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Evaluation of the Impact of Calcium Contamination on the Drilling Operations: Various Case Histories from Nahr Umr Field, Iraq

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Abstract

Small quantities of calcium (< 200 mg/L) are acceptable, even desirable, in most water-based muds. A background level of calcium acts as a buffer against the presence of undesirable carbonate alkalinity. However, drilling operations will be impeded due to high concentrations of calcium, and have major adverse effects on water-based muds.

Calcium contamination can be occurred due to using hard make-up water ($Ca^{++} > 400$ mg/L) for mud mixing purposes, drilling anhydrite and gypsum formations, and penetrating cement. In the first case history, a hard make-up water ($Ca^{++} >$ 600 mg/L) was utilized to mix the spud mud to drill the surface hole in Well-19, Nahr Umr field, which in return caused altering drilling mud properties negatively, while the second case history is from Well-14, Nahr Umr field, which was associated with penetrating anhydrite lithology in the Rus formation. Plainly, drilling anywhere in Nahr Umr field, one of Iraq's largest oilfields, requires penetrating the Rus formation, which is notorious for calcium issues and thus a great source of information on mud contamination events. The second case history represented big obstacles due to the contamination of high quantities of calcium ions. Some problems were faced during drilling the Rus formation, such as drilling mud clotting and very high yield point (Yp), gel strength, and filtration.

The last case history has demonstrated the impact of penetrating cement in Well-23, Nahr Umr field on drilling operations. Many challenges were faced, including but not limited to, the phenomenon of fake yield point, plastic viscosity increasing, cutting bed, mechanical stuck pipe, high alkalinity, high filtration, and thick mud cake. Hence, non-productive time and a high cost were represented in this well due to high contamination of calcium ions from cement ($Ca^{++} > 1600$ mg/L).

The reason behind these problems was that drilling mud was not resistant, and it didn't contain the required chemical additives that are responsible for controlling and precipitating calcium ions. Therefore, drilling fluid was contaminated with high quantities of calcium. Additionally, mud was uncontrollable and dysfunctional. These problems were solved by using more chemical additives, preparing new resistant mud with a very low calcium content and mix it with the old mud, or converting the mud type from sodium-based mud to calcium-based mud by dumping a big part of the contaminated mud and replace it with lime mud.

The aim of this paper is to understand the assessment of the effect of utilizing hard make-up water, penetrating anhydrite formations, and drilling cement on the drilling operations and how to control calcium ions contamination during drilling practice to minimize the cost and non-productive time.

Introduction

Calcium can be presented in make-up water (particularly sea water), formation water and mixed salt evaporite formations. Also, calcium is encountered in greatest quantity when drilling cement gypsum, or anhydrite. Calcium ions (Ca^{++}) flocculate bentonite based muds and other water-based muds containing reactive clays giving rise to changes in rheology (decrease in plastic viscosity, increase in yield point and gel strength, and facing inefficient hole cleaning) and loss of filtration control. The presence of increased calcium levels can be verified from chemical analysis of the filtrate. The combination of high calcium levels and high pH will precipitate most common polymers used in water-based muds – loss of rheology and filtrate control will result (Basra Oil Company, 2008).

When the mud gets contaminated with calcium ions during drilling operations, it must be treated to avoid unfavorable changes in mud properties. The hardness of the fluid is a controlling factor in the mixing ability and effectiveness of all drilling fluid additives. The single largest contributor to total hardness is divalent calcium ion. For this purpose, hardness is referred to as calcium hardness. Excessive calcium hardness, above 200 mg/L, leads to inefficient hydration of bentonite and polymer products (Baroid Drilling Fluids Handbook, 1997).

The Nahr Umr field is a super-giant field located in Southern Iraq which covers approximately 600 km^2 area with an estimated 33 billion bbls STOIIP (stock tank oil in place) in multiple reservoirs such as the Mishrif and Zubair Formations. The field is currently in the production stages of the commercial plan, development, field assessment, and reservoir characterization. One of the time-consuming problems in the Nahr Umr field is calcium contamination due to using hard make-up water ($Ca^{++} > 400$ mg/L) for mud mixing purposes, drilling anhydrite and gypsum formations, or penetrating cement (Basra Oil Company, 2010).

