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Flat-rheology oil-based drilling fluid for deepwater drilling

Xin Zhao, Zhengsong Qiu*, Jiangen Xu, Chao Zhao, Jian Gao

School of Petroleum Engineering, China University of Petroleum, Qingdao 266580, China

Email: qiuzs63@sina.com

ABSTRACT

In offshore deepwater drilling, the temperature is rather low near the seabed. The resulting thickening of conventional oil-based drilling fluid causes increase in equivalent circulating density. When the density surpasses the formation fracture pressure gradient, a series of problems, including lost circulation, may occur, causing huge economic losses. A desirable drilling fluid is desperately needed to solve the rheology-related problems. In view of this, this paper analyzes how oil-based drilling fluid acquires the flat-rheology characteristics, and selects preferred additives, e.g. base oil, emulsifier, organic clay and weighting materials, based on their effects on the rheological properties of drilling fluid. On this basis, the author successfully synthetizes a rheology modifier and develops a flat-rheology oil-based drilling fluid. The performance of the proposed drilling fluid is experimentally evaluated. The results indicate that the variations of the yield point, 10-min gel and θ6 reading of the proposed drilling fluid are controlled within 25% in the temperature range of 4–75 °C when the density is below 2.1 g/cm^3. Besides, the proposed drilling fluid boasts good shale inhibition and filtration performance as well as strong contamination resistance to NaCl, $CaCl_2$ and drill cuttings. In this way, this paper provides a desirable solution to rheology-related problems in deepwater drilling.

Keywords: Flat-Rheology, Oil-Based Drilling Fluid, Deepwater Drilling, Low Temperature, Equivalent Circulating Density.

1. INTRODUCTION

The offshore deepwater area is abundant in oil and gas resources. During deepwater drilling, the near-seabed low temperature has a significant effect on the rheological properties of drilling fluid. One of the most commonly used drilling fluids in complex formation is oil- or synthetic-based drilling fluid. Despite the advantages of high penetration rate, wellbore stability, etc., this type of drilling fluid is rapidly thickened and even gelatinized in the low-temperature deepwater environment, resulting in increase of the equivalent circulating density (ECD). Because of a narrow safe-density window in deepwater formation, the high ECD will cause lost circulation of drilling fluid, exert a tremendous impact to deepwater drilling operations, and significantly increase the cost of drilling fluid [1–3]. For the application of oil- or synthetic-based drilling fluid in deepwater drilling, the concept of “flat rheology” has been proposed. With the aim of effectively controlling the ECD and reducing the loss of drilling fluid, the concept is about maintaining a relatively stable yield point, and 10-min gel and θ6 reading of the drilling fluid in the temperature range 4.4–65 ℃ [4–6]. Previous studies have shown that the base oils commonly used in oil-based drilling fluid (OBM), such as mineral oils, diesels, and vegetable oils, are significantly affected by temperature. To reduce the temperature influence, the flat-rheology synthetic-based drilling fluid has been developed by some drilling service companies through the improvement of key additives of rheology modifiers and emulsifiers and the invention of synthetic-based oils with low viscosity at low temperature. The new drilling fluid could mitigate the rheology problem [7, 8] of traditional oil- or synthetic-based drilling fluid in deepwater drilling. Nevertheless, the rheology-related problems have not been completely solved for it is still difficult to maintain the variation of rheological parameters of oil- or synthetic-based drilling fluid within 30% in the temperature range 4–65 ℃. This calls for a better solution to the problems. In light of the wide availability, inexpensiveness and convenience in the preparation and maintenance of the OBM, this paper creates a rheologically stable OBM between 4–65 ℃ and even 4–75 ℃ by taking mineral oil as the base oil, optimizing the emulsifier, organic clay, and weighting materials, and developing a novel rheology modifier. This study provides technical support for drilling fluid, and thereby improves the safety and efficiency of deepwater drilling.

