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Full length research paper

Environmentally Friendly Water-Based Drilling Fluid for Drilling of Water-Sensitive Formations

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Abstract

Drilling of shale and clay-rich geological formations are always challenging because of their instability and water sensitivity. Oil-based drilling fluids (OBDF) are widely used in drilling operations, especially in highly technical wells. OBDF systems perform much better than water based drilling fluid (WBDF) in borehole stabilization and they allow faster penetration rates. Additionally, one of the most important features of OBDF is its high lubricity especially for deviated wells. Although OBDF prevents many problems of drilling the shale formations, they have negative impacts on the environment. So, there are many efforts to replace them by a water based and environmentally friendly drilling fluid. In this research, by investigation of drilling history and according to the results of studies accomplished on Iranian shale formations, a water-based and environmentally friendly drilling fluid has been developed. This fluid has improved properties such as high filtration control, reduced formation damages, diminished clay activities, stability against high temperature, cutting stability, acidity alteration and compatibility with any contaminations which may be entered to the drilling fluid during the drilling operations. Lubrication and cutting (shale cuttings) removal of this developed fluid are superior. New additives containing meshed solid particles, inhibitive agents and synthesized polymers were used to develop this fluid

Keywords: Environmentally friendly drilling fluid; Borehole Instability; Shale; Water Based Drilling Fluid; Oil Based Drilling Fluid; Glycol

INTRODUCTION

Principal components of drilling fluids are water, oil/gas, and chemical additives. These components form the basis of the classification of drilling fluids. Drilling fluids are suspension of solids in either water or oil, which can be mixed with other substances, called additives (Apaleke et al., (2012).The principal functions of the drilling fluids are to: (1) carry cuttings from beneath the bit, transport them up the annulus, and permit their separation at the surface; (2) cool and clean the drilling bits; (3) reduce friction between the drilling string and the side of the hole; (4) maintain the stability of uncased sections of the borehole; (5) prevent inflow of fluids from permeable rocks penetrated; (6) form a thin, low permeable filter cake which seals pores and other openings in formations that penetrated by the bit, and (7) assist in the collection and interpretation of information available from drilling cuttings, cores and electrical logs(Apaleke et al., 2012, Hossain and Al-Majeed,2012) Generally, drilling fluids could be classified into three major categories. Water Based Drilling Fluid (WBDF); Oil Based Drilling Fluid (OBDF); and Gas Based Drilling Fluid (GBDF) (Apaleke et al., (2012).

Oil-based drilling fluids have some advantages that make them especially desirable to drill certain types of formations such as shale and clay-rich geological formations. OBDFs cause fewer problems during the drilling of shale formations and allow drilling of salt zones with minimal dissolving of salt. They generally provide with better performance in very hot or very cold environments. However, there are more costs and potential pollution problems which make it a bad choice for environmentally sensitive areas. OBDFs are in varying degrees of toxicity. Also, it is difficult and expensive to dispose them in an environmentally friendly manner (Adesina et al., 2012). Basically, due to increases in environmental legislation against the disposition of OBDF and increases in environmental awareness, there is need for drilling companies to come up with superior drilling fluids. Drilling fluids should have little or no aromatic contents. Also, it is necessary to be biodegradable and end having no health hazard to drilling crews and the host community (Adesina et al., 2012).In short, there is the urgent need for the drilling fluids industry to provide alternatives for OBDFs (Adesina et al., 2012).Hence, environmental and economical considerations have led to increasing use of water-based drilling fluids in operations where OBDFs have previously been preferred, including high-temperature, high pressure (HTHP) wells (Jorge and Steve, 2010).

Development of environment-friendly drilling fluid

The current trend in drilling fluid development is to come up with novel environmentally friendly drilling fluids that will rival the OBDF in terms of low toxicity level, performance, efficiency and cost. Several researchers have come up with formulations of drilling fluid with minimal but not zero environmental impact. Hossain et al. (2012) formulated an improved water based drilling fluid based on soluble silicates capable of drilling through heaving shale which is environmentally friendly(Hossain and Al-Majeed,2012). But this is not recommended because silicate has the potential to damage the formation. Van Oort et al. (2003) suggested the use of micro-sized spherical mono-sized polymer beads as a blend to WBDF to improve lubrication (Van Oort, 2003).Thaemlitz et al. (1999) formulated a new environmentally friendly and chromium-free drilling fluid for HPHT drilling based on only two polymeric components (Thaemlitz et al., 1999). Brady et al. (1998) came up with a poly-glycol enriched water based drilling fluid that will provide high level of shale inhibition in fresh water and low salinity water based drilling fluid (Brady et al., 1998).

However, this formulation has a defect in that for it to perform optimally, electrolytes must be present. Nicora et al. (1998) developed a new generation dispersant for environmentally friendly drilling fluids based on zirconium citrate. The zirconium citrate functions to improve the rheological stability of conventional water based fluids at high temperature. However, this formulation has a limitation in that the concentration of zirconium citrate may be depleted in the drilling fluid due to solids absorption (Nicora and Burrafato, 1998). To avoid some of the above mentioned problems, Dasunmu et al. (2010) developed an environmentally friendly drilling fluid which can effectively replace oil based drilling fluid by using eco-friendly polymers derived from tamarind gum and tragacanth gum (Dasunmu and Jashua, 2010). Tamarind gum is derived from tamarin seed while tragacanth gum is from astragalusgummifier. This formulation is also cheaper and has less damaging effect on the formation. Hector et al. (2002) developed a formulation with a void toxicity based on a potassium-silicate system (Hector et al., (2002).

