

## Research Article

# Research and Application of Evaluation Methods for Functional Characteristics of Oil-Based Drilling Fluid in Shale Gas Wells

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Received 22 September 2020; Revised 9 January 2021; Accepted 27 February 2021; Published 18 March 2021

Academic Editor: Guanglong Sheng

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Intelligent unconventional reservoir optimal production control technology is a comprehensive technology, involving geology, reservoir simulation, and efficient drilling and completion. Efficient drilling and completion provides a flow channel for unconventional oil and gas exploitation and a wellbore with good integrity for reservoir transformation, which is an important link in the efficient development of unconventional oil and gas. The application of industry standard method to evaluate the performance of oil-based drilling fluid has the problem of poor correlation. It cannot reflect the difference of performance among oil-based drilling fluid systems, which lacks the significance for field construction. Based on shale expansion, rolling dispersion experiment, and microporous membrane filtration loss test, the physicochemical mechanism of borehole wall instability in shale formation was investigated. The evaluation methods of shale lubrication, antiaccretion test, slake durability, buck hardness test, etc. are put forward, and the formula of oil-based drilling fluid is optimized. The lubrication and antiaccretion experiment method can effectively and intuitively characterize the cleaning and lubrication effect of drilling fluid on drilling tools. The slake durability evaluation method simulates the collision between drill cuttings and the drill string and well wall. The bucking hardness experiment is through testing the cuttings and the hardness change after drilling fluid action reflects its inhibitory effect. The new methods were used to evaluate the oil-based drilling fluid used in 4 wells in the Changning block. It was found that the drilling fluid of CN209H2 well adhered to the steel column with at least 0.41 g of cuttings; the recovery rate of the drilling fluid resistance of CN209H1 was up to 87.70%, and YX1200 oil-based drilling fluid plugging agent was selected through the microporous membrane experiment. In the process of drilling the well CN209H5, the new oil-based drilling fluid formulation improved the lubrication performance by 44%, accompanied by 95.48% recovery rate and less than 10 mL HTHP fluid loss at the same time. The research results show that the oil-based drilling fluid system optimized according to the new method can significantly inhibit shale hydration and dispersion and can effectively solve the problem of unstable performance of traditional oil-based drilling fluids in the Changning block.

## 1. Introduction

In recent years, it is urgent to think deeply about the profound impact of the unconventional oil and gas revolution on the global energy industry. Intelligent unconventional reservoir optimal production control technology is a comprehensive technology, involving geology, reservoir simulation, and efficient drilling and completion. Efficient drilling and completion provides a flow channel for unconventional oil

and gas exploitation and a wellbore with good integrity for reservoir transformation, which is an important link in the efficient development of unconventional oil and gas. At present, we are gradually moving into unconventional oil and gas reservoirs. However, in the process of exploitation, the wall stability of mud shale is prominent. These problems bring great difficulties to safe, fast, high-quality, and efficient drilling and also put forward higher and more comprehensive requirements for drilling fluid technology. The traditional