This paper is a combination of case histories and analysis of the successfulness of the real treatments used to control high calcium contamination events in the Nahr Umr field. The implemented remedies were minutely collected from mud drilling reports and analyzed to better comprehend this issue. Analysis and understanding of these case histories will contribute to having a rigorous reference for avoiding or at least mitigating calcium contamination in these formations. The problem and the required actions which were presented in this paper is focused on the Nahr Umr field. However, this study can serve as a practical strategy for avoiding or mitigating high Ca^{++} contaminations for fields with similar geological properties.

Insights into Calcium Contamination and Unwanted Consequences

One of the main resources for contaminating water-based drilling fluids is calcium ions. The drilling mud can be contaminated with Ca^{++} by various resources, such as the makeup water, during penetrating anhydrite or gypsum formations, or drilling cement. When the drilling mud is contaminated with calcium ions, the continuous liquid phase (water) and clay-based systems will be drastically altered negatively, and the reason behind that is sodium ions will be replaced by the calcium ions on the clay surface through a base exchange. In addition, the bound layer of water on the clay platelets will be minimized, which in return the hydration or swelling characteristics will be minified. Due to the effects of calcium contamination, the drilling mud will be deflocculated, resulting in an increased fluid loss, yield point, and gel strengths and decreasing the density and plastic viscosity (Amoco Production Company, 1994).

If the drilling fluid was contaminated by cement, the diagnostic will be easy by the fact that knowing ahead of time when cement will be drilled. The physical and chemical indications of lime or cement and gypsum or anhydrite contaminations are slightly different. Lime and cement contaminations result in increasing yield point, fluid loss, mud cake thickness, pH and alkalinities. However, gypsum and anhydrite contaminations are also characterized by an increase in yield point and fluid loss as these effects are the result of the divalent cation (Ca^{++}) in the drilling fluid. Alkalinities and pH decrease with anhydrite contamination because $CaSO_4$ and H_2O liberate H^+ ions. An increase in detectable Ca^{++} is also likely since there is not a high pH to limit its solubility (Amoco Production Company, 1994).

Make-Up Water Contamination and Treatment

The drilling mud will be contaminated when using make-up water with quantities of calcium greater than 400 mg/L (particularly using sea water or hard water) for mixing the mud, calcium ions will interact with the mud system and cause undesirable changes in mud properties. **Table A.1** (Appendix A) illustrates the composition of seawater. Due to the replacement of the sodium ions by the calcium ions on the clay surface through a base exchange, thus causing undesirable changes in mud properties such as poor hydration of bentonite with mixed water, increasing yield point and gel strength, maximizing filtration, building thick mud cake, reducing the density and plastic viscosity. That will also cause the added thinners to the mud system to be ineffective (Basra Oil Company, 2010).

Hence, make-up water that will be used for mixing drilling mud has to be tested for hardness to determine the calcium content. If Ca^{++} in make-up water is equal or higher than 400 mg/L, it has to be treated and precipitate the calcium content prior to using it for the mud preparation. The best chemical additive that has to be used to remove or reduce calcium content is sodium carbonate (Na_2CO_3). Sometimes, if Na_2CO_3 isn't available in the field, other options that are usually used are caustic soda (NaOH) or regular water (soft water) (Basra Oil Company, 2008).

Anhydrite/ Gypsum Contamination and Treatment

''Anhydrite and gypsum are calcium sulfate compounds ($CaSO_4$) which are sometimes encountered while drilling. Gypsum is calcium sulfate with water of crystallization ($CaSO_4$. $2H_2O$), while anhydrite is the anhydrous (waterless) form of calcium sulfate ($CaSO_4$). These may occur as thin stringers or massive beds'' (Amoco Production Company, 1994).

Calcium sulfate contamination is slightly different from cement contamination since both of them release calcium ions, which in turn cause flocculation. Unlike cement, calcium sulfate does not cause a pH increase because it supplies sulfate ions in lieu of hydroxyl ions. Even though sulfate ions will cause flocculation of clay solids, its impact is small compared to calcium ions (Basra Oil Company, 2008).

