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ORIGINAL ARTICLE

An experimental study to evaluate the efficiency of silicate drilling fluids on the stabilization of shale layers

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Abstract
Regarding the increasing production from unconventional reservoirs, especially shale reservoirs, it is essential to determine appropriate drilling fluid in drilling operations to have maximum efficiency. Selective performance of drilling fluids may increase the formation penetration rate and increase the drilling efficiency. This paper compares the three types of drilling fluids to compare their rheological properties and provide the best drilling fluid composition for shale stabilization. This paper can bring reliable experimental results for petroleum industries, especially drilling operations, to reduce the formation damage and shale instabilities in subsurface formations. To perform the tests under the same conditions, the formulation of all samples is the same in terms of both utilized polymers to determine the effect of other compositions in selected drilling fluids. For the silicate drilling fluid, since silicates perform well at higher pH (potential of hydrogen), the pH of the silicate drilling fluid is increased to 11 by the addition of sodium hydroxide (NaOH). The lowest decrease in fluid viscosity is related to silicate fluids, indicating the more excellent thermal stability of these types of drilling fluid than glycol and potassium chloride (KCl). Plastic viscosity (PV) is about 20 cP for silicate drilling fluids, while it has the minimum value for glycol drilling fluids after heating. It is about 7.5 cP. Apparent viscosity (AV) is about 23 cP for silicate drilling fluids, while it has the minimum value for glycol drilling fluids after heating. It is about 11 cP. The yield point (YP) before heating is almost the same for different fluids, but after heating the drilling fluids, the reflux point for silicate and glycol drilling fluids is significantly reduced. The yield point is about 6.5 Ib/100ft^2 for silicate drilling fluids, while it has the maximum value for glycol drilling fluids after heating. It is about 8 Ib/100ft^2.

Keywords Shale stability · Silicate drilling fluids · Rheological properties · Shale layers

List of symbols

AV	Apparent viscosity, cP
PV	Plastic viscosity, cP
YP	Yield point, Ib/100ft^2
pH	Potential of hydrogen
NaOH	Sodium hydroxide
KCl	Potassium chloride
Na_2Co_3	Sodium carbonate
PHPA	Partially hydrolyzed polyacrylamide

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Introduction

Common problems in the drilling of shale formations are significant issues in petroleum industries due to shale instabilities, the wellbore size interfering with corrosion and erosion, and the blockage of the pore spaces and throats (Lyu et al. 2021; Gholami et al. 2021). Moreover, the effect of fluid on the shear strength of the formation will be minimal in shale layers. Due to the low inclination limit and the properties related to the strength of the drilling fluid made by the dispersion of this type of shale, the pressure drop has caused the drill string or drill pipes to collapse into the well. Clay rings can create obstacles to the flow of mud in the annular space and increase the pressure of the annular space.

When the pressure drop of the annular space reaches above average, they create a fracture risk and correspond to the lost circulation issue. On the other hand, if the mud weight is not appropriate, the tightness conditions of the well will prevail with repeated surveying operations for cleaning the lost equipment. Therefore, installing the drill pipe will be more complex, and achieving a good result from the initial cementing operation will be more unsafe (Xu et al. 2021; Loizzo et al. 2017; Al-Refai and Gratia 2016).

If heavyweight drilling fluid is used, the volume of barite and necessary chemicals has been increased, and there is no beneficial process during the operations. Formation failure may also occur due to the poor and insufficient rheological characteristics in these sensitive areas. The speed of drilling pipes into the well and the amount of mud pumped at the beginning of the mud circulation in drilling operations are considered essential factors. Fracture of the formation, in any case, will significantly reduce the tendency of the shales to remain stable. If the shale contains moderate to high sodium and calcium montmorillonite, oil-based drilling fluid will provide the most incredible formation stability. In addition, the use of a reverse emulsion mud system has had good results in the drilling of shale layers. The shales have remained stable due to the use of calcium chloride and sodium chloride in the aqueous phase of the drilling mud. So far, many studies have been conducted on the causes of well instability in water-sensitive shale formations; however, the successful results have not yet been widely used in drilling operations. The main reason for this is that the condition and properties of in situ stresses, strength, and hydrophilic stresses of shales cannot be measured using conventional methods (Wang et al. 2018; Bailey et al. 1998; Sorić et al. 2004).