2. EXPERIMENT

2.1 Materials

The #3 mineral oil, #0 diesel, #5 mineral oil, and biodiesel are purchased from Qingdao Moisturizing Oil Co., Ltd.; the emulsifier, organic clay, wetting agent, filtration reducer, and conventional OBM are obtained from Drilling Engineering and Technology Company of Sinopec Shengli Oilfield Service Corporation for contrast experiments; the rheology modifier SDRM is synthesized in the lab; anhydrous calcium chloride ($CaCl_2$) and calcium oxide (CaO) are procured from Sinopharm Group Chemical Reagent Co., Ltd.; the drill cuttings are acquired from wells in the South China Sea for cuttings recovery rate experiments and contamination resistance tests.

2.2 Methods

Capable of raising the yield point, the novel rheological modifier SDRM is synthesized in two steps. The specific procedure goes as follows: Place a four-necked flask in an oil bath, and add dimer acid and diethanol amine at the mole ratio of 1.1:1 into the flask. Let the reaction proceed at 140 ℃ for 40 min. After that, lower the temperature of the oil bath to 70 ℃, and add diethylenetriamine into the flask. Maintain the temperature at 140 ℃ for 60 min and obtain the reaction products.

Prior to testing, the drilling fluid has been rolled at 150 ℃ for 16 h, and then stirred at 11,000 r/min for 30 min. The rheological properties of the OBMs are measured with a ZNN-D6 six-speed rotational viscometer at different temperatures [9,10]. The apparent viscosity (AV), plastic viscosity (PV), yield point (YP), gel strength after 10 min standing (10-min Gel) and 6 r/min reading (θ6 reading) can be obtained. The methods mentioned in references [10–13] are adopted for the drill cuttings recovery rate experiments and filtration experiments.

3. RESULTS AND DISCUSSIONS

3.1 Development of the flat-rheology oil-based drilling fluid

3.1.1 Mechanical analysis on flat-rheology characteristics of oil-based drilling fluid

The “flat-rheology” characteristics are achieved through the interactions of appropriate polymer rheology modifiers, organic clay, and emulsified water droplets, as well as the combined use of a base oil and other additives, which are not easily thickened at low temperature. Specifically speaking, the polymer should contain hydrophobic groups that can be partially dissolved in the oil phase and adsorbed on the surface of the organic clay. After the introduction of acylamino and other polar groups, a grid structure will form due to electrostatic attraction or hydrogen-bonding interactions with emulsified water droplets. In the low-temperature deepwater environment, the molecular chain of polymer viscosifier will curl, which dampens the thickening effect. In this case, the grid structure is mostly maintained by the organic clay. Further increase in temperature will lead to gradual unfolding of the molecular chain of the polymer, and stronger interactions between polymer molecules and between polymer molecules and solid particles. In this way, the grid structure of the drilling fluid is enhanced. Owing to the complementation between different components, the drilling fluid acquires the flat-rheology characteristics.

After analyzing the OBM’s acquisition of flat-rheology characteristics, the author goes on to examine the components of OBM for the purpose of developing the flat-rheology oil-based drilling fluid.

3.1.2 Optimization of base oil

The base oil is the dispersing medium of any OBM. Its viscosity has a direct influence on the viscosity of the drilling fluid. Assume that other components of the OBM remain unchanged, the drilling fluid will have more stable rheological properties if the temperature-induced variation in base oil viscosity is insignificant. The author conducts an experiment on the viscosity variation of different base oils in a temperature range in a typical wellbore of deepwater drilling. (Figure 1) The results show clear viscosity increase of all the base oils with the falling temperature. Of course, the degree of increase differs among the base oils. The #3 mineral oil and synthetic-based oil have the lowest viscosities. The #0 diesel also has low viscosity. The viscosity of biodiesel is heavily impacted by temperature because of its content of the mixture of fatty acid methyl esters. The paraffin in biodiesel precipitates at a low temperature, resulting in poor flowability. This explains why the biodiesel viscosity decreases so rapidly with temperature increase. As for the #5 mineral oil, its viscosity obviously increases at a low temperature. In consideration of the toxicity, cost and the rheological properties at a low temperature, the author chooses the #3 mineral oil as the base oil for the flat-rheology oil-based drilling fluid.

