Design and application of green drilling fluid of strong inhibition

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Abstract. Borehole instability problem is always common when intersecting the brittle shale formations using either water-based mud or oil-based mud. An extensive wellbore stability drilling fluid was carried out mainly focused on integrating a variety of anti-collapse technology and the rigorous environmental protection. In this paper, a set of the environmental friendly drilling fluid system of strong inhibition was designed and developed based on the multi-element concept of inhibition, plugging, flocculating and environmental protection, combined with the characteristics and brittle shale and the special environmental requirements. In this system, KCOOH and SIAT are taken as the inhibitors, PAC-LV as the fluid loss agent, KPAM as the flocculant and nano-barite as the weighting and plugging material to improve the quality of mud cake and reduce the solid content of the system.

1. Introduction
The stability of borehole wall in brittle shale is variable and dynamic, so the measures shall be considered from multiple aspects such as the inhibition of drilling fluid, the filtration reduction, the solid phase control performance is crucial. In this paper, therefore, a set of green drilling fluid system of strong inhibition was designed by selecting green and efficient inhibitor, fluid loss agent and flocculant and taking nano-barite as the weighting and plugging material. And this system is applied in the operational zone of Chad and the application effect is satisfactory.

2. Development of green drilling fluid of strong inhibition
2.1. Selection of inhibitor
The inhibitor is chose by sell test, dispersion test and clay content comparison test according to related standard. The results are shown in Figure 1, Table 1 and Table 2.

The results of swelling, dispersion and clay content tests are analyzed comprehensively[1,2]. It is indicated that potassium formate is the most remarkable in inhibiting shale swelling and its optimal content is 8%. The shale dispersion inhibiting capacity of SIAT and HPAG is the strongest and their optimal content is 1.5%. The maximum clay content of SIAT is much higher than that of HPAG, so SIAT is better in keeping the rheological stability of drilling fluid system. Therefore, potassium formate and SIAT are combined to be the drilling fluid agent.
Figure 1. Linear swelling rate of cuttings.

Table 1. Rolling recovery rate of cutting (100℃).

| Drilling fluid agent       | Recovery rate (%) |
|---------------------------|-------------------|
| Distilled water           | 19.36             |
| 1.5%SIAT                  | 92.21             |
| 1.5%HPAG                  | 95.13             |
| 2.5%HPAG                  | 95.19             |
| 8%KCOOH                   | 86.27             |
| 1.5%SIAT+8%KCOOH          | 91.02             |
| 1.5%HPAG+8%KCOOH          | 91.5              |

Table 2. Comparison of maximum clay content.

| Bentonite (%) | 2%SIAT | 2%HPAG |
|---------------|--------|--------|
|               | AV (mPa.s) | PV (mPa.s) | YP (Pa) | AV (mPa.s) | PV (mPa.s) | YP (Pa) |
| 12            | 2       | 1       | 1.022   | 3         | 3         | 0       |
| 16            | 2       | 2       | 0       | 3.5       | 2         | 1.533   |
| 20            | 3       | 3       | 0       | 6.5       | 4         | 2.555   |
| 24            | 4       | 3       | 1.022   | 10.5      | 4         | 6.643   |
| 26            | 5       | 4       | 1.022   | \        | \        | \       |
| 28            | 8       | 7       | 1.022   | \        | \        | \       |

2.2. Selection of flocculant

Three types of flocculants (i.e., KPAM, EMP and FA-367) are tested and evaluated according to SY/T 5233-2014, and the evaluation results are shown in Table 3.

It is shown in Table 3 that the flocculation time of KPAM is the shortest and its flocculation effect is the best. The filtration reduction capacity of FA-367 is the best, its flocculation time is the longest and its flocculation effect is the worst. Therefore, KPAM is adopted as the flocculant of the drilling fluid system.