The advantage of this formulation apart from being environmentally friendly is that cuttings from the use of this drilling fluid can be used as fertilizers. Warren et al. (2003) developed a formulation based on water-soluble polymer amphoteric cellulose ether (ACE) which is cheaper, low in solids content, environmentally friendly but with some potential to damage the formation (Warren et al., 2003). Davidson et al. (2004) developed a drilling fluid system that was environmentally friendly (Davidson et al., 2004). It also removes free hydrogen sulphide which may be encountered while drilling based on ferrous iron complex with a carbohydrate derivative (ferrous gluconate). Ramirez et al. (2005) formulated a biodegradable drilling fluid (Ramirez et al., 2005). It maintains borehole stable and makes it possible to drill through the sensitive shale formations based on aluminum hydroxide complex (AHC). This formulation contains some blown asphalt and hence posses some environmental problems. Dosunmu et al. (2010) developed an oil based drilling fluid based on vegetable oil derived from palm oil and ground nut oil (Dosunmu and Ogunrinde, 2010). The fluid did not only satisfy environmental standards, it also improved crop growth when discharged into farm lands. All these efforts of the researchers brought the drilling fluid technology in a responsible position which is environmentally friendly and cost effective up to some extent. However, these formulations do not have zero environmental impact yet (Apaleke et al., 2012).

In this study, a systematic experiment design method was employed to obtain an environmentally friendly WBDF formulation to reduce wellbore stability problems which are linked to the shale formations.

Investigation of wells instability parameters

True characterization of shale formations is the first step to design inhibitor fluids. In order to have precise shale characterization tests, shale samples must retain their initial properties and characteristics. General information such as field's location, depth, temperature, general geology of the region, structural geology and tectonic information and so forth were available from different references. The other step of characterization is the history of drilled wells in the area of interest. Formations characteristics, drilling fluid and its properties, the contact time of drilling fluid and the formations, encountered problems' types and the selected solutions for those problems and their results are of accessible data from drilling history that are very helpful in this investigation. The next step of investigation was direct identification of shale samples. In this step, qualitative and quantitative mineralogy of shale samples have been investigated. Characterizing experiments were SEM photos from shale samples, measuring ion exchange capacity of core

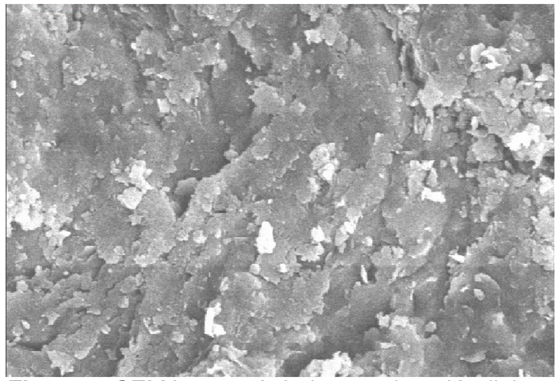


Figure 1: SEM image of shale sample 1; Kaolinite hexagonal crystals tightly held in a nonporous matrix of calcite and quartz

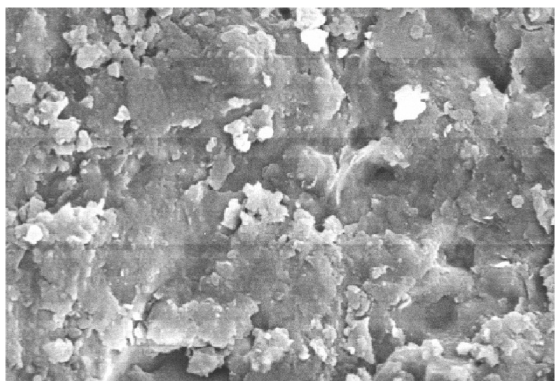


Figure 2. SEM Image of Shale Sample 2; Kaolinite Crystals in a Matrix of Calcite and Quartz

Table 1. CEC of formation samples determined by methylene blue test.

Sample	PH	CEC (milliequivalent/100 gr)
1	2.32	2.1
2	2.45	4
3	2.8	8.1

samples and gamma ray spectrometry. The SEM images, figures1 and 2, show the presence of kaolinite clay minerals in a matrix of quartz and calcite and the non-existence of permeability and porosity (or the state of zero porosity and zero permeability). Table 1 shows the results of the methylene blue test. Kaolinite has low cation exchange capacities. Results of CEC show the low activity of clay minerals. Swelling clays have high CEC values. So, the results confirm the absence of swelling clay minerals in shale samples. Also, XRD (X-ray Diffraction) experiments were conducted on Bulk samples. Due to existence of some clay minerals, clay minerals extraction experiments using thermal, normal and ethylene saturated methods were also conducted on samples to and the samples were collected. Figures 3, 4 and 5 show the XRD patterns of the samples.