The rheological properties will be increased in lightly-treated muds even with small amounts of $CaSO_4$. The severity of flocculation depends on clay content. Viscosity will fluctuate and seepage loss may become difficult to control. In addition, thick mud cake will be built when $CaSO_4$ causes calcium concentration to increase above 400 mg/L. A base exchange occurs in which sodium montmorillonite becomes calcium montmorillonite as calcium ion concentrations further increase. Flow properties tend to decrease, and fluid loss becomes very difficult to control (Amoco Production Company, 1994).

$CaSO_4$ contamination can be treated by many methods. Using chemically precipitating calcium from solution, the drilling fluid can be maintained as a low-calcium, or it can be converted to a gypsum system. Sodium carbonate (soda ash) is the best option to remove the calcium ion for smaller amounts of $CaSO_4$ contamination. Initially, chemical titration tests have to be performed to obtain the filtrate alkalinity (P_f), mud alkalinity (P_m), and methyl-orange (M_f) to firmly maintain them within the allowed limits, then excess CaSO4 can be estimated from the filtrate versenate (V_F), whole mud versenate (V_T), and volume fraction of water from retort analysis (F_W) using the Equation 1 (Amoco Production Company, 1994).

$$\text{Excess } CaSO_4 \text{ (lb/bbl)} = 2.38\ [(V_T) - 0.48\ (V_F)\ (F_W)] \ \ldots \text{ (Eq. 1)}$$

Based on value of excess $CaSO_4$ that is calculated from Equation 1, the excess $CaSO_4$ can be classified as low, medium, and high as shown in **Table A.2** (Appendix A). It is advisable to have low excess $CaSO_4$ in drilling mud to avoid the unwanted consequences due to medium or high excess $CaSO_4$.

Approximately 0.093 lb/bbl of soda ash is required to precipitate 100 mg/L of Ca^{++}. Caution should be exercised to avoid overtreatment. When Ca^{++} concentration is reduced to 300-350 mg/L, treatment should be suspended. The reaction between gypsum or anhydrite with soda ash is shown in the reaction below (Basra Oil Company, 2006; Basra Oil Company, 2007):

$$Ca^{++} + SO_4 + 2Na^+ + CO_3 \longrightarrow CaCO_3 + 2Na^+ + SO_4$$

$$CaSO_4 + Na_2CO_3 \longrightarrow CaCO_3\downarrow + NaSO_4$$

Soluble sodium sulfate (Na_2SO_4 ions) is formed from this reaction and could cause flocculation problems after prolonged treatments. For this reason, it is generally necessary to convert to a calcium-based fluid when massive anhydrite is to be drilled with a freshwater system (Basra Oil Company, 2010).

Cement Contamination and Treatment

The cement contamination will be faced during penetrating the plugs and casing shoe. Many factors will determine the extent of contamination and its effect on mud properties which are solids content, type and concentration of deflocculants, and the quantity of cement incorporated. ‘’One 94-lb sack of cement can yield 74 lb of lime. When cement is completely cured only about 10% is available; whereas, when it is soft (green) as much as 50% of the lime may be available to react. It is the calcium hydroxide (lime) in cement, reacting with solids, that causes most of the difficulty associated with cement contamination’’ (Amoco Production Company, 1994).

Flocculation due to the cement contamination will be very high with freshwater bentonite systems, the unwanted consequences are increased rheology, pH, and fluid loss. The severity of flocculation can be maximized or minimized based on the quantity and quality of solids presented and the solubility of the Ca^{++}. Thus, if there is a high level of cement contamination, and there is no potential to treat the mud, it might be better to convert the system to a calcium-based mud, if that didn’t work, it is good to isolate the contaminated fluid and dump it (Amoco Production Company, 1994).