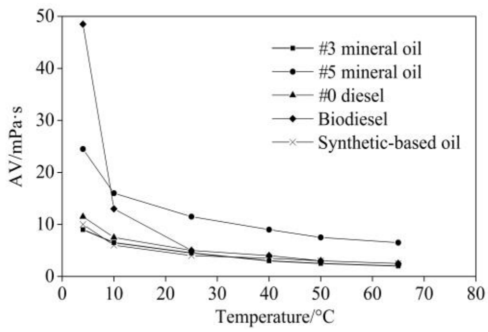


Figure 1. Variations in viscosities of different base oils as a function of temperature

3.1.3 Optimization of emulsifier

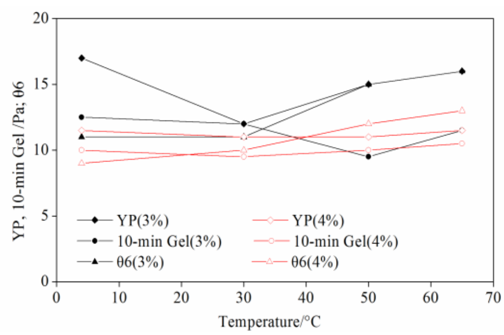
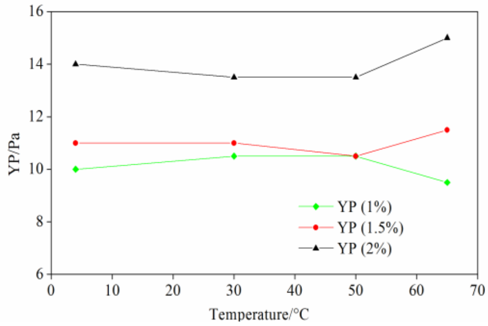


Figure 2. Effect of concentration of emulsifier on rheological properties of OBM

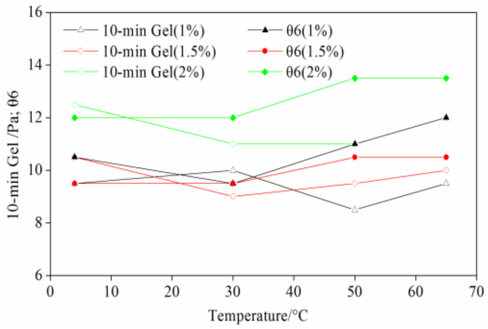
The author prepares an emulsion at an oil/water ratio of 70:30 with the #3 mineral oil and 20% $CaCl_2$ brine, and measures the emulsion-breaking voltages of the emulsion added with six normally used emulsifiers, respectively. The measured results show that the KHEMUL emulsifier has the strongest capability of stabilizing the emulsion. Further experiments are performed to highlight the effects of the concentration of KHEMUL emulsifier on the emulsion-breaking voltage and rheological properties of the OBM. The emulsion is proved to be stable for the emulsion-breaking voltages of the drilling fluids in the experiments always stay above 2,000 V when the concentration of KHEMUL is 3% or 4%. As shown in Figure 2, the variation in yield point, 10-min gel and θ6 reading of drilling fluid reaches the minimum when the emulsifier concentration is 4%, indicating that the level of concentration helps the OBM acquire the flat-rheology characteristics. As a result, the author selects 4% KHEMUL as the emulsifier for the flat-rheology oil-based drilling fluid.

3.1.4 Optimization of organic clay

The organic clay is used to improve the viscosity and high-temperature stability and lower the filtrate volume of the OBM. Similar to the base oil, the organic clay is crucial to the viscosity increase of the OBM at a low temperature. Through the evaluation of several kinds of organic clays, it is demonstrated that the concentration increase of organic clay will push up the viscosity of the OBM. After the optimization, SGT-2 is determined as the optimal organic clay. Figure 3 reveals that the main rheological properties of the OBM are moderate and not significantly influenced by the temperature when the concentration is 1.5%. Therefore, the author decides to use 1.5% SGT-2 as the organic clay for the flat-rheology oil-based drilling fluid.



