcite and Barite weighted samples. However, the general trend of decreasing of fluid filtrate viscosity with temperature is ranged between 1.30 cp and 0.40 cp (Fig. 6).

3.3. Filter cake thickness, porosity & permeability

A measurement of the thickness of the filter cake is usually detailed in 1/32 inch (see, Tables 6, 7 and Fig. 7). The filter cake thickness was measured after completing the fluid test by subtracting the ceramic disk thickness from the total thickness of the ceramic disk with filter cake. The results show that the measured thickness of the filter cake ranges from 3.655 to 4.30 mm, and increases with increasing order of fluid density. Thus the drilling fluid which has 12.0 ppg of mud weight has a great mud cake thickness (Fig. 6). On the other hand, the results show that the filter cake thickness of drilling fluid which has a $CaCO_3$ as weighting material

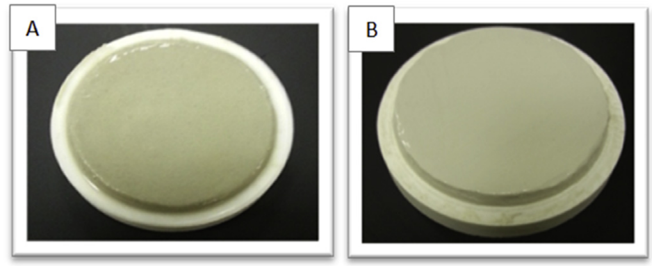

Fig. 7. The filter cake samples obtained from filtration loss tests, a) Samples with different densities (smaple3) and b) $CaCO_3$ weighting fluid (smaple1).

has more thickness (6.0 mm) than the filter cake thickness of drilling fluid that has a $BaSO_4$ as weighting material (4.76 mm) (see, Table 7). Two representative fluid samples are demonstrated in Fig. 7 to show the thickness of the filter cake of drilling as obtained from filtration loss test.

Regarding the porosity of the filter cake for the drilling samples of different densities, a general behavior of porosity increasing with decreasing of fluid density is indicated (see, Table 8). The results show that porosity of filter cake ranges from **0.735** (sample 6) to **0.859** (sample 3). Meanwhile, Table 9 summarizes the obtained filter cake porosities for the $CaCO_3$ & $BaSO_4$ weighting materials. It clarifies that the $CaCO_3$ filter cake porosity (0.520) is less than that of the $BaSO_4$ weighted material (0.814).

Table 10 shows the average permeability of the filter cake for the seven fluid samples used in the first experiment, while Fig. 8 exhibits the relationship between the cumulative filtrate volume and time. A varying range **of 0.21** to **1.144**µd is recorded for the measured filter cake permeability. A little filter cake permeability is recorded as compared with the permeability of the ceramic disk. For the $CaCO_3$ and $BaSO_4$ weighting fluids, the results show that the average permeability of the filter cake of the Calcium Carbonates has a higher value (1.555 µm) than the second one (1.434 µm in case of $BaSO_4$) (Table 11). This is matched with the higher measured filter cake thickness and volume of the first water-based drilling fluid (4.761*/32in* and 11.0 cm^3/30min) as compared with those recorded for the second sample (3.611*/32in*, and 6.65 cm^3/30min). Fig. 9 shows the graphical presentation of the cumulative filtrate volume recorded for $CaCO_3$ and $BaSO_4$ samples with time.

3.4. Filter disk porosity & permeability

The final porosity of ceramic disk was measured by the difference in weight of disk in dried and saturated conditions at end of the filtration test (T = 212 °F & P = 200 psi). Table 12 summarizes the effect of density on the final measured porosity of the ceramic disk for the seven used fluid samples. In general, a reduction trend of the ceramic disk porosity (16.22–24.86%) can be indicated with increasing the fluid density. More interested to find that the drilling fluid (9.50 ppg) has higher porosity/less reduction rate than other drilling fluids (Fig. 10). However, a much more and nearly constant rate of porosity reduction seems to be achieved for drilling fluids of density 10 ppg and more. For the effect of the $CaCO_3$ and $BaSO_4$ drilling fluids on porosity of ceramic disk, a reduction of porosity of the ceramic disk in the order of 9.14% (final ϕ of 33.62%) to 11.35% (final ϕ of 32.80) is observed for both of the two fluids, respectively (see, Fig 11 and Table 13).