The cement contamination will be treated using sodium bicarbonate ($NaHCO_3$). The aim of using this chemical additive is to control pH while removing calcium and excess lime from the system as the inert, insoluble calcium precipitate. When sodium bicarbonate reacts with lime, a hydrogen ion is liberated which reacts with a free hydroxyl ion to form a water molecule, so resulting to further minimize the pH and allow more lime to go into solution as shown in the following reaction (Basra Oil Company, 2013):

$$Ca^{++} + 20H^- + Na^+ + H^+ + CO_3 \longrightarrow CaCO_3 + Na^+ + OH^- + H_2O$$

$$Ca(OH)_2 + NaHCO_3 \longrightarrow CaCO_3 + NaOH + H_2O$$

To estimate the excess lime, chemical titration tests has to be performed. The filtrate alkalinity (P_f), mud alkalinity (P_m) and volume fraction of water from retort analysis (F_w) can be determined, and then excess lime can be estimated by Equation 2. To chemically remove 100 mg/L of calcium originating from lime would require approximately 0.074 lb/bbl of sodium bicarbonate. (Amoco Production Company, 1994).

$$\text{Excess lime (lb/bbl)} = 0.26[P_m - (F_w)(P_f)] \qquad \text{Eq. (2)}$$

Based on the value of excess lime that is calculated from Equation 2, the excess lime can be classified as low, medium, and high as shown in **Table A.3** (Appendix A). It is advisable to have a low excess lime in the drilling mud to avoid the associated unwanted consequences due to medium or high excess lime.

Due to using sodium bicarbonate for removal the calcium ions from the drilling mud, unwanted side effects will be faced. Therefore, chemical additives such as rehydrated bentonite, Carboxymethly Cellulose (CMC) or Polyanionic Cellulose (PAC) should be utilized to gain the desired rheological properties and to restore filtration and filter cake characteristics (Basra Oil Company, 2008).

It is practically applicable to do pretreatment for the drilling mud to make it resistant fluid before penetrating the cement; however, it is crucial to avoid overtreating with sodium bicarbonate since it will be as detrimental to drilling fluid properties as the cement contamination. Hence, it is not advisable to pretreat the mud with more than 0.5 lb/bbl of sodium bicarbonate. One method to prevent overtreatment is to treat only soluble calcium and wait to treat lime when it goes into solution on subsequent circulations. When excess lime approaches 0.5 to 0.2 lb/bbl, treatments should be discontinued (Amoco Production Company, 1994).

As a supportive chemical additive, it is good to add lignosulfonate and chrome-lignite in conjunction with sodium bicarbonate to have supplementary pre-treatment or post-treatment since they buffer the pH and aid in deflocculating the system. However, lignosulfonate and chrome-lignite can’t be used alone to do pre-treatment or post-treatment for calcium contamination due to drilling the cement (Basra Oil Company, 2008).

It is advisable to use low-gravity solids content prior to penetrating cement since high clay solids concentration is a major reason of mud flocculation and increasing plastic viscosity, yield point, gel strength, filtration, and mud cake thickness. **Figures A.1** and **A.2** (Appendix A) demonstrate polyacrylamide polyacrylate hydrolysis at high pH and precipitation of the polyacrylate calcium, respectively (before and after the treatment) (Basra Oil Company, 2008).

Case 1: Using Hard Make-Up Water (Ca^{++} > 600 mg/L) to Mix the Spud Mud to Drill the Surface Hole, Well-19, Nahr Umr Field

Typically, a simple type of fresh-water bentonite (spud mud) is used to drill the shallow depths formation such as the surface hole in Nahr Umr field. Most commonly a 24” bit is used to drill through the surface hole. Due to the big hole size and high drilling rate, high viscosity mud is used to drill the surface hole to have a high efficiency of cutting lifting, which leads to an efficient hole cleaning. The chemical additives of the spud mud (in case soft water used to mix the mud) are shown in **Table A.4** (Appendix A) (Basra Oil Company, 2011).

In case soft water isn't available in the rig site, then hard water will be used to mix the spud mud to drill the surface hole; therefore, sodium carbonate (Na_2CO_3) will be used to precipitate the calcium content in make-up water below 400 mg/L to provide a good homogenous and hydration between the bentonite and water, and to avoid the phenomenon of the aggregation and flocculation. **Table A.5** (Appendix A) illustrates the blend of the spud mud if hard water was used (Basra Oil Company, 2011).

