Kufa Journal of Engineering
Vol. 16, No. 1, January 2025, P.P. 13-25
Article history: Received 8 January 2024, last revised 26 April 2024, accepted 26 April 2024

IMPACT OF WATER IMPURITIES ON DRILLING FLUID PROPERTIES: A CASE STUDY

Amel Habeeb Assi

Petroleum Engineering Department, College of Engineering, University of Baghdad, Baghdad, Iraq, E-mail: amel@coeng.uobaghdad.edu.iq.

https://doi.org/10.30572/2018/KJE/160102

ABSTRACT

As diagnosed, water is an essential component in the preparation of water base mud, but drilling fluids cannot be prepared with high-purity water (practically and economically unavailable), as water may sometimes contain salts and ions such as chlorides and sulfates, negatively affecting the quality and properties of the mud. This research aims to find the effect of impure water on the drilling fluid and then provide the necessary solutions and treatments for that. Samples of water were used and examined, and they contained a percentage of calcium ions at a rate of 800gm/liter, 1000 gm/liter, and 1400 gm./liter, this is unacceptable, so soda ash was used to reduce the above percentages. On the other hand, the water samples had a salinity of 20,000, 30,000, and 40,000 ppm/liter, which is undesirable, so it is preferable to dilute the mud by adding water. The results showed the effect of the presence of those salts on the effectiveness of the added polymers, as well as causing problems with CMC, as it reduces its performance in increasing the viscosity of the mud. The results showed that the acceptable percentage of calcium should be less than 400 mg/liter, and salinity should not exceed 10000 ppm/liter. The results also proved the negative effect of the presence of sulfate in the water on the properties of the drilling fluid, as it reduced its viscosity and pH. This was treated by adding caustic soda to the drilling mud to increase the pH. It was also noted that the addition of caustic soda led to an increase in the viscosity of the drilling mud. What is novel in this research is that it is possible to treat contaminated drilling mud by adding environmentally friendly materials such as micro-silica to reduce the effect of contamination with calcium ions.

KEYWORDS

Salinity, Calcium ion, Drilling fluid, Sulfate, Properties, Oil well.

1. INTRODUCTION:

Drilling mud is chemicals that are mixed with water to form a drilling fluid, and during the drilling process, this liquid is pumped by huge pumps into the drilling pipes to reach the bit, and it comes out through the holes to rush from the bottom of the well up until it reaches the surface (Amel and Faleh, 2020).It carries with it the rock crumbs resulting from the drilling process, and on the surface the mud passes through a filter that separates the rock crumbs from the mud and then pushes the mud again after treatment into the drilling pipes to return to what is known as the drilling mud cycle (Abdel-Karim et al.,2021). Water-based fluids (WBFs) are used to drill approximately 80% of all wells (Assi and Haiwi, 2021). The base fluid may be fresh water, seawater, brine, or saturated brine (Andreozzi et al.,2008). The type of drilling mud chosen depends on the expected well conditions or the period set for drilling the well (Assi,2023). Water is the main part in which the rest of the material is distributed, and it is what gives the ability to the drilling fluid to move the flow (Abbas, et al.,2019). Also, sometimes water is added to the drilling mud to reduce the density of drilling mud, as it is economically inexpensive (Al-Dujaili et al.,2021). In some oil sites, there is a problem in obtaining pure water, as water that contains percentages of salts and ions is used, so the mud engineer must conduct a test for the water that will be used to prepare the mud (Amel and Haiwi, 2023). Water contaminated with ions and salts may be coming from the excavated formations of what is termed formation water. In this case, the mud is treated with some treatments to treat the drilling mud from contamination with formation water (Assi,2020). (Al-Fandi and, Hadid 2020), found that if the concentration of dissolved salts in water increases, the viscosity of the drilling mud and its yield point will be affected, as each increases. The treatment is done either by adding water or diluents, as this leads to the precipitation of polluted salts. (Idan et al.,2021) have verified that if the percentage of calcium exceeds 50 mg/liter in the water, this will lead to an increase in viscosity and the treatment is by adding either sodium carbonate or barium carbonate to precipitate the calcium ion. John confirmed that the treatment of mud contaminated with calcium ions using sodium bicarbonate is better than treatment using sodium carbonate or barium carbonate, since 2.2 kilograms of sodium bicarbonate precipitates calcium sulfate. (Assi and Rasheed, 2024) have proven that the impure water is not only when preparing the mud but also has a second source, which is during the excavation of the formations, where it comes from it. The pollutants of the drilling mud system come during the excavation of the formations from multiple sources such as excavated salt, hard water/brine flow, carbonates, calcium, bicarbonates, and magnesium. Different contaminants execute different effects on the clay, necessitating the use of different treatments to prevent them from occurring later in drilling problems (Alameedy et al.,2023). (Ayad et al., 2015) laboratory study confirmed that the high percentage of solids (salts and ions) in the water negatively affects the drilling fluid, which means an increase in viscosity, an increase in the thickness of the mud cake, an increase in the leachate and an increase in density, which may cause the problem of loss and reduce the speed of drilling. Based on the studies presented above, it is evident that the concentration of ions in water has a notable impact on drilling mud. Previous research has focused on ways to mitigate this impact, but this study aims to establish the acceptable levels of these ions in water. Additionally, this study explores the use of eco-friendly materials to reduce pollution caused by these ions. The main objective of this research is to study the effect of ions and salts present in the water, whether they are in the water used to prepare the mud or coming from the formation water, on the properties of the drilling fluid and the possibility of treating it to reduce its effect on the drilling mud. This is an interesting point as by adding environmentally friendly materials such as micro silica to contaminated drilling mud, it is possible to reduce the negative effect of ions contamination. This could be a major breakthrough in the field of drilling mud processing.