Table 14 exhibits the data representing the change in permeability and permeability reduction on the ceramic disk properties. These data are plotted to obtain the optimum mud weight for less damage (Fig. 12). A reduction trend of the permeability of the ceramic desk "much similar to that of the porosity of the desk" is

Table 7
Thickness of filter cake h_c ($CaCO_3$ & $BaSO_4$).

Fluid reference	Thickness of ceramic disk mm	Thickness of ceramic disk + mud cake mm	Thickness of mud cake mm	Thickness of mud cake $^1/_{32}$ in
Sample 1 $CaCO_3$	6.35	12.35	6.0	4.76
Sample 2 $BaSO_4$	6.35	10.9	4.55	3.61

Table 8
Porosity of filter cake $\varnothing_c$ (samples with different densities).

Fluid reference	Weight of dry ceramic disk g	Weight of wet ceramic disk g	Wet weight of CD & MC g	Net wet wt. of MC g	Dry weight of CD & MC g	Net dry wt. of MC g	Average grain density ρ_g g/cc	Porosity $\varnothing_c$
Sample 1	38.466	45.302	57.386	12.084	42.751	4.285	2.15	0.796
Sample 2	39.868	45.420	59.878	14.458	43.766	3.901	2.11	0.85
Sample 3	39.537	46.387	59.290	12.903	43.281	3.744	2.50	0.859
Sample 4	40.275	47.195	63.136	15.941	46.3760	6.101	2.65	0.810
Sample 5	39.114	45.524	64.233	18.709	46.964	7.850	2.623	0.784
Sample 6	39.770	45.359	63.250	17.891	48.862	9.092	2.86	0.735
Sample 7	39.388	45.044	6.517	24.473	51.224	11.836	2.99	0.761

Table 9
Porosity of filter cake $\varnothing_c$ ($CaCO_3$ & $BaSO_4$).

Fluid reference	Weight of dry ceramic disk g	Weight of wet ceramic disk g	Wet weight of CD & MC g	Net wet wt. of MC g	Dry weight of CD & MC g	Net dry wt. of MC g	Average grain density ρ_g g/cc	Porosity $\varnothing_c$
Sample 1 $CaCO_3$	39.821	46.606	73.441	26.835	57.778	17.957	2.189	0.520
Sample 2 $BaSO_4$	40.060	47.523	66.045	18.522	51.716	11.656	2.755	0.814

Table 10
Average filter cake permeability using Li et al.'s (2005) method (samples with different densities).

Fluid reference	Filtrate rate ($m^3/m^2.s$)	Delta P_m (ΔP_m) (Pa)	Mu (μ) (Pa.s)	Delta Pc (ΔPc) (Pa)	Average cake permeability (m^2)	Average cake permeability (μd)
Sample 1	8.63×10^{-7}	1.5759	0.22×10^{-3}	1378998.424	5.032E-19	0.510
Sample 2	1.35×10^{-6}	3.3618	0.35×10^{-3}	1378996.638	1.080E-18	1.098
Sample 3	9.37×10^{-7}	1.5555	0.20×10^{-3}	1378998.455	5.160E-19	0.523
Sample 4	3.804×10^{-7}	0.6315	0.20×10^{-3}	1378999.369	2.069E-19	0.210
Sample 5	1.008×10^{-6}	1.9244	023×10^{-3}	1378998.076	6.640E-19	0.673
Sample 6	1.211×10^{-6}	2.4125	0.24×10^{-3}	1378997.388	8.260E-19	0.837
Sample 7	1.341×10^{-6}	3.0050	0.27×10^{-3}	1378996.995	1.130E-18	1.144