A real case history will be presented in this paper to show the impact of the hard water that was used to mix the spud mud without pre-treatment. In this case history, make-up water with $Ca^{++} > 600$ mg/L was utilized to mix the spud mud and drill the surface hole in Well-19, Nahr Umr field without adding sodium carbonate to precipitate the calcium content. As a result, bad consequences were faced in terms of inappropriate drilling fluid properties and high cost. Drilling problems were encountered, and large quantities of chemical additives were also used to achieve the required properties of the drilling mud in the mixing tank. **Table A.6** (Appendix A) demonstrates the concentrations of the spud mud that was used to drill the surface hole in Well-19, Nahr Umr field (Basra Oil Company, 2011).

The desired properties of the drilling mud were obtained by mixing the materials in **Table A.6** in the mixing and active tanks; however, after pumping the mud in the wellbore under the sub-surface conditions, it started to lose its properties gradually. The aggregation and flocculation issues were started with bentonite and inefficient hole cleaning was faced. In addition, seepage losses were maximized. Consequently, the drag and over-pull (pack off) problems were faced during the tripping in and out, respectively. Then, the rig was shut down and the mud was treated by adding soft water, bentonite, and sodium carbonate to the original mud. After adding these additives, the mud was treated and the desired mud properties were retrieved again. Then, the drilling operations were resumed for the surface hole, and it was completed without any issues. In short, some drilling obstacles, non-productive time, and more consumption of chemical additive will be encountered due to utilizing hard water to mix the spud mud for penetrating the surface hole. Therefore, it is practically applicable to use soft water, or pretreated hard water with sodium carbonate in order to blend fresh-water bentonite mud (spud mud) for penetrating the surface hole (Basra Oil Company, 2011).

Case 2: Drilling the Rus Formation, Well-14, Nahr Umr Field

The Rus formation is an anhydrite formation with white, firm, moderately hard, no porosity, massive, occasionally soft, no oil show, with a thickness between 140–190 meters. Many wells were suffered calcium contamination problem that was associated with drilling mud clotting, very high viscosity, and high filtration due to high contamination of Ca^{++}. It is required to have a very keen observation for the drilling properties during drilling the Rus formation. In addition, adding the required chemical additives to the drilling mud will help to make the mud more resistant to Ca^{++} contamination (Basra Oil Company, 2012).

However, in this case history, fresh-water bentonite was used to drill the Rus formation without adding sodium carbonate or thinners materials to this mud. In different words, the mud wasn't pretreated with the required chemical additives to make it resistant to contamination. As a result, the mud was contaminated with a high concentration of calcium and sulfate compounds ($CaSO_4$). The drilling properties drastically altered negatively, and the mud was almost dysfunctional. Many problems have been encountered, including but not limited to, inefficient hole cleaning, mechanical stuck pipe, bentonite flocculation and aggregation, drilling mud clotting, high filtration, thick mud cake, pH reduction, and bacterial issues (Basra Oil Company, 2012).

To avoid more unwanted issues, the crew decided to suspend the drilling operations and shut down the rig to do the required actions. The drilling string was pulled out to the casing shoe of the 13-3/8" surface casing to be saved from open hole issues. Then, the contaminated mud was treated by mixing it with a new resistant mud to maintain the drilling mud properties. The new mud consisted of the additives shown in **Table A.7** (Appendix A) (Basra Oil Company, 2012).

55 m^3 of the new mud was mixed with the original contaminated mud to treat and enhance the mud properties and to make it resistant mud during penetrating the Rus formation. After that, the drilling operations were resumed using the treated resistant mud to drill the Rus formation. Due to adding the new mud to the old mud, the mud properties were significantly enhanced, and the Rus formation was successfully drilled without any issues. In conclusion, it is necessary to pre-treat the mud with sodium carbonate and lignosulphonate before drilling anhydrite formations to minimize non-productive time and cost.

Case 3: Drilling Cement, Well-23, Nahr Umr Field

As mentioned previously, in most drilling operations, cement contamination occurs two or more times when casing strings are cemented and the plugs are drilled out. In addition, cement penetration will usually be faced during drilling the cement plug that is used to stop severe or complete losses in the thief zones. Real case history will be presented in this section to show the impact of penetrating the cement. Initially, 9-5/8" intermediate casing has been run to secure the intermediate hole in Well-23, Nahr Umr field. This casing string has been set on the top of the Sadi formation. Then, 8.5" bit was used to drill the production hole; however, the bit had to drill the cement between the float collar and casing shoe (three joints) and a few meters in the Sadi formation (Basra Oil Company, 2012).