2. MATERIAL AND METHODS

In this research, four samples of water with different percentages of salts and elements were used to demonstrate the effect of this on the properties of the drilling fluid, as shown in Table1. As for the used base drilling mud components, they are listed in Table 2. Table 3 shows the chemical specifications of tap water according to the World Health Organization (WHO) for the year (2004) and the Iraqi Standard No. (417) of (2001). There are many steps that must be followed before conducting the tests to obtain good and reliable results, including: the nature of the information required, determining the analyzes necessary to provide us with this information, and finally selecting the analytical methods to be used (Zhao et al.,2022). Chemical analyses of water are performed to identify and measure the chemical elements and properties of specific waters, including pH, major cations and anions, trace elements, and isotopes. Water chemistry analysis is widely used to determine potential uses for water or to study its interaction with its environment. Chemicals such as arsenic, chromium, cadmium, mercury, and lead pose a significant risk to human health. These chemicals should not be present in water. Similarly, substances like nitrate, barium, ammonium, and chloride, as well as radioactive materials, must not exceed limit values. The presence of these harmful chemicals indicates that the water is polluted. Water hardness refers to the amount of dissolved ions such as calcium, iron, manganese, and magnesium in the water. Magnesium and calcium ions are the most common in natural water, so the sum of these ions is expressed as the hardness of the water (Dolz et al., 2007). Water chemical analysis is often the basis for studying water quality and pollution. Among the most commonly analyzed elements are pH, from cations of sodium, potassium, calcium, magnesium, and silicon, from anions of chlorine, fluorine, sulfates, and traces of minerals, and the metals rubidium, titanium, iron, magnesium, and others, in addition to unstable volatile substances such as carbon dioxide and hydrogen sulfide. and oxygen, and isotopic ratios such as oxygen isotopes. Different methods are used to determine the amounts or ratios of elements, with some relying on standard laboratory equipment and others requiring advanced equipment like inductively coupled plasma mass spectrometry, (Tavakkoli et al.,2014). It is possible to measure water quality by using a Total Dissolved Solid (TDS-3) device, which stands for Total Dissolved Solids, and measures the percentage of dissolved salts in water. Oxygen and hydrogen sulfide are usually measured by titration. Ion chromatography is a sensitive and reliable technique that can measure the amounts of lithium, ammonium, sodium, potassium, calcium, and magnesium among other components. Spectrophotometry is used to measure the iron component of water samples. A saturated calomel electrode and a glass electrode are often used together to determine the pH of water. As for temperature and pressure, the measurement was at room temperature 20-22°C or (68-72°F). As for the pressure, it was atmospheric pressure, i.e. pressure = 1 atm. or 1.0132 bar. The drilling fluid sample was tested and prepared according to American Petroleum Institute (API) standards. 22.5 grams of bentonite was used with 350 cubic centimeters of water, as this is the drilling fluid to which the materials used in the study were added. The clay sample was kept for 24 hours for hydration, and then the following clay properties of density, rheology, and alkalinity were measured. Fig.1 shows the research methodology.

Table 1. Chemical composition of the used water samples.

Elements	sample 1	sample 2	sample 3	sample 4
dissolved solids	1000	1500	2000	2500
iron	1	0.3	2	2.5
manganese	0.1	0.1	0.2	0.3
Total hardship	250	500	550	600
chloride	250	250	200	200
sulfites	400	400	500	700
fluoride	1.2	1	1	1
Sodium	250	20,000	30,000	40,000
free chlorine	1	0.3-2	1	1
calcium	150	800	1000	1400
nitrates	non	50	non	non

Table 2. Chemical composition of the used drilling fluid

component	concentration	property	value
water	100%	viscosity	22Cp
bentonite	15%	density	9.07
Barite	6%	pH	9.5
CMC	1.5%	yield point	18 lb./ft^2
Caustic Soda	0.50%	salinity	280000 mg/l
Soda Ash	2.5%	10 sec Gel	18.4 lb./100ft^2
Xanthan	0.5%	10 min Gel	31 lb./100ft^2
KCl	5%	filtration	4.5 cc
anti-foam	0.70%	funnel viscosity	48sec

Table .3 Water specifications according to the World Health Organization and Iraqi Standard No. 417

Elements	acceptable concentration "World Health Organization" (PPM)	acceptable concentration Iraqi specif. (PPM)
dissolved solids	1000	1500
iron	1	0.3
manganese	0.1	0.1
Total hardship	250	500 250
chloride	250	
sulfites	400	400
fluoride	1.2	1
Sodium	250	200
free chlorine	1	0.3-2
calcium	150	200
nitrates	non	50
The color	15 TCU	10 TCU
pH	6.5-8.5	6.5-8.5

