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Original article

Silicon Ethoxide as reversible surfactant in reversible drilling mud and the mud's effect on permeability

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ABSTRACT

Decades of innovation, research and improvements have left drilling fluid vastly different from a mixture of water and clay but are now referred to as non-Newtonian fluids. For optimum well performance for new wells, drillers are to make a choice between drilling with pseudo oil based mud to achieve stability in difficult trajectories and risk permeability impairment; or drill with water based drilling fluid and risk possible drilling instability. Reversible emulsion based muds which can be converted using an acid-base chemical switch from water-in-oil (W/O) to oil-in-water (O/W) emulsion have been suggested as solution in literature. The effect of this acid-base chemical-switch reaction with drilling equipment and personnel prompted this study. Silicon Ethoxide was identified and applied in this study because it has the properties of a reversible surfactant and can be used to formulate a reversible mud that will not react with the drilling equipment nor the formation. Different measurements of Silicon Ethoxide were used, ranging from 5 ml to 45 ml, but we achieved reversibility from 30 ml. Three different base oils (EDC-99, Palm Kernel Oil and Polytriethanolamine) were also used. With the reversed emulsion mud systems, reduction in permeability within the range of 16–19 mD which is minimal was recorded. Thus, this mud system can be used close to the reservoir during drilling operation without encountering significant permeability impairment.

1. Introduction

Drilling operation can be associated with uncertainties due to the nature of formations encountered during the process. The success and cost of completing an oil or gas well many depend to a substantial extent on the properties and compositions of the mud used. Noteworthy advancements and breakthroughs have been recorded in recent years; these technological advancements have positioned the industry around the globe to exploit successfully reservoirs that were not technically and economically possible before now. Decades of innovation, research and improvements have left drilling fluid vastly different from a mixture of water and clay but are now referred to as non-Newtonian fluids (Baldino et al., 2018; Okoro et al., 2015). After prediction and forecast, poor productivity of promising new wells can often be traced to undesirable interaction of the insitu formation fluids and drilling fluid which leads to formation damage. Dabiri et al. (2013) introduced this damage as an unwanted problem that affects exploration of oil and gas reservoirs operationally and economically.

Minimizing these damages when drilling oil and gas wells has an impact on the field development. Additives used for optimizing the rheology of the mud, emulsion stability, lubricity and other wellbore problems contain compounds that can adsorbed on the formation. These adsorption process often introduce permeability impairment by blocking the formation pores when it occurs close to the reservoir; Also, long chain polymers, particularly in low permeability porous media where the pores can be bridged by molecules of the polymer (Okoro et al., 2015).

For optimum well performance for new wells, drillers are forced to make a choice between drilling with pseudo oil based mud to achieve stability in difficult trajectories and risk permeability impairment; or drill with water based drilling fluid and risk

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possible drilling instability (Ali et al., 2004). Conventionally, oil based mud in the wellbore is often displaced to a drill-in fluid when drilling the reservoir section (mud change-over). According to Ali et al. (2004), this displacement process oil mud, mud filtercakes and the oil wet state on the wellbore are not completely removed by the clean-up chemicals introduced during the process. Thus, forming an emulsion in the wellbore made up of displacement fluid and the non-displaced oil mud filtercakes. These emulsion and non-displaced filtercakes can flow into the reservoir section, causing formation damage.

Reversible emulsion based muds which can be converted using an acid-base chemical switch from water-in-oil (W/O) to oil-in-water (O/W) emulsion were suggested as solution (Arvind and Frederick, 1999; Ali et al., 2004; Growcock and Harvey, 2005). Popov et al. (2013) called them an inventive approach to harness both optimum performance in drilling and completion operations from a mud system. The reversible switch alters the strength of the emulsifier hydrophilic end alone in the formulated mud to form Oil-in-water or water-in-oil emulsions. Growcock and Harvey (2005) studied these mud systems and observed that the reversibility using the acid-base chemical switch only alters the base fluid that is in continuous phase. The mud system is reversed from oil external base fluid to water external base fluid by acid switch and can be reversed to the initial emulsion using a base (Arvind and Frederick, 1999).