Drilling mud utilized to drill cement is chrome lignosulfonate-chrome lignite (FCL-CL) mud, and it consisted of additives shown in **Table A.8** (Appendix A). However, this mud wasn't pre-treated by $NaHCO_3$ to make it resistant mud prior to drilling the cement (Basra Oil Company, 2012).

Due to unavailability of sodium bicarbonate in the rig site, sodium carbonate, lignosulphonate, and chrome-lignite were used since the mud engineer thought that they could compensate sodium bicarbonate; however, they weren't successful to control the cement contamination, which caused increasing the rheological properties and seepage losses. Also, something strange occurred specifically with yield point which was the fake Yp phenomenon. Rheometer/viscometer was used to measure Yp, and it was high; however, inefficient hole cleaning and cutting bed were faced. This phenomenon occurred due to high contamination with cement so that Ca^{++} concentration was > 1600 mg/L. As a result, Yp was highly maximized due to contamination and not because of bentonite and the desired chemical additive. Bentonite lost the dispersion property due to the mud clotting. In addition, aggregation and flocculation were tremendously presented in the drilling mud (Basra Oil Company, 2012).

Filtration was uncontrollable in spite of using CMC-LV with high concentration. The reason behind that was very high alkalinity (pH = 13) due to cement and lime contamination. Thus, CMC-LV was precipitated and it was ineffective. Moreover, adding more CMC-LV contributed to reducing the viscosity. CMC-LV was dysfunctional since the mud was converted from sodium base to calcium hydroxide (lime) base, and CMC-LV doesn't work well in calcium-based mud. In this case, the best chemical additive that has to be used to control the filtration in calcium-based mud is starch and not CMC-LV (Basra Oil Company, 2012).

Pill tank was used to mix the required chemical additive such as sodium bicarbonate, sodium carbonate, lignosulphonate, chrome-lignite, and CMC-LV in various concentrations to treat the mud. However, they weren't successful to treat the mud. Both non-productive time and high cost were associated with this problem due to inappropriate actions. That is because when cement contamination reaches a high level of excess lime where it is no longer practical to treat out using conventional additives, it is better to convert the system to a calcium-based mud. Hence, the mud was converted from sodium-based mud to calcium-based mud by dumping a big part of the contaminated mud and replace it with lime mud as shown in **Table A.9** (Appendix A) (Basra Oil Company, 2012).

After that, the new lime mud was successfully used to drill the cement and the Sadi formation without cement contamination issues. Therefore, it is practically applicable to pretreat the mud with sodium bicarbonate prior to drilling cement or convert the mud from sodium-based to calcium-based to be resistant drilling mud (Basra Oil Company, 2012).

Conclusions

A contaminating agent can be material either solid, gaseous, or liquid, with a damaging impact on chemical and physical properties of drilling mud. Low gravity reactive solids are the most common contaminants in drilling mud. The most common types of contaminations of water-based muds are salt (sea water, magnesium, calcium, chloride, and native water), anhydrite, gypsum, cement, and acid gas such as CO_2 and H_2S.

Calcium contamination is a very common and serious issue during drilling operations, and most fields in the world suffer from this issue due to using hard make-up water, drilling anhydrite or gypsum formations, or penetrating cement. Hence, it is required to do pre-treatment with the appropriate chemical additives and maintaining the properties of drilling fluid.