3. THEORY AND CALCULATIONS:

The water used in preparing the drilling mud should be fresh, and this is often not available in the oil sites. Therefore, the mud engineer must do a water test before using it to prepare the drilling mud to measure the percentage of salinity and calcium ions. Calcium ions and salinity have a significant impact on the properties of the drilling fluid and on the materials used in its preparation, such as polymers, as these salts slow down the effectiveness of the polymers. Equations 1 and 2 were used to find the viscosity and yield point of drilling mud. In this research, sodium carbonate, barium carbonate, and sodium bicarbonate were added to precipitate calcium ions, as in equations 3, 4, and 5. As for salinity, the treatment was using water. When sodium chloride dissolves in water, the sodium chloride framework disintegrates as the sodium and chloride ions become surrounded by polar water molecules. These solutions consist of an aqueous mineral compound with the formula $[Na(H_2O)_8]^+$ with a Na–O distance of 250 Pico meters. Chloride ions are also strongly dissolved, each surrounded by an average of 6 molecules of water, as in equation 6. Also, these ions and salts are not limited to the water in which the mud is prepared, but they may be coming from the excavated formation waters, through which the drilling fluid passes back to the surface and carries with it part of that water, including the salts and gases it contains. For this reason, this study included a case study of a well in Iraq.

$$\mu p = \emptyset 600 - \emptyset 300 \quad (1)$$

$$yp = \mu p - \emptyset 300 \quad (2)$$

$$CaSo_4 + Na_2Co_3 \rightarrow Na_2So_4 + CaCo_3 \quad (3)$$

$$CaSo_4 + BaCo_3 \rightarrow BaSo_4 + CaCo_3 \quad (4)$$

$$Ca(OH)_2 + NaHCo_3 \rightarrow CaCo_3 + NaOH + H_2O \quad (5)$$

$$2NaCl + 2H_2O \rightarrow 2NaOH + H_2 + Cl_2 \quad (6)$$

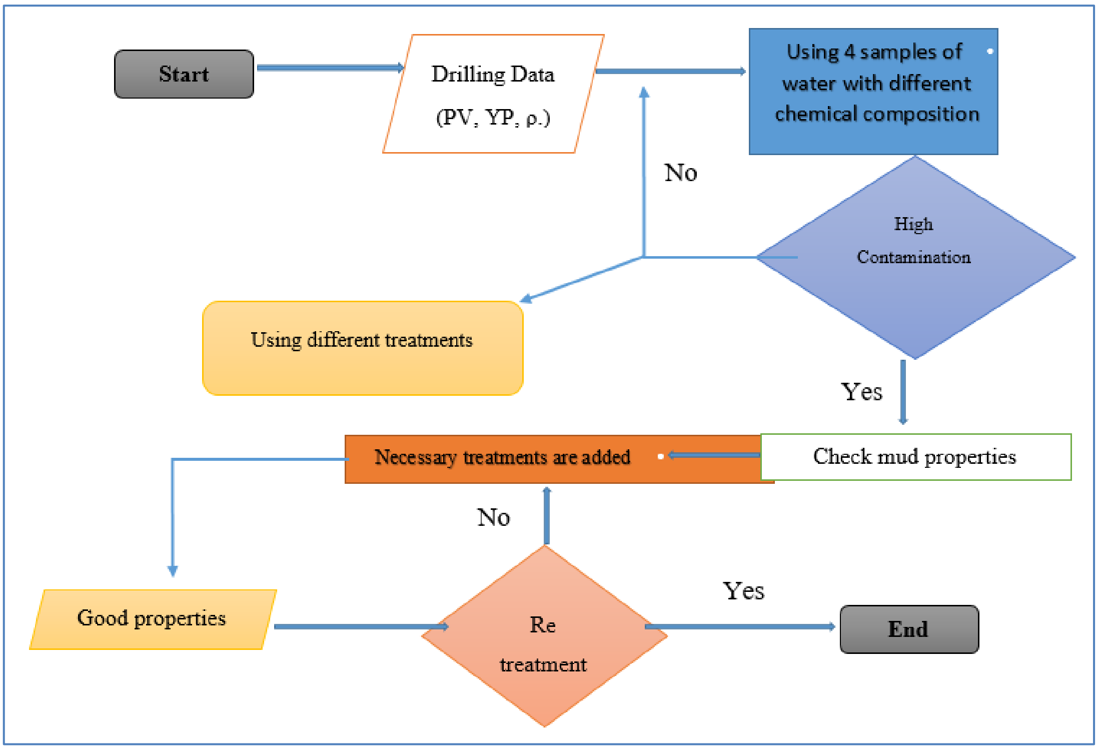

Fig. 1 : Research Methodology .

4. RESULTS AND DISCUSSION:

The research aimed to investigate the impact of the chemical composition of different water samples on drilling mud. Four water samples were studied in the experiment. The study revealed that the presence of calcium ions and salts led to an increase in the density of the clay. As the water samples varied, the treatment composition differed as well. Lime, sodium carbonate, and barium carbonate were used in treating these water samples. Fig. 2 illustrates the effect of the chemical composition of the water on clay density. The second model demonstrated the best performance and came closest to replicating the properties of the original drilling mud, followed by the third model. On the other hand, the fourth model had the worst performance due to its high levels of calcium and salts, which were approximately 1400mg/l and 40000ppm, respectively.