evaluation method of oil-based drilling fluid cannot adapt to the complexity of unconventional reservoir formation and needs to be improved. It also puts forward more comprehensive requirements for drilling fluid technology. Traditional oil-based drilling fluid evaluation methods can no longer adapt to the complexity of the formation and need to be comprehensively improved [1–6]. Changning block, as an important shale gas production block in China with the proven reserves of  $1.061 \times 10^{13} \text{ m}^3$ , has been built up to  $7.8 \times 10^{10} \text{ m}^3$  of shale gas production capacity by September 2019 [7, 8]. The regional structure is located at the junction of Sichuan Basin and Yunnan-Guizhou Plateau, between the low-steep structural area in the middle uplift of ancient depression in southern Sichuan and Loushan Fold Belt. The shale at the bottom of Wufeng Formation-Longmaxi Formation has high gas content with developed shale bedding and strong brittleness. This shale formation is easy to hydrate and disperse, which is prone to complicate well conditions such as unstable drilling fluid performance and wellbore instability [9–11]. The drilling fluid-based on crude oil was developed in foreign countries around 1920. In 1960s, Gray and Chenevert [12, 13] concluded that the reasons of shale wellbore instability arose from the physical and chemical reaction between wellbore and drilling fluid rather than a pure mechanical problem. In 1969, Chenevert conducted a study on the swelling pressure produced by shale hydration, which proposed that the hydration stress as a function of shale-water reactivity. Since 1980s, researchers in China have studied the chemical action of oil-based drilling fluid on shale based on laboratory experiments. Compared with water-based drilling fluid, oil-based drilling fluid has the advantages of good inhibition, strong antipollution ability, good reusability, etc. With the development of unconventional oil and gas drilling in Changning block, the traditional oil-based drilling fluid exposed to problems such as insufficient inhibition and poor plugging performance, which can no longer meet the requirements of field construction [14–17]. In view of the unstable performance and insufficient inhibition of traditional oil-based drilling fluid during the unconventional oil and gas drilling in Changning block, this paper studies the evaluation method of functional characteristics of oil-based drilling fluid. The simulation conditions of traditional shale dispersion experiment are improved. A new hardness change testing method was proposed which could measure the interaction between cuttings and drilling fluid. According to the new method, the plugging agent and lubricant for oil-based drilling fluid are optimized. The optimized oil-based drilling fluid can strengthen the hydration inhibition of shale surface and improve the performance, so as to reduce the complex situation such as wellbore instability and has important reference significance for improving recovery of unconventional reservoirs.

## 2. Materials and Methods

**2.1. Materials.** The organic bentonite used in the experiment was provided by Zhejiang Anji Bentonite Co., Ltd. After testing, it can be used in the oil-based drilling fluid slurry formulation system. The main emulsifier, auxiliary emulsifier, and

oil-based lignite were provided by Shengli Oilfield Branch of Sinopec. Sodium chloride and calcium chloride are analytical grades, purchased from Sinopharm Chemical Reagent Co., Ltd.; potassium chromate purchased from Shanghai Aladdin Biochemical Technology Co., Ltd.; microporous membranes contain  $22 \mu\text{m}$  and  $45 \mu\text{m}$  specifications, purchased from Shanghai Xingya Purification Material Factory. In addition, an electronic balance (with an accuracy of  $0.0002 \text{ g}$ ), a high-speed mixer, a PHS-25 pH meter, a high-temperature roller furnace, an extreme pressure lubrication meter, etc. are also needed. The high temperature roller furnace is made by Qingdao Tongchun Instrument Co., LTD. The extreme pressure lubrication instrument is made by Qingdao Senxin Mechanical and Electrical Equipment Co., Ltd. All experimental materials can be used without further purification.

**2.2. Methods.** Experimental research to analyze the interaction between shale and drilling fluid requires the establishment of corresponding evaluation methods. The method of evaluating the inhibition of drilling fluid is mainly to test the effect of drilling fluid and shale from different angles of macro or micro under relatively simulated experimental conditions. The drilling fluid inhibition evaluation methods used before include shale expansion test, shale dispersion test, cation exchange capacity test, shale adsorption isotherm test, capillary adsorption time test, and shale stability index test. The shale expansion test evaluates the ability of drilling fluid to inhibit the shale expansion by recording the shale expansion rate over time. The shale dispersion experiment is a direct method to quantitatively evaluate the drilling fluid's inhibition of mud shale dispersion [18]. The method of cation exchange capacity is to determine the hydration expansion trend of mud shale by determining the intermediate equivalent expansive clay content. The shale adsorption isotherm experiment predicts the hydration and expansion trend of the formation by measuring the water absorption characteristics of the shale under different equilibrium conditions. The shale stability index indicates the combined effect of the hydration expansion, dispersion erosion, and strength of the formation mud and shale on the wellbore stability under the interactions between drilling fluid and shale formation. These evaluation methods are able to test the inhibition of