



A review of the various treatments of oil-based drilling fluids filter cakes

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Abstract

Treatment of the filter cake layer after drilling is essential for better cement integrity and to retain the original reservoir permeability. Compared to water-based filter cake, oil-based mud filter cake removal is more sophisticated as oil encloses the filter cake's particles. Therefore, oil-based mud clean-up requires wettability alteration additives (mutual solvents and/or surfactants) for permitting acid/filter cake reaction. With an appropriate acid, microemulsions were reported to be very efficient in cleaning oil-based filter cakes, due to their low interfacial tension and high acid solubility. The objective of this paper is to provide an overview of the different techniques and treatment solutions utilized in oil-based filter cake clean-up. Furthermore, a synopsis of the various treatments for drilling fluids densified with different weighting materials is presented. Subsequently, the research limitations and opportunities have been highlighted for future work. In the light of the review that has been presented in this paper, it's recommended to conduct further investigation on some areas related to filter cake removal. The removal of filter cake formed from weighting materials other than barite, calcium carbonate, ilmenite, and manganese tetroxide needs to be investigated thoroughly. Additionally, the overall efficiency of oil-based mud removal needs to be studied under wide ranges of temperature, salinity, and pH. The utilization of surfactant-free microemulsions in filter cake treatment could also be investigated.

Keywords Filter cake · Filter cake removal · Oil-based drilling fluid · Weighting materials

Introduction

Drilling fluids are designed to facilitate the drilling operation by performing different functions such as downhole tools lubrication, rock cuttings suspension, and transportation to the surface (Fink, 2012; Gordon et al., 2008). The drilling fluids should also provide an adequate hydrostatic pressure which must be greater than the formation pressure to provide an overbalance, which is required to avoid flow from the formation into the wellbore and to keep the wells under control. Nonetheless, this excess pressure means some of the drilling fluid will invade the penetrated formation and may

cause formation damage, reduction in the permeability, and consequently additional cost (Iskan et al., 2007; Zhang et al., 2020). This drilling fluid invasion affects rock mechanical properties as well (Karakul, 2018).

Deposition of the solid particles from the drilling fluid onto the face of the permeable rock results in a thin layer with a permeability of less than 0.01 md known as a filter cake (FC) as shown in Fig. 1 (Civan, 1994; Hanssen et al., 1999). The mud invasion into the drilled formation, and hence, the formation damage is diminished by the filter cake formation (Argillier et al., 1999). In this way, the filter cake formation and its characteristics are considered as principal features of any drilling fluid (Bourgoyne, 1986; Hossain and Al-Majed, 2015; Rabia, 2001).

In addition to rock pores plugging, external filter cake can plug the completion screens and gravel pack, and subsequently, the productivity/injectivity of the wells will reduce significantly; hence, it requires to be treated efficiently (Davison et al., 2001; Jiao and Sharma, 1992; Quintero et al., 2005). These drilling-related damages are more severe in horizontal wells due to longer exposure to the drilling fluids

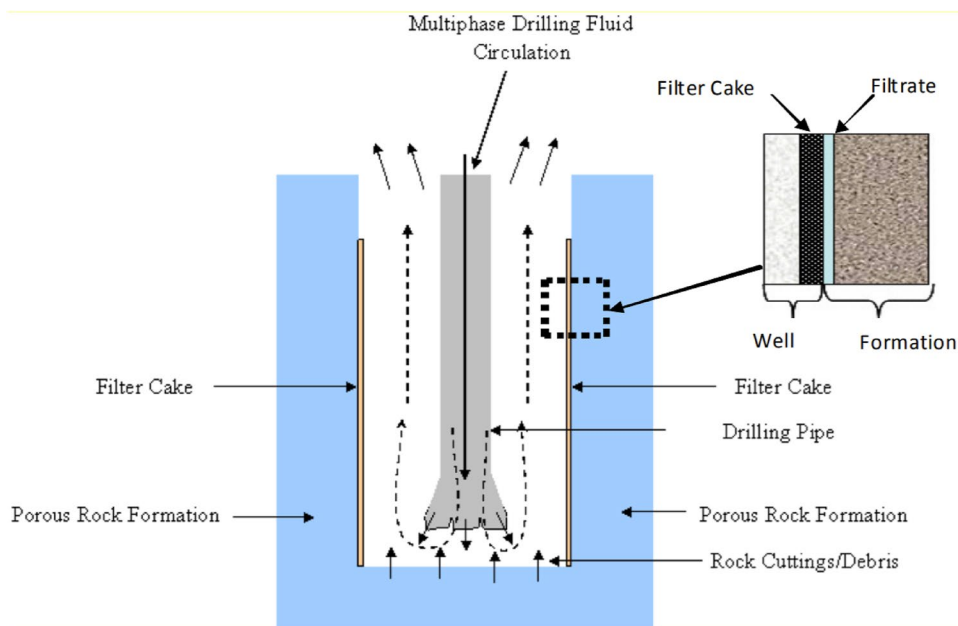
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Fig. 1 Formation of the filter cake (Kabir and Gamwo, 2011)



compared to vertical wells (Frick and Economides, 1993; Thomas and Sharma, 1998). The significance of formation damage varies depending on the drilling fluid properties, reservoir characteristics, and pressure (Brege et al., 2012). Recent researches showed that the utilization of nanomaterial enhanced the filtration properties of the drilling fluids (Ikram et al., 2020; 2021).

Even though the filter cake formation is very important during the drilling process to minimize the drilling fluid invasion into the drilled formation, however, efficient removal of the filter cake layer after the drilling process is a must to ensure better cementing integrity and to eliminate restriction on well productivity or injectivity (Davidson et al., 2012; Fink, 2012; Huang et al., 2019; Zain and Sharma, 1999). For efficient cementation, the face of the rock should receive the cement to form a strong bond, and this could be restricted if the filter cake is not efficiently removed (Wang et al. 2016).

In our recent publication, Siddig et al. (2020a), a comparison of the different approaches for the treatment of water-based filter cakes is reported. The objective of this paper is to report and summarize the different approaches for the removal of the filter cakes formed by oil-based drilling fluids. The diverse chemical treatments available for the removal of filter cakes containing various weighting materials are also presented in this manuscript. In the light of the review covered, future research opportunities have been highlighted.