The effect of this acid-base chemical-switch reaction with drilling equipment and personnel prompted this study. Most of these reversible surfactants are strong invert emulsifiers in the presence of lime and regular emulsifiers in the presence of water-soluble acid (Okoro et al., 2015). Silicon Ethoxide was identified and applied in this study because it was found to have the properties of a reversible surfactant and could be used to formulate a reversible mud that will not react with the drilling equipment nor the formation. This reversible surfactant wettability can be altered using ethanol which has less impact on the drilling equipment and tools. Surfactants are amphiphilic molecules that have a hydrophobic tail group with often with carbon chain length and a hydrophilic head group.

2. Surface and interface activity of surfactant

According to Jean-Louis (1994), surfactants active surfaces are amphiphilic and are represented with the symbol H-L. Hydrocarbon chain has a general lipophilic or hydrophobic part of the molecule (L); while the hydrophilic part of the molecule (H) encompasses heteroatoms such as Phosphorous, Nitrogen, Oxygen and Sulphur. Although there are some substances with the amphiphilic type of molecular formula. Theoretically, the overall behaviour of each L-H ionic or neutral molecule which exhibits dual polar affinity, depends essentially on the balance of its hydrophilic and lipophilic features. Moreover, a surfactant solution always exhibits its distinguishing property, whereby if H possess a strong affinity for the solvent, L undergoes a repulsion from it and vice versa. When a surfactant concentration in a solution is high enough, micelles is formed by the surfactant molecules.

It has been observed that at oil-water interface and air-water surface, the medium exhibits sharp and strong changes in polarity in a perpendicular direction to the interface or surface; thus, favouring the orientation of H-L molecules (Jean-Louis, 1994).

The hydrophilic head is saturated with the aqueous solution in this perpendicular position, while the hydrophobic "tail" is positioned at the polar environment in this arrangement.

The available studies by various researchers on the reactions that Silicon Ethoxide (**$Si\ (OCH_2CH_3)_4$**) and its characterization have shown that it can serve as a reversible surfactant (De et al., 2000; Matsuoka et al., 2000; Kamiya et al., 1987; Donatti et al., 2002; Brinker, 1988).

3. Methodology

The experimental studies involve the following:

1. Formulation of reversible emulsion mud with Silicon Ethoxide as reversible surfactant, this process is similar to conventional synthetic base mud formulations and API standard, was applied during the process (Drilling Fluids, API 13B).
2. Rheology study of the reversible emulsion mud, and
3. The effect of the reversible mud on permeability of selected core samples

3.1. Mud formulations and rheology study of reversible emulsion mud

The experimental studies involve the following:

1. Formulation of reversible emulsion mud with Silicon Ethoxide as reversible surfactant, this process is similar to conventional synthetic base mud formulations and API standard, was applied during the process (Drilling Fluids, API 13B).
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3. The effect of the reversible mud on permeability of selected core samples.

The addition of each additive in their proper sequence during mixing of the mud optimizes the performance of each system. A homogeneous mixture of the reversible emulsion drilling fluid was achieved using the API recommended standardized methods for laboratory, recommended practice: standard procedure for field testing water-based and oil-based drilling fluids (Drilling Fluids, API 13B) was followed in the mud formulation; before performing the rheology tests using the Hamilton Bench mixer. An oil water ratio of 75:25 was used to formulate the mud sample (Tables 1).

Different measurements of Silicon Ethoxide were used ranging from 5 ml to 45 ml, but we achieved reversibility from 30 ml. Three different base oils (EDC-99, Palm Kernel Oil and Polytriethanolamine) were also used. EDC-99 is an industrial base oil; thus, we used it as control for the other sourced base oils selected as optimum base oil from literature (Alamu et al., 2008; Al-Sabagh et al., 2010). The first formulation was done without a secondary emulsifier, this step was necessary in other to know if Silicon Ethoxide can function as a surfactant in a mud system.

The procedure for mixing the mud systems are as follow:

1. Addition of the required quantity of base oil to the mixing vessel;
2. Addition of Organophilic Clay as required;
3. Addition of the primary emulsifier and secondary emulsifier as required;
4. Addition of lime as required;
5. Addition of brine;
6. Addition of filtration control additives when required;
7. Mixing of the above for several minutes to ensure a good emulsion was formed; and
8. Addition of weighting material as required for the desired density was added.

