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Experimental Study on Preventing Formation Damage Due to Clay Swelling Caused by Water Based Drilling Fluid Using Aluminum Ion Based Clay Inhibitor

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Abstract

Formation damage is an unfavorable challenge that occurs during drilling. The present study reports the applicability of aluminum complex (AC, the combination between Al ion of aluminum sulfate (AS) and ethylenediaminetetraacetic (EDTA)) as a permanent clay swelling inhibitor in water-based drilling fluids. That is used to reduce formation damage in the near wellbore. This complex is an environmentally friendly and inexpensive additive in water-based drilling fluids (WBDFs) as a clay swelling inhibitor. In this study, some experiments, including free swelling, bentonite sedimentation, compatibility, and core flood analysis, were performed. The results have shown that AC solution can act properly as a clay swelling inhibitor at an optimal concentration of AC around 5.4 wt.%. Moreover, the compatibility test indicated that the AC additive is compatible with other common additives in WBDF. The results show that adding 8.1 wt.% of AC solution has the lowest permeability reduction compared to other concentrations. Furthermore, core flooding results showed that AC solution can act as a permanent clay inhibitor compared to KCl, a temporary inhibitor. Ultimately, the AC solution performance was not much sensitive to salinity.

Keywords: Formation Damage, Clay Swelling Inhibitor, Environmentally Friendly, Aluminum Complex (AC)

Introduction

Wellbore instability is a trouble occurrence during drilling because of waste of time and over costs. Water sensitive formation during drilling with water based drilling fluid can make formation damage.Formation damage is an unfavorable operational and economic challenge during drilling [1]. According to reports, nearly 97 percent of reservoir rocks contain swellable and non-swellable clays. In the drilling industry, swelling clays are commonly observed because clay is a water sensitive mineral [2]. It is known that clay minerals can create considerable formation damage to hydrocarbon reservoirs [3]. Clay minerals may cause formation damage through three various mechanisms: clay swelling, fine migration, and mineral reactions [4]. Formation damage is defined as reducing the initial amount of a formation permeability based on several operations like drilling, workover etc. It can be an irreversible process and can impose significant effects on the economy of production operations [5]. Some experimental works on sandstone showed that sandstone containing clay is the main cause of formation damage due to swelling of Smectite clays resulting from their unique structure [6].

Chemically, the clay minerals are composed of aluminum silicate or a combination of iron and magnesium silicate [7]. If the aluminum atoms are replaced with lower valence atoms such as magnesium, the surface charge of clay will be negative [8]. This charge is neutralized by cations between clay layers that can be replaced together [9]. As clay is exposed to water due to water invasion during drilling or water injection, water penetrates to clay interlayer and hydrates exchangeable cations. Furthermore, the distance between the clay layers will be increased [8]. The schematic of this reaction is shown in Figure 1.

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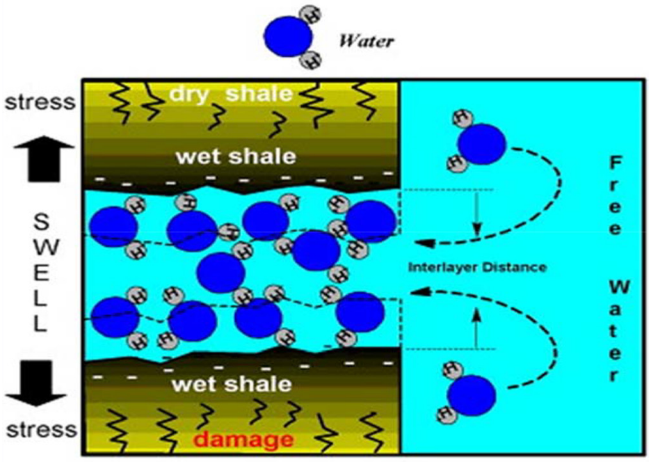

Fig. 1 A schematic of clay swelling [10].

There are three methods to minimize clay swelling; these methods are (1) cation exchange, (2) encapsulating clay surfaces by inhibitors, and (3) wettability alteration of clay surface toward hydrophobicity [11]. Oil-based mud (OBM) can act as a clay swelling inhibitor. However, using these fluids is limited due to environmental restrictions and economic considerations [12]. According to the problems mentioned above, preparing a water-based drilling fluid with a high-performance inhibitory effect similar to oil-based drilling fluid became a challenge in the petroleum industry [13]. Therefore, some additives called clay inhibitors are added to water-based drilling fluids. The most famous and conventional clay inhibitor is potassium chloride that can control clay swelling due to two propertises: (1) cationic size and (2) hydrational energy [14]. Environmental concerns of chloride pollution limit the use of cations from simple salts such as KCl and NaCl on land drilling operations around the world [15].

Also, using KCl will be followed by high disposal costs and excessive filtration loss due to vast clay flocculation [16].