In Fig. 3, it can be seen the use of sodium carbonate, barium carbonate, and lime to treat clay samples from the effect of calcium ions on viscosity. The presence of calcium causes an increase in viscosity up to a concentration of 1000 mg/l. This happens because, at low concentrations, the diffusivity of these salts and ions is high and their interaction is fast. Conversely, at high concentrations, the diffusivity is low and the interaction is slow. Table 4 summarizes other laboratory results for clay samples after treatment with sodium carbonate, barium carbonate, caustic soda, and water. The addition of certain substances caused some changes in the properties of the samples. The pH increased because of the formation of sodium hydroxide, the yield point decreased because of the precipitation of calcium ions, and the density decreased because of the addition of water. Sample No. 4 didn't show any response to the treatments due to its high calcium ion concentration of approximately 1400 mg/l. Therefore, the most effective treatment is to add lime to convert it into lime mud. This is because the viscosity increases when lime is added, as in Fig. 4. It's important to note that calcareous drilling fluid is considered an inhibitive drilling fluid. Fig. 5 shows the effect of calcium concentration on the activity of xanthan. The presence of calcium ions at rates higher than 800 mg/l causes polymers, including xanthan, to be less efficient or ineffective.

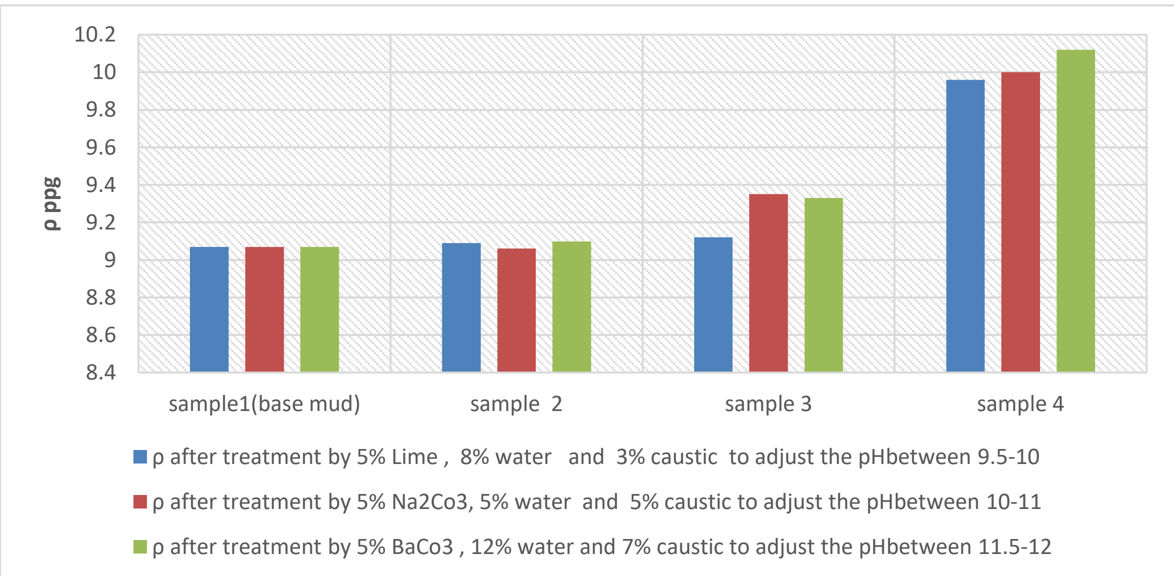

Fig. 2 Relationship between density and the four samples of mud

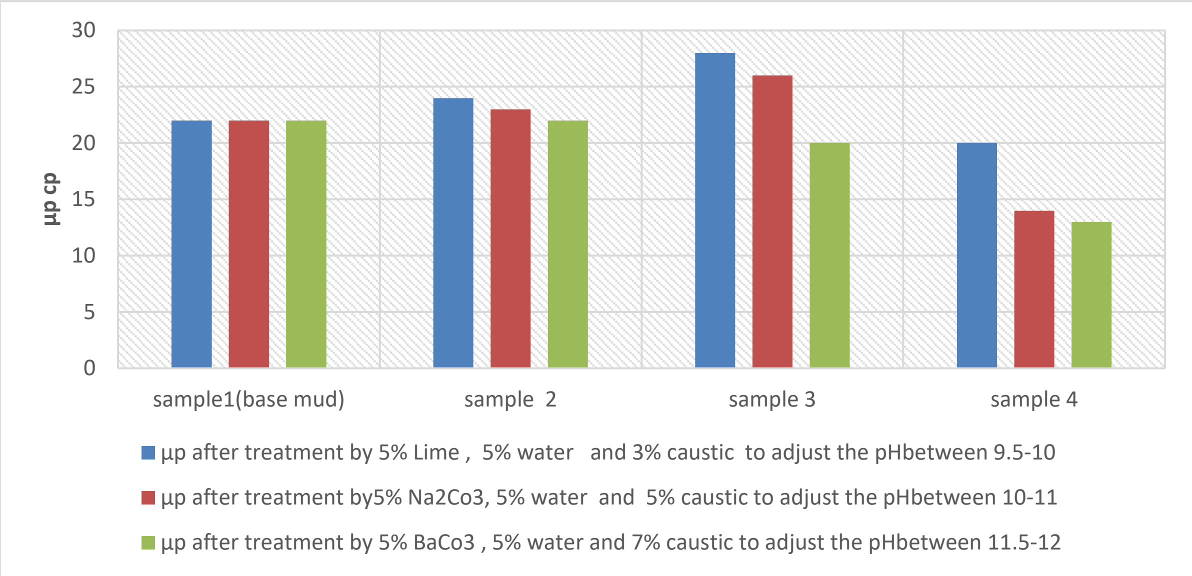

Fig. 3 Relationship between plastic viscosity and the four samples of mud

Table 4. laboratory results for the tested mud samples.