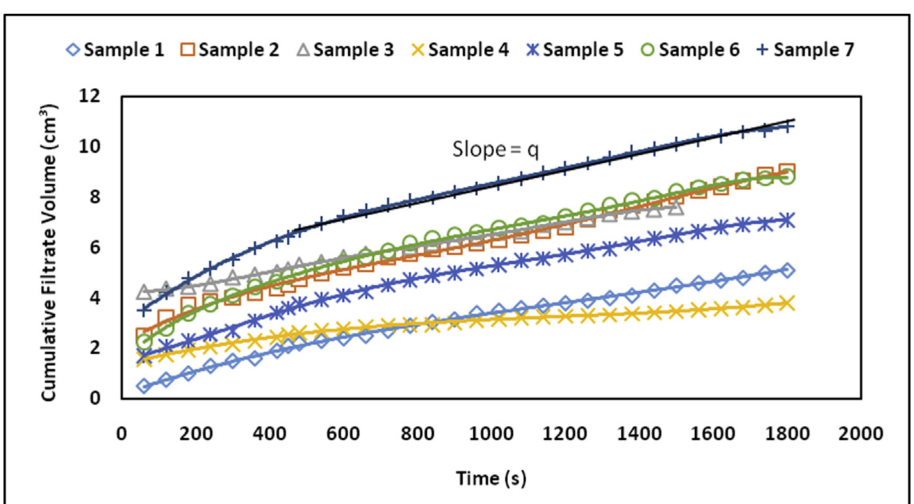

Fig. 8. Cumulative filtrate volume recorded for samples with different densities (Li et al., 2005).

Table 11
Average filter cake permeability for $CaCO_3$ and $BaSO_4$ drilling fluids (Li et al., 2005).

Fluid reference	Filtrate rate ($m^3/m^2.s$)	Delta P_m (ΔP_m) (Pa)	Mu (μ) (Pa.s)	Delta Pc (ΔPc) (Pa)	Average cake permeability (m^2)	Average cake permeability (μD)
Sample 1 $CaCO_3$	7.84×10^{-7}	2.9285	0.45×10^{-3}	1378997.072	1.535E-18	1.555
Sample 2 $BaSO_4$	9.137×10^{-7}	3.5646	0.47×10^{-3}	1378996.435	1.416E-18	1.434

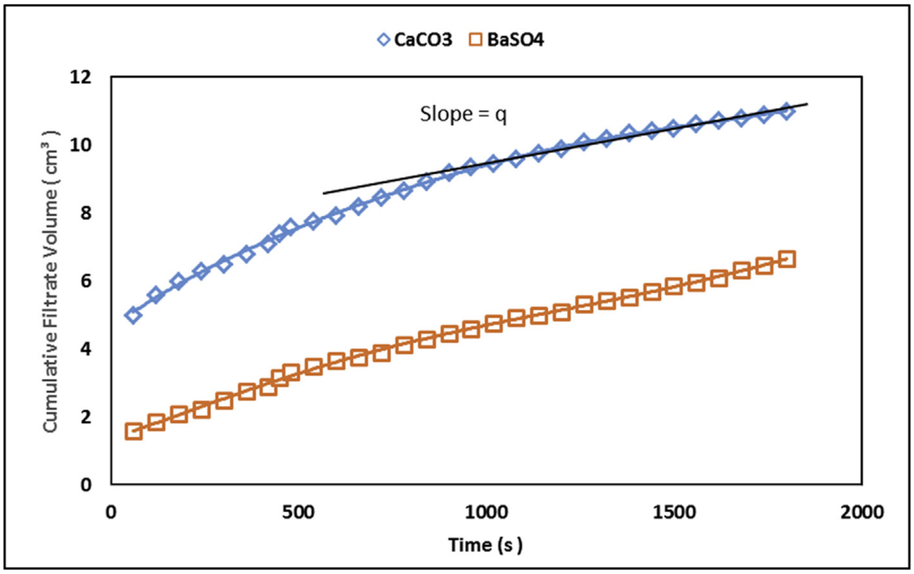

Fig. 9. Cumulative filtrate volume recorded for CaCO3 and $BaSO_4$ samples with time (Li et al., 2005).

Table 12
Density effect on porosity of the ceramic disk.

Fluid reference	Density of drilling fluids lb/gal	Initial porosity %	Final porosity %	Porosity reduction %
Sample 1	9.0	37.0	31.0	16.22
Sample 2	9.2	37.0	32.22	12.92
Sample 3	9.5	37.0	33.0	10.81
Sample 4	10.0	37.0	28.0	24.32
Sample 5	10.5	37.0	27.88	24.65
Sample 6	11.0	37.0	28.01	24.30
Sample 7	12.0	37.0	27.80	24.86