It should be noted this salt can act as just a temporary clay swelling inhibitor [17]. It is recommended that KCl can be used in combination with polyacrylamide. Employing polymers as clay inhibitors in water-based drilling fluids can cause some problems. These polymers have a relatively high molecular weight that can cause formation damage by blocking some pore throats [18]. Many types of polymeric, amine-based, ionic liquids and surfactant-based clay inhibitors have been employed for oil field applications [19]. Nowadays, some studies focus on using microemulsion to reduce the effect of drilling fluid invasion in sandstone reservoirs [20]. On the other hand, some studies employed other materials to minimize the formation damage and borehole instability using organophilic clay treated with trimethyl octyl ammonium bromide, novel in-house synthesized gemini surfactant, and a high molecular weight polymer [19]. Polyoxyethylene Quaternary Ammonium Gemini has been used as a new surfactant by Zeeshan Tariq et al.

The new surfactant will maintain the in-situ permeability and avoid formation damage. The results showed that permeability did not change significantly in the case of gemini surfactants [21].

Hydroxyl-aluminum has been used since 1971 as a clay stabilizer [22]. An aluminum complex was synthesized as a clay stabilizer in drilling fluid during the drilling of gumbo shales in 1973 [23].

A polymeric compound named cationic inorganic aluminum-zirconium was used as a clay stabilizer during water injection to sandstone matrix containing Smectite clay. This polymer could properly play a permanent clay inhibitor role [24]. The major obstacle of using clay stabilizers containing aluminum ions in drilling mud is the precipitation of aluminum hydroxide.

The range of drilling fluid pH is 8.5 to 10. Thus, conventional salts containing aluminum such as aluminum sulfate, and aluminum chloride cannot be employed in drilling fluid. To use these salts in drilling fluid and prevent aluminum hydroxide precipitation, a complex agent that chelates aluminum ions is required [15].

It has been shown that the presence of alumina nano-particles optimizes the stability of formations containing ions like shale [25].

In another study, a novel hybrid aqueous alkali alumino silicate (AAAS) as a shale-swelling inhibitor in water based mud (WBM) has been investigated. The AAAS was a mixture of sodium, aluminum, and silicon oxides. The results showed that its inhibition performance was better as compared to the sodium silicate solution and KCl solution [26]. A new cationic surfactant that can act as a shale inhibitor and a water blocking agent has been investigated [27]. It also showed acceptable performance compared to common shale inhibitors used in the industry. The present study is focused on a clay inhibitor that contains aluminum.

The main objective of this study is to use a combination of aluminum sulfate (AS) and ethylenediaminetetraacetic (EDTA), a complexing agent, for the first time as a permanent clay swelling inhibitor in drilling fluids for reducing formation damage in the near wellbore. To achieve this objective, free swelling test, bentonite sedimentation test, compatibility test, and core flood analysis were conducted. In addition, KCl inhibitor is considered for comparison with AC solution performance.

Materials and Methods

Materials

Sodium bentonite (from the Smectite family) with a cation exchange capacity of 67.5 meq/100g was supplied from the National Iranian South Oil Company (NISOC). Its X-ray diffraction is presented in Table 1. KCl and NaOH (purity >99%) were provided by Merck company. Aluminum sulfate ($Al_2(SO_4)_3.18H_2O$) was supplied from Samchun, South Korea. EDTA was utilized as a complexing agent. Their specifications are given in Table 2. In Figure 2, the structural formula of EDTA is shown.

Preparation of Aluminum Complex (AC)

Aluminum sulfate salt and EDTA were used to make the aluminum complex. At first, EDTA solution (EDTA+ deionized water (DW)) was prepared at a certain concentration. The pH of this solution was 4.5.

Table 1 Mineral composition of sodium bentonite powder achieved by X-ray diffraction.

Mineral composition	Montmorillonite	Anorthite	Quartz	Cristobalite	Muscovite	Gypsum
wt.%	64	14.5	10.5	9	1.5	0.5

Table 2 Specification of aluminum sulfate and EDTA.

Product name	Chemical formula	Molar mass (g/mole)
Aluminum sulfate	$Al_2(SO_4)_3.18H_2O$	342
EDTA	$C_{10}H_{16}N_2O_8$	292.24

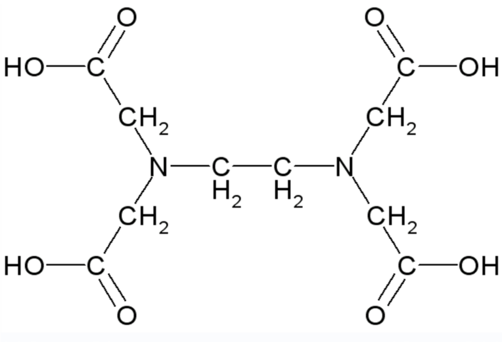

Fig. 2 The structural formula of EDTA.

Then its pH was increased to 9 by adding NaOH. A certain amount of aluminum sulfate (AS) salt was added to the prepared solution under room temperature and atmospheric pressure. AS salt in DW has acidic properties; therefore, after adding this salt to the prepared solution, the pH of the new solution was decreased to nearly 3.9. The molar ratio of aluminum ion to EDTA in the solution is one. According to Figure 3, it could be found out that aluminum ion was chelated with EDTA negative ion.