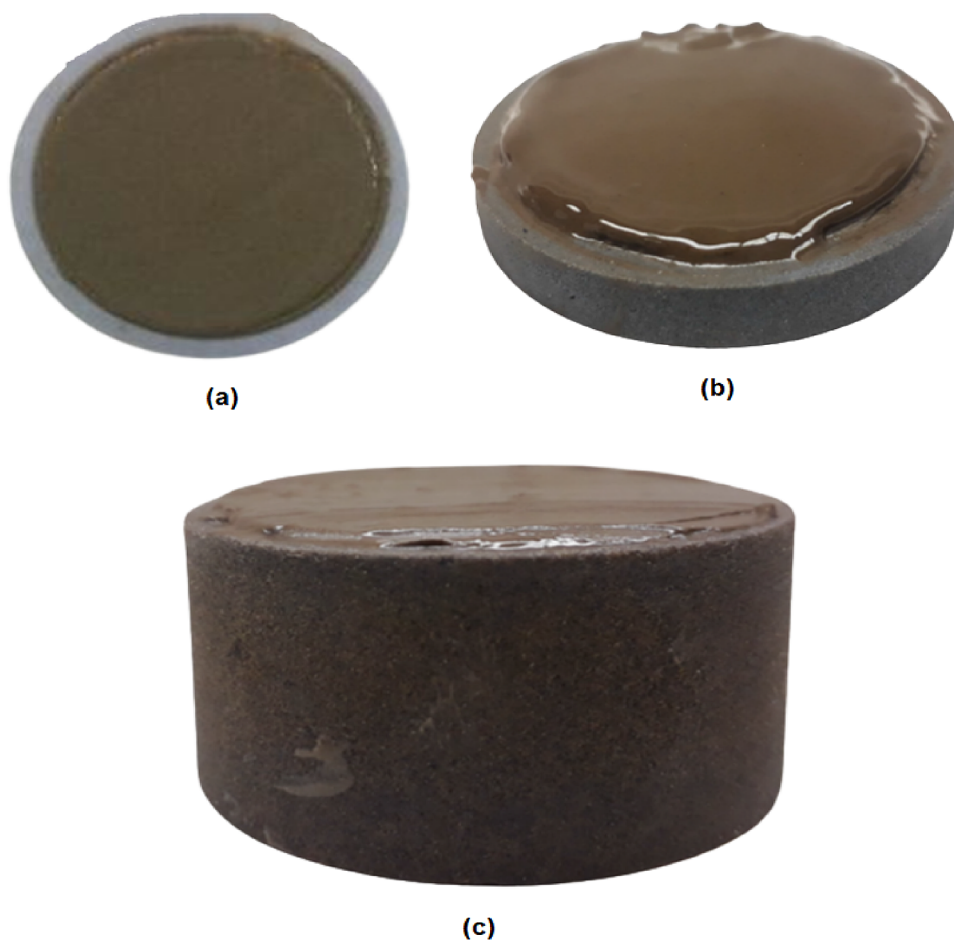
Filter cake characterization

Different techniques have been employed to examine and characterize the filter cake formed on filter paper, ceramic disc, or core sample (see Fig. 2). These methods incorporating the scanning electron microscope (SEM), computer tomography (CT) scan, nuclear magnetic resonance (NMR), and X-ray fluorescence (XRF). The thinner, less permeable, faster to form, and easier to remove is considered to be a better filter cake (Mahmoud and Elkatatny, 2017).

Filter cake properties such as permeability, porosity, toughness, thickness, structure, particle size distribution are the key elements that influence the fluid invasion into the drilled formations, and therefore, they affect the formation productivity (Ba geri et al., 2013a; Li and He, 2015). These properties are affected by various factors such as the type of weighting material and polymers contained in the drilling fluid, in addition to the clay content, salinity, and sand content of the filter cake layer (Ba geri et al., 2019a, 2015; Yao et al., 2014). Furthermore, previous studies showed that utilization of nanomaterials in drilling fluids improved the filter cake characteristics and resulted in thinner and more compacted filter cake layers (Boyoun et al., 2019; Rafati et al., 2018; Sharma et al., 2012; Smith et al., 2018).

Several studies showed that the weighting materials are the dominant component of the filter cake and they

Fig. 2 Filter cake formed on **a** filter paper, **b** ceramic disc and **c** core sample



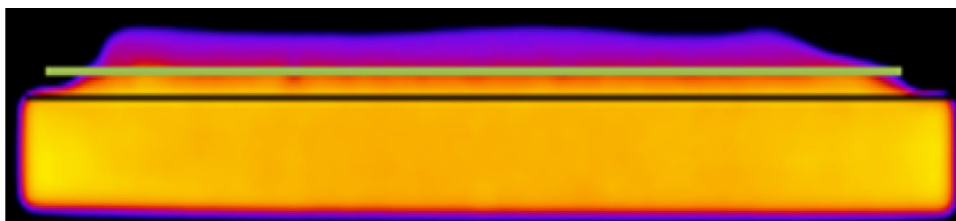
compose up to 80% of the FC layer by weight (Ba geri et al., 2017a; 2015; 2013b). CT scans showed that the FC consists of multiple layers with varying properties, the layer next to the formation surface (the inner layer) mainly comprises the weighting material while the farther layer (the outer layer) contains the polymeric additives as illustrated in Fig. 3 (Elkatatny et al., 2012a; 2011; Elkatatny et al., 2013a; Elkatatny and Nasr-El-Din, 2012a). The formation of more complex and heterogeneous layers is also expected in case of long exposure to the drilling fluids as in the extended reach wells (Hamzaoui et al., 2018). This heterogeneity significantly affects not only the filter cake filtration performance but also the effectiveness of

its removal process (Burnett, 1995; Caenn et al., 2017; Chellappah et al., 2010).

Solvents of different weighting materials

Weighting materials are used in the drilling fluids to increase their weight and, hence, maintain sufficient over-balanced hydrostatic pressure required throughout the drilling operation to control the well. The weighting material should render the drilling fluid with the required density while maintaining good rheology and low solids sagging tendency (Mohamed et al., 2019a; Zamora and Bell, 2004). As affirmed in the previous section, the weighting material

Fig. 3 CT scan shows filter cake that consists of two layers (Elkatatny et al., 2011)



and polymeric additive are the main components of the filter cake; therefore, finding an efficient polymer breaker and a solvent for the weighting material plays a vital role in the success of the filter cake cleanup process.

Enzymes and oxidizers are used as polymer breakers (Imqam et al., 2014). Ammonium persulfate and sodium persulfate are common oxidizers used in the oil industry (Sarwar et al., 2011). On the other hand, several solvents are used for dissolving the weighting material dominant layer of the filter cake. In this section, the various acid solvents that are available for each weighting agent are presented.

Barite

Barite (BaSO_4) is the most regularly used weighting material since the 1930s (Pehrson and Keiser, 1945). However, it has some shortcomings such as low acid solubility (Al-Bagoury and Steele, 2012), formation damage (Al-Bagoury, 2014; Guo et al., 2012), sagging issues, high plastic viscosity (Aldea et al., 2001; Mohamed et al., 2019a; Almutawa et al., 2021), and inability to be utilized in formate brines (Howard, 1995). In expansion to that, barite is not soluble in organic acids or hydrochloric acid (HCl), and this makes barite filter cake removal a sophisticated and expensive process (Bern et al., 2010).