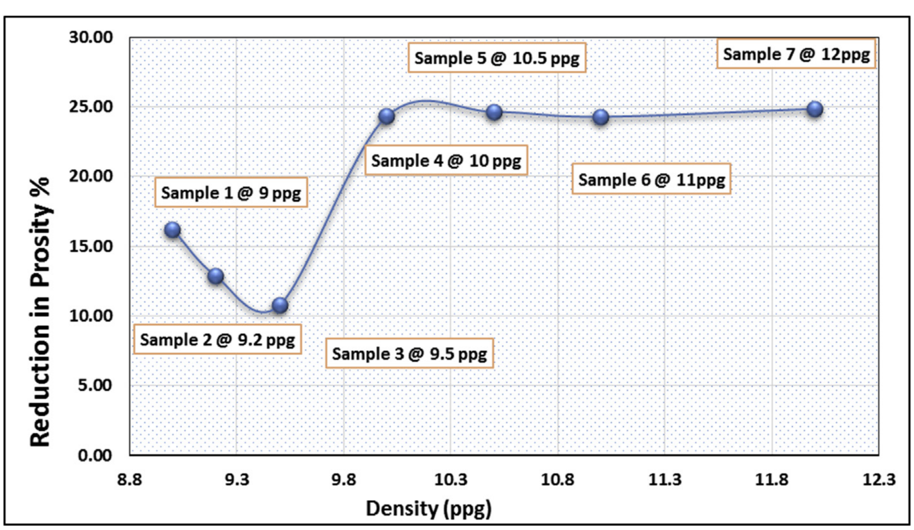

Fig. 10. Density effect on reduction of poroisty of the ceramic desk.

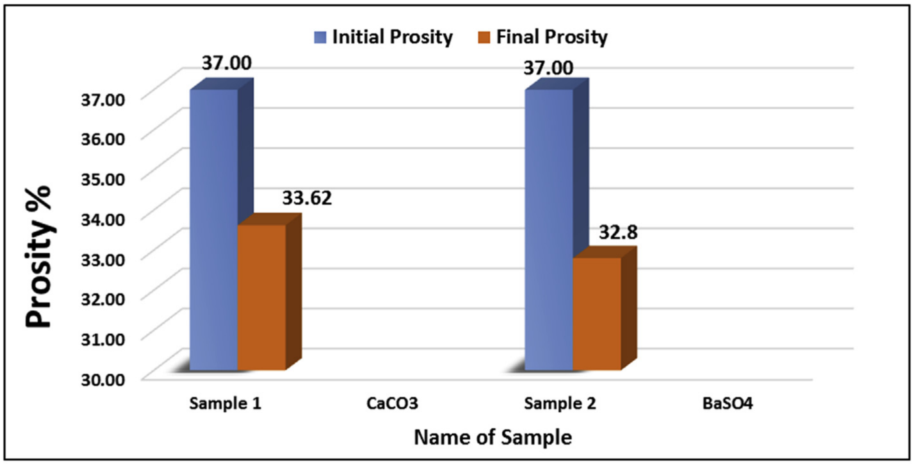

Fig. 11. Effect of the drilling fluids ($CaCO_3$ and $BaSO_4$) on poroisty of the ceramic desk.

Table 13
Effect of drilling fluids ($CaCO_3$ and $BaSO_4$) on porosity of ceramic disk.

Fluid reference	Weight of dry sample W_d.	Weight of saturated sample W_s.	Pore volume (V_p)	bulk rock volume (V_b)	Final porosity %	Porosity reduction %
Sample 1 $CaCO_3$	39.964	46.725	6.761	20.1100	33.62	9.14
Sample 2 $BaSO_4$	40.268	46.874	6.606	20.1100	32.80	11.35

Table 14
Density effect on the permeability of ceramic disk (permeability reduction).

Fluid reference	Density of drilling fluids lb/gal	K initial, (mD)	K final, (mD)	Damage ratio (DR), %	Reduction in permeability, %
Sample 1	9.0	775	456	59	41
Sample 2	9.2	775	512	66	34
Sample 3	9.5	775	550	71	29
Sample 4	10.0	775	336	43.35	56.65
Sample 5	10.5	775	332	43	57
Sample 6	11.0	775	336	43.4	56.6
Sample 7	12.0	775	329	42.45	57.55

observed. The analysis of the results shows that a reduction ratio in the order of 41% is obtained at mud weight 9.0 ppg and continues to decrease to reach up to nearly 29% for mud weight of 9.50 ppg. Above 10.0 ppg the effect of the mud weight density on formation damage is stabilized at nearly constant value. Thus, at this level the mud weight has more effect on the final measured permeability giving rise to big permeability reduction up to 57.55%.