Sample 1	**Sample 2**	**Sample 3**	**Sample 4**
viscosity	viscosity cp	viscosity cp	viscosity cp
22	25	29	19
Yp lb./100ft^2	Yp lb./100ft^2	Yp lb./100ft^2	Yp lb./100ft^2
18	23	25	15
pH	pH	pH	pH
9.5	9.8	10	10.3
ρ mud ppg	ρ mud ppg	ρ mud ppg	ρ mud ppg
9.07	9.3	9.5	9.9

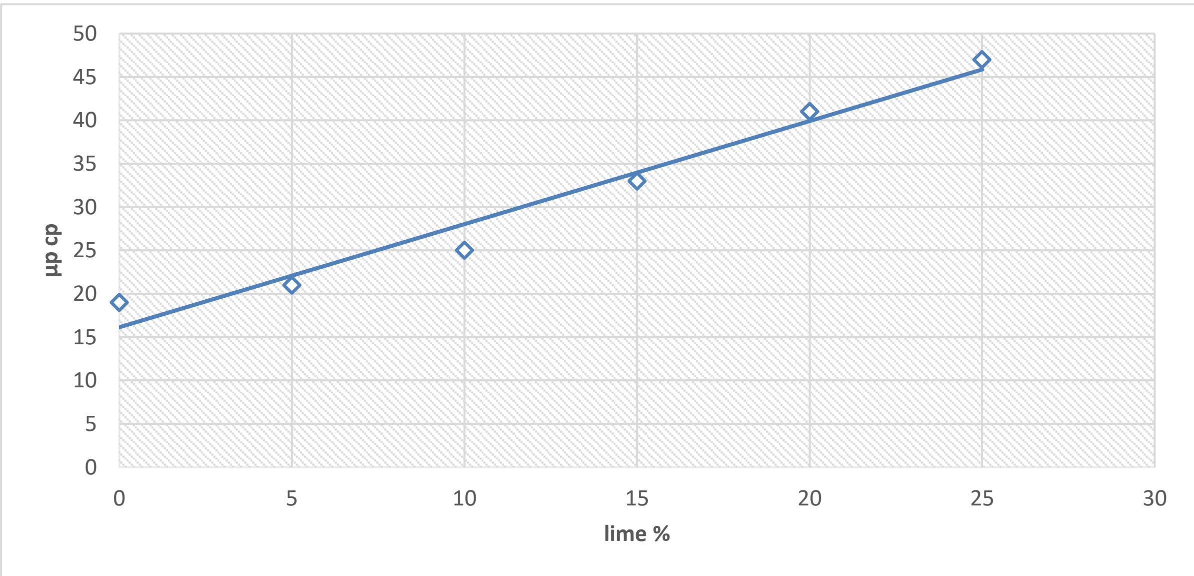

Fig. 4 Relationship between plastic viscosity and lime concentration for sample 4

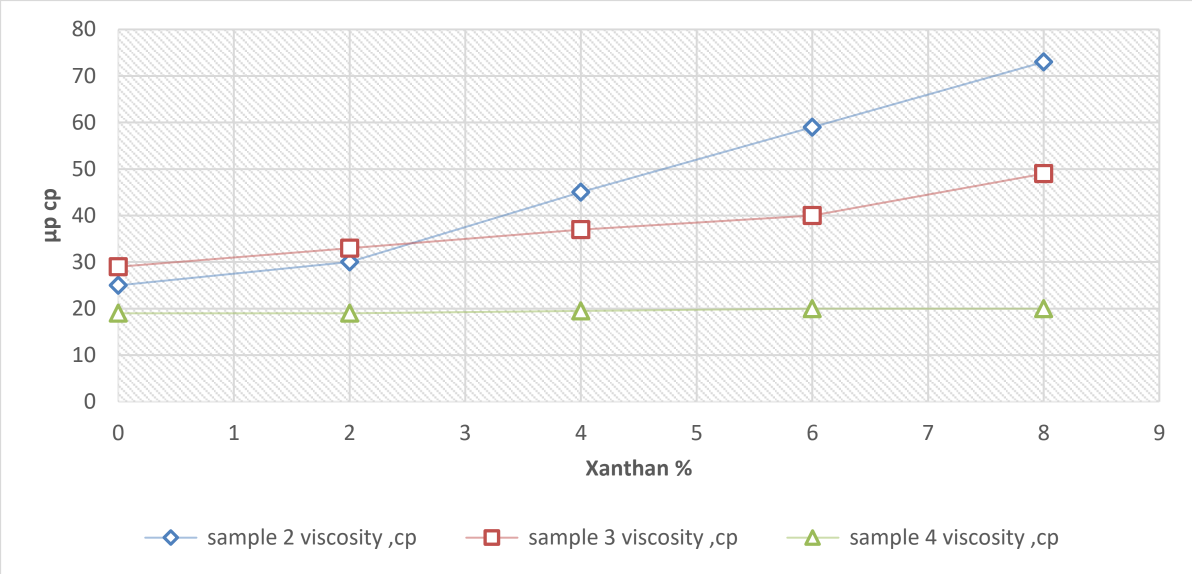

Fig. 5 Relationship between plastic viscosity and xanthan concentration for 3 samples