Lakatos et al. (2002) investigated the use of different chelating agents to dissolve barite and concluded that ethylenediaminetetraacetic acid (EDTA) and diethylenetriamine pentaacetic acid (DTPA) are preferred when both technical and economical perspectives are taken into consideration.

To enhance the barite solubility in chelating agents, Ba geri et al. (2017b) added catalysts (converting agents) to a solution that consists of chelating agents (EDTA or N-hydroxyethylenediaminetriacetic acid (HEDTA)) at a pH of greater than 12.0. Ba geri et al. (2017a) studied the performance of three different converting agents namely potassium formate, potassium chloride, and potassium carbonate when mixed with a treatment solution of potassium-based DTPA chelating agent. They reported that the addition of the converting agent improved barite solubility from 67 to 95%, and out of the three catalysts, potassium carbonate gave the most noteworthy solubility enhancement.

Further studies used a high pH solution of potassium carbonate (K_2CO_3) with potassium hydroxide (KOH) to convert the barite to barium carbonate which is easier to dissolve. Then, treatment solution of HCl was used to dissolve the originally formed barium carbonate (Mahmoud and Elkhatny, 2017; 2019). However, the use of HCl to dissolve barium carbonate is not favored because it produces harmful barium chloride. Another solution suggested by the authors is to generate the high pH condition using the treatment solution of the EDTA at a high pH of

12.0 with K_2CO_3 or KOH as a convertor. The use of the EDTA solution introduced another advantage over that for the HCl which is the ability to remove the barite filter cake in a single stage because of the compatibility of the EDTA solution and the polymer breakers. In this study, the compatible polymer breaker was potassium persulfate; however, other studies reported incompatibility between the EDTA and the polymer breakers. For instance, Ba geri et al. (2017b) tested the compatibility of EDTA with three different enzymes and found all of them incompatible.

One issue identified in using chelating agents for barite FC removal is that the resulted barite chelates may release barite into formation pores. This is due to its high affinity to other minerals, which can cause secondary damage, especially in the case of non-uniform filter cake thickness (Al Jaber et al., 2020). Figure 4 illustrates the mechanism of the secondary damage related to barite removal operation. Ba geri et al. (2019b) used NMR and micro-CT scans before and after the filter cake treatment with a chelating agent and reported a noticeable change in pore geometry of the core samples.

Ilmenite

Late in the 1970s, the use of ilmenite (FeTiO_3) in drilling fluid was introduced as a low-cost weighting material contrasted with standard barite (Blomberg and Melberg, 1984; Haaland et al., 1976). It also has lower pollution problems compared to barite (Al-Bagoury, 2014; Rae et al., 2001).

The high abrasiveness of ilmenite is its main shortcoming, one solution to solve this issue is to use micronized ilmenite (Al-Bagoury and Steele, 2012; Saasen et al., 2001), which likewise improves the drilling fluid filtration properties and reduces its sagging tendency (Elkhatny, 2012). Another demerit of ilmenite is the high magnetic susceptibilities that may influence the efficiency of directional drilling equipment's operation (Tehrani et al., 2014); however, this could be depreciated by reducing the magnetite content (Xiao et al., 2015).

Ilmenite is soluble in sulphuric acid (H_2SO_4) and HCl and its reaction with these acids produce titanium dioxide (van Dyk et al., 2002; Fouda et al., 2010; Al-Bagoury, 2014). The dissolution rate of the ilmenite in H_2SO_4 is highly affected by the ilmenite particle size (Han et al., 1987). Habib et al. (2006) reported that when methanol is added to HCl, the ilmenite dissolution was increased. Elkhatny et al. (2013b) compared the solubility of ilmenite in different treatment solutions of HCl, EDTA, HEDTA and glycolic acid, and they reported that the highest ilmenite solubility was achieved with HCl solution, while the lowest was when glycolic acid was used.

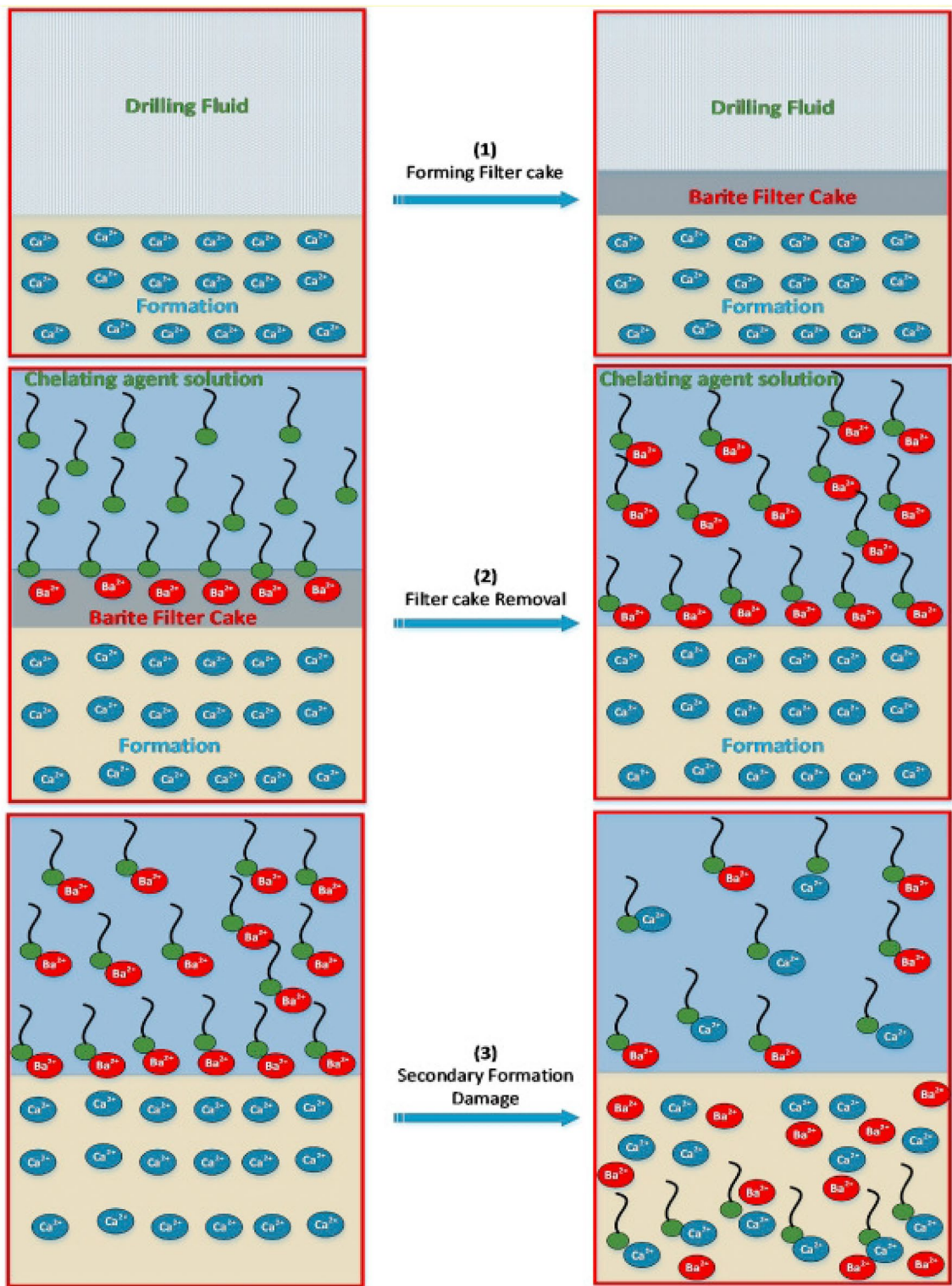


Fig. 4 Mechanism of secondary damage during barite filter cake removal (Ba geri et al., 2019b)