(a) Variations in YP

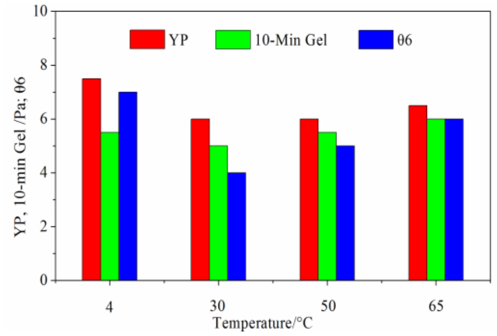


(b) Variations in 10-min gel and θ6 reading

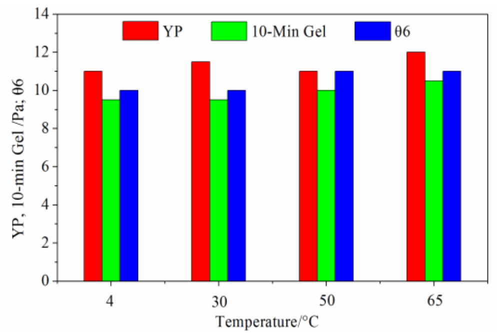
Figure 3. Effect of concentration of organic clay SGT-2 on rheological properties of OBM

3.1.5 Development of rheology modifier

The rheology modifier is another key component for controlling the rheological properties of the OBM. In order to give the OBM "flat rheology" characteristics, an appropriate rheology modifier must be selected. As mentioned in Section 2.2, the author synthetizes a novel rheology modifier SDRM. Experiments are carried out to investigate the effect of SDRM on the rheological properties of the OBM. According to Figure 4, the addition of SDRM brings a minor impact to the temperature-induced variations of the rheological properties of the OBM; in contrast, the introduction of a conventional rheology modifier results in significant temperature-induced variations of rheological properties of the OBM. For the OBM with 2% SDRM, the yield point is 11–12 Pa, the 10-min gel is 9.5–10.5 Pa, and the θ6 reading is 10–11 if the temperature falls in the range of 4–65 °C. For the OBM with 2% HRP (conventional rheology modifier), however, the yield point is 6–7.5 Pa, the 10-min gel is 5–6 Pa, and the θ6 reading is 4–7 if the temperature also falls in the said range. Therefore, the addition of SDRM has effectively increased and stabilized the rheological parameters of the OBM, causing better suspension of cuttings and weighting materials. Further optimization experiments demonstrate that the optimal concentration of SDRM is 2–2.5%.



(a) 2% conventional rheology modifier HRP



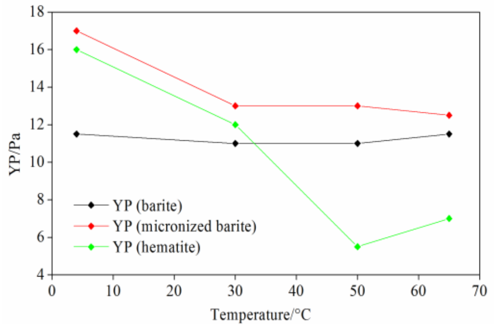
(b) 2% SDRM

Figure 4. Effect of rheology modifier on rheological properties of OBM

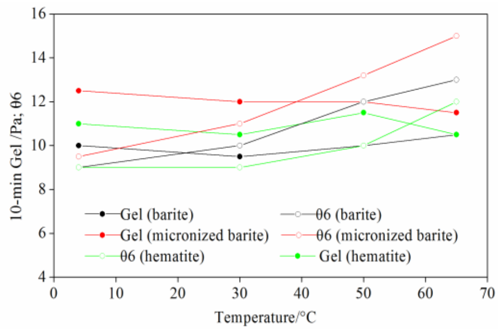
The SDRM contains long-chain alkyl groups, which can improve its solubility in the OBM and get adsorbed on the surface of the organic clay. A grid structure will form through the electrostatic attraction or hydrogen-bonding reaction between polar groups like acylamino, and the organic clay & emulsified water droplets. The grid structure will also appear among the polymer molecules through binding or hydrogen-bonding reactions. In this way, the OBM has higher yield point, and better suspension of cuttings and weighting materials.