Moreover, petro-physical graphs were used to determine the location, type and the amount of shale formations. In addition, these graphs were used to predict formation pore pressure and determination of wellbore instability like wellbore collapse. Due to some studies and identifications which were performed on Iranian shale formations, these formations' properties might be classified as follow:

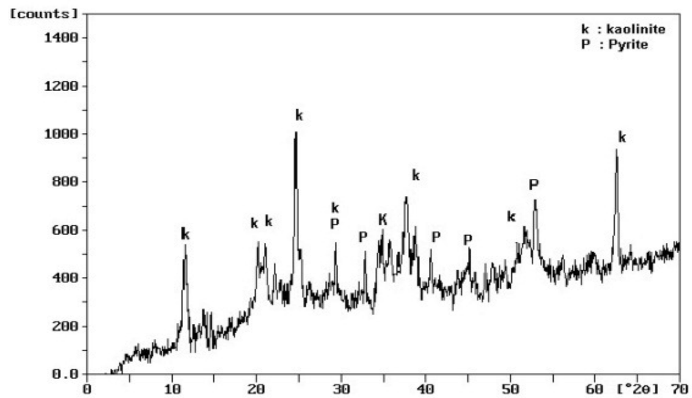


Figure 3. XRD Pattern of the Sample 1

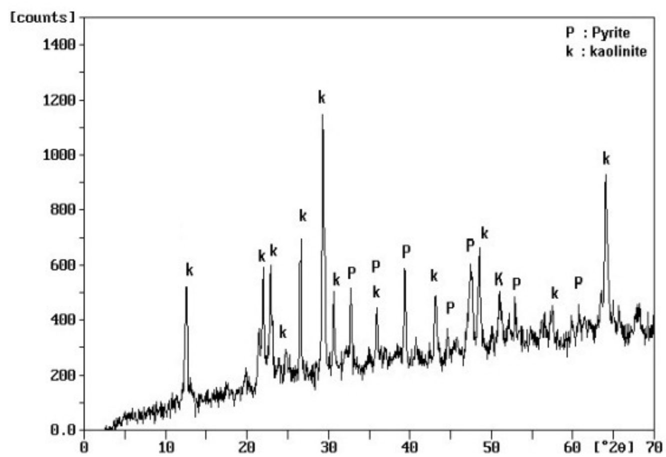


Figure 4: XRD Pattern of the Sample 2

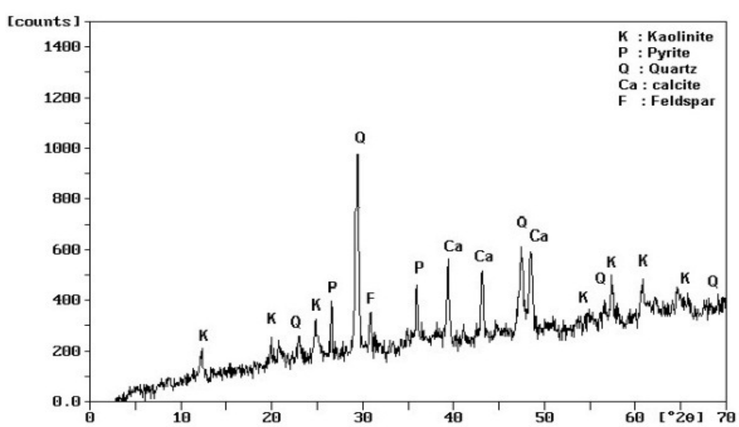


Figure 5. XRD Pattern of the Sample 3

1. The most important instability in shale formations of investigated field is shale swelling and washout.
2. Water intrusion into the shale cracks or hydration of clay minerals and shale flocculation or even mechanical instability as a result of tectonic tensions in brittle formations could also be the reason of shale's washout. Also, the effects of drilling fluid hydration and reaction between rock and fluid or plastic deformation could be

the reason of wellbore collapse in drilling operations in these fields.

3. Based on the relative well stability of drilling using OBDFs, the main reason for shale instability in investigated fields found to be the reaction of the shale with WBDFs.

4. Instability as a result of high pressure is also eliminated because of the normal pressure of these fields' formations.

5. Wellbore instability could have mechanical origin too, since OBDFs do not necessarily stabilized the wellbore

Wellbore instability control

Based on the field's geology and drilling and petro-physics data, existence of both swelling and washing out shale rocks have been proved. Considering the possibility of the effects of different parameters on the shale instability, a proper WBDF with the following properties is recommended:

1. Minimum probability of reaction with shale (hydration and swelling).
2. Controlled rheological properties in order to reduce the shale instability.
3. Minimum lost filtration.
4. Mud weight in a proper range.
5. Stability against temperature and contaminations.
6. Ionic exchange stabilizing capability.
7. Low damages to the pay zone.

MATERIALS AND METHODS

Materials

Considering the wellbore condition and expected drilling fluid properties and based on several experiment, the best proper materials and additives have been chosen to formulate this environmentally friendly WBDF which are as follows. Note that the drilling fluid weight is 75 pcf and it could be easily changed into other mud weights.

a. Sea water:

Seawater is the most common and available water.

b. Sodium Bicarbonate:

To remove water hardness and improve initial drilling fluid which has contaminated with cement or lime (divalent ions removal).

c. Polymers; filtrate loss controlling:

Some advantages of these Polymers are listed as follows:

1) New and quite synthetic with similar polyacrylamide functions.
2) Filtration loss controller in high temperature.
3) Applicability in alkaline salt and soiled alkaline environments.
4) Stability against contaminants.
5) Provide proper mud cake.
6) Having a thinner effect.
7) Non-damaging to the formation (dissolved in acid).
8) Environmentally friendly.

d. PHPA polymer:

Partially hydrolyzed polyacrylamide (PHPA) is a polymer which has shale covering effect.

e. Viscosifying polymer:

XC biopolymer is used to provide viscosity.

f. Salts:

Potassium chloride and sodium chloride are two types of salt that have been used in drilling fluid formulation.

g. Glycol:

Glycol is added as a shale stabilizer.

h. Solid bridging material:

A new design of sized grain calcium carbonate together with polymer is used to control filtration loss (weight adjustment and drilling fluid providing).

i. Potassium Hydroxide:

Potassium Hydroxide is used to increase pH and supply potassium's ions in drilling fluids contain potassium. (pH adjustment)

Testing procedure

A stepwise program to design a drilling fluid to be suitable for drilling a shale formation could have the following steps:

1. Drilling fluid weight determination
2. Drilling fluid rheology characterization
3. Designing to prevent drilling fluid and filtration invasion into the formation.
4. Alteration of clay mineral to less active minerals.
5. Drilling fluid pH control.
6. Investigation of the electrolyte contaminates' effects on the drilling fluid.
7. Investigation of the stability in high temperature and durability.
8. Pay zone damage determination.
9. Investigation of drilling fluid lubricity.