After formulating the mud, the densities of the mud systems were determined with the mud balance instrument. The Fann Model 35, 6-speed VG meter was used in this study to measure viscosity. The drilling fluid was subjected to shear rates and their

Table 1
Mud Formulation for 75:25 Oil-Water Ratio.

	Additives	75:25 OIL WATER RATIO		
		Palm Kernel Oil	Polytriethanolamine	EDC-99 Base Oil
1	Oil Volume (ml)	260	260	260
2	Water Volume (ml)	90	90	90
3	$CaCl_2$ (g)	48	48	48
4	Primary Emulsifier (ml)	30	30	30
5	Secondary Emulsifier (ml)	20	20	20
6	Organophilic Clay (g)	4	4	4
7	Barite (g)	120	120	120
8	Lime	2	2	2
9	Caustic Soda	3	3	3

corresponding shear stresses obtained through calculation using Fann rheometer dial readings.

3.2. Formation damage test

The design of apparatus for testing of reservoir core samples with fluids varies with specific objectives and applications. The schematic drawing given in Fig. 1 indicates that primitive core testing systems consist of a core holder, a pressure transducer controlling the pressure difference across the core, an annulus pump to apply an overburden pressure over the rubber slieve containing the core plug, a reservoir containing the testing fluid such as a drilling mud or filtrate, a displacement pump to pump the testing fluid into the core plug, and an effluent fluid collection container, such as a test tube.

There is no temperature control on this system. It operates at ambient laboratory conditions.

When mud filtrate invades the formation surrounding a borehole, it will generally remain in the formation even after the well is cased and perforated. This mud filtrate in the formation reduces the effective permeability to hydrocarbons near the wellbore. It may also cause clays in the formation to swell, reducing the absolute permeability of the formation.

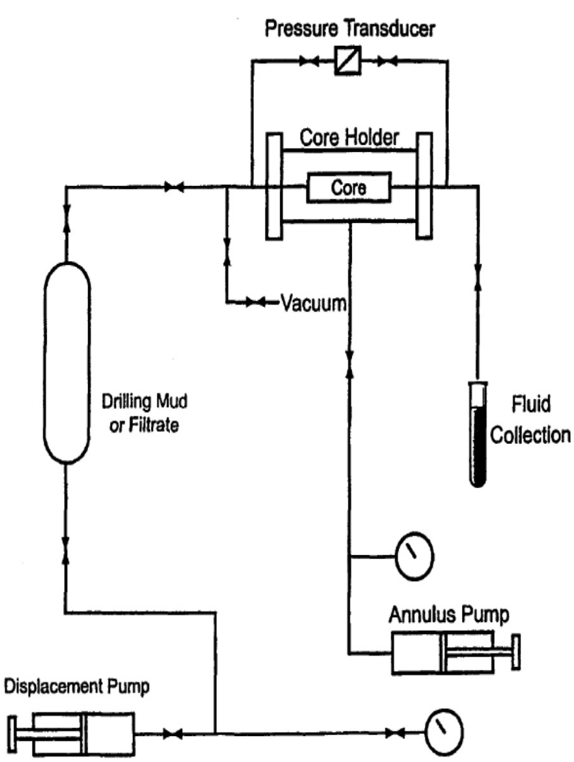

Fig. 1. Primitive drilling fluid evaluation system.

4. Results and discussion

The formulation of the reversible emulsion mud system with Palm Kernel oil (non-treated) as base fluid for 75:25 oil-water ratio formed a thick gel when lime was introduced during mixing (Fig. 2). Probably because of free fatty acids present in the Palm Kernel base oil. Formulation with both ECD-99 and Polytriethanolamine (Poly) gave an excellent Emulsion mud system for 75:25 oil-water ratio. The rheological properties of the mud systems were checked before (ambient temperature) and after hot rolling at 120°F for 24 h.

From the calculations of plastic viscosity and yield point for the reversible invert emulsion mud systems, it can be deduced from the low value of plastic viscosity that the percentage by volume of solids in suspension in the formulated mud systems are low. Also the high values of the yield point indicate increase in the attractive forces by the chemical treatment.

Further analysis was carried out on the reversible mud systems formed with the imported base oil to measure the fluid rheology before and after hot rolling test. The values of Shear Rate (γ) and Shear Stress (τ) were calculated for the mud system. The Rheogram (which is a graph of Shear Rate versus Shear Stress) was developed for the reversible muds before hot rolling (ambient temperature) and after hot rolling at 120°F for 24 h (Fig. 3).