Calcium carbonate

One of the low damaging weighting materials is calcium carbonate (CaCO_3) as it has high acid solubility. The fundamental impediment to the use of calcium carbonate in drilling fluid is that it has a relatively low specific gravity in contrast to the other weighting materials, which means an immense amount of CaCO_3 is needed to accomplish a similar density obtained by the other weighting materials.

Several acid precursors-based treatments for calcium carbonate filter cakes removal have been presented, namely acetic acid precursor (Nasr-El-Din et al., 2005; Siddiqui et al., 2006), formic acid precursor (Al-Anzi et al., 2009; Leschi et al., 2006), and lactic acid precursor (Al-Otaibi et al., 2006; Elkhatny and Nasr-El-Din, 2012b). According to Rostami and Nasr-El-Din (2010a; 2010b), the addition of the esters to the drilling fluids' formulation doesn't significantly affect their rheological properties. Nasr-El-Din and Al Moajil (2007) examined the performance of the three acid precursors and reported that the formic acid precursor resulted in the most efficient CaCO_3 removal.

In addition to the organic acids, the performance of different chelating agents in removing CaCO_3 filter cake had been studied by several authors (Navarro-mascarella and Luyster, 2011; Parlar et al., 1998; Tibbles et al., 2003). Collins et al. (2011) introduced a filter cake breaker that consists of a biodegradable chelating agent to dissolve calcium carbonate filter cake. The chelating agent performance was compared with breakers that contain organic acid precursors. The chelating agent outperformed the organic acid in terms of solubility, corrosion rate and removal efficiency.

Magnesium tetroxide

Manganese tetroxide (Mn_3O_4) is a comparatively new type of weighting agent that has a high specific gravity, low sagging tendency, and better thermal stability; however, it has higher plastic viscosity and yield point compared with CaCO_3 or barite (Al-Yami and Nasr-El-Din, 2007; Svendsen et al., 1995).

Al Moajil et al. (2008) studied the Mn_3O_4 filter cake removal using different solutions of HCl, citric, formic, lactic, and acetic acids and they found that the dissolution of Mn_3O_4 was higher in HCl solution. Even though the high concentration of HCl yields high removal efficiency, it is not recommended to use HCl with a concentration of higher than 4 wt.%, since high HCl concentrations release toxic and corrosive chlorine gas particularly at high temperatures (Al Moajil and Nasr-El-Din, 2010). It is noteworthy that manganese citrate precipitates may occur from a reaction of Mn_3O_4 with certain solvents such as N, N-dicarboxymethyl glutamic acid tetrasodium salt (GLDA), oxalic, citric, and tartaric acids (Al Moajil and Nasr-El-Din, 2013a).

The use of glycolic acid as a treatment solution for the Mn_3O_4 FC removal was studied by Elkhatny et al. (2012b), and the results of this study showed that the effectiveness of the glycolic acid on removing the Mn_3O_4 filter cake was lower than that for HCl. Alternatively, Elkhatny et al. (2013c) presented a treatment solution based on a combination of HCl and glycolic acid with high removal efficiency and safe HCl concentration. Similarly, Al-Moajil and Nasr-El-Din (2013b) presented HCl and lactic acid mixture for Mn_3O_4 filter cake removal.

Hematite

Another weighting material that has been introduced as an alternative to barite is iron oxide, also called hematite (Walker, 1983). When compared to barite, hematite has almost the same specific gravity and produces a drilling fluid with similar rheological properties as barite (Tovar et al., 1999). Similar to ilmenite, abrasiveness and magnetic susceptibility are the main disadvantages of hematite (Bland et al., 2006; Tehrani et al., 2014; Walker, 1983). It also has a sagging tendency (Basfar and Elkhatny, 2020), which can be reduced by decreasing the hematite particles size; however, micronized hematite has higher fluid loss than regular size hematite (Tehrani et al., 2014). Hematite is soluble in sulfuric acid and HCl and has low solubility in nitric acid (Liu et al., 2003; Matsumoto et al., 1994; Sidhu et al., 1981; Weast, 1979). Even though there is a good number of publications that discuss the filter cake removal topic, the cleanup of FC formed from hematite in the drilling fluid is not available in the literature.

Table 1 summarizes the acid solvent recommended for each weighting material discussed in the previous sections. Further investigation on the removal of filter cake layers consisting of weighting materials of hematite and magnetite is recommended. To the best of our knowledge, the removal of filter cake generated by these weighting materials is not investigated thoroughly in publications.

Treatment solutions performance indicators

Solubility of the weighting material

The ability of the treatment solution to dissolve the weighting material is an essential for proper filter cake cleanup. In the solubility test, a known weight of weighting material is soaked in a specific volume of the solution for the designed duration. Afterward, the remaining weighting material will be filtrated out of the solution and its weight will be measured again and the solubility can be calculated using either Eq. 1 or Eq. 2.

Table 1 The recommended acid solvents for different weighting materials

Weighting material	Acid solvent	comments	references
Barite	Chelating agent + catalyst	<ul style="list-style-type: none"> • Different chelating agents have been used (EDTA, HEDTA, DTPA, GLDA) • Potassium carbonate found to be the most efficient catalyst 	(Ba geri et al., 2017a, b; Mahmoud and Elkatatny, 2017, 2019)
Ilmenite	HCl	HCl has a higher solubility for ilmenite compared to chelating agents	(Elkatatny et al., 2013b)
Calcium carbonate	Organic acids and acid precursors	Calcium carbonate has high acid solubility	(Al-Otaibi et al., 2006; Leschi et al., 2006; Nasr-El-Din et al., 2005; Nasr-El-Din and Al Moajil, 2007)
Manganese tetroxide	HCl, HCl/glycolic acid mixture, or HCl/lactic acid mixture	Dissolution of Manganese tetroxide with high HCl concentration releases toxic gases	(Al Moajil et al., 2008; Al Moajil and Nasr-El-Din, 2013b; Elkatatny et al., 2013c)
Hematite	HCl, H ₂ SO ₄ and nitric acid	Not studies in filter cake removal	(Liu et al., 2003; Matsumoto et al., 1994; Sidhu et al., 1981; Weast, 1979)

$$\text{Solubility (wt.\%)} = \frac{W_{\text{before}} - W_{\text{after}}}{W_{\text{before}}} * 100\% \quad (1)$$

$$\text{Solubility (g/L)} = \frac{W_{\text{before}} - W_{\text{after}}}{V} * 100\% \quad (2)$$

where W_{before} = weight of the weighting material before soaking in the treatment in grams, W_{after} = weight of the weighting material after soaking in the treatment in grams, V = volume of treatment solution in liters.