The purpose of this study was to gain the most appropriate chemical composition, rheological properties, low filtrate loss, clay and shale stability and alteration to less active ones, cutting stabilization, reduction of formation damage, drilling fluid stability against high temperature, pH alteration and mixing with contaminations in drilling fluid. The best formula for the proposed drilling fluid has been designed at the weight of 75 pcf which is shown in table 2. Basically, by performing various experiments and replacing some materials and changing the amounts of the components the required properties of the desired drilling fluid have been reached. Drilling fluid properties have been measured firstly after 24 hours aging and then at the temperature of 140 °F, after 16 hours hot rolling at 250 °F which are shown in Table 3.As the results are shown in Figure 6 and Table 3, the drilling fluid rheology before and after the hot rolling is

Table 2. Environmentally friendly WBDF components

No.	Component	Amounts	Mixing Time
1	sea water	300 cc	
2	Sodium Bicarbonate	2 gr	1 min
3	Synthesized polymers, Filtrate loss controller	3+5 gr *	20 min
4	PHPA polymer	1.5 gr	20 min
5	XC biopolymer	1.3 gr	20 min
6	KCl	20 gr	10 min
7	NaCl	86 gr	10 min
8	Glycol	20 cc	10 min
9	solid bridging material (Sized Calcium Carbonate)	8 gr	5 min
10	Potassium Hydroxide	0.5 gr	5 min

* Two kinds of polymers have been used

Table 3. Environmentally friendly WBDF components

No.	Fluid properties	After Hot rolling	Before hot rolling
1	apparent viscosity (cp)	19	32
2	plastic viscosity (cp)	10	27
3	yield point (lbf/100 ft^2)	15	24
4	10 sec gel strength (lbf/100 ft^2)	3	6
5	10 min gel strength (lbf/100 ft^2)	4	7
6	filtrate loss (cc)	2	-
7	pH	8	8
8	drilling fluid weight (pcf)	75	75

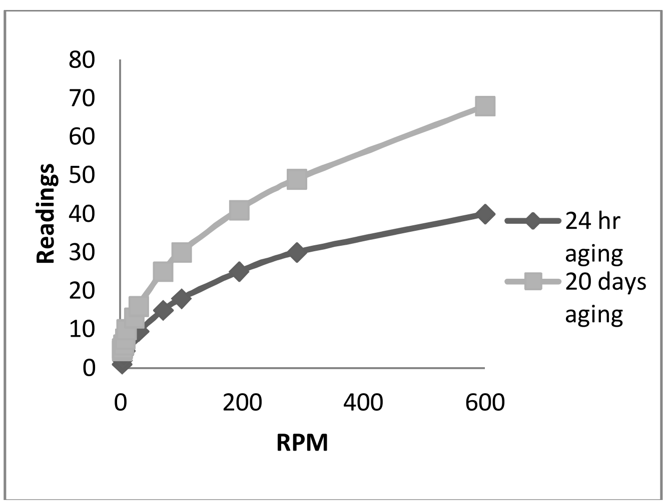


Figure 6. Drilling fluid rheology

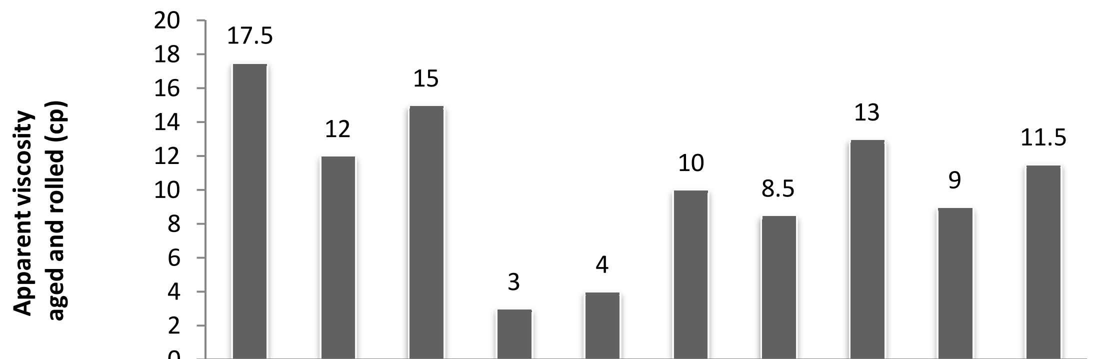
highly appropriate. Also, filtrate loss has been diminished by temperature because of special synthesized polymers which have been used in the formulation. Mud cake unity and thickness are also suitable in wellbore that will lead to prevent well diameter reduction and eliminate the risk of differential pressure sticking.