The ultimate objectives of this paper are recognizing the origin of each calcium contamination, explaining how to handle changing properties, and determining how the mud can be treated and retrieved its original characteristics. Based on this work, the following points were concluded:

- Summarize the real case histories from drilling data with integrated analysis will provide a coherent image for how to solve the challenging problems, which are related to calcium contamination. Thus, it is essential to provide more case histories to be developed as practical and substantial resources that will serve as reference material for controlling calcium content problems at the well-site for drilling personnel.
- It is desirable to use soft make-up water to mix fresh-water-based mud if applicable. If not, hard make-up water has to be pretreated with calcium carbonate prior to adding the required chemical additive. Ca^{++} has to be reduced in hard make-up water to 200 mg/L or less.
- It is practically applicable to add calcium carbonate with thinners such as lignosulphonate prior to drilling anhydrite or gypsum formations to make the drilling mud more resistant to contamination.
- Calcium carbonate with thinners such as lignosulphonate and chrome-lignite aren't sufficiently effective to treat cement contamination. Therefore, sodium bicarbonate has to be added to the drilling mud before penetrating the cement.
- Overtreating the drilling mud with sodium carbonate and sodium bicarbonate while drilling cement can be as detrimental as cement contamination. Thus, an appropriate amount of sodium carbonate and sodium bicarbonate should be used to avoid side effects.

Acknowledgments

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Appendix A

Table A.1. The Composition of Sea Water (Basra Oil Company, 2010)

Components	Parts Per Million (ppm)
Sodium	10550
Chloride	18970
Sulfate	2650
Magnesium	1270
Calcium	600
Potassium	380
Bromine	65
Other Components	80

Table A.2. Classification of Excess $CaSO_4$ (Basra Oil Company, 2007)

Low Excess $CaSO_4$	Medium Excess $CaSO_4$	High Excess $CaSO_4$
P_f = 4 - 5	P_f = 2 - 3	P_f = 0.5 - 1
M_f = 5 - 8	M_f = 6 - 11	M_f = 11 - 14
P_m = 6 - 8	P_m = 4 - 5	P_m = 2 - 3
Excess $CaSO_4$ (Ib/bbl) = 0.5 - 1	Excess $CaSO_4$ (Ib/bbl) = 1.5 - 3	Excess $CaSO_4$ (Ib/bbl) = 4 - 6

Table A.3. Classification of Excess Lime (Basra Oil Company, 2007)

Low Excess Lime	Medium Excess Lime	High Excess Lime
P_f = 1- 2	P_f = 2 - 4	P_f = 4 -10
P_m = 3 - 6	P_m = 6 -18	P_m = 18 - 46
Lime (Ib/bbl) = 1-3	Lime (Ib/bbl) = 4 - 30	Lime (Ib/bbl) = 30 - 80

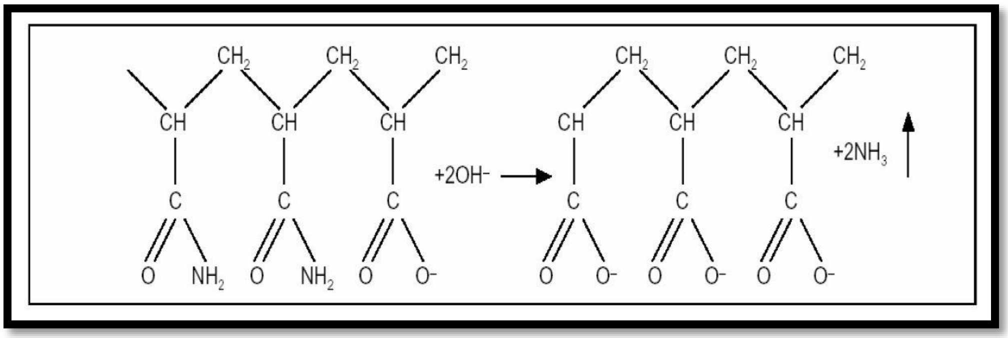

Figure A.1. Cement Contamination before Treatment (Eni Company, 2010)