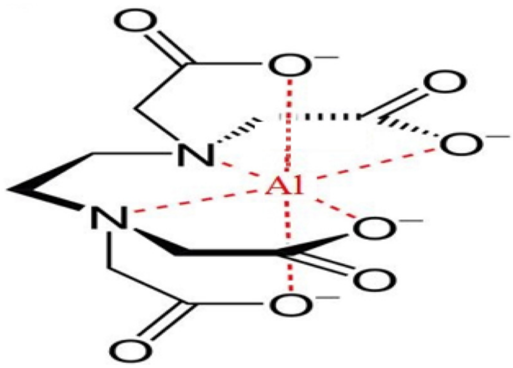

Fig. 3 Schematic structure of EDTA+ Al ion.

Experimental Test Procedure

Free Swelling Test (FST)

The free swelling test is commonly used for identifying expansive clays, and it predicts the swelling potential. FST is measured by increasing clay volume that is poured in distilled water and other solutions. This test is an optical method for investigating clay inhibitor power, but it has not high accuracy. This method is just used for comparison between two or more clay inhibitor power [28]. In the present study, 5 g of sodium bentonite powder was poured into nine graduated cylinders. Different concentrations of AC and KCl solutions were prepared. One cylinder was filled with diesel oil and the other with the AC and KCl solutions and distilled water. The final volume of the clays in each of the cylinders was recorded after 24 h. Free swell index (FSI) was calculated using Equation 1:

$$FSI\,(\%) = (\frac{V_s - V_d}{V_d})*100 \qquad (1)$$

where, V_s is volume of the clay specimen read from the graduated cylinder containing solutions, and V_d is the volume of the clay specimen read from the graduated cylinder containing diesel oil instead of water base solution.

Bentonite Sedimentation Test (BST)

When bentonite clay is placed in a solution containing inhibitor, the bentonite precipitates tend to increase. It will be seen well-defined boundary between bentonite sediments and the supernatant section [29]. Recording sediments volume as a function of time is a good indication for clay inhibitor power. In the present study, different concentrations of AC and KCl solutions were prepared. Then, 0.5 g of sodium bentonite powder was added to prepared clay inhibitor solutions. A magnet stirrer was employed to stir these solutions with 500 RPM for 30 minutes. Afterwards, 50 ml of these dispersions containing clay inhibitor solution and bentonite were placed in the test tube and carefully sealed. Changing in sodium bentonite sediments volume was recorded by the ratio of $\frac{V_s'}{V_t}$ as a function of time. Here, Vs' is the occupied volume of sediments (ml), and V_t is total volume which is equal to 50 ml.

Compatibility Test

Compatibility between clay inhibitors and water-based drilling fluids (WBDFs) additives is one of the most important characteristics of clay inhibitors. This test was carried out by adding a certain amount (wt.%) of clay inhibitors to the base fluid. Then, the prepared drilling fluid samples were aged for 4 hours at 105 °C in the rolling oven. This test is implemented for measuring rheological properties of drilling fluid, including plastic viscosity (PV), yield point (YP), gel strength (GS, 10 minutes) and filter loss. The base drilling fluid was prepared by adding 4wt.% of partially polyacrylamide, 1wt.% of starch, 1wt.% of barite in deionized water.

Core Flood Analysis

Core flooding analysis was implemented for investigating formation damage due to clay swelling in the dynamic state. This test was designed for calculating initial permeability (before adding clay inhibitor solution) and return permeability

(after adding clay inhibitor solution). In this test, a synthetic porous medium was made from quartz grains with a grain size between 90-280 μm. The porous medium was prepared with 90% quartz grains and 10% by weight bentonite powder. It should be noted that the total mass of the sand pack is equal to 200 g. This mixture of quartz grains and bentonite powder was adequately blended. Afterwards, it was pressurized until 1000 psi.
The porous medium was well homogenized in a core holder with 3.81 cm in diameter and a length of 12 cm. Then, 1200 psi overburden pressure was applied to the sand pack. Eight core flood tests were designed in this part (Table 3).
In all tests, in the first step, the sand pack was flooded and saturated by different flow rates (0.1, 0.3, 0.5 ml/min) of $CaCl_2$, and permeability of the sand pack in this situation was measured as initial permeability (reference permeability).
The injection brine was prepared using $CaCl_2$ because of formation water is often saturated with this salt. Comparison of reference permeability and return permeability gives appropriate indication of formation damage due to clay swelling.
Then, other solutions, including inhibitor solutions and DW were injected into the sand pack with different rates (0.1, 0.3, 0.5 ml/min) for 4 hrs. At the end of each step, $CaCl_2$ was injected to obtain return permeability. To increase the precision of measurement, two measurements were made in each flow rate. Darcy law was used to measure sand pack permeability as bellow (Equation 2);

$$k = \frac{m\,\mu l}{0.004A} \tag{2}$$

where q is the flow rate (ml/min), k is permeability (mD), A is the cross-section (cm^2), Δp is the pressure drop of the sand pack (psi), μ is fluid viscosity (cP), and l is sand pack length (cm), and m is the slope of plot q vs. Δp. A schematic sketch of the core flooding apparatus is shown in Figure 4.
The test number eight was considered to investigate the effect of formation fluid salinity on AC performance.

Table 3 Designed core flood tests.