RESULTS AND DISCUSSION

This drilling fluid has been recognized as a suitable and high performance substitute for OBDFs because of some reasons such as being environmentally friendly, its superior performance in stabilizing of shale formations,

Table 4: Lubricity effect comparison between two different drilling fluids

OBDF friction coefficient (psi)	36138
Formulated WBDF' friction coefficient (psi)	35687



	plain sample	sample contaminated with seawater	sample contaminated with bentonite	sample contaminated with lime	sample contaminated with cement	sample contaminated with Acid	sample contaminated with sodium hydroxide	sample contaminated with calcium hydroxide	pre-treated sample for exposing to cement	pre-treated sample contaminated with cement
Apparent viscosity	17.5	12	15	3	4	10	8.5	13	9	11.5

Figure 7. Contaminations' effects on apparent viscosity

low cost, its excellent lubricity and most importantly it won't damage the reservoir formation and maintain the productive zones' permeability after the drilling operation. Toxicity of this WBDF is considerably low and disintegrate of that in the environment is satisfying. Combination of capabilities such as ion exchange capacity, shale encapsulation because of polymers and Glycols' inhibitory effects along with low filtrate loss can increase the shale inhibitory of this environmentally friendly WBDF up to an OBDF. Moreover, this formulated WBDF prevent from balled-up bit. Also, it's able to release the stuck pipes. In general, it can be claimed that it was tried to consider all parameters that has effect on wellbore stability in shale and clay-rich formations. However, more studies in this field still are recommended.

Analyzing of pollutant's effects on the formulated drilling fluid

During the drilling operations, the drilling fluid would be contaminated by various impurities and its physical and chemical properties would constantly change. Common impurities in the drilling industry are sea water, activated solids (clay), lime, acid gas, cement, gypsum (which may enter to the drilling fluid system in liquid phases) solids and gases during the drilling of different formations. Therefore, an appropriate drilling fluid must be designed with minimum changing capacity in physical and chemical properties against impurities. If necessary, it should be capable to being treated chemically and physically (physical removal) easily. Experiments have been continued by adding impurity to analyze their effects and to consider the appropriate treatments for them during the operations. Hence, Drilling fluid samples have been exposed respectively to 15 volume percent of sea water, 15 gr bentonite, 5.8 gr lime, 5.8 gr cement, 2 cc of pure sulfuric acid and 5.8 gr calcium hydroxide, 5.8 gr sodium hydroxide . Then, the samples' properties have been examined at the temperature of 140°F, after 24 hours aging and 16 hours hot rolling at 250 °F. Figures 7 to 13 show the properties of contaminated fluid samples compared to the plain drilling fluid properties.

Drilling fluid durability

In this analysis, the drilling fluid samples have been aged and hot rolled for 16 hours under temperature of 250°F.

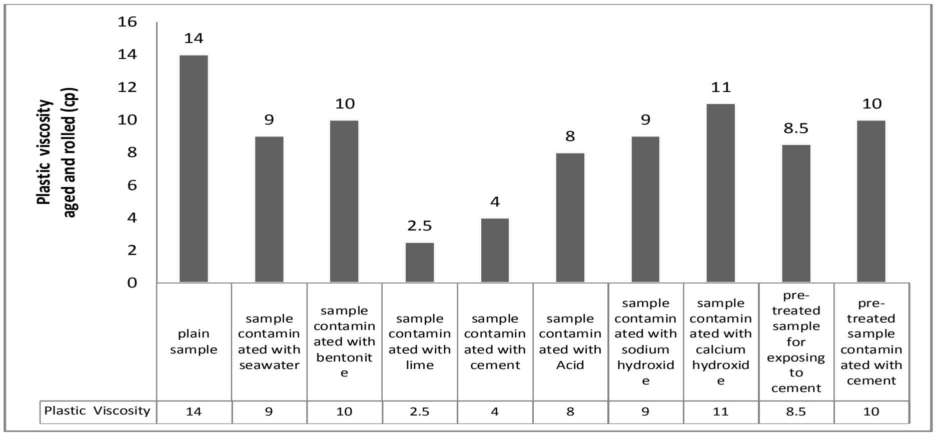


Figure 8. Contaminations' effects on plastic viscosity

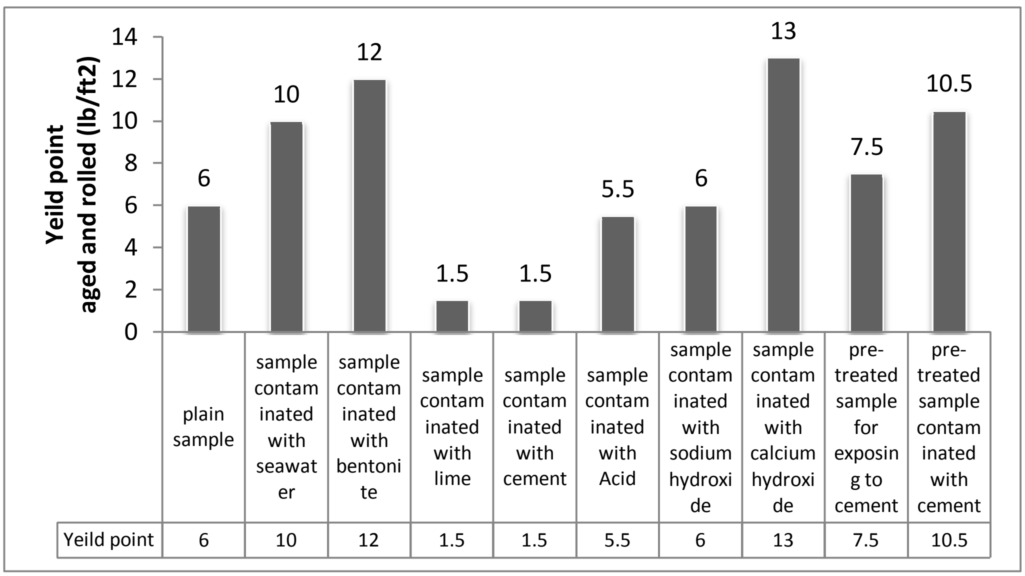


Figure 9. Contaminations' effects on yield point

Then, the properties of drilling fluid have been measured. Next, it has been placed in a sealed container for 20 days and after that period the properties have been measured again. Obtained results show superior stability of this samples over time and no physical changes (two phases) found in fluid system by passing time and rheological properties of the fluid remains relatively constant. Rheological changes by time have been compared with plain fluid sample's properties in Figures 14 and 15.