4.1. Reversibility test

Reversibility test in this study is a physical observation test for the mud system, the reversible change from oil-wet to water-wet for one laboratory barrel of mud (350 ml) was obtained using

Fig. 2. Formation of thick gel-mud with Palm Kernel Oil.

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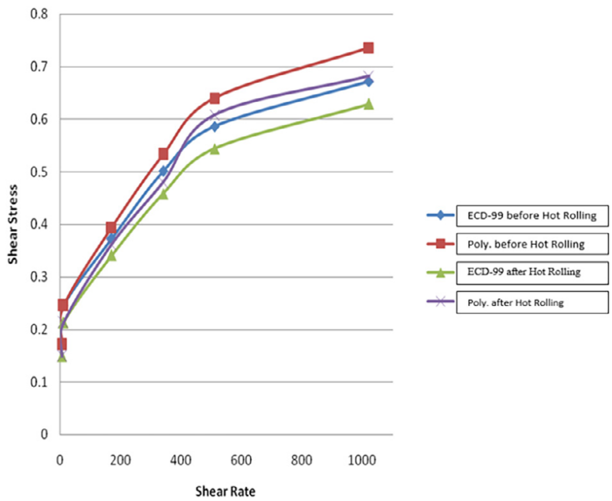

Fig. 3. Rheogram for 75:25 O/W ratio before and after Hot Rolling for the Two Base Oil.

80 ml of 40% ethanol concentration. Fig. 4 showed that the mud reversibility for this study and that of FazePro Invert Emulsion change was similar (Chiriac, 2014 – A study for M-I Swaco).

The beaker in Fig. 4(a) showed an Oil-wet condition with distilled water; it can be observed that the mud behaves as an oil-wet substance because it did not dissipate in the water. Different fluids migrate in different ways depending on their density, viscosity and the wettability. The mode of migration helps to define the distribution of the fluids and one of the fundamental forces that drive, stabilize, or limit fluid movement is gravity. Using gravity effect, we observed that it dropped to the bottom of the beaker without mixing with the water due to higher density and surface tension. Also the oil-in-water emulsion have shear thinning behaviour and the droplets do not allow creaming but it still flow easily. Water-wet, in the beaker with distilled water (Fig. 4(b)) it was observed that the mud behaves as a water-wet substance because it can be seen dissipating in the distilled water and the effect of surface tension is not very significant.

The water-wet condition during this reversible switch is the idea situation for drill-in mud systems. This wetting condition will have minimal effect on the pore fluids and will reduce the reservoir impairment that the oil-wet mud will naturally induce when filtrate enters the reservoir formation. The overriding factor that necessitate this study, is the severity of near wellbore damage by incursion of oil-wet mud systems in the reservoir. This reversible surfactant will readily reverse and minimize the effect of the skin introduced by oil-wet mud systems.

4.2. Effect of drilling mud on well productivity

The main factor that increases the severity of formation damage are the degree of filtrates and solids in the reservoir and their reaction with the formation after their contact. Thus, Laboratory tests are used to determine and simulate these operations in order to know the governing parameters and their possible contribution to formation damage. These tests assist in determining the comparative contributions of several mechanisms to formation damage (Civan, 2000). The fluid-rock interactions were adopted in this study.

5. Permeability reduction and formation damage

When a mud filter invades the reservoir surrounding the perforation, it usually remains in the formation even after the well completion operations. This mud filtrate reduces the effective permeability near the wellbore. It can also cause swelling if it is a clay formation, thus reducing the absolute permeability of the formation.

Having satisfied all the conditions, permeability was determined using Darcy's equation as shown below:

$$Q = \frac{kA\Delta P}{\mu L} \tag{1}$$

where

Q – Fluid flow rate
k – Permeability
ΔP – Change in pressure
μ – Fluid viscosity
L – Length of the core
A – Cross sectional area of the core

Rock permeability, k is a very important rock property because it controls the directional movement and flow rate of the reservoir fluid in the formation (Yong and Jienian, 2008; Shenglai et al., 2008). The matrix damage in the sandstone reservoir core samples was estimated and the permeability estimated. Laboratory test helped to determine the relative contributions of the mud systems to formation damage.