Compatibility with the Polymer Breaker

The compatibility between the solvent and polymer breaker determines the number of stages required in the cleanup operation. If they are incompatible, the polymer breaker will be soaked first followed by the solvent in a two-stage process (see Fig. 5).

Removal efficiency

After building the filter cake on the face of core sample or ceramic disc, the HPHT cell will be used to soak the filter cake on the treatment solution for the predetermined duration and conditions. The removal efficiency can be determined from the weights before the filter cake formation, after forming the filter cake and after the removal using the Eq. 3.

$$\text{Removal Efficiency (wt.\%)} = \frac{W_2 - W_3}{W_2 - W_1} * 100\% \quad (3)$$

where W_1 = weight of the saturated core/disc, g, W_2 = weight of the filter cake containing core/disc, g, W_3 = core/disc weight after the removal process, g

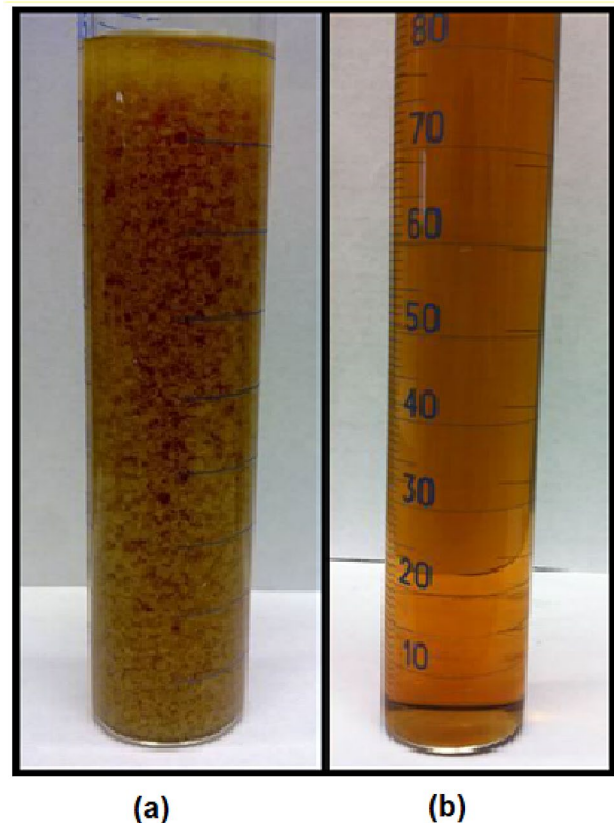


Fig. 5 Compatibility between the acid solution and polymer breaker: **a** not compatible **b** compatible (Elkatatny et al., 2012b)

Retained permeability

The removal efficiency described in the previous section measure the weight percentage of dissolved filter cake, however, that doesn't necessarily reflect the regained permeability. By measuring the permeability before forming the filter

cake and after the treatment, the retained permeability can be calculated by Eq. 4.

$$\text{Retained Permeability (\%)} = \frac{K_{\text{after}}}{K_{\text{before}}} * 100\% \quad (4)$$

where K_{before} = permeability of the core before forming the filter cake, K_{after} = permeability of the core after treating the filter cake.

Corrosion rate

The corrosion rate of the treatment solution determines whether additional corrosion inhibitor will be needed or not. Corrosion is tested by hanging a corrosion coupon inside the solution at the designed temperature and duration, and then, the corrosion rate can be calculated from the weight of the coupon before and after the test as in Eq. 5.

$$\text{Corrosion rate (lb/ft}^2\text{)} = \frac{CW_{\text{before}} - CW_{\text{after}}}{SA} \quad (5)$$

where CW_{before} = weight of the coupon before the test in lb, CW_{after} = weight of the coupon after the test in lb, SA = surface area of the coupon in ft^2 .

Oil-based mud filter cake removal

According to their main liquid continuous phase, drilling fluids are classified as water-based drilling fluids (WBDF) and oil-based drilling fluids (OBDF). In addition to the environmental concerns, OBDFs have a higher cost when compared to WBDFs, that's why WBDFs are commonly used, considering the fact that the mud cost around sixth of the overall drilling cost (Caenn and Chillingar, 1996; Jensen et al., 2004; Khodja et al., 2010). However, OBDFs have significant advantages over WBDFs such as their lower fluid loss, stable rheology, better hole cleaning ability, high thermal stability, and efficient performance when drilling through a shale formation (Ding et al., 2004; Enright et al., 1992; Patel et al., 2007; Sayindla et al., 2017). These features make the OBDFs favored in drilling through the reservoir formations (Vickers et al., 2012).

In general, OBDFs filter cake cleanup is a sophisticated, expensive, and time-consuming process (Al-Otaibi et al., 2004; Davis et al., 2004). The treatment of WBDFs filter cakes relies principally on finding an adequate polymer breaker and acid solvent for the weighting material (Siddig et al., 2020a). In the OBDFs filter cake, there is oil encompassing the filter cake formation, therefore, adding material/s to alter the wettability of the FC surface is a must, in this case, to allow for the treatment acid to react

with the filter cake particles (Davidson et al., 2006; Davidson et al., 2001). Mutual solvent, surfactant, or both are normally added to the OBDFs filter cake removal solution to change the filter cake wettability (Binmoqbil et al., 2009; Quintero et al., 2005). Filter cake removal should be designed cautiously acknowledging the compatibility between the different fluids involved, inappropriate cleanup process leads to pore-throat plugging and increase the formation damage which will affect the hydrocarbon production from the producing formations (Alimuiddin et al., 2016; Binmoqbil et al., 2009). In the next sections, different treatments available in the literature to clean up OBDFs filter cakes are addressed.

Mutual solvents and acid mixture

Mutual solvents are chemicals soluble in water, oil, and acidic solutions and used to remove hydrocarbon deposits and to control the wettability, and subsequently, they are used for reservoir stimulation and to remove hydrocarbon-based formation damage (Hall, 1975; Hamberlin et al., 1990).

Field applications of a treatment solution for OBDF's filter cake with calcium carbonate as a weighing material were presented by Davidson et al. (2006). The treatment consists of viscosified brine, mutual solvent, and formic acid precursor (FAP). The mutual solvent used was ethylene glycol mono-butyl ether (EGMBE). They reported a return permeability of 97%, and the filter cake was broken faster than a WBDF filter cake that was treated with FAP and brine without adding mutual solvents.