Shales account for about 75% of drilled formations worldwide and cause 90% of well instability problems. Formation instability is a common problem observed during drilling operations. It is estimated that more than 5–10% of drilling operations' total cost corresponds to formation instability problems. Problems caused by the instability of the formations include the following; stuck pipes, poor well cleaning, well closure, drilling rig movement problems, poor well drilling conditions, loss of large volume of cement and drilling mud, low quality of cement operation due to the irregular shape of the well, and the equipment loss inside the well caused doing diversion drilling (Yu et al. 2012).

Silicate drilling fluid is an aqueous base fluid prepared by adding soluble silicates (sodium or potassium silicate) to the drilling fluid composition. Silicate fluids in terms of environmental compatibility, cost preparation, and maintenance are appropriate in addition to desirable rheological properties. They are preferred fluids to replace the oil-based fluids introduced in drilling constructions. Silicate fluid was first used in 1930 but was discontinued due to its high viscosity (Guo et al. 2006; Tian et al. 2019; Lei et al. 2021). Nowadays, with the modifications made to the soluble silicates used in the fluid composition, it has been introduced as a shale inhibitory fluid with suitable efficiency (Jiang 2019; Patel and Santra 2020). Water-soluble sodium or potassium silicate is prepared by melting Na_2Co_3 or K_2Co_3 with Sio_2 silicate at 1000–1200 C.

Shale performance depends on the difference between mud and shale water mobility and membrane efficiency. Membrane efficiency can be increased by increasing the materials that block the openings of the cavities so that the return flow of water to the fluid may be much more intense. The combination of these factors is what silicate fluid does. The pH of silicate fluid is about 11–12. In this case, the silicate is mono-silicate or relatively small oligomers. Such oligomers are still small enough to penetrate micropores (several nanometers). This paper compares the three types of drilling fluids to compare their rheological properties and provide the best drilling fluid composition for shale stabilization. This paper can bring reliable experimental results for petroleum industries, especially drilling operations, to reduce the formation damage and shale instabilities in subsurface formations. To perform the tests under the same conditions, the formulation of all samples is the same in terms of both utilized polymers to determine the effect of other compositions in selected drilling fluids. For the silicate drilling fluid, since silicates perform well at a higher pH, the silicate drilling fluid's pH is increased to 11 by the addition of NaOH.

Materials and methods

A primary solution to deal with shale instability is to use an oil-based drilling mud in which the chemical potential of the aqueous phase is balanced with the chemical potential of the cavity fluid to prevent a reaction between them. This solution is based on the principle that shale is chemically active and can react with drilling fluid components, leading to instability and loss of rock strength. Synthetic base drilling fluids have also been developed and are not harmful to the environment; however, they are mostly expensive. Therefore, it seems that a long-term and effective solution to meet the industry goal of reducing the cost of drilling operations. Furthermore, it can provide the environmental constraints to develop a new water-based drilling fluid that performs similarly to the oil drilling mud on the shale stabilization.

Determination of drilling fluid rheology

Appropriate determination of drilling fluid properties in terms of rheology characteristics is an effective way to reduce wellbore (Xu et al. 2007). From a theological point of view, it should be tried to keep the smoothness of the mud and the consistency of the gel as low as possible, and the mud should be designed in such a way as to clean the well properly. This can sometimes be done by adding surfactants, but the most successful method is to add asphaltene due to its high performance in wellbore cleaning. Examination of rheological properties during drilling operations can be an accurate indicator to determine the stability or instability of the shale formation. For example, changes in plastic viscosity and gel consistency can indicate the entry of clay particles in the shale formation into the drilling fluid. By controlling the flow regime of the drilling fluid in the well, the abrasion of the formation can be prevented due to the turbulent flow of the drilling fluid or the creation of high incisions in the drilling bit nozzles in soft shale structures. Therefore, proper rheological characteristics design can also effectively achieve the goal of wellbore stability in shale formations (Guo et al. 2007).

Materials

At the beginning of the experiments, three samples of silicate fluids were prepared for a general understanding of the behavior of these fluids. Table 1 shows the formulations and materials used to prepare these three fluid samples. In the formulation of these samples, seawater has been used to make the formulation more realistic with the conditions (close to formation brine properties) in the subsurface regions.

