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Interference of Sodium Chloride on Shale Stabilization with Potassium Chloride in Drilling Fluid

Majid Naeimavi[1], Fereydoon Khazali[1]*, Mohammad Abdideh[2], and Zohreh Saadati[1]

[1]*Department of Chemistry, Omidiyeh Branch, Islamic Azad University, Omidiyeh, Iran*
[2]*Department of Petroleum Engineering, Omidiyeh Branch, Islamic Azad University, Omidiyeh, Iran*

Abstract
The shale formation drilling often generates a wide range of problems if ordinary water-based muds are employed. Furthermore, the alteration of shale formation has complicated the development of adequate drilling fluids. The control of shale instability by the exchange of potassium cations with shale structure is well accepted in the drilling fluid industry. In the cases where seawater or brackish water is used as a base, the presence of Na+ and Cl- in the drilling fluid can disrupt the shale cation exchange process. In this study, KCl fluids with concentrations of 1 to 15 wt% were prepared and analyzed with linear swelling, capillary suction time, and dispersion experiments on shale inhibition property, and then NaCl was added to potassium fluids at different concentrations. The different result of mixed salt fluid and KCl fluids indicated that the presence of sodium chloride could affect the potassium yield in the drilling fluid. Moreover, the low concentration of NaCl/KCl showed better results for shale inhibition, although the increase in NaCl concentration caused high swelling and decreased KCl efficiency in drilling fluid. Ultimately, it was found that the addition of 1 – 5wt% NaCl to 3 – 5wt% KCl was preferable to stabilizing old shale formation. But to drill active and young shale formation, the use of KCl alone in the liquid was recommended.

Key words: Drilling Fluid, KCl Fluid, Shale Swelling, Shale Inhibition.

INTRODUCTION
During the oil well drilling operations, wellbore instability is a great source of concern, leading to a waste of drilling time and some extra costs. This issue is primarily observed in shales formation; in addition, it includes roughly 75% of all formations drilled in the drilling industry [1]. Other mineral deposits including sand, dolomite, salt, etc. make up the remaining 25%. The instability of the wellbore could be associated with the clay sheet dispersion into ultrafine colloidal particles that affects the drilling fluid properties directly. The cost of problems caused by wellbore instability is estimated at $ 1 billion per year. Thus, oil-based drilling fluids that contained a high level of salt were designed to resolve these problems [2]. However, after decades, due to imposing environmental constraints on supplying raw materials which were unprofitable, the use of oil-based fluids was limited and diminished [3]. Traditional water-based fluids were no longer meeting the needs of the drilling industry because cost and time management in the industry was more considered, and the drilling companies were looking to reduce drilling time, costs, and problems. Therefore, many researchers have been encouraged to design new water-based drilling fluids that could have the benefits of oil-based fluids in shale control but had no disadvantages and negative effects on the environment [4].

Hence, various chemical and additives used in drilling fluids as shale problem controllers have been proposed researchers [5, 6, 7]. One of the most suitable inhibitors suggested in the last few decades was potassium ion [8]. Potassium ion is widely used in drilling fluids as water-based fluid component designed to control the borehole instability to water-sensitive (shale) formation drilling. Cationic mud (usually associated with anionic polymers) reduces the swelling and erosion conjugated with shale sloughing [1-3]. The shale stabilization by these additives was linked to swelling control caused by cation exchange modulation and replacement of the mineral's origin cations (Mg^{+2}, Na+, and Ca^{+2}) by K+. Several studies in the petroleum drilling literature showed that based on the shale types, the KCl concentration required to reduce shale swelling and dispersion is between 3 to 20wt % [1, 4-7]. But there is currently little information

**Corresponding author:* Fereydoon Khazali, Department of Chemistry, Omidiyeh Branch, Islamic Azad University, Omidiyeh, Iran
E-mail addresses: fereydoon.khazali@iauo.ac.ir
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about cation exchange interferences that may reduce the potassium ion effects in drilling fluids or few studies that can estimate the extra concentration of potassium requirement in drilling fluid to overcome the contaminates that affect cation exchange process.