Ali et al. (2007) compared the performance of different OBDF/calcium carbonate cleanup solutions of the HCl, diesel, and a mixture of diesel, mutual solvent and glycol acid precursor (GAP). Regarding the returned permeability, the later solution outperformed the others. Xiao et al. (2015) proposed removing the ilmenite OBDF filter cake by soaking the filter cake for 2 h in a mutual solvent before soaking it for 4 h in HCl (5–15 wt.%).

In another study, Mohamed et al. (2019b) introduced a blend of mutual solvent (5 vol.% EGMBE) and a biodegradable acid (50 vol.%) to clean calcium carbonate-based filter cake. Their outcomes exhibited a complete regain in a sandstone core permeability and some stimulation in a limestone core.

From the studies shown above, it can be deduced that a combination of mutual solvent and acids can adequately remove calcium carbonate filter cakes. We recommend studying the effect of temperature on the removal efficiency of treatments that include a mutual solvent. Other mutual solvents rather than EGMBE can likewise be investigated to be used in filter cake cleanup solutions.

Acid plus surfactant

Surfactants are chemicals that can lower the interfacial tension between different fluids and they have been used in the oil industry for various purposes such as emulsifiers, wettability alteration agents, dispersants, and defoamers (Salazar et al., 2011; Skalli et al., 2006; Yan et al., 1993; Yan and Sharma, 1989).

Binmoqbil et al. (2009) applied a solution consisting of formic acid precursor (15 vol.%) and surfactant (2 vol.%) in brine to dissolve oily calcium carbonate FC. The surfactant's purpose is to reverse the filter cake's wettability, allowing the acid and calcium carbonate reaction to take place. The studied treatment was able to completely retain the original permeability of the sandstone core sample.

Similarly, Al-Otaibi et al. (2010) reported a successful application of a mixture of brine, acetic acid (10 vol.%), and surfactant (21 vol.%) to remove the oil-based FC at both field and laboratory scale. Vickers et al. (2012) reported the ability of a similar treatment to that suggested by Al-Otaibi et al. (2010) to enhance the gas injectivity into a depleted sandstone reservoir. Zhou et al. (2018) presented a surfactant/oxidant system to remove OBDF filter cake in a single stage and reported that temperature and salinity considerably affect the performance of the surfactant in the cleanup process.

The surfactant performance in enhanced oil recovery was found to be considerably affected by pH, surfactant concentration, salinity, and temperature. We recommend studying the effect of all those factors on the removal efficiency of acid-surfactant filter cake treatments.

Mutual solvents, surfactant, and acid mixture

Al-Kuait et al. (2012) presented field applications of a filter cake breaker that comprised of mutual solvent (2.5 to 5 vol.%), water wetting surfactant (0.5–1 vol.%), in addition to an organic acid precursor (OAP). The field applications demonstrated a significant improvement in the productivity of six out of eight wells that had been treated.

Mahmoud and Elkatatny (2019) presented several removal techniques for barite filter cake removal for OBDFs and WBDFs. The treatment of OBDF contained a chelating agent (0.6 M high pH EDTA), catalyst (10 wt.% potassium

carbonate), surfactant (0.1 wt.%), and mutual solvent (15 vol.% EGMBE) used in different proposed procedures. One method is to soak the filter cake into the mutual solvent for 4 h before soaking it into a mixture of K_2CO_3 and EDTA for another 24 h. Another method is to combine the mutual solvent altogether in the solution and soak the filter cake for 24 h in a single stage. In the first scenario, the removal efficiency was 83%, compared to 78% in the latter, but the single-stage method requires less time.

Siddig et al. (2020b) investigated a single-stage calcium carbonate removal solution that contains a mutual solvent (15 wt.% EGMBE), nonionic surfactant (3 wt.%), and acetic acid (15 wt.%). They compared the removal efficiency with and without adding the mutual solvent and reported a significant increase when the mutual solvent was added. They additionally reported that the mutual solvent resulted in a decrease in solubility at high temperatures.

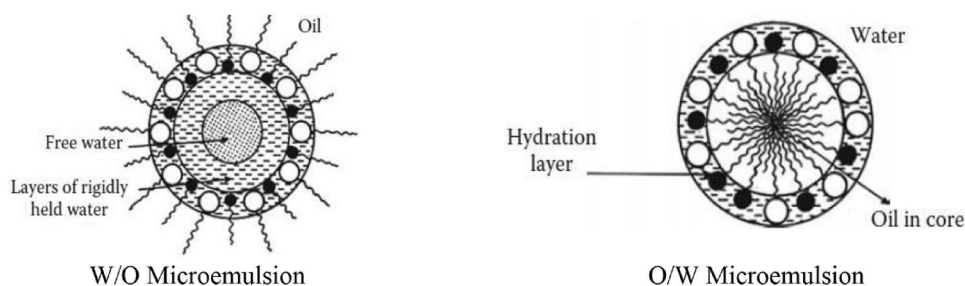
Adding both surfactant and mutual solvent to the acidic treatment for FC removal was reported to be more efficient compared to the surfactant/acid mixture. However, this means an increase in treatment cost that needs to be assessed compared to performance enhancement.

Microemulsions

Schulman and McRoberts (1946) introduced the microemulsions (ME), which were employed in the oil industry in the 1970s (Ahmed and Elraies, 2018; Healy and Reed, 1973). The microemulsion is a clear, stable, and homogenous fluid that consists of different immiscible fluids separated by a monolayer of surfactant (see Fig. 6) (Zana and Lang, 1987; Bohlen et al., 1992; Ezrahi et al., 1999). Adding alcohol to the surfactant will result in stabilized oil/water microemulsion (Quintero et al., 2005). The most common MEs are known as surfactant based microemulsions (SBME) and they consist of water, oil, surfactant, and co-surfactant, and they have smaller droplets size (less than 100 nm) compared to conventional emulsions (Quintero et al., 2007, 2005).