Meanwhile, for the two utilized drilling fluids, the results show that the fluid of $CaCO_3$-based weighting material, has less reduction in permeability (25%) than the $BaSO_4$-based fluid (30.30%) (see, Fig. 13 and Table 15).

Based on the analyses done upon the seven water-based drilling samples of different densities, it appears that the optimum mud weight which has less damage is in the range of 9.0–10.0 lb/gal (samples 1–3). But it seems that water-based drilling fluids of density 9.50 lb/gal is better to use than that of 9.0 and 9.20 lb/gal samples due to its less effect of the filter desk porosity and permeability (less reduction on the porosity and permeability). A measured reduction values of 10.81% and 29% are given for both of the porosity and permeability by the 9.50 lb/gal drilling fluid sample as compared with 16.22, 12.92% and 41%, 34% for both of 9.0 and 9.20 lb/gal samples, respectively. While for the $BaSO_4$ and $CaCO_3$-fluid based samples, the Calcite exhibits a less reduction on both of the porosity and permeability than Barite.

3.5. Scanning electron microscopy (SEM) analysis

The scanning electron microscopy analysis of the filter cake created by 9.50 lb/gal water-based drilling fluid (sample 3) is shown in Fig. 14. This sample was selected based on the concluded results considering the less reduction in permeability of ceramic disk that the 9.50 lb/gal water-based drilling fluid produced. The SEM analysis indicates that four main elements are found. These elements are Aluminum (Al), Silicon (Si), Molybdenum (Mo) and Barium (Ba), however the percentage of Ba in the filter cake is higher than other components (Fig. 14 right, Sample 3). On the other hand, the SEM analysis of filter cake produced by $CaCO_3$ drilling fluid is shown in Fig. 15. Calcium (Ca), Aluminum (Al), Silicon (Si) and Carbon (C) elements are the major detected elements. The Ca element (34%) constitutes the main component, and then comes the percentages of the other elements (Si, Al, Ca, etc).

The structure and morphology of the two investigated samples (left side of Figs. 14 and 15) indicates that the 9.5 lb/gal mud sample exhibits well-produced intra-granular pore structure and relatively crystal size as compared with the $CaCO_3$ sample.

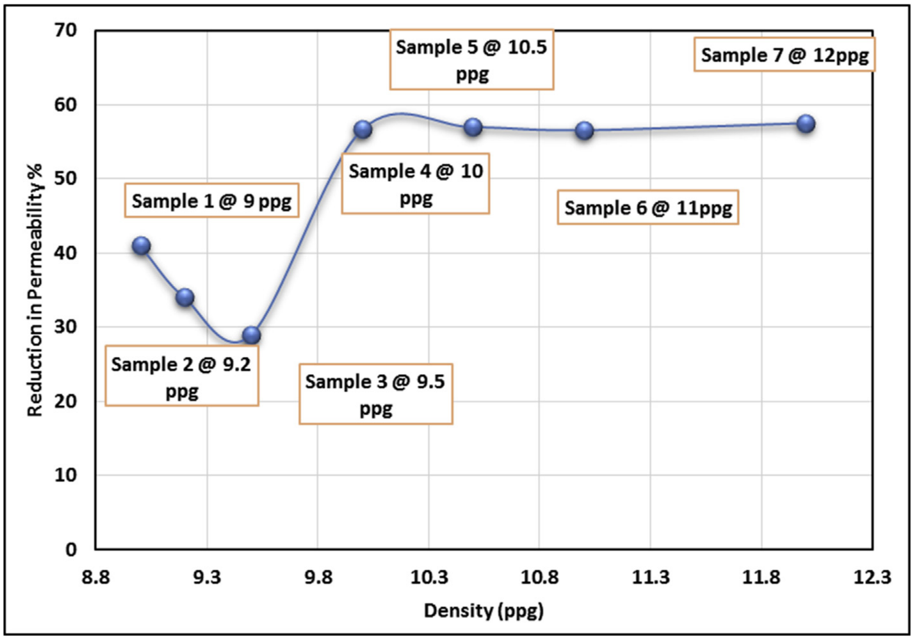

Fig. 12. Effect of the density on reduction in permeability of the ceramic desk.