5. CASE STUDY:

Formation water has almost the same effect, as it is considered the second source of salts and ions that affect the drilling mud. The percentage of contamination of the drilling mud of one of the wells (well X) in southern Iraq was measured from a depth of 120 meters to 3200 meters, where the measurement was a measure of the ratio of the solid matter with the depth as in Fig.6. Whereas, the Dammam Formation at a depth of 720 meters contains saline and sulfuric waters, and the Umm Al Radhumah Formation at a depth of 995 meters contains sulfuric waters. Also, the Formation of the Tayarrat contains sulfuric and salty waters. Where the field treatments are according to the percentage of contamination. If the percentage of pollution is less than 5%, then the slurry is diluted with water. If it is greater than 5% and less than 15%, viscosity thinners are added. In the case of a percentage higher than 15%, materials with the precipitation of salts as in the figure, where silica fume was added to increase the viscosity as shown in Fig. 7. Finally, in case the percentage is higher than 20%, it is preferable to get rid of the mud, because in this case the treatment is considered expensive. Table 5 represents a case study of drilling mud returning from the well. The properties of the drilling fluid were measured before drilling, then its properties were measured after contamination with formation water, and finally its properties were measured after conducting the necessary treatment. Where the table indicated that there is pollution that led to an increase in salinity due to the presence of sodium chloride salts in the formation water and a decrease in the pH value as a result of the formation water containing a percentage of hydrogen sulfide and an increase in viscosity due to the presence of calcium and magnesium salts. As for the treatment, it was by using water at a rate of 10% for dilution to reduce density and reduce salinity. Caustic soda was added at a rate of 3% to increase the pH, and finally, each of sodium carbonate and sparseness at a rate of 5% was added to precipitate calcium ions and reduce the viscosity, respectively. It is observed that the rate of pollution increases by 5% for every 250 meters drilled as the drilling progresses.