Lubricity analysis

An appropriate drilling fluid must has lubricity effects and decrease the friction between drill string and the wellbore and diminish drag and torque forces. Having low torque and drag forces are very critical and important especially in directional drilling. Some additives such as glycol and synthesized polymers are responsible for lubricity properties in this proposed environmental friendly and WBDF. Lubricity can be measured by using of "E-P MUD TESTER". The friction coefficient of this formulated drilling fluid has been compared with an OBDF. The results are shown in Table 4 illustrate satisfactory performance of the proposed formulated WBDF. It proves that its lubricity is so close to OBDFs lubrication effect.

Ion exchange capacity and reduction of clays activities

Inhibitor fluids are able to alter the clay's nature to less active clays(inorganic clays). Application of potassium salt in WBDF formulation has been led to potassium

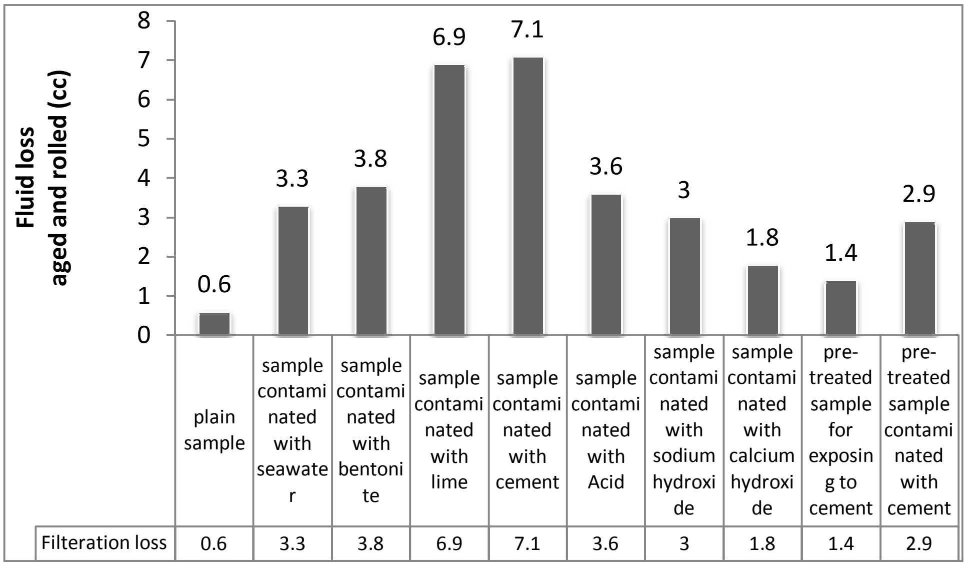


Figure 10. Contaminations' effects on filtrate loss

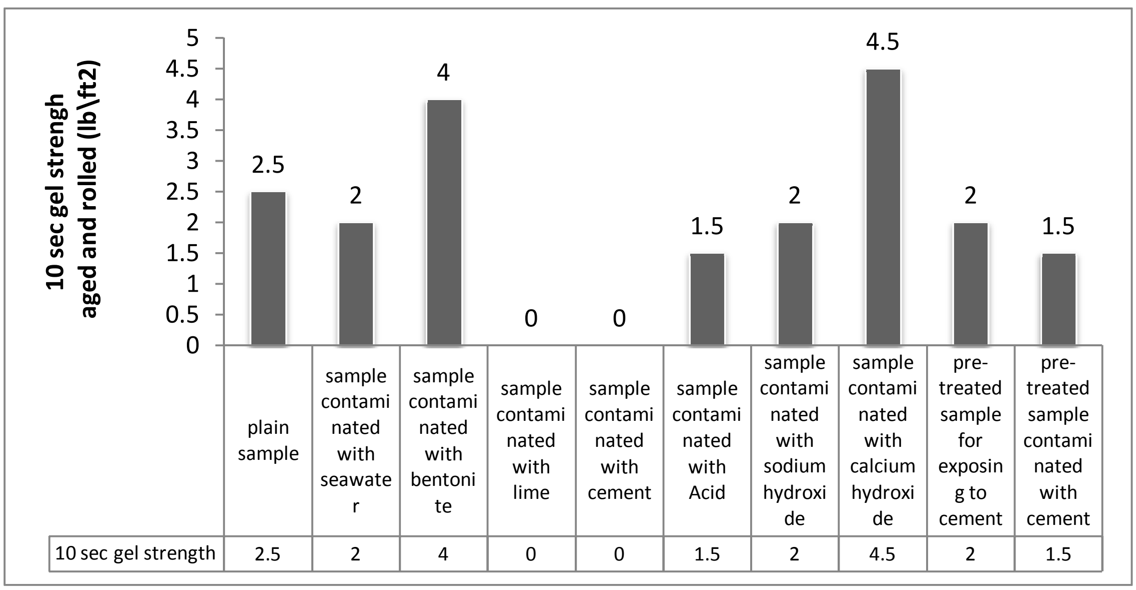


Figure 11. Contaminations' effects on 10 sec gel strength

Cations exchange and consequently to more stable shale (Van Oort, (2003). Increasing of rolled drilling cuttings' hardness and compaction is a valid proof of successful improvement of this environmentally friendly drilling fluid. Although, all additives are high soluble in common acids and elimination of probable damages are uncomplicated, reduction of formation damage is a valuable result of utilized polymers those are responsible for decreases in filtrate losses and has been provided a thin low permeable mud cake.