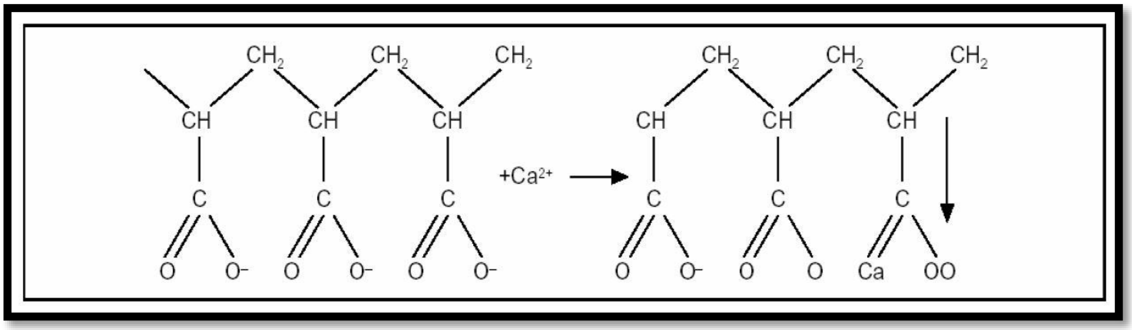

Figure A.2. Cement Contamination after Treatment (Eni Company, 2010)

Table A.4. The Composition of Spud Mud (Ca^{++} < 400 mg/L) (Basra Oil Company, 2011)

Name of Material	Concentration (kg/m^3)	Purpose
Soft water (Ca^{++} < 400 mg/L)	As needed	The continuous phase (base-mud)
Caustic soda (NaOH)	2 - 3	pH control
Bentonite	70 - 80	Dispersed phase (viscosifiers)

Table A.5. The Composition of Spud Mud ($Ca^{++} > 400$ mg/L) (Basra Oil Company, 2011)

Name of Material	Concentration (kg/m^3)	Purpose
Soft water ($Ca^{++} > 400$ mg/L)	As needed	The continuous phase (base-mud)
Sodium carbonate (Na_2CO_3)	0.5- 2	For calcium precipitation
Caustic soda (NaOH)	1 - 2	pH control
Bentonite	70 - 80	Dispersed phase (viscosifiers)

Table A.6. The Composition of the Spud Mud Used in Well-19 ($Ca^{++} > 600$ mg/L) (Basra Oil Company, 2011)

Name of Material	Concentration	Purpose
Soft water ($Ca^{++} >600$ mg/L)	48 m^3	The continuous phase (base-mud)
Caustic soda (NaOH)	4 kg/m^3	pH control
Bentonite	110 kg/m^3	Dispersed phase (viscosifiers)

Table A.7. The Composition of the New Mud (Basra Oil Company, 2012)

Name of Material	Concentration	Purpose
Soft water ($Ca^{++} < 100$ mg/L)	55 m^3	The Continuous phase (base-mud)
Sodium carbonate (Na_2CO_3)	2 kg/m^3	For calcium precipitation
Caustic soda (NaOH)	2 kg/m^3	pH control
Bentonite	70 kg/m^3	Dispersed phase (Viscosifiers)
Low Viscosity Carboxymethly Cellulose (CMC-LV)	8 kg/m^3	Fluid loss control
Lignosulphonate	7 kg/m^3	Thinner

Table A.8. The Composition of FCL-CL Mud (Basra Oil Company, 2012)

Name of Material	Concentration	Purpose
Soft water ($Ca^{++} < 100$ mg/L)	77 m^3	The continuous phase (base-mud)
Sodium carbonate (Na_2CO_3)	1.5 kg/m^3	For calcium precipitation
Caustic soda (NaOH)	2 kg/m^3	pH control
Bentonite	60 kg/m^3	Dispersed phase (viscosifiers)
CMC-LV	6 kg/m^3	Fluid loss control
Lignosulphonate	5 kg/m^3	Thinner
Chrome-Lignite	2 kg/m^3	Thinner

Table A.9. The Composition of Lime Mud (Basra Oil Company, 2012)

Name of Material	Concentration	Purpose
Soft water ($Ca^{++} < 100$ mg/L)	62 m^3	The Continuous phase (base-mud)
Caustic soda (NaOH)	3 kg/m^3	pH control
Bentonite	30 kg/m^3	Dispersed phase (viscosifiers)
Salt clay (attapulgite)	80 kg/m^3	Dispersed phase (viscosifiers)
Starch	6 kg/m^3	Fluid loss control
Lignosulphonate	4.5 kg/m^3	Thinner
Chrome-Lignite	1.5 kg/m^3	Thinner
Lime	3 kg/m^3	Calcium hydroxide base