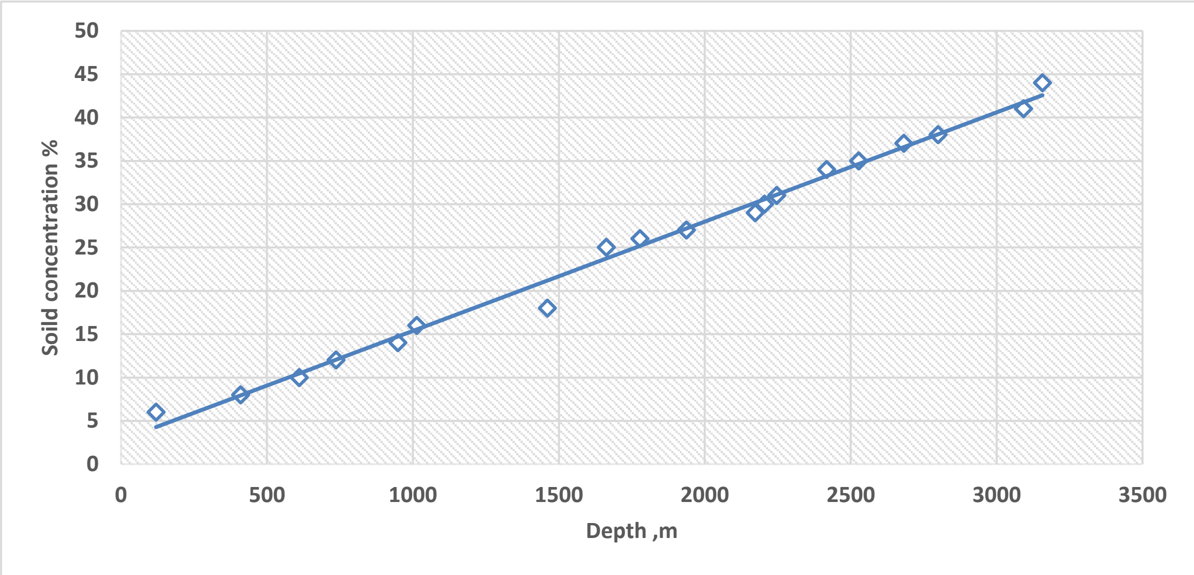

Fig. 6 Relationship between depth and solid concentration for well X

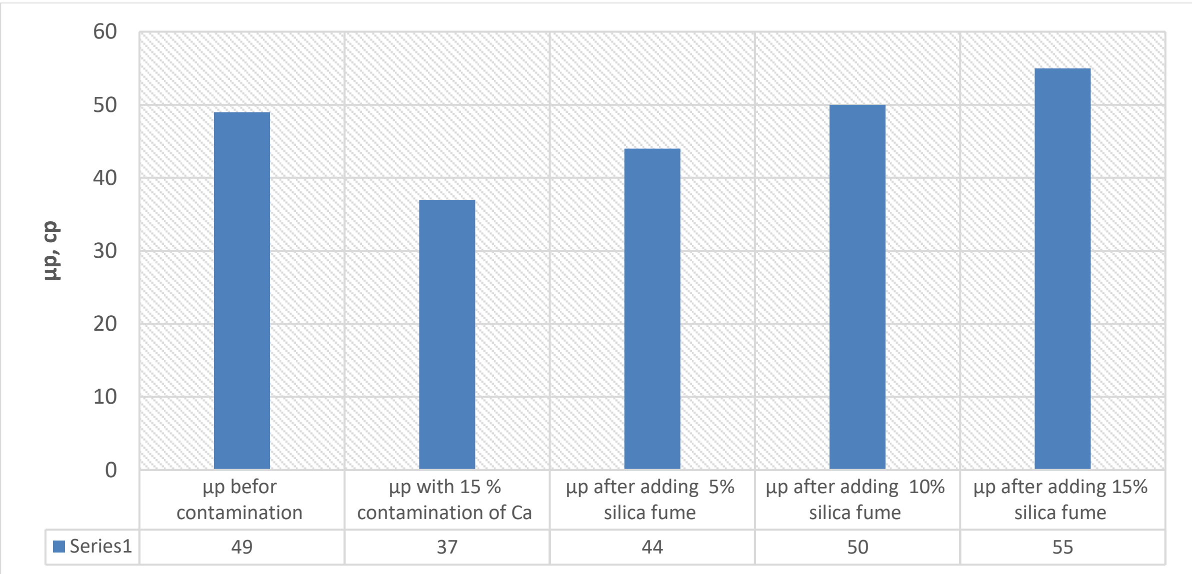

Fig. 7 Relationship between µp and silica fume concentration for well X

Table 5. mud sample properties for well X

Property	Original mud(before drilling)	Return mud(after drilling)	Mud after treatment
salinity	287,000 (mg/l)	465,000 (mg/l)	292000 (mg/l)
sulfate	Non	1694 mg/l	22 mg/l
density	1.18 gm/cc	1.38 gm/cc	1.185
viscosity	48 Cp	64 Cp	49
pH	9.76	9.9	9.75
$CaCl_2$	355gm/l	25,450 gm/l	387gm/l
$MgCl_2$	76 gm/l	4828 gm/l	85 gm/l

6. TREATMENTS COSTS:

It is necessary to point out the costs of the treatments that were used in the study, as Table 6 shows the price of the materials used and the quantity that was used in the study. The cost of treating one liter was $0.013, meaning with a simple calculation, the cost of treating 1000 liters is only $13. This is considered a reasonable number in light of water scarcity. The study included treating contamination with calcium or sodium ions only because of their significant impact on the properties of the drilling fluid, as proven by the results of the study.

Table :6 Cost of treatment of one 1 liter of water.

Material	price ($/ton)	Quantity (gm)	Cost ($/ L)
silica fume	200	10	0.02
Na_2CO_3	180	5	0.009
NaOH	60	1	0.0006
Lime	70	2	0.0014

7. CONCLUSIONS:

After the laboratory study of mud and water samples in addition to the case study of one of the wells in southern Iraq, the following conclusions can be reached:

1-One of the most important conclusions of this study is that the concentration of calcium ions in the water in which the clay is prepared should not exceed 400 mg/l. If this percentage is exceeded, sodium carbonate or barium carbonate should be added at a rate of 5% to precipitate calcium.

2-In the event that the concentration of calcium ions is equal to 1400 mg / l as it is in sample No. 4, treatment using either sodium carbonate or barium carbonate is useless. Therefore, in this case, it is preferable to convert the drilling fluid into a calcareous drilling fluid using lime, as the addition of lime leads to an increase in viscosity.

3-Calcium salts can have a significant negative impact on the effectiveness of polymers, such as xanthan. As the concentration of calcium ions in water increases (between 1000-1400 mg/l), the effectiveness of xanthan decreases.

4-Sodium and calcium salts increase the viscosity at a concentration of 1000 mg/l or less, where the reaction is fast. In case the concentration is higher than that, it works to reduce the viscosity due to the increase in concentration and slow reaction.

5-The contamination with calcium or sodium ions can come from the formation of water during well drilling. In this case, the sludge returned from the excavations must be treated using, for example, water to reduce the salinity. It is also possible to add micro silica to increase the viscosity and reduce filtration. As water treatment leads to a decrease in viscosity, therefore micro silica is added to avoid this.

6-As drilling progresses, the pollution rate increases by 5% for every 250 meters drilled for the studied well.

8. RECOMMENDATIONS:

A potential recommendation for future work is to explore the feasibility of utilizing the water that gets extracted along with the oil during production. It would be beneficial to investigate whether the extracted water can be subjected to appropriate treatments to make it safe for industrial purposes, such as preparing drilling fluids.