Drilling fluid-shale interactions

Due to the lack of enough shale samples, bentonite was used to examine ability of drilling fluid in stabilizing the shale and clay-rich geological formations. Bentonite is a kind of shale that contains 100% of inorganic Montmorillonite clays and is known as the worst kind of swelling shale. In this test API -13AI (Recovery Hot Rolling) standard has been used to analyze how much this fluid will act as an inhibitor. In this test, 21.3 gr of

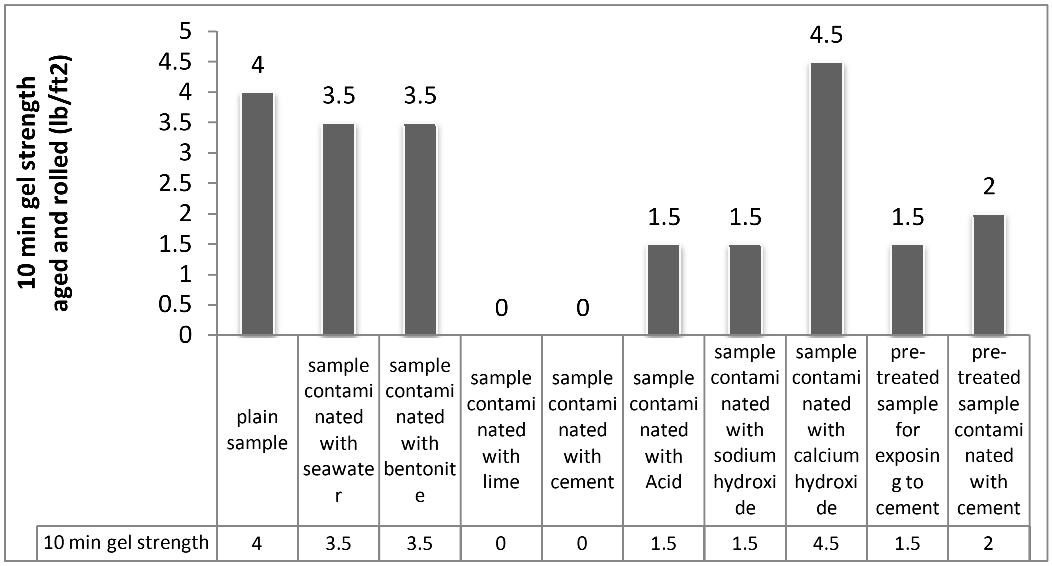


Figure 12. Contaminations' effects on 10 min gel strength

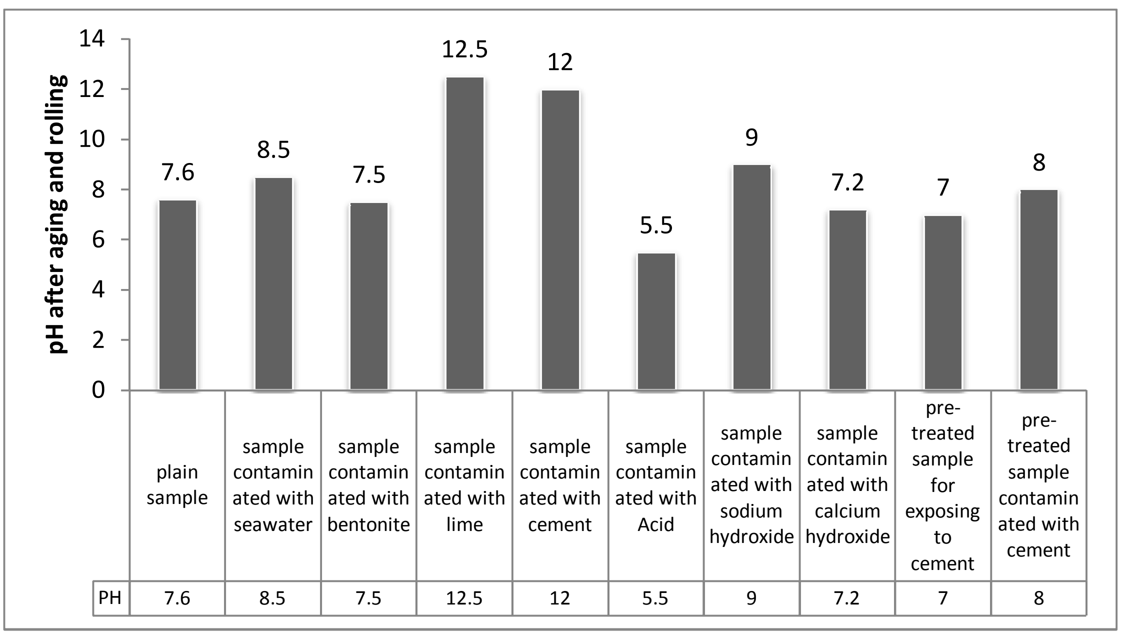


Figure 13. Contaminations' effects on drilling fluid's pH

bentonite particles (mesh size of 5-10) has been chosen and hot-rolled for 17 hours at 250℉ in the formulated WBDF. 19.4 gr of bentonite particles have been retrieved on 35 mesh screen after drying by heater. In other words, in this WBDF 96.4 % of bentonite particles are recoverable.