3.1.6 Optimization of weighting materials

The heavy addition of weighting materials has a negative impact to the rheological property, filtration property and lubricity of drilling fluid. In this research, the author examines how conventional barite, micronized barite, and hematite affect the rheological properties of the OBM through several experiments. Figure 5 shows that the most stable rheological properties are achieved with conventional barite as the weighting material. In the temperature range of 4–65 °C, the variation in YP does not exceed 1 Pa. In comparison, the YP of hematite tripled as the temperature falls from 65 °C to 4 °C. The YP of micronized barite also soars at 4 °C.



(a) Variations in YP



(b) Variations in 10-min gel and θ6 reading

Figure 5. Effect of weighting material on rheological properties of OBM

3.1.7 Formula of the oil-based drilling fluid with stable rheological properties

Owing to the limitation of space, the optimization process of filtration reducer, wetting agent and other additives are not covered in depth here. In view of the results of additives optimization, the formula of the OBM with stable rheological properties in the temperature range of deepwater drilling should be: 70–85% #3 mineral oil + 4% KHEMUL + 2% KP-WET (wetting agent) + 15–30% $CaCl_2$ aqueous solution (20 wt%) + 0.5% CaO + 2.5% SDRM + 3% BZFL (filtration reducer) + 1.5% SGT-2 + barite.

3.2 Performance evaluation of the proposed oil-based drilling fluid

3.2.1 Evaluation of rheological and filtration properties

The author prepares the OBMs with different densities, hot-rolls them at 150 °C for 16 h, and probes into their rheological and filtration properties through experiments. The results are displayed in Table 1. It is discovered that when the density is below 2.1 g/cm^3, the yield point, 10-min gel, and θ6 reading of the proposed OBM remain stable in the temperature range (4–65°C and even 4–75°C) of the deepwater wellbore, and the variations of rheological parameters are no greater than 25%. This means the drilling fluid does exhibit flat-rheology characteristics. The rheology parameters of the OBM also satisfy the rheological requirements of flat-rheology drilling fluid in Literature [6]. In addition, the OBM showcases excellent filtration property as its filtrate volume is only 3.4–5.6 mL under high-temperature (150 °C) and high-pressure (3.5 MPa). The high-temperature and high-pressure condition are usually encountered when drilling deep formation [14,15].

Table 1. Rheological and filtration properties of OBMs with different densities

Density /(g·cm^{-3})	O/W ratio	T/ºC	AV /mPa·s	PV /mPa·s	YP /Pa	θ6	10-min Gel /Pa	Filtrate volume/mL
1.1	70:30	4	74.0	63.0	11.0	10.0	10.5	3.4
		30	37.5	28.0	9.5	10.0	10.0	
		65	31.0	21.0	10.0	12.0	10.5	
		75	28.0	19.0	9.0	9.5	9.5	
1.8	80:20	4	96.5	85.0	11.5	8.5	10.5	4.0
		30	50.0	39.0	11.0	8.0	9.0	
		65	35.0	24.5	10.5	10.0	10.0	
		75	31.0	21.0	10.0	10.0	9.5	
2.1	80:20	7	141.0	128.0	13.0	11.0	13.0	5.6
		30	72.0	59.0	13.0	10.0	12.5	
		65	53.0	41.0	12.0	12.0	12.0	
		75	50.0	38.0	12.0	12.5	12.0	

To better characterize the flat rheology of the proposed flat-rheology oil-based drilling fluid (FR-OBM), the author compares the rheological properties of the FR-OBM (1.8 g/cm^3) and those of the conventional OBM. The results are shown in Figure 6. The comparison manifests significant temperature-induced variations in the rheological properties of the conventional OBM. At a low temperature, the conventional OBM experiences sharp increases in yield point, 10-min gel, and θ6 reading. The changes lead to excessively high ECD and large surge pressure, which in turn causes lost circulation of the OBM. On the contrary, the FR-OBM boasts moderate yield point, 10-min gel, and θ6 reading at 4–65 °C, which puts the ECD under control.