Test number	Injected fluid in the first step	Injected fluid in the middle step	Injected fluid in the final step
1	5wt.% $CaCl_2$ brine	DW	5wt. % of $CaCl_2$ brine
2	5wt.% $CaCl_2$ brine	1.35wt. % of AC solution	5wt. % of $CaCl_2$ brine
3	5wt.% $CaCl_2$ brine	2.7wt. % of AC solution	5wt. % of $CaCl_2$ brine
4	5wt. % $CaCl_2$ brine	5.4wt. % of AC solution	5wt. % of $CaCl_2$ brine
5	5wt. % $CaCl_2$ brine	8.1wt. % of AC solution	5wt. % of $CaCl_2$ brine
6	5wt. % $CaCl_2$ brine	3wt. % of KCl brine	5wt. % of $CaCl_2$ brine
7	5wt. % $CaCl_2$ brine	8.1wt. % of AC solution then DW	5wt. % of $CaCl_2$ brine
8	7wt. % $CaCl_2$ brine	8.1wt. % of AC solution	7wt. % of $CaCl_2$ brine

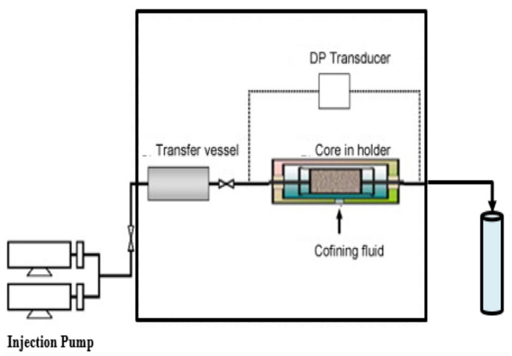

Fig. 4 Schematic of core flooding apparatus.

Results and Discussion
Free Swelling Test

The results of the FSI of sodium bentonite powder exposed to AC and KCl solutions are presented in Figure 5. It is necessary to note that amount of FSI related to DW was 185. The inhibition role of AC solution on sodium bentonite swelling was investigated at different concentrations (1.35, 2.7, 5.4 and 8.1%wt.) of this solution. According to Figure 5, the amount of FSI was decreased by increasing the amount of AC concentration.
The difference between amounts of FSI of 5.4 wt.% and 8.1 wt.% of AC solution was nearly little. Thus, it can be concluded that optimized concentration of AC solution is around 5.4 wt.%. To better understand AC solution performance as a clay inhibitor and for comparison, KCl was used as a conventional clay inhibitor at four concentrations (0.5, 1, 3 and 5 wt.%). As expected, the amount of FSI was reduced by increasing the concentration of KCl, as seen in Figure 5. By comparing the results, it is realized that AC solution performance is comparable with KCl as a conventional inhibitor. The Al ion, when complexed with EDTA, complexing agent, no longer reacts with hydroxyl ions to form Al $(OH)_3$. This complex has four primary valences and six secondary valences. It is reasonable to assume that these secondary valences are coordinated to water molecules by linkage to oxygen and oxygen on the clay surface. Therefore, it reduces the interaction of clay with water and minimizes clay swelling. Thus, AC can be an inhibitor that reduces the swelling of clay.

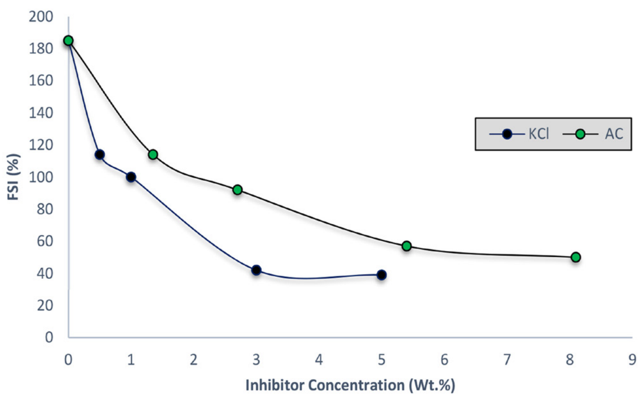

Fig. 5 FSI of sodium bentonite exposed to different concentrations of AC and KCl solutions.

Bentonite Sedimentation Test (BST)

Figures 6 and 7 show sodium bentonite sedimentation behavior in the presence of inhibitors, including AC and KCl solutions, respectively. According to the results, sodium bentonite could form stable dispersion in DW. Because sodium bentonite has negative charges on its surface, it is easily dispersed in DW. Therefore, bentonite does not precipitate in DW after 24 hours. Figure 6 indicates that sedimentation of bentonite started in the first minutes, but a major part of sedimentation occured after 3 hours. After that, the rate of precipitation was slow, and finally, the precipitation of sodium bentonite became constant. It should be noted that amounts of bentonite sedimentation decreased by increasing the concentration of AC solution.

Final ratio of sedimentation volume to total volume for four concentrations (1.35, 2.7, 5.4, 8.1%wt.) of AC solution were 0.25, 0.17, 0.1, 0.06, respectively. The final sedimentation volume of AC solution at concentrations of 5.4 wt.% and 8.1 wt.% are close together. Therefore, it can be concluded that a concentration of 5.4 wt.% can be the best concentration for using AC solution.

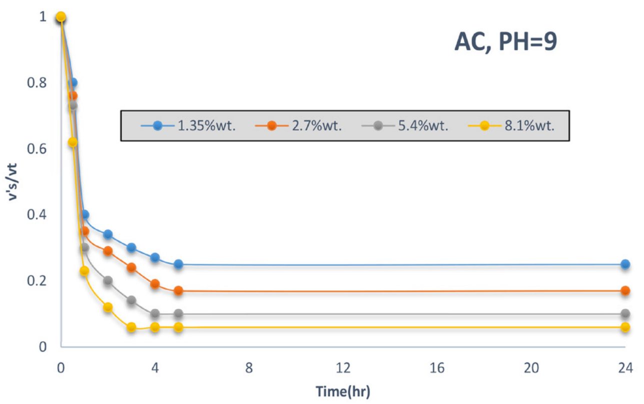

Fig. 6 Behavior of sodium bentonite sedimentation in different concentrations of AC solution.

As shown in Figure 7, a major part of sedimentation occurs at 1 hour. KCl has an ionic structure, and the magnitude of flocculating of this structure is high. Therefore, the rate of sedimentation of bentonite in KCl solution is faster than in AC solution (AC solution is a non-ionic compound). Also, in this case, the final precipitation volume was decreased by increasing KCl concentration (0.5, 1, 3 wt.%). Final ratio of sedimentation volume to total volume for three concentrations (0.5, 1, 3%wt.) of KCl solution were 0.14, 0.1, 0.05, respectively. Comparing the performance of AC and KCl shows that AC solution can act properly as a clay inhibitor. Based on what was discussed in introduction about disadvantage of KCl, the AC solution can be a good inhibitor instead of KCl.

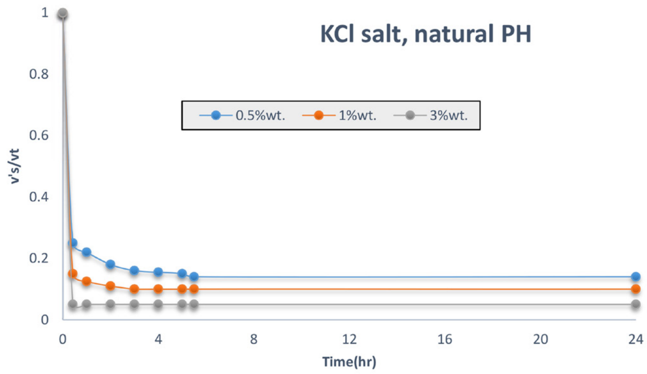

Fig. 7 Behavior of sodium bentonite sedimentation in different concentrations of KCl solution.

Compatibility Test

This test measured rheological properties and fluid loss of interest drilling fluid before and after adding special additive under certain conditions. Significant changes in rheological properties and fluid loss indicate that added additives to WBDF are not compatible with other additives in drilling fluid. The ratio of each parameter for modified fluid by clay inhibitor additive to non-modified fluid (base fluid) was used to observe any change. The AC and KCl solutions were used to investigate the compatibility of these materials with additives present in the base fluid. In this case, 3 wt.% of AC and 3 wt.% of KCl. were added to base fluid, and its rheological properties were measured again. Results of this test are presented in Table 4. According to Table 4, the AC solution was compatible with other additives present in WBDF. Although the fluid loss of drilling fluid containing KCl was high. Fluid loss of AC solution was close to fluid loss of base fluid. The reason is that the AC solution is a neutral combination; therefore, its flocculating properties are nearly negligible.

Table 4 Effect of clay inhibitors on fluid loss and rheological properties of WBDFs.

Test fluid	$\frac{*PV}{\#PV}$	$\frac{*YP}{\#YP}$	$\frac{*Gel\,10\,min}{\#Gel\,10\,min}$	$\frac{*APLFL}{\#APLFL}$
Modified base fluid by 3 wt.% of AC	18/22=0.81	19/15=1.26	5/4=1.25	12.5/12=1.04
Modified base fluid by 3 wt.% of KCl	19/22=0.86	16/15=1.07	5/4=1.25	23.5/12=1.96

*Modified fluid
Base fluid

Core Flood Analysis

Results of performed eight tests at the first step and final step are presented in Table 5. CaCl2 was injected into the sand pack at different rates (0.1, 0.3, 0.5 ml/min) at both the first and final steps. Then corresponding differential pressure of the sand pack was monitored and recorded. It should be noted that because we wanted to investigate only the effect of clay swelling on permeability changes, low flow rates were selected by us to conduct experiments. In Table 5, initial permeability, return permeability, return permeability to initial permeability ratio, and length of eight used sand packs are presented.

Table 5 Initial and return permeability of sand packs for eight tests.

Test number	Length (cm)	Initial perm. (k_1, mD)	Return perm.(k_2, mD)	Permeability Reduction
1	12.1	33.96	8.23	75.76%
2	12.25	34.11	17.99	47.25%
3	11.95	35.38	26.21	25.92%
4	12.25	32.77	25.79	21.3%
5	12.1	33.17	29.35	11.51%
6	12	32.63	24.6	24.61%
7	11.85	36.12	31.06	14%
8	11.95	31.97	27.83	12.94%

According to Table 5, return permeability was strongly decreased after DW injection to the sand pack at the intermediate step. It is due to the interaction between DW and clay particles present in the sand pack, resulting in swelling clay. In this case, amount of permeability reduction compared to initial permeability was 75.76%. Based on Table 5 and Figure 8, it can be concluded that differential pressure values of the sand pack at the same flow rate were decreased by increasing AC concentration. It shows that the return permeability to the initial permeability ratio of the sand pack improves by increasing AC concentration. The results show adding 8.1 wt.% of AC solution has the lowest permeability reduction compared to other concentrations. Test number six was designed to compare KCl solution performance as conventional clay swelling inhibitor with AC solution performance. The results show that adding 3wt.% of KCl gives 24.61% permeability reduction compared to the initial permeability of the sand pack. As expected, KCl is a strong clay swelling inhibitor that can minimize permeability reduction due to drilling fluid invasion.

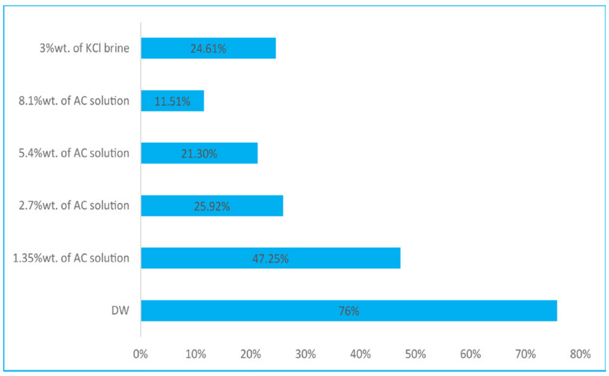

Fig. 8 Permeability reduction after injection of AC and KCl inhibitor in different concentrations.

The objective of test number seven was to show whether the effect of AC solution to inhibit clay swelling is permanent or not. To assess this objective, 8.1 wt.% of AC solution was injected into the sand pack. Then, DW was injected. Results of the final step of this test showed that the permeability of the sand pack was reduced by 14% compared to the initial permeability. Comparison of tests, number five and seven, indicate that using AC solution at middle step can improve return permeability to initial permeability ratio of sand pack. As a result, AC solution can have a permanent effect on clay swelling. Clay stabilizing additives can be classified into two main groups: temporary and permanent. Temporary clay is an inhibitor that inhibits clays swelling and migration but is easily removed by the formation-produced fluids following the treatment. The most common temporary clay stabilizers are simple inorganic salts such as KCl. However, a permanent inhibitor inhibits clays swelling [8]. Test number 8 was considered to investigate the effect of formation fluid salinity on AC performance. This test showed that AC solution performance is not much sensitive to the salinity of formation fluid. Figures 9 to16 show pressure drop and flow rate during each test (from 1 to 8).

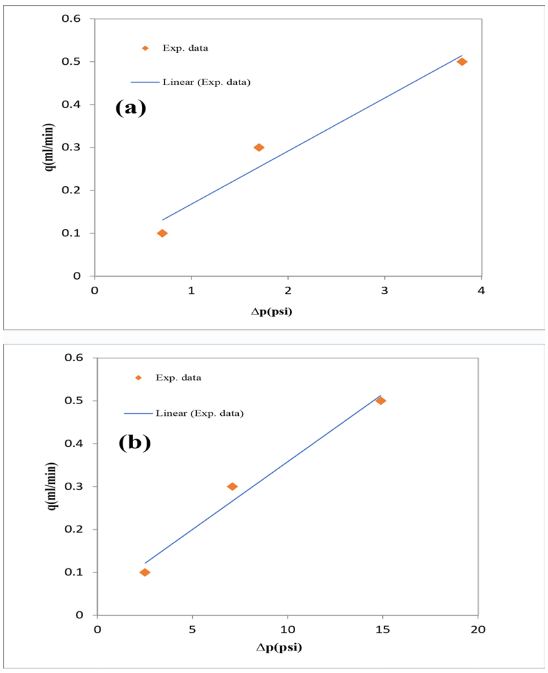

Fig. 9 Results of test number one of core flood (a): first step, (b): final step.

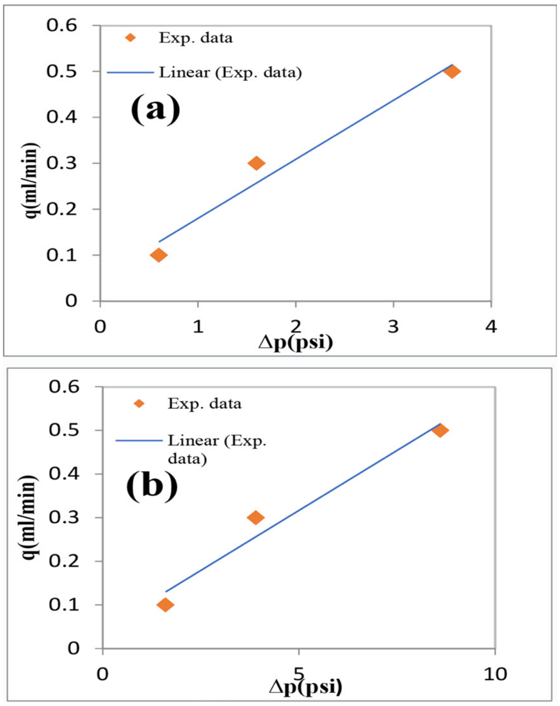

Fig. 10 Results of test number two of core flood (a): first step, (b): final step.

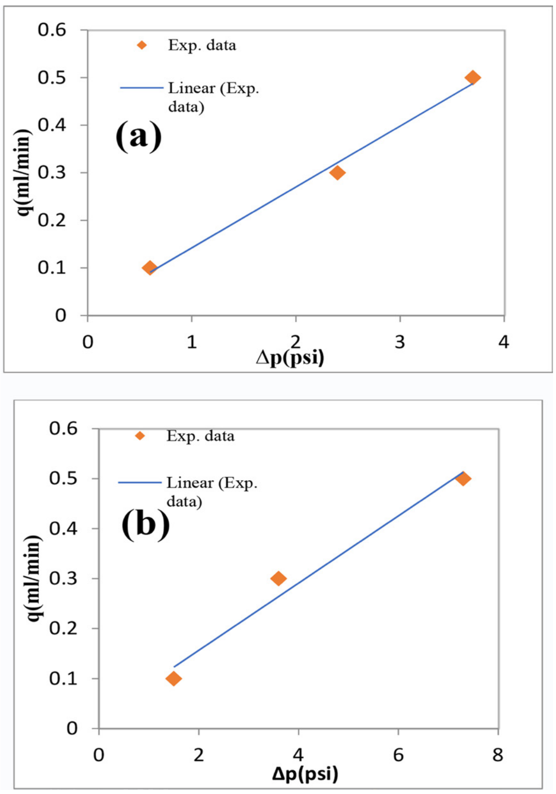

Fig. 11 Results of test number three of core flood (a): first step, (b): final step.

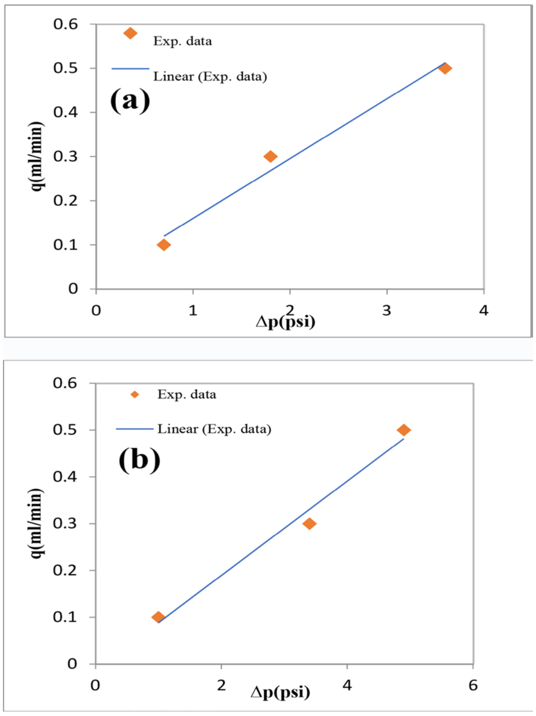

Fig. 12 Results of test number four of core flood (a): first step, (b): final step.

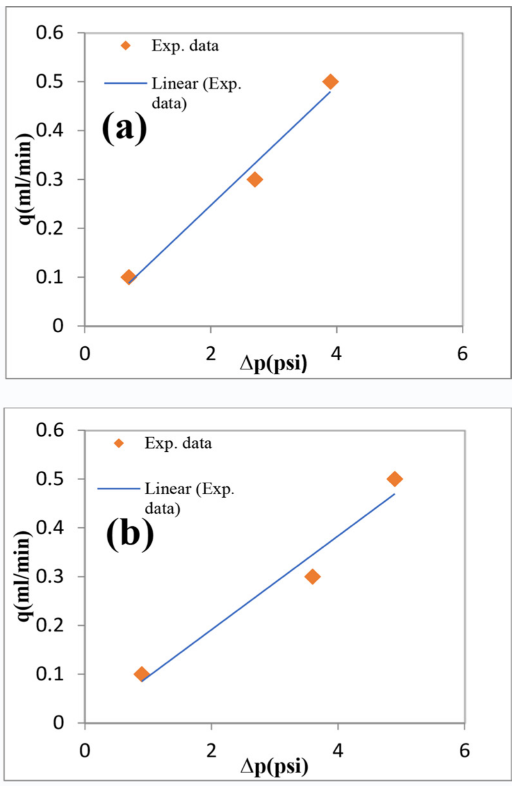

Fig. 13 Results of test number five of core flood (a): first step, (b): final step.

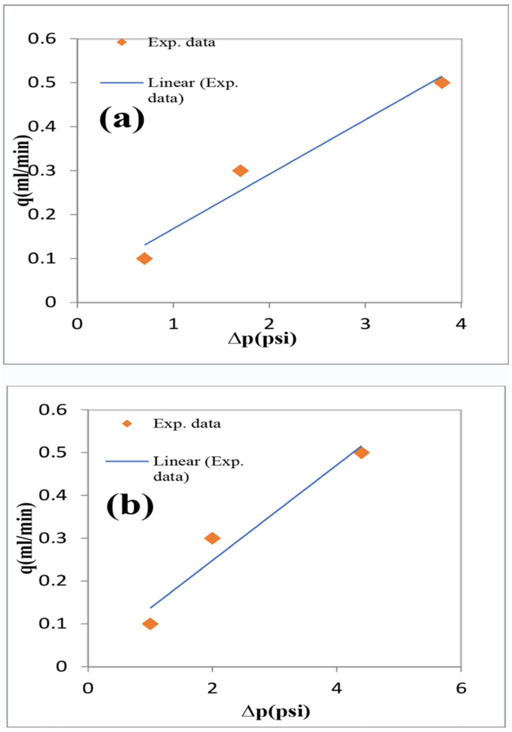

Fig. 14 Results of test number six of core flood (a): first step, (b): final step.

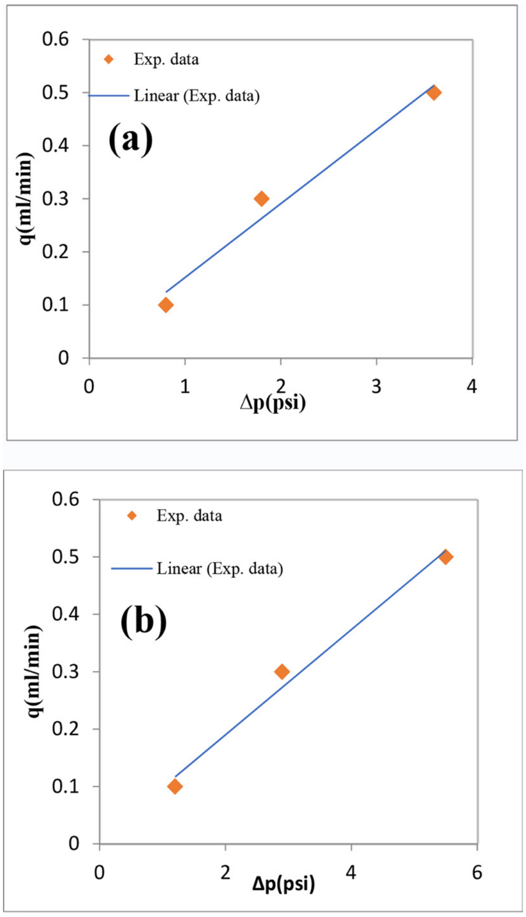

Fig. 15 Results of test number seven of core flood (a): first step, (b): final step.

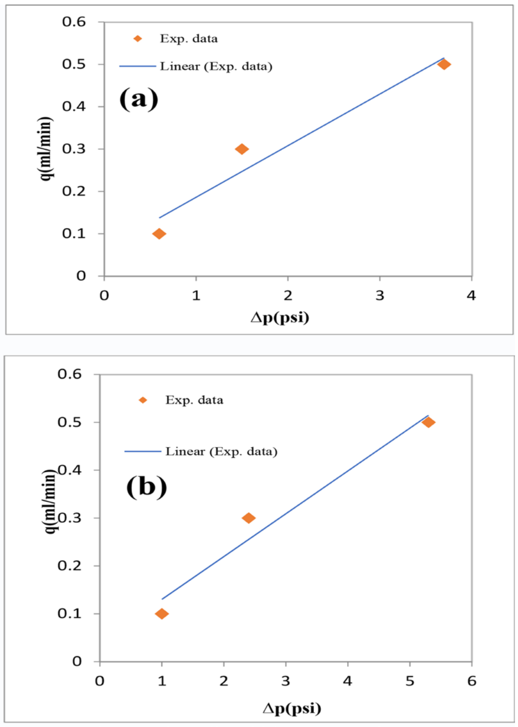

Fig. 16 Results of test number eight of core flood (a): first step, (b): final step.

Conclusions

The overall goal of this study was to investigate the applicability of the aluminum complex (AC) as a permanent clay swelling inhibitor for reducing formation damage due to clay swelling in the near wellbore during drilling. Based on different tests conducted, the following conclusions are drawn.

1) According to the obtained results, AC solution can be a clay swelling inhibitor as KCl.
2) The best concentration of AC solution is around 5.4 wt.%.
3) AC solution is compatible with other additives present in WBDF.
4) Fluid loss of drilling fluid containing AC is less than drilling fluid containing KCl.
5) Adding AC in injected water, in sand pack, prevents permeability reduction. The results show by increasing AC concentration, return permeability to initial permeability ratio of sand pack improves. The results show adding 8.1 wt.% of AC solution has the lowest permeability reduction in comparison with other concentrations
6) AC solution can act as a permanent clay inhibitor compared to KCl that is a temporary inhibitor.
7) By increasing the concentration of CaCl2 from 5% to 7%, in the same concentration of AC (8.1%), the permeability reduction in more CaCl2 concentration is close to low concentration. Therefore, AC solution performance as a clay inhibitor is not very sensitive to salinity.

Acknowledgment

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Nomenclatures

AAAS: Aqueous Alkali Alumino Silicate

AC: Aluminum complex
AS: Aluminum sulfate
EDTA: Ethylenediaminetetraacetic
GS: Gel strength
PV: Plastic viscosity
OBM: Oil-based mud
WBDFs: Water-based drilling fluids
YP: Yield point

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