Methods

1. Selecting shale particles ranging in sizes from 125 to 225 nm were dried for one day at the temperature of 120 °C (Shen et al. 2011).
2. Provide standard salt saturation solutions.
3. Desiccator with a built-in valve to create a vacuum condition.
4. Daily, weigh the sample and return it to the desiccator; repeat step 4 and weigh the sample again. The end of the step occurs when the difference between the measured weights is negligible. At this time, an equilibrium condition is established, which causes not to absorb water anymore.
5. Equilibrium time for each shale sample is recorded, which is approximately 5 to 7 days.

Shale stability

In order to evaluate the efficiency of silicate drilling fluids in the stabilization of shale layers, two samples of silicate drilling fluid and base drilling fluid (without silicate) according to the experiments performed in the previous section have been made according to the formulation presented in Table 2.

Experimental results

Silicates plastic-based drilling fluids were reintroduced to the drilling industry in the 1990s. These low-cost and environmentally friendly fluids have unique properties that make them very suitable for stabilizing shales. Soluble silicate fluid penetrates the shale and reacts rapidly with the polyvalent ions of the fluid in the voids (such as Ca^{2+} and Mg^{2+}) to become insoluble and precipitate. The neutral to acidic pH of the fluid will also create voids in the silicate gel. The barrier created by the precipitated and gelled silicates will prevent further mud infiltration. At high temperatures (above 105 °C), a cementitious material forms on the surface of the clay particles through a compression reaction. This particular material prevents the swelling and spreading of clay. Moreover, the addition of potassium chloride can increase system inhibition.

The rheological properties of different fluid samples, including Apparent viscosity (AV), Plastic Viscosity (PV), and Yield Point (YP), as well as the gel strength properties

Table 1 Materials and components for the preparation of for each drilling fluid type

No	Composition	Unit	KCl mud	Silicate mud	Glycol mud
1	Sea water	cc	650	650	650
2	Na2Co3	gr	0.30	0.30	0.30
3	Poly drill	gr	7	7	7
4	Poly thin	gr	1	1	1
5	PHPA	gr	1	1	1
6	KCl	gr	20	–	–
7	Silicate	cc	–	60	–
8	Glycol	cc	–	–	60

Table 2 Compostion of two different drilling fluid to meaasure shale stability

Composition	Unit	Base mud	Silicate mud
Sea water (550,000 ppm)	bbl	1	1
Potassium chloride	lb	16	16
Sodium carbonate	lb	1	1
Sodium hydroxide	lb	0.5	0.5
PAC-LV	lb	8	8
XC-polymer	lb	1	1
Sodium silicate	%v/v	–	10%
Barite	lb	As required	As required

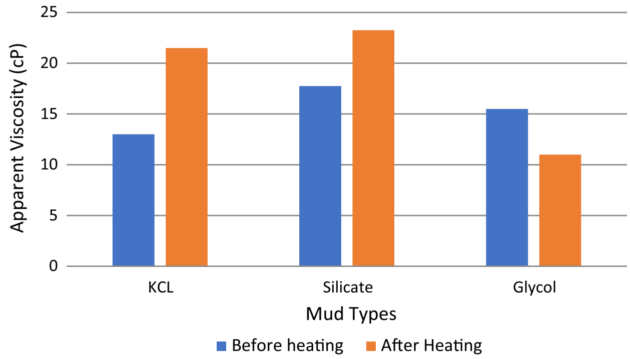

Fig. 1 Apparent viscosity for different drilling fluids

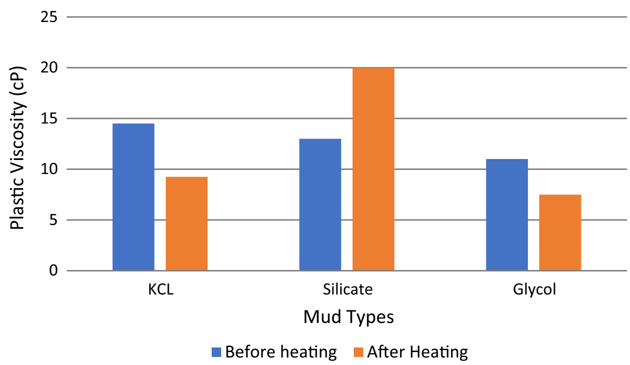

Fig. 2 Plastic viscosity for different drilling fluids

for different samples, have been measured. In the silicate sample, the apparent viscosity increased after heating, which corresponds to the incompatibility of the polymers with silicate drilling fluid (at the high pH) (see Fig. 1). This issue has been investigated by the previous literature (Guo et al. 2006). Apparent viscosity is about 23 cP for silicate drilling fluids, while it has the minimum value for glycol drilling fluids after heating. It is about 11 cP.