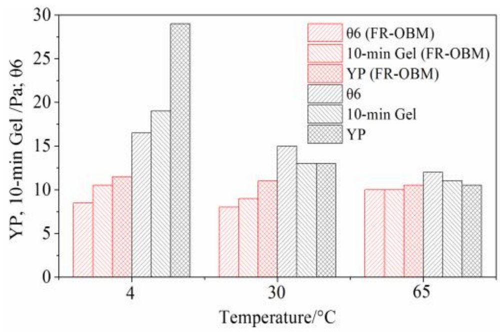
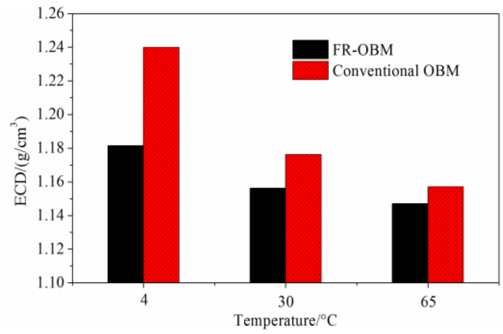
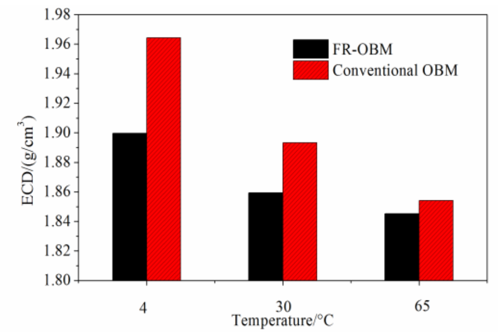


Figure 6. Comparison of rheological properties of OBMs with a density of 1.8 g/cm^3

The ECDs of the FR-OBM and conventional OBM are compared in deepwater drilling conditions. According to the rheological parameters in the temperature range 4–65 °C, the ECDs of the two drilling fluids at different temperatures are calculated by the Drillbench software. The results are shown in Figure 7. Compared to the conventional OBM, the FR-OBM does better in reducing the ECD, especially under the low-temperature deepwater conditions. Hence, it is possible to mitigate or eliminate the risk of lost circulation of drilling fluid with the FR-OBM during the drilling of deepwater shallow formation with a narrow safe-density window.



(a) density= 1.1 g/cm^3



(b) density=1.8 g/cm^3

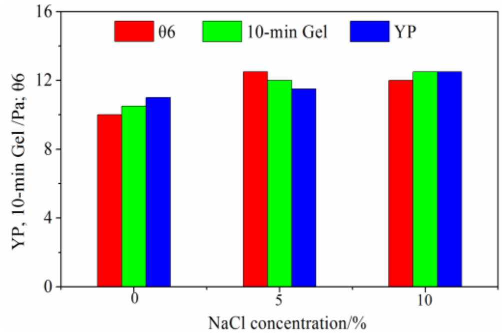
Figure 7. Comparison of ECDs for different OBMs