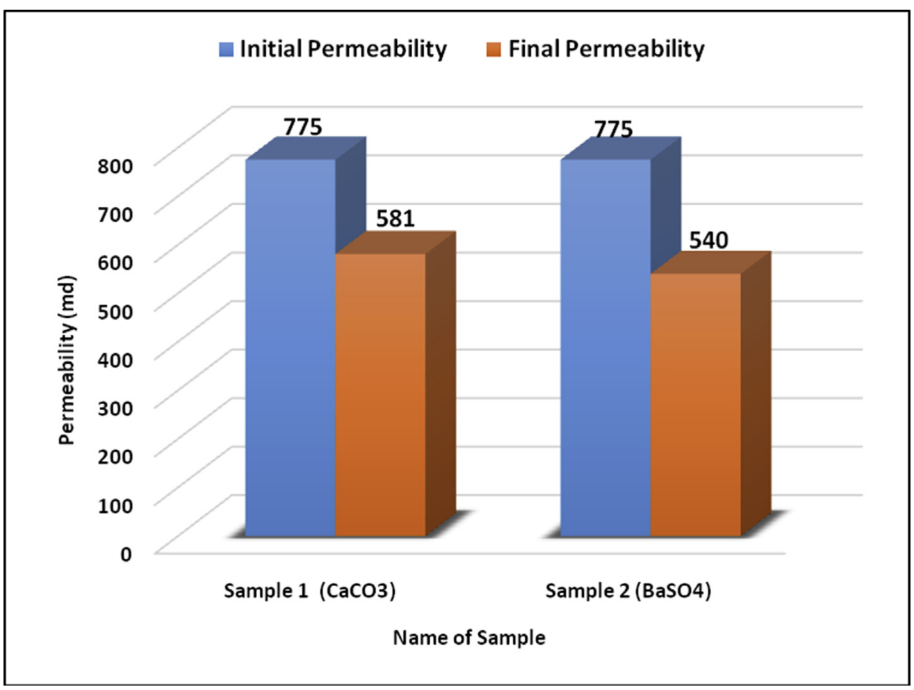

Fig. 13. Effect of the drilling fluids ($CaCO_3$ and $BaSO_4$) on the permeability of the ceramic desk.

Table 15
Effcet of drilling fluids ($CaCO_3$ and $BaSO_4$) on the permeability of the ceramic disk.

Fluid reference	K initial, (mD)	K final, (mD)	Damage ratio (DR), %	Reduction in permeability, %
Sample 1 $CaCO_3$	775	581	75	25
Sample 2 $BaSO_4$	775	540	69.7	30.3

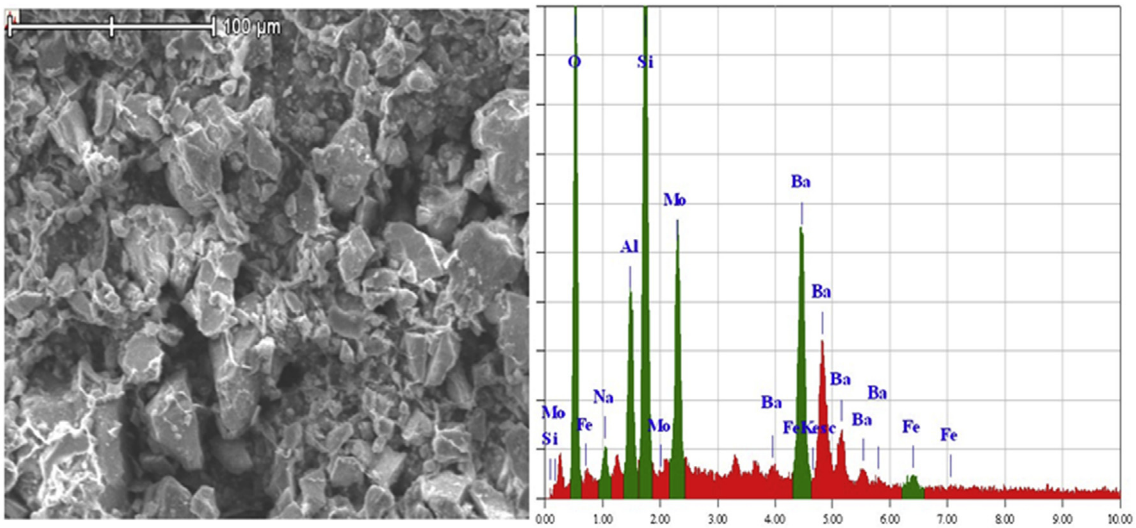

Fig. 14. SEM analysis of filter cake of drilling fluid of density of 9.5 lb/gal (Sample 3).