Another type of MEs is the surfactant-free microemulsions (SFME), which do not require the presence of the surfactant (Song et al., 2020). SFMEs have been introduced in 1977; however, they are not as common as SBMEs (Smith et al. 1977). SFME typically consists of water phase, oil

Fig. 6 Microemulsions (Addagalla et al., 2016)



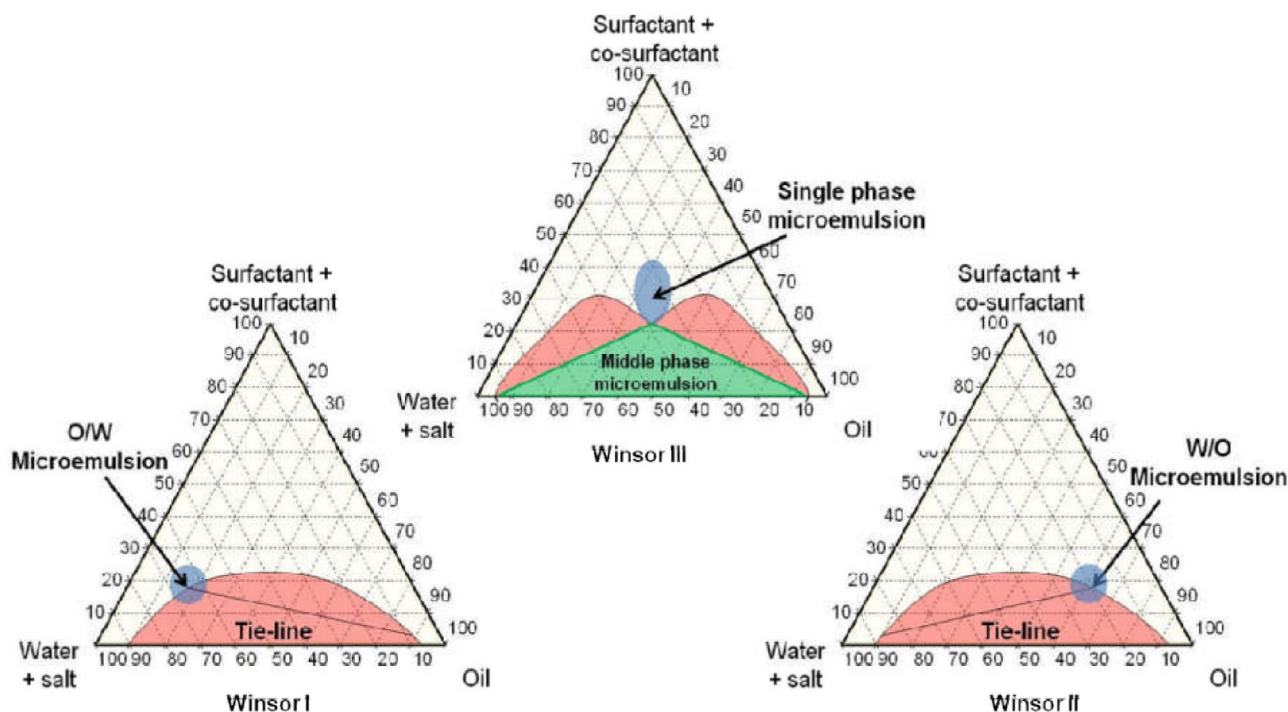


Fig. 7 Types of microemulsions (Quintero et al., 2011)

phase and amphi-solvent, and the latter should be soluble in both of the two immiscible phases (Hou and Xu, 2016). In contrast to SBMEs, fewer SFME system have been introduced in literature, even though both have almost similar properties (Liu et al., 2018).

MEs are infinitesimally heterogenous, homogeneous at the visible level, have high oil solubility, and extremely low interfacial tension (Salager, 1988). Figure 7 shows the phase behaviour and different types of microemulsions. These characteristics of the MEs facilitate solubilizing the oil, make the solid particles water-wet and consequently improve the OBDP filter cake clean up, especially when joined with acids (Brege et al., 2012; Darugar et al., 2012; Unsal et al., 2015).

Quintero et al. (2005) investigated a microemulsion-based treatment for calcium carbonate/barite filter cakes. The used a microemulsion comprised of water, surfactant, solvent, and co-surfactant added to brine, the microemulsion concentration range from 10 to 30% with acid concentration up to 7.5% in brine. They stated that soaking barite filter cake into the microemulsion, even without acid addition, made the filter cake more loose, porous, and changed the wettability of its solid particles. In their outcomes, combining acetic and hydrochloric acids to the microemulsion effectively removed the filter cake layer. For similar filter cakes, Quintero et al. (2007) presented a treatment in which formic acid is added to the microemulsion, and likewise, it was able to successfully break the filter cakes.

Lavoix et al. (2007) presented field applications on two wells in which a combination of acetic acid and ME was used to clean up filter cake residues that plugged the standalone screens. The filter cakes formed from OBDP were weighted with calcium carbonate. The treatment was able to reestablish the expected productivity index in each of the two wells. Another field application of alike treatment for standalone screens plugging by calcium carbonate filter cake was presented by Pietrangeli et al. (2014). The treatment solution consisted of brine (53–75 vol.%), surfactant (15–20 vol.%), acetic acid (10–15 vol.%), co-surfactant (0–5 vol.%), and a linker (0–2 vol.%). Using this solution, the filter cake residues were effectively removed and the completion screens were unblocked.

Quintero et al. (2011) and Addagalla et al. (2016) reported that the performance of filter cake cleanup using ME relies on numerous factors such as temperature, salinity, oil type, type of acid/s, surfactant, and co-surfactant type. Accordingly, ME formulation should be customized for each field/well application and several tests should be conducted to guarantee optimum performance (Brege et al., 2012). These tests include stability, fluids compatibility, and wettability alteration (Pietrangeli et al., 2014).

Recently, several authors presented a microemulsion pre-flush pill to clean the oil-based filter cake before pumping the cement and hence optimize the cementation integrity. Curbelo et al. (2019) and Araújo et al. (2020) presented biodegradable ME pre-flush, Curbelo et al. (2019)

used vegetable oil plus the surfactant and the brine, while Araújo et al. (2020) investigated glycerol, freshwater and glycerol/water mixture as aqueous phases. Wanderley Neto et al. (2020) studied preflush that consisted of brine, surfactant, kerosene and n-butanol as co-surfactant. According to the authors, the compatibility between the preflush and the cement slurry is essential for a better cement bond. They also indicate the significance of wettability alteration on the quality of the cementation. The tested ME yielded a 100% areal clean-up efficiency and was compatible with the cement slurry.

da Silva et al. (2020a) presented an experimental investigation on the utilization of the produced formation water in microemulsion filter cake treatment that resulted in 100% removal efficiency. In addition to the produced water, the microemulsion is formed by kerosene, Butanol and Lauryl alcohol ethoxylates as surfactants. da Silva et al. (2020b) reported that the cosurfactant/surfactant ratio has a significant impact on the treatment in terms of wettability alteration and removal efficiency.

All the presented MEs applications are conventional SBME, and to the best of the authors' knowledge, no surfactant-free microemulsion treatment for filter cake removal has been presented in the literature. Therefore, studying the application of SFME in filter cake clean-up will be a valuable addition.

A summary of the different studies discussed the OBDF filter cake removal is presented in Tables 2 and 3. Table 2 presents a summary of the experimental procedures, while Table 3 summarizes the main findings on different treatments.

Limitations and future perspectives

Although a considerable number of publications have explored various aspects of filter cake removal, the review undertaken in this paper found that some areas in this topic require further investigation. The cleanup of filter cakes created by certain weighing materials, such as hematite and magnetite, for example, has not been adequately researched. It's also a good research area to investigate how salinity,

temperature, and pH affect the overall efficiency of oil-based filter cake removal.