2.3. Selection of fluid loss agent

Rheological property and filtration reduction performance of base mud adding drilling fluid agent before and after aging under 100℃ are compared based on six-speed viscosity measurement and API fluid loss test[3-5], and the results are shown in Table 4.
Table 3. Evaluation test results of flocculants.

| Flocculant | Flocculation time (s) | Fluid loss (mL) |
|------------|-----------------------|-----------------|
|            | Base mud              | After adding 0.4 g | After adding 1.2 g |
| KPAM       | 114                   | 30.4            | 15.4           |
| EMP        | 252                   | 30.4            | 18.2           |
| FA-367     | 360                   | 30.4            | 9.8            |

Table 4. Evaluation results of fluid loss agent.

| Aging (16 h) | AV (mPa·s) | PV (mPa·s) | YP (Pa) | G''/ G' (Pa/ Pa) | FL API (mL) |
|--------------|------------|------------|---------|-----------------|-------------|
| Bentonite    | 1          | 3.5        | 2       | 1.5             | 0.5/0.5     | 70          |
|              | 2          | 4          | 4       | 0               | 0.5/0.5     | 85.5        |
| Bentonite +0.5%PAC-LV | 1          | 8          | 7       | 1               | 0.5/0.5     | 11.4        |
|              | 2          | 13         | 12      | 1               | 0.5/0.5     | 20.4        |
| Bentonite +0.5%PAC-LV +8%KCOOH | 1          | 4          | 4       | 0               | 0.5/0.5     | 10.4        |
|              | 2          | 5          | 4       | 1               | 0.5/0.5     | 14.8        |
| Bentonite +0.5%DSP-2 | 1          | 9.5        | 7       | 2.5             | 0.5/0.5     | 13.6        |
|              | 2          | 14.5       | 11      | 3.5             | 0.5/0.5     | 32          |
| Bentonite +0.5%NH4HPAN | 1          | 3.5        | 3       | 0.5             | 0.5/0.5     | 27.4        |
|              | 2          | 4          | 3       | 1               | 0.5/0.5     | 33          |
| Bentonite +0.5%ISP | 1          | 4.5        | 3       | 1.5             | 0.5/0.5     | 42          |
|              | 2          | 3.5        | 3       | 0.5             | 0.5/0.5     | 96          |

1- Before hot rolling; 2- After hot rolling

It is shown in Table 4 that the filtration reduction capacity of PAC-LV is the best, and it is improved further after 8% KCOOH is added. API fluid loss before the aging is less different from that after the aging. Therefore, it is recommended to adopt PAC-LV as the fluid loss agent of the drilling fluid system.

2.4. Improvement of plugging performance by introducing nano-barite

In order to improve the plugging performance of drilling fluid but not increase its solid content, we attempt to combine nano-barite[5,6] with API barite in the drilling fluid system so that the double action of barite (i.e., plugging and weighting) can work while the content of inert solid particles in the system is reduced. Nano-barite can be dispersed in water-based drilling fluid by surface modification.

The formula of green drilling fluid is 2.5% bentonite+1% PAC-LV+0.5% KPAM +8% KCOOH+1.5% SIAT+2% ISP-1+3% Polycol-1 + barite (3% nano-barite+97% API barite) (1.5 g/cm³).

3. Performance test of green drilling fluid of strong inhibition

3.1. Environmental performance test

The chemical toxicity, biodegradability and biotoxicity of the drilling fluid system were measured[7]. The results are shown in table 5. It can be seen that the selected additives of drilling fluid and the final "green" drilling fluid system meet the requirements of relevant national environmental protection standards in terms of heavy metal content, biodegradability and biotoxicity.
Table 5. Environmental performance of the green drilling fluid of strong inhibition.

| Index       | PH | Hydrocarbon / (mg.kg\(^{-1}\)) | Cd / (mg.kg\(^{-1}\)) | Hg / (mg.kg\(^{-1}\)) | Pb / (mg.kg\(^{-1}\)) | Cr / (mg.kg\(^{-1}\)) | As / (mg.kg\(^{-1}\)) | EC\(_{50}^c\) / (mg.L\(^{-1}\)) | BOD\(_5^c\)/COD\(_c\) |
|-------------|----|--------------------------------|------------------------|-----------------------|------------------------|------------------------|------------------------|-------------------------------|-------------------------|
| Estimated   | 8.87 | 194                             | 0.4                    | 0.01                  | 2.69                   | 7.5                    | 1.92                   | 115000                        | 0.49                     |
| Specified   | 7–10 | ≤3000                            | ≤20                    | ≤15                   | ≤1000                  | ≤1000                  | ≤75                    | ≥30000                        | ≥0.100                   |