Considering high swelling potential of bentonite, this noticeable bentonite recovery demonstrates the capability of formulated WBDF in stabilizing of the shale and clay-rich geological formations. For comparison, the results of shale cuttings recovery test for different kinds of fluids are shown in Figure 16. According to this figure, shale recovery of this WBDF is more than others and it has the closest percentage to OBDF percentage which is approximately 100%. Also, recovered particles are more rigid than before which is due to the effect of

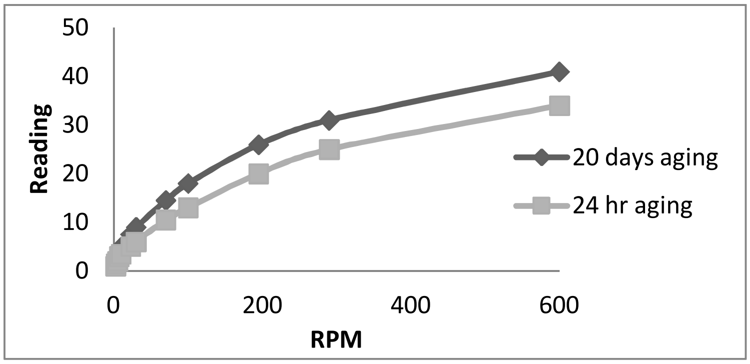


Figure 14: Drilling fluid durability

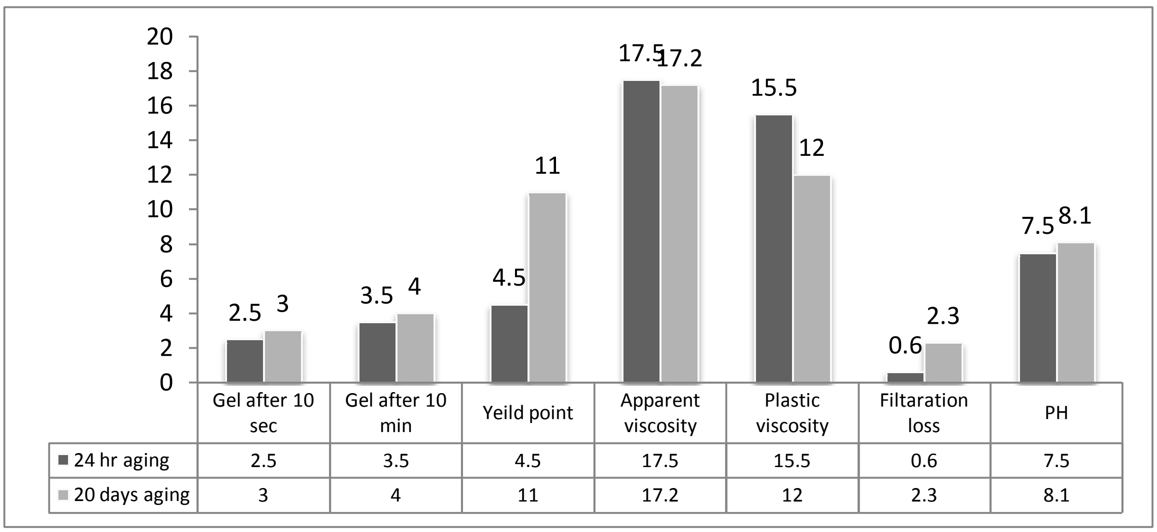


Figure 15 Formulated drilling fluid's properties over time

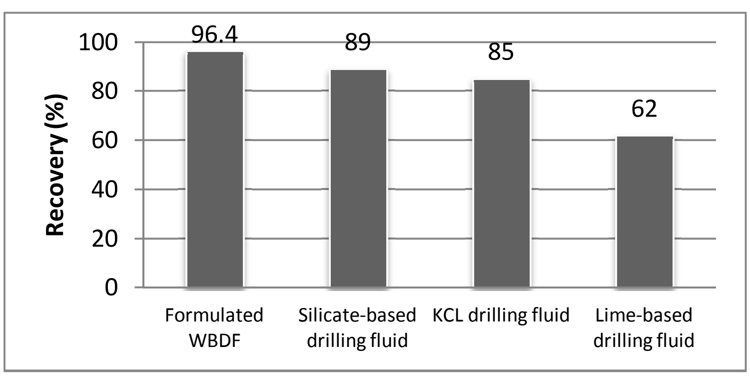


Figure 16. Shale recovery comparison in different kinds of drilling fluids

environmentally friendly formulated WBDF on shale. Increase in rigidness of these particles would improve the wellbore stability.

CONCLUSION

The aim of this study was to formulate an environmentally friendly WBDF which is high efficient on shale and clay-rich formations in Iranian oil and gas fields. The obtained results clearly illustrate the appropriate performances of the formulated WBDF in the well conditions. Results indicate high capability of this drilling fluid to tolerate different impurities except cement and lime. However, the effects of these two impurities on the drilling fluid properties are easily adjustable by using of current optimizing operations at the drilling rig. Furthermore, experimental results show excellent lubricity effect which is so close to OBDFs lubricating levels. Moreover, This WBDF is strongly shale-inhibitive and is comparable to OBDFs. In addition, this WBDF has very low toxicity level and it's decomposition in the environment is acceptable. In short, this environmentally friendly WBDF technical's performances are highly improved without causing any noticeable environmental impact on surrounding environment, ecosystems or habitats. So, it can be a reliable substitute for OBDFs.

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