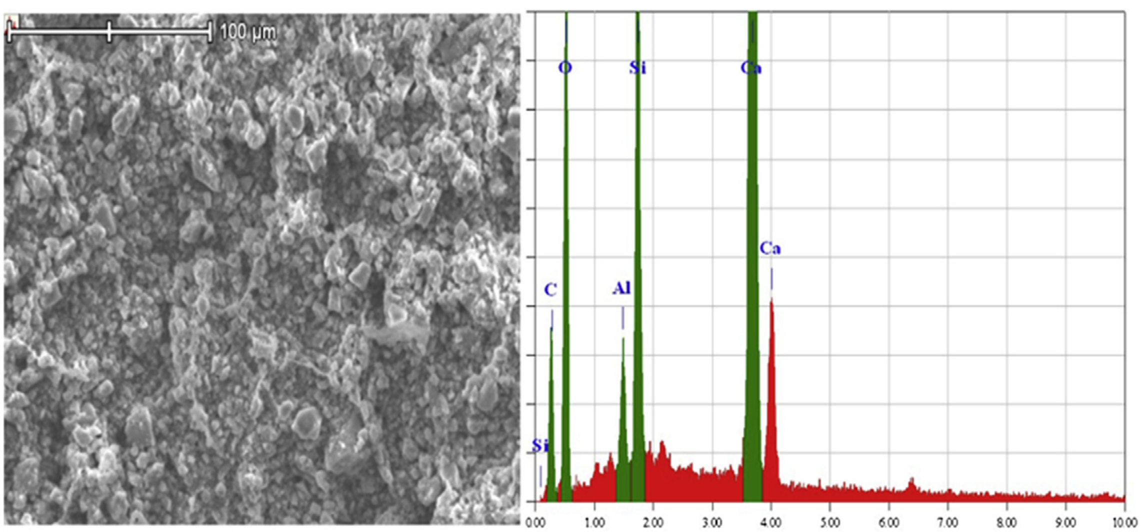

Fig. 15. SEM analysis of $CaCO_3$ filter cake.

4. Conclusions

This study dealt with investigating the effect of mud density and weighting materials on drilling fluid filter cake properties and formation damage using experimental methodology on specific ceramic disks. The specifications of the utilized ceramic disks are 10 μm, 775 mD and 37% for mean pore size distribution, permeability and porosity, respectively.

The applied methodology involves preparation of seven samples of water-based drilling fluids at different densities (9.0–12.0 lb/gal) to select the optimum mud weight which has less damage, from one hand and preparation of two water-based drilling fluids with same composition but with different weighting materials, i.e. $BaSO_4$ and $CaCO_3$, from the other hand.

Based on the analysis and interpretation of the laboratory measurements, the following are the main concluded points:

- Among the seven used mud densities, optimum mud weigh of 9.5 lb/gal was selected, considering the less reduction in permeability of ceramic disk, it produced. Above 10.5 ppg the effect of the mud weight density on formation damage is stabilized at constant value.
- The density of mud filtrate decreases gradually with increasing the temperature. The effect begins to be effective at a temperature above 120 °F. For Barite and Calcite weighted samples, a reasonable decrease of the density of the filtrate in the order of 1.052–1.036 g/cm^{3}and of 1.0–0.976 g/cm^3, is recorded with increasing temperature.
- Fluids of $CaCO_3$-based weighting material, has less reduction in the porosity (9.14%) and permeability (25%) of the filter disk properties than the $BaSO_4$-based fluid.
- The produced filter cake porosity increases (from 0.735 to 0.859) with decreasing of fluid density in case of drilling samples of different densities.
- The filtration loss tests indicated that $CaCO_3$ filter cake porosity (0.520) is less than that of the $BaSO_4$ weighted material (0.814). The thickness of the filter cake of the $BaSO_4$-based fluid is relatively big and can cause some problems.
- SEM micrograph observations are matched with porosity and permeability measurements. A decrease in permeability values

for the filter cakes derived with the fluids treated with Barite is observed more than that of Calcite.

A recommendation is given to minimize the utilization of Barite as a drilling fluid. Aside from its recorded bad effect on the filter disk properties as concluded from this study, it also has a bad effect on the quality logging process as it attenuates the gamma rays emitted from the geological formations, hence led to low count rate and error in the final reservoir evaluation.

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