Figure 2 shows the plastic viscosity before and after heating for different fluids. Here, the lowest decrease in fluid viscosity is related to silicate fluids, indicating the greater thermal stability of these types of drilling fluid rather than glycol and KCl. Plastic viscosity is about 20 cP for silicate drilling fluids, while it has the minimum value for glycol drilling fluids after heating. It is about 7.5 cP.

Figure 3 shows the changes in the yield point before and after heating for different fluids. As can be seen, the amount of YP before heating is almost the same for different fluids, but after heating the drilling fluids, the reflux point for silicate and glycol drilling fluids is significantly reduced, which has an inverse pattern with formate drilling fluids (Davarpanah 2019). The yield point is about 6.5 Ib/100ft^2 for silicate drilling fluids, while it has the maximum value

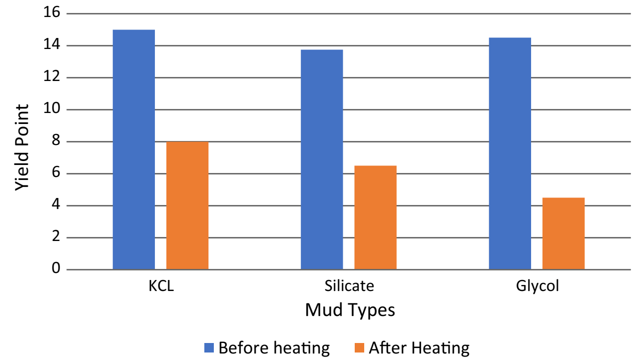

Fig. 3 Yield Point for different drilling fluids

Table 3 Rheological properties

Rheological characteristics	Unit	base mud	Silicate mud
$\theta 600$	–	145	125
$\theta 300$	–	95	80
Apparent viscosity	cp	63.75	60.25
Plastic viscosity	cp	51	44
Yield point	lb/100ft2	58	50
Gel 10 s/10 min	lb/100ft2	6/12	10.5/12
pH	–	11.5	12.25
API fluid loss	ml	7.25	23.75
Mud weight	PCF	120	1020

for glycol drilling fluids after heating. It is about 8 Ib/100ft^2. Therefore, the filtration loss of glycol and silicate drilling fluids decreases significantly after heating. In addition, the filter cake created in the silicate drilling fluids is very thick than other drilling fluids.

Shale stability

The cause of shale instability is defined as a mechanical issue regarded as stress change versus the shale strength and chemical concepts related to the interactions between fluid and shale/fluid interaction, pressure diffusion, capillary pressure, and the invasion of borehole fluid into the shale formations (Lal 1999). A summary of drilling fluid properties is shown in Table 3 to compare and provide the best drilling fluid composition.

Discussion and conclusion

Although oil-based drilling fluids have been considered the preferred fluid for drilling sensitive permeable shale structures, in recent years, environmental, safety, health, and economic problems with oil-based drilling fluids have led to modifications to water-based drilling fluids in the drilling industries. Selection of suitable drilling fluid for successful shale layers depends on the shale composition such as mineralogical composition, physical properties of shale such as hardness, brittleness, the volume of fractures, fluidity characteristics of the formation, distribution, and size of cavities. The most features of this paper are as follows;

- The lowest decrease in fluid viscosity is related to silicate fluids, indicating the greater thermal stability of these types of drilling fluid rather than glycol and KCl. Plastic viscosity is about 20 cP for silicate drilling fluids, while it has the minimum value for glycol drilling fluids after heating. It is about 7.5 cP.
- Apparent viscosity is about 23 cP for silicate drilling fluids, while it has the minimum value for glycol drilling fluids after heating. It is about 11 cP.
- The amount of YP before heating is almost the same for different fluids, but after heating the drilling fluids, the reflux point for silicate and glycol drilling fluids is significantly reduced.
- The yield point is about 6.5 Ib/100ft2 for silicate drilling fluids, while it has the maximum value for glycol drilling fluids after heating. It is about 8 Ib/100ft2. Therefore, the filtration loss of glycol and silicate drilling fluids decreases significantly after heating. In addition, the filter cake created in the silicate drilling fluids is very thick than other drilling fluids.

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Data availability All the data used in this paper are included in the text.

Declarations

Conflict of interest The authors declare no conflict of interest.

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