In most of the covered studies, the filter cakes were built in HPHT filter press for 30 min to 3 h, and then, the filter cakes were exposed to the treatment. However, in reality, the filtration process can take much longer time, especially since the wells will be suspended before applying any treatments, therefore the study of time impact would be a good addition to this field.

The utilization of surfactant-free microemulsions in the treatment of oil-based filter cake is not studied presented in the literature. Investigating the application of SFME both technically and economically would be a worthwhile contribution.

Lessons learnt

In this paper, the treatment solutions of different weighting materials were summarized and a review of the different studies on OBDF's filter cake removal is presented. Based on the conducted review, the accompanying assertions are to summarize what has been canvassed in this paper:

- In general, oil-based FC removal is more sophisticated than water-based FC as the former requires a wettability alteration method in addition to the polymer breaker and the acid needed to dissolve the filter cake particles.
- Without wettability alteration, an oil film that encloses the solid particles restrains the reaction between the acid and the filter cake. This wettability adjustment is obtained by the addition of mutual solvents and/or surfactants to the treatment solution.
- The performance of these additives is affected by the temperature, salinity, pH, and surfactant concentration.
- Including both the surfactant and mutual solvent in the treatment was found to be more efficient compared to the addition of surfactant only.
- Due to their low interfacial tension and high acid solubility, microemulsions were founded to be very effective in oil-based drilling fluid cleanup when added to an adequate acid.

Table 2 Experimental procedure for the OBDF filter cake removal studies

Author/s	Filter cake formation	Treatment performance test/s
(Quintero et al., 2005)	Porous medium: Ceramic disc, Berea sandstone core Filtration duration: 1 to 4 h Filtration on: permeability plug apparatus	*Retained injection permeability tests using sandpack and Hassler permeameter Treatment duration: 2 to 16 h
(Davidson et al., 2006)	Porous medium: Ceramic disc Filtration duration: 2 h Filtration on: dynamic displacement flow loop	*Retained injection permeability tests using dynamic displacement flow loop
(Quintero et al., 2007)	Porous medium: Ceramic disc Filtration conditions: 3 h at 1000 psi and 150 °F Filtration on: HPHT filtration cell	*Retained injection permeability tests using Sandpack Permeameter Treatment duration: 3 to 20 h
(Ali et al., 2007)	Porous medium: Ceramic disc and sandstone carbonate core Filtration duration: 4 h Filtration on: static HPHT filtration cell	*Retained permeability using a flow loop Treatment duration: 16 h
(Lavoix et al., 2007)	Porous medium: Ceramic disc Filtration conditions: 3 h at 500 psi and 20 °C Filtration on: static HPHT filtration cell	*Removal efficiency by weight Treatment duration: overnight
(Binmoqbil et al., 2009)	Porous medium: Ceramic disc Filtration conditions: 3 h at 500 psi and 188 °F Filtration on: static HPHT filtration cell	*Solubility *Retained permeability using core flooding equipment Treatment duration: 24 h
(Al-Otaibi et al., 2010)	Porous medium: Ceramic disc and sandstone core Filtration conditions: 3 h at 500 psi and 188 °F Filtration on: static HPHT filtration cell	*Removal efficiency by weight *Retained permeability using core flooding equipment Treatment duration: 24 h
(Al-Kuait et al., 2012)	Porous medium: Ceramic disc Filtration conditions: 3 h at 500 psi and 150 °F Filtration on: static HPHT filtration cell	*Retained permeability using HPHT cell Treatment duration: 24 h
(Pietrangeli et al., 2014)	Porous medium: Ceramic disc Filtration conditions: 3 h at 360 psi and 140 °F Filtration on: static HPHT filtration cell	*Injection and production retained permeability Treatment duration: 68 h
(Xiao et al., 2015)	Porous medium: sandstone core Filtration conditions: 3 h at 300 psi and 300 °F Filtration on: static HPHT filtration cell	*Retained permeability using core flooding equipment Treatment duration: 6 h
(Addagalla et al., 2016)	Porous medium: sandstone core Filtration conditions: 1 h at 315 °F Filtration on: static HPHT filtration cell	*Filter cake wettability
(Mahmoud and Elkatatny, 2019)	Porous medium: Ceramic disc Filtration conditions: 1/2 h at 300 psi and 300 °F Filtration on: static HPHT filtration cell	*Compatibility *Solubility *removal efficiency by weight Treatment duration: 24 h
(Mohamed et al., 2019b)	Porous medium: sandstone and limestone cores Filtration conditions: 1/2 h at 300 psi and 212 °F Filtration on: static HPHT filtration cell	*Retained permeability using core flooding equipment *Corrosion test Treatment duration: 24 h
(Siddig et al., 2020b)	Porous medium: Ceramic disc and sandstone core Filtration conditions: 1/2 h at 300 psi and 212 °F Filtration on: static HPHT filtration cell	*solubility *removal efficiency by weight *Retained permeability using core flooding equipment *Corrosion test Treatment duration: 24 h

Table 3 Summary of the OBDP filter cake removal studies

Treatment	Acid used	Weighting material/s	Author/s	Remarks
Water or diesel + Mutual solvent + acid	FAP	Calcium carbonate	(Davidson et al., 2006)	Either soak a filter cake into the mutual solvent for several hours then add the acid solution or mix the mutual solvent with the acid and soak in one-step
	GAP		(Ali et al., 2007)	
	green acid	Ilmenite	(Mohamed et al., 2019b)	
	HCL		(Xiao et al., 2015)	
Brine + Surfactant + acid	FAP	Calcium carbonate	(Binmoqbil et al., 2009)	The surfactant reverses the wettability that allows acids reaction with filter cake's solid particles
	acetic acid		(Al-Otaibi et al., 2010; Vickers et al., 2012)	
Water + Mutual solvent + Surfactant + acid	OAP	Calcium carbonate	(Al-Kuait et al., 2012)	Adding mutual solvent to the treatment solution improved the removal performance compared to when only the surfactant was used
	Acetic acid		(Siddig et al., 2020b)	
	EDTA and K ₂ CO ₃	Barite	(Mahmoud and Elkhatny, 2019)	
Microemulsions + acid	HCl/acetic acid	Barite, calcium carbonate or both	(Quintero et al., 2005)	Soaking in microemulsions reverse the wettability of the FC
	formic acid		(Quintero et al., 2007)	
	Acetic acid	Calcium carbonate	(Lavoix et al., 2007; Pietrangeli et al., 2014)	It results in a porous and loose FC
	Inorganic Acid	Barite	(Addagalla et al., 2016)	When combining an adequate acid to ME, the filter cake could be removed efficiently

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Declarations

Conflict of interest The authors declare no conflict of interest.

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