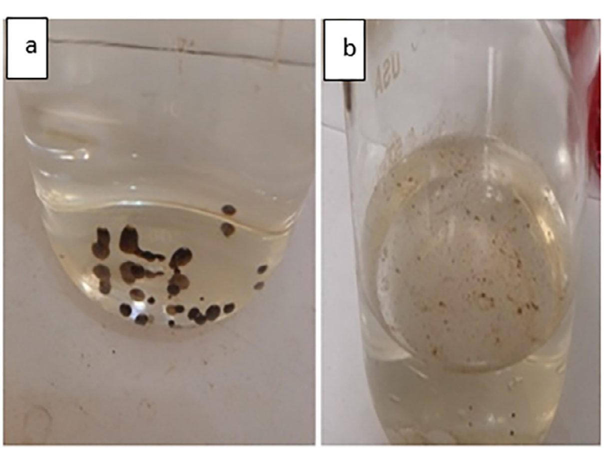

Fig. 4. The Reversible Change for this Study.

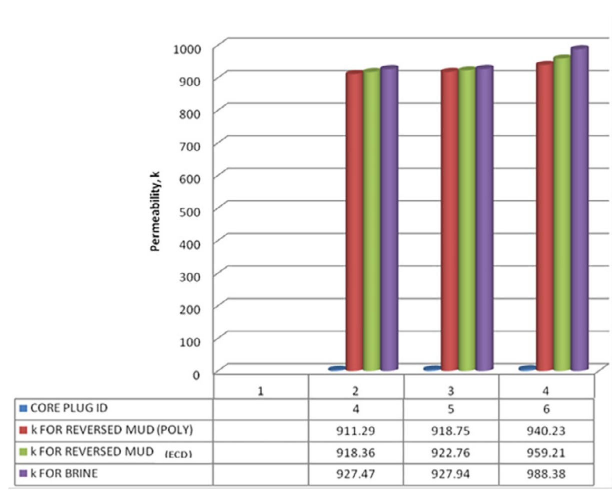

Fig. 5. Reversed Invert Emulsion Mud Permeability Impairment result.

The core samples were used to perform the reservoir impairment test. The cores were dried and weighed before saturating it with brine. The saturated samples were weighed and the pore volume calculated. The permeability was measured before injecting the reversed mud system at a constant flow rate. The core samples were removed from the core-holder and the formed filter cake was removed by acidification; which is the field practice. Then, brine was re-introduced to estimate the permeability after the solid-fluid interaction test.

With the reversed emulsion mud systems, reduction in permeability are within the range of 16–19 mD which is minimal. The corresponding permeability values after circulating with brine and reversed mud system are presented in Fig. 5. This could be as a result of no or negligible pore throat plugging by the reversible surfactant and the reversed mud system. The core samples used did not show reduction in permeability that can affect producibility after flooding the cores with the reversed mud system.

The low range value for permeability impairment can be due to the compatibility of the reversed mud system filtrate and the in-situ brine, making the impact of the invasion minimal.

6. Conclusion

The reversible invert emulsion drilling mud designed in this study exhibited a Non-Newtonian characteristic. The mud system formulated with Silicon Ethoxide surfactant was reversed from oil-wet to water-wet using 80 ml of 40% ethanol. Thus, eliminating the acid-base chemical switch proposed in literature. The formation damage test showed that the permeability impairment from this reversed mud system was minimal (16–19 mD). Thus, it will not significantly reduce the producibility of the reservoir when used as a drill-in mud system; because many oil and gas wells do not produce to their maximum capacity due to formation damage.

The proposed reversible drilling fluid system and the reversible surfactant will minimize formation damage, lower overall well costs acquired during mud change-over/displacement and optimize production.

Conflicts of interest

The authors declare that, there are no conflict of interest regarding the methodology used and the results obtained in this research.

Novelty

Identification and application of Silicon Ethoxide as reversible surfactant for formulation of Invert Emulsion mud, that will not react with the drilling equipment nor the formation.

This Reversible emulsion based muds can be converted using Ethanol, rather than the conventional acid-base chemical switch from water-in-oil (W/O) to oil-in-water (O/W) emulsion.

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