3.2.2 Evaluation of shale inhibition

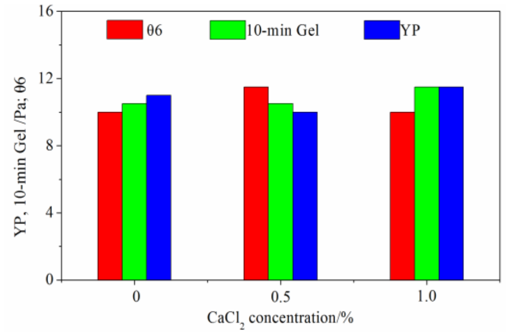
The drill cuttings recovery rate experiments are conducted to evaluate the shale inhibition performance of the FR-OBM. The lower the recovery rate, the stronger the hydration and dispersion of the shale, and the more unstable the wellbore. The recovery rates of different types of shale cuttings in pure water are 2.1–6.4%, indicating that the shales from deepwater formations are highly prone to hydration and dispersion. In comparison, the recovery rates of these shales in the FR-OBM are as high as 91.2–97.8%. Therefore, the FR-OBM can effectively inhibit the shale hydration and dispersion, and prevent the ensuing wellbore instability.

3.2.3 Evaluation of contamination resistance

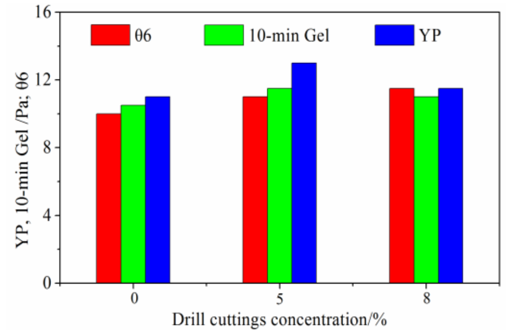
Different concentrations of NaCl, $CaCl_2$, and drill cuttings are investigated experimentally to disclose their influence on the rheological properties of the FR-OBM at 4 °C. As shown in Figure 8, the results indicate that the addition of NaCl causes the rheological parameters to rise slightly. As the NaCl concentration is increased from 0 to 10%, the yield point and 10-min gel of the FR-OBM remain at 10.5–12.5 Pa, and the θ6 reading remains at 10–12.5. Meanwhile, the FR-OBM maintains stable rheological properties in the presence of $CaCl_2$, which is usually lower than 1%. As the concentration of $CaCl_2$ is increased from 0 to 1%, the yield point and 10-min gel of the FR-OBM remain at 10–11.5 Pa, and the θ6 reading remains at 10–11.5. In addition, in the presence of 5–8% drill cuttings, the yield point and 10-min gel of the FR-OBM maintain at 10.5–13 Pa, and the θ6 reading maintains at 10–11.5. The results reflect the excellent contamination resistance of the FR-OBM. Therefore, the rheological properties of the FR-OBM will remain stable during drilling operations even if it is contaminated by NaCl, $CaCl_2$, or drill cuttings.



(a) NaCl



(b) $CaCl_2$



(c) drill cuttings

Figure 8. Contamination resistance performance of the FR-OBM (at 4 °C)

4. CONCLUSIONS

Upon analyzing the OBM's acquisition of flat-rheology characteristics and optimizing the drilling fluid components, the author determines the formula of an OBM with flat-rheology characteristics: 70–85% #3 mineral oil + 4% KHEMUL + 2% KP-WET + 15–30% $CaCl_2$ aqueous solution (20 wt%) + 0.5% CaO + 2.5% SDRM + 3% BZFL + 1.5% SGT-2 + barite. When the density is below 2.1 g/cm^3, the variations of the yield point, 10-min gel and θ6 reading of the proposed drilling fluid are controlled within 25% in the temperature range of 4–65 °C and even 4–75 °C, and the ECD of the drilling fluid is effectively controlled. In comparison with conventional OBM, the FR-OBM maintains very stable rheological properties and low ECD. Moreover, the filtrate volume of FR-OBM is only 3.4–5.6 mL under high-temperature (150 °C) and high-pressure (3.5 MPa), an evidence to its excellent filtration performance. Besides, the recovery rates of drill cuttings in the FR-OBM are as high as 91.2–97.8%, indicating that the proposed drilling fluid can effectively inhibit shale hydration and dispersion. In addition, the FR-OBM is proved to have good contamination resistance to NaCl, $CaCl_2$ and drill cuttings. Suffice it to say that this paper provides a solution to rheology-related problems in deepwater drilling.

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