Shale Inhibition Fluid

To dominate the problem caused by water-sensitive shale, oil drilling fluid was proposed in the mid-1930s. OBM reduces ion transferring between drilling fluid and formation by converting the wellbore to the semi-permeable membrane, which decreases the absorption power of shale. It seems that with the use of oil-based mud, all the problems of the hole stability are solved [9], Oil-based muds do not stop the ion transport completely, and in some cases, the problems of clay hydration are still remaining [10]. In addition, the recent environmental constraints and the high cost of oil-based fluid additives have led the drilling industry to adopt a water-based drilling fluid.

In this view, in the 1960s, some additives such as lignosulfonate were introduced to shale drilling [10]. One of lignosulfonate mud disadvantages is unacceptable contamination such as chromes in the chrome-lignosulfonate additive. Also, its application relates to sodium-clay swelling properties. For this reason, the water-based drilling fluid system is now classified into two main categories: (1) inhibition fluid and (2) non-inhibition fluid systems.

Non-inhibiting systems use bentonite, lime and lignosulfonate mud and do not suppress shale instability. Reversely, an inhibitive mud system prevents swelling and decreases the wellbore instability [11].

Inhibition with Potassium Ion

In the early 1970s, the drilling industry found potassium chloride as an effective shale inhibitor material [12, 13]. The potassium ion required to use in drilling fluids is generally provided from potassium chloride. In some cases, other sources of potassium such as potassium sulfate, potassium hydroxide, potassium acetate, potassium carbonate, potassium nitrate, and potassium sorbate are used [14]. The effect of potassium ion on shale and its instability control properties are related to the clay/shale chemistry. Moreover, K+ is in the fit size to keep the space between the sheets of clay that are negatively affected by the unsaturated substitution in the octagonal structures. When potassium ion is placed in the clay lattice through the cations exchange process, it is close to the capital of sheet negative charges in comparison with other exchangeable cations, and clay is maintained with high bonding power, i.e. potassium coupled with other lattice ions on montmorillonite or swellable clays and holds them together by van der Waals bonds. That occurrence depends on the highest tendency of potassium cation to substitute sodium and calcium in clay structure. These K-montmorillonites which are not swallowed as active clays seem like Ca/Na-montmorillonite. After O'Brien's studies, which sustained the position of potassium chloride in drilling fluid technology, other researches on the use of potassium chloride in the laboratory were published by Clark and his colleagues. Their results in the field were distributed utilizing a new high molecular weight polymer named partially hydrolyzed polyacrylamide (PHPA) [15]. This polymer is absorbed on the clay surface and prevents the shale's cutting to disperse in drilling fluid and encapsulate the clay particles. Also, it prevents water-shale interactions. Both laboratory tests and field applications have effective shale inhibition capabilities compared to applying potassium chloride individually. But shale is not controlled completely, and the prosperity of this system is heavily related to solid control and speed of clay separation system. Furthermore, in the 1990s, polyglycols, glycol, and glycol derivatives were provided and used with K+ mud and K+-polymer systems to enhance inhibition. KCl/polymer drilling fluid somewhat solved this problem apparently. But some researchers found out that the extra cation exchange of potassium has a reverse result in the inhibition process, for example, if there are extra cationic ions in the mud, they can exchange with fixed potassium ions on the clay lattice structure, [16]. Therefore, in this study, the factors affecting the efficiency of the cation exchange process in shale inhibition are investigated, and the involvement of dissolved sodium chloride ions in the cation exchange method is determined by laboratory tests.