9. REFERENCES:

Abbas, A.K, Assi, A.H., Abbas, H., Almubarak, H., Saba, M.A.(2019) .'Drill bit selection optimization based on rate of penetration: Application of artificial neural networks and genetic algorithms' Society of Petroleum Engineers - Abu Dhabi International Petroleum Exhibition and Conference ADIP , https://doi.org/10.2118/197241-MS2019

Abdel-Karim A., Sameh H. Ismail, Ahmed M. Bayoumy, M. Ibrahim, and Gehad G. Mohamed, (2021).'Antifouling PES/CuFe3O4 mixed matrix membranes: Quantitative structure–activity relationship (QSAR) modeling and wastewater treatment potentiality', Chemical Engineering Journal, Vol. 407, 126501, 2021. https://doi.org/10.1016/j.cej.2020.126501

Alameedy U., A. Wattan, A.H. Assi, M. Al-JawaD, (2023) 'Empirical Correlation for Determination of Shear Wave Velocitiesfrom Wireline Logs in West Qurna Oil Field'. *Petroleum and Petrochemical Engineering Journal*, Vol.7,NO 2,pp.1-16. https://doi.org/10.23880/ppej-16000346

Al-Dujaili, A.N., Shabani, M., AL-Jawad, M.S. (2021). 'Characterization of flow units, rock and pore types for Mishrif Reservoir in West Qurna oilfield, Southern Iraq by using lithofacies data'. Journal of Petroleum Exploration and Production Technology, 11(11), 4005–4018. https://doi.org/10.1007/s13202-021-01298-9.

Al-Fandi, E.I., Hadid, N.A., (2020) 'Sequence stratigraphy, depositional environments and reservoir characterization of Sa'di Formation in East Baghdad and Halfiya oilfields'. The Iraqi Geological Journal.21–35. https://doi.org/10.46717/igj.53.1C.2Rx-2020-04-02

Amel H. A., Haiwi A.A. (2023), 'Aspects that affected by crude oil prices after Covid-19 and the impression of that in Iraq', AIP Conf. Proc. Vol.2809 (1), 040012. https://doi.org/10.1063/5.0143513

Amel H.A., Faleh H.M. Almahdawi,(2020). 'Experimental study of micro silica behavior and its effect on Iraqi cement performance by using x-ray fluorescence analysis'. Iraqi Geological Journal. Vol.53, No. 2E .https://doi.org/10.46717/igj.53.2E.5Ms-2020-11-27

Andreozzi R., M. Canterino, I. Di Somma, R. L. Giudice, R. Marotta, G. Pinto,A. Pollio.(2008). 'Effect of combined physico-chemical processes on the phytotoxicity of olive mill wastewaters.' Wat. Res., 42, 1684–1692. https://doi.org/10.1016/j.watres.2007.10.018

Assi A.H., (2023). 'The Geological Approach to Predict the Abnormal Pore Pressures in Abu Amoud Oil Field Southern Iraq'. Iraqi National Journal of Earth Science.23(2):250-265. http://dx.doi.org/10.33899/earth.2023.140601.1088

Assi A.H., Haiwi, A.A., (2021). 'The Effect of Weighting Materials on the Rheological Properties of Iraqi and Commercial Bentonite in Direct Emulsion'. Iraqi Geological Journal, 54(1F), 110-121. 2021-06-30 https://doi.org/10.46717/igj.54.1F.10ms

Assi, A.H.'' The effect of some materials on funnel viscosity reading in water base mud Iraqi Geological Journal,53(1), pp. 32–43

Assi, A.H., Rasheed, Z.F. (2024) 'Studying the Effect of Geological Formation and Formation Water on Drilling Fluid Performance (Case Study)'. Pet. Chem. 64, 739–746. https://doi.org/10.1134/S0965544124050013

Ayad,A. S. Safaa, A.H. Assi (2015). 'Bit Performance in Directional Oil Wells', *Journal of Engineering.*21(11),80-93. https://doi.org/10.31026/j.eng.2015.11.05

Dolz M., J. Jiménez, M. Hernández, J. Delegido, A (2007). 'Casanovas,''Flow and Thixotropic of Non-Contaminating Oil Drilling Fluids Formulated with Bentonite and Sodium Carboxymethyl Cellulose', *Journal of Petroleum Science and Engineering*, 57(4). Pp.22-33. https://doi.org/10.1016/j.petrol.2006.10.008

Idan, R. M., Salih, 2020, A. L. M., Al-Khazraji, O. N. A., Khudhair, M. H. 'Depositional environments, facies distribution, and porosity analysis of Yamama Formation in majnoon oilfield'. Sequence stratigraphic approach. Iraqi Geological Journal, 53(1D), 38-52 https://doi.org/10.46717/igj.53.1D.4Rw-2020-05-03

Tavakkoli M., S. Panuganti, V. Taghikhani, M. Pishvaie, W. Chapman,(2014) 'Understanding the polydisperse behavior of 299 asphaltenes during precipitation', *Fuel journal*, vol. 117 No. 7, pp. 206-217, https://doi.org/10.1016/j.fuel.2013.09.069

Zhao, J., Huang, W., Gao, D. and Zhao, L., (2022). 'Mechanism analysis of the regular pipe sticking in extended-reach drilling in the eastern South China Sea'. 56th U.S. Rock Mechanics/Aeromechanics Symposium. https://doi.org/10.56952/arma-2022-0563