3.2. Mud cake quality evaluation

At present, there is no mature and unified method for mud cake quality evaluation[8]. In this paper, the permeability and compressive strength of mud cake is evaluated by means of pressure transmission tester and HPHT core filtration tester.

Fresh water is taken as the upstream test solution and its pressure is kept at 5 MPa. The green drilling fluid system of extra low solid content is taken as the downstream test solution. And the natural shale core with micro-fractures is adopted and its permeability is 15 mD. The change of the pressure of closed downstream test solution over the time is measured and recorded, seeing Figure 2.

![Figure 2. Pressure transmission test of green drilling fluid.](image)

From Figure 2, the pressure of downstream test solution is kept at 1.6 MPa within 8000 min and rises to 3 MPa 12000 min later. Therefore, the mud cake derived from this system can slow the transmission of fluid pressure effectively within 200 h, guaranteeing the borehole wall stability effectively.

![Figure 3. Breakthrough pressure of green drilling fluid.](image)

The breakthrough pressure of the mud cake which is formed after the core is treated with the green drilling fluid system is measured by using CL-II HTHP core filtration tester. Test results are shown in
Figure 3. In this figure, breakthrough pressure 1 is the core breakthrough pressure curve which is measured in API drilling fluid system, and breakthrough pressure 2 is the one measured after the core is treated with the drilling fluid system containing nano-barite and API barite. Due to the introduction of nano-barite, the permeability and strength of mud cake is reduced effectively and the core breakthrough pressure is increased significantly.

4. Field application
Chad operational zone is located in the Africa Rift Basin. A large amount of shale is developed in the Lower Cretaceous, so excessive drawing blocking, collapse and electric logging sticking happen frequently in the process of drilling.

The environment friendly drilling fluid is successfully used in cluster wells on three platforms (D 1-14, D 1-22 and D 1-17) in Chad operational zone shown in Figure 4. No borehole wall instability happens, drilling fluid density is decreased from 12.8 ppg to 12.5 ppg, average drilling cycle is shortened and the primary success ratio of electric logging is increased to 100%, which are shown in Figure 5.

![Figure 4. Density of drilling fluid in Platform D1-14 and D 1-17](image)

![Figure 5. Drilling index comparison between wells on three platform.](image)
5. Conclusions
In the green drilling fluid system of extra low solid content, KCOOH and SIAT are selected as inhibitor, PAC-LV as fluid loss agent, KPAM as flocculant, and the combination of nano-barite and API barite as the weighting and plugging material. This system presents the following characteristics.

(1) The agents in this system all satisfy the environmental requirements, so they are suitable for the operation in the environmentally sensitive operational zones, and the harmless treatment cost of drilling fluid is reduced significantly;

(2) This system is of strong inhibition and it can inhibit shale from hydrating and dispersing. Its clay content is high, so the rheological property of drilling fluid system can be kept stable effectively;

(3) This system can envelope the drilling cuttings efficiently and quickly and carry them to the surface, so the inferior solid phase in the system is removed effectively, its viscosity and shear force are kept at lower level and the rate of penetration is increased;

(4) The combination of nano-barite and API barite is adopted in this system. The weighting and plugging properties of barite is exerted so fully that the plugging and compressive strength of mud cake are improved effectively. Thus, effective protective layer is formed on the borehole wall to keep its stability.

The green drilling fluid system of extra low solid content is particularly suitable for shale formation with developed micro-fractures. It is characterized by strong pollution resistance and stable rheological property. Besides, it contains fewer agents and its maintenance is simple. Therefore, it is in agreement with the environmental requirements.

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