Interferences of Potassium Ion Fixation

Cation exchange capacity is the number of cations existence in a solution that can be replaced with compensated ions at the surface of clay layers in a water phase. Earth alkali metals such as Ca, Mg, and alkali metals like K, and Na and NH_4 ions are often replaceable together in clay sheets. Interchangeable cations are also located outside of clay building units such as space between dispersed sheets. The structure of clay is not changed when cations are exchanged. To determine the minerals interchangeable ion value, the cation exchange capacity term (CEC) must be defined. This is related to the number of cations exchanged in meq (milliequivalents) per 100 grams of shale at pH = 7 [17]. Shale containing large amounts of negative ions has high CEC. The cation exchange power varies, related to clay type and ions in which they are present, the quantity and intensity of hydration, cation concentrations, valence, and types of shale minerals. When several types of cations (divalent and monovalent) mixed under the normal conditions in drilling fluid, their replacement power is in descending list:

$H^{+} > Al^{+3} > Ca^{+2} > Mg^{+2} > K^{+} > NH4^{+} > Na^{+} > Li^{+}$

[18].

In concentration competition, the above ion ordering is different. High concentration ions have more significant effects on fluids. The high concentration of one ion type or several types of ion in a fluid cause distinct properties such as high ionic strength, high conductivity, and lower water activity [19]. Some of these properties can affect the shale inhibition by cation exchange method; in other words, an increase in salt causes some negative chemical effects such as ion aggregation, asymmetry, and electrophoresis (Fig 1). These affect K+ role (fixing into clay structures and shale inhibition).

To increase the weight of drilling fluid with minimum solids and prevent the polymers from fermentation and per treat the mud to drill in the salty formation, usually a saturated drilling fluid is preferred [20]. Thus, they add KCl only or add NaCl to KCl fluid to saturate the mud. In this case, drilling fluid engineers do not have knowledge from KCl performance mixed with NaCl. Is the KCl concentration enough to shale inhibition before adding NaCl? Must more KCl be added to recover prior performance and dominance over NaCl interferences? These questions are answered in this study by experimental methods.

MATERIALS AND METHODS

Shale Sample

Montmorillonite minerals as shale samples used in this study were provided from Kashan, where the biggest clay mine of Iran is there, for producing drilling grade Bentonite. This type of clay mineral meets required specifications, API 13A. XRD pattern described the more mineralogy detail of the shale sample (Fig 2).

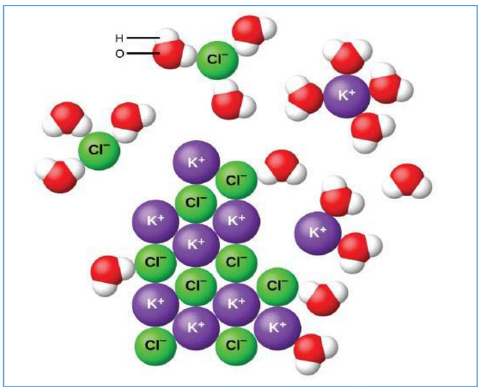

Fig 1 High concentration effects of ionic fluid [21].

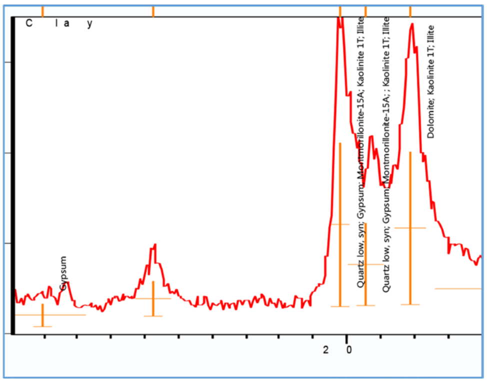

Fig 2 XRD pattern of shale samples.

The shale samples were placed in dryer oven for 24 h at 110 ˚C. Afterwards, they were homogeneously powdered, and then they were compacted for 30 min with compactor under 6000 psi to be used for the linear swelling test as shale wafers (Fig 3). On the other hand, the shale powder was used for another test.

Fluid Samples

To investigate the application of K+ ions on shale samples, the cation exchange capacity and the CEC interferences caused by sodium chloride, which commonly used in drilling fluid, were determined. The provided pure materials are Merck Chemicals products (Table 1).

Fig 3 Shale samples converted to shale wafers.

Table 1 Properties of KCl and NaCl.

	KCl	NaCl
Solubility in water (g/l) (20 °C)	347	358
Melting point (°C)	773	801
Molar mass (g/mole)	74.55	58.44
Density (g/cm³)	1.98	2.17
Boiling point (°C)	1413	1461

Note: Caustic soda is added to provide the basic condition (pH: 9-10) as a common pH condition for drilling fluid in the industry.
Then, NaCl was added to the 8 selected samples of KCl fluid shown in Table 2 with concentration 2%, 4%, 6%, 8%, 10% and 12 wt.%.

Table 2 KCl-fluid samples (F. Vol. 350 cc).

Sample No.	D. Water (ml)	KCl (g)	KCl (wt.%)	Caustic soda (g)
1	348	3.5	1	0.5
2	347	7.07	2	0.5
3	345	10.67	3	0.5
4	344	14.35	4	0.5
5	342	18.03	5	0.5
6	341	21.77	6	0.5
7	340	25.55	7	0.5
8	338	29.4	8	0.5
9	337	33.29	9	0.5
10	335	37.21	10	0.5
11	334	41.22	11	0.5
12	332	45.23	12	0.5
13	331	49.34	13	0.5
14	328	53.46	14	0.5
15	326	57.66	15	0.5

15 samples of KCl fluid with different concentrations (1 wt.% to saturate) were prepared for the experimental study, as seen in Table 2. Then, NaCl was added to KCL-fluid as the interference with various quantities.

Dynamic Swelling Test

In this study, the effect of potassium ions on shale swelling was measured by linear dynamic swell meter (Fig 4). Some wafers were provided by compressing 5 g or 10 g of powdered shale cuttings (under 6000 psi for 30 min) using a compactor. Afterwards, the wafers were placed into linear swell meter cell assembly (LSCA) located on a stirring hot plate and linear micrometer.

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4	344	14.35	4	0.5
5	342	18.03	5	0.5
6	341	21.77	6	0.5
7	340	25.55	7	0.5
8	338	29.4	8	0.5
9	337	33.29	9	0.5
10	335	37.21	10	0.5
11	334	41.22	11	0.5
12	332	45.23	12	0.5
13	331	49.34	13	0.5
14	328	53.46	14	0.5
15	326	57.66	15	0.5

Fig 4 Linear Swell meter [22].

The drilling fluid stirred with a magnetic bar was placed in the bottom of all cells. In the following, 150 ml of fluid were poured into cells by syringe. Finally, the software that connected to LSCA records the swell data as a function of time under ambient condition.

Capillary Suction Time Test

In the oil/gas well drilling industry, some of the methods and devices have been introduced and developed to understand and measure the interactions between drilling fluids and wellbores. Method of capillary suction time (CST) is one of these methods, which was first used in 1970 to evaluate the moisture content of the remaining sludge from urban water treatment. Subsequently, it was used to evaluate the interaction of water-based drilling fluid filtrates and wellbore [23]. The device is organized from a 5 cm funnel located in the middle of the plate and two electrodes, which the one is spaced 0.5 and the other is spaced 1 cm away from the funnel (Fig 5). A timer is also connected to these two electrodes. After pouring 5 ml of the drilling fluid into the funnel, the special paper under the funnel becomes wet and the moisture spread uniformly throughout the paper. When the moisture reaches the first electrode, the timer starts, when the moisture reaches the second electrode, the timer stops the time; the elapsed time noted as the CST for the measured fluid.

Fig 5 Capillary Suction Timers [22].

Cuttings Dispersion Tests

It is accepted that a good inhibitive drilling fluid can keep the shale cuttings in size when they are raised along the well annulus. In addition, this test can simulate the cutting dispersion in drilling fluid very well [24]. To do this, shale cuttings sieved by sieve mesh No. 5 and No. 10. The cuttings remained between these mesh sizes were used for this test. Moreover, 20 g of shale fragments were added to 350 cc of fluid, and then fluid rolled under 200 ˚F for 16 h. After the hot rolling is over, the drilling fluid passes through sieve No. 35 (Fig 6). Then mesh was washed with potassium chloride solution. Afterwards, the recovered shale cuttings were dried at 105 ˚C in Oven. Percentage of recovered shale cuttings was also calculated as follows:

$$\%\,Recovery = \frac{initial\,weight - final\,weight}{initial\,weight} * 100 \quad (1)$$

Fig 6 Shale Recovery test (left: before the test, Right: after tests).

Results and Discussion

Linear Swell Test

One-dimensional swelling is an indicator of shale expansion ability. As seen in Figure 7, potassium chloride addition significantly reduces the shale swelling, and it makes clay-rich wafers not more expand. Lower swell levels which were read from the graph of swelling measures were in 15 wt.% of KCl concentration. This point is related to enough cations which are provided to exchange and stabilize the shale. In Van Oort's researches, to minimize the swelling property on active and young shale, 15 wt.% of KCl may be needed [25]. However, we found out that the used shale samples were active and clay-rich.

Figure 8 shows that the shale stabilization with KCl was affected by NaCl existence. Eight samples of KCl fluid were selected to be evaluated.

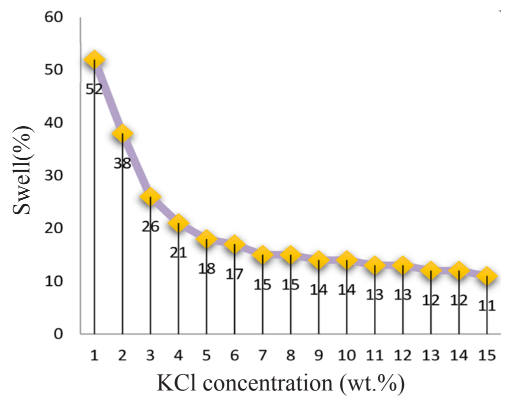

Fig 7 Linear swell of pure KCl fluid with different concentrations.

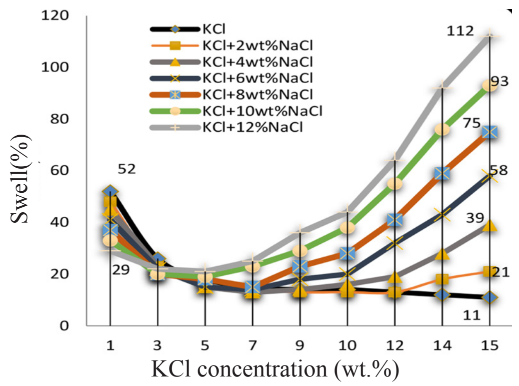

Fig 8 Linear swell of KCl-fluid + NaCl with different concentrations.

The graphs in Figure 8 show that NaCl with different concentrations has a varied effect on KCl efficiency. High concentrations of NaCl cause more interference in the KCl application.

In Figure 8, it is also explained that the low concentration of NaCl can help KCl (to) stabilize shale, but increasing NaCl quantity develops shale swelling. However, when NaCl is added to saturate the drilling mud in some cases (when the borehole was salty/shale mixed formation), unknowingly, mud engineers decrease the KCl efficiency by adding NaCl to the mud.

Note: As a main result, swelling tests covered the other shale-fluid interaction test. The swelling test includes the factors that affect shale instability by drilling fluid the same as osmotic diffusion, chemical potential differences, ionic penetration, and capillary suction. Thus, other test results were compared with the application result obtained from the swell test.

Capillary Suction Time

To evaluate the ability of fluids inhibitory to stabilize shale and prevent water absorption and swelling, 10 g of shale samples were added to 350 ml of fluid samples. The lower amount of water absorbed by the shale samples (free water there is in the fluid) related to better results of the inhibition. Therefore, the paper wetting time was longer, and the capillary suction time was shorter. For example, when 10 g of shale samples was added to distilled water, due to swelling and absorption of more water by the clay, the wetting time of the special paper was increased (CST increased), but when potassium chloride was added to the drilling fluid, the capillary suction time was reduced. Capillary Suction Time (CST) test performed with changing in potassium chloride concentrations as 1 to 15 wt.% by weight. Figure 9 shows the CST alteration against the increase in KCl concentration. Moreover, dissolved KCl in water decreases the water activity and increases the ionic strength. The plot has a negative slope related to an increase in concentration of KCl, hence the clay which dispersed in fluid is controlled by K^+ ions well.

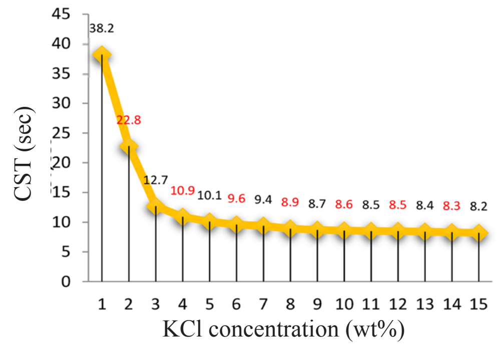

Fig 9 CST vs. increase in KCl concentration.

CST depends on the volume of free water released by the clay inhibitors. Any drilling fluid additive that has the ability to protect or stabilize clay sheets and prevent water absorption is considered as an inhibitor additive. Therefore, as shown in Figure 10, when KCl is used alone, it shows a direct ratio of inhibitory properties to an increase in concentration.

In Figure 10, it is seen that nine concentrations of KCl fluid were selected to assess the effect of NaCl which is added, the plots show that increasing NaCl to the low concentration of KCl fluids decrease the CST quickly. At low concentration of NaCl, factors the same as similar ions decrease water activity and thereby help KCl to control shale dispersion well. But with an increase in NaCl quantity, repulsive forces [26], ionic strength, and ionic aggregation increased that affected KCl efficiency in the shale control application.

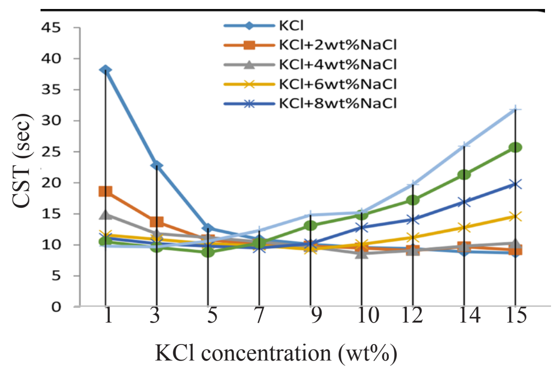

Fig 10 NaCl effect on KCl fluid in CST measuring.

Cuttings Dispersion Test

Hot rolling dispersion API tests were performed to observe long-time contact between shale and drilling fluids. To make suppression view of shale recovery in different concentrations of KCl, 20 g of shale samples were poured in roller oven cells that have different concentrations of KCl and after 16 h, they were recovered, dried, weighed and calculated in order to initial weight.

Figure 11 shows that increasing potassium concentration to 15 wt.% causes the positive slope in the plot. Additionally, recoveries to 10 wt% of KCl concentration were optimum, and extra added KCl to mud had not effective signs. However, for this shale sample, the major part of shale recovered to 10 wt.% KCl.

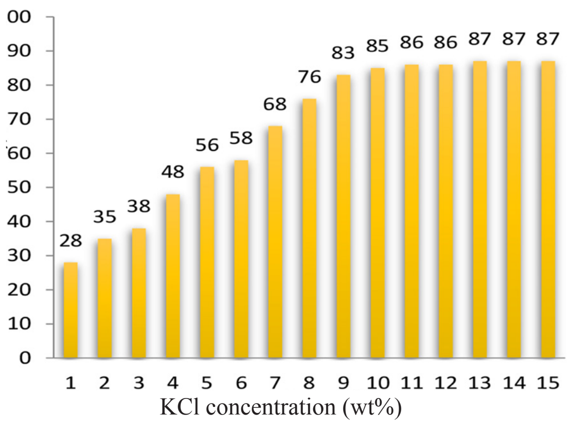

Fig 11 Shale recoveries vs. KCl concentration.

According to graphs shown in Figure 12, the shale recovery results were more affected with NaCl adding in order to two previous tests (CST and swelling). Where NaCl is added to the fluid, P.V. (plastic viscosity) undoubtedly increased, which high PV relates to high friction. Therefore, shale samples when rolled in cells, they were more crushed and more converted to fine pieces which decreased the shale recovery percentage. Additionally, with an increase in NaCl concentration, the destructive effects of NaCl on shale dispersion was increased, and KCl shale recovery efficiency was decreased.

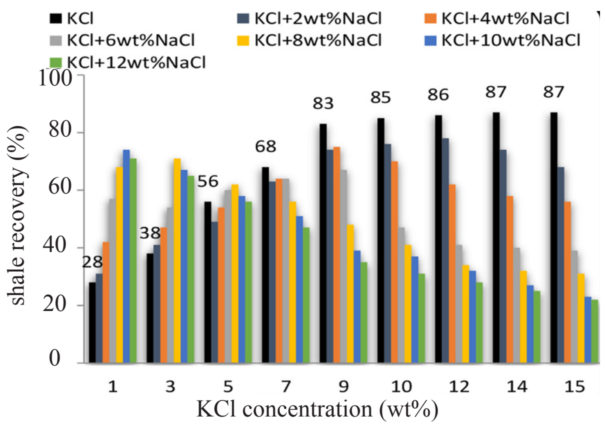

Fig 12 KCl-fluid shale recoveries influenced by NaCl.

Conclusions

The experimental results obtained from the three types of shale-fluid interaction tests showed approximately the same trend. NaCl affected the inhibitory property of KCl fluids, although the test points were slightly different. Accordingly, the beneficial results obtained from the study are:

• To stabilize the young shale such as clay used in this study, for the best results in shale swelling and clay dispersion try not to add as much NaCl to the drilling fluids as possible.

• The use of NaCl and KCl mixture at low concentration for shale stabilization with moderate activity in drilling fluid, a better shale inhibition is appeared. In other words, NaCl makes KCl fit between the clay sheets well and improves the cation exchange process.

• In high concentrations of NaCl, potassium ions compete with Na+ in shale entrances, although the diameter of the potassium hydrated ion is smaller and its hydration energy lower; in addition, the high concentration of NaCl causes ion accumulation, an asymmetric effect, and the electrophoresis effect. That these interferences cause the K+ ion to be better fixed or prevented between the clay sheets. At concentrations between 7 wt% and 15wt%, when sodium chloride reduces potassium yield, an average of 5.7% yield reduction is obtained for 1wt% sodium chloride added.

• In view of the above, inevitably, if salt is already present in the drilling fluid, by calculating its amount, for shale stabilization purposes, more potassium must be added to the mud because some of it is used to overcome the electrical and ionic deterrent forces.

• It is recommended that for controlling stabilization of young shale which requires more than 7 wt% KCl, NaCl should not be added to saturate the mud or to retain polymers. But to inhibit low-activity shale (old shale) and save costs, the combination of NaCl and KCl in drilling fluids can be used.

Nomenclatures

CEC: Cation exchange capacity
LSCA: Linear swell meter cell assembly
CST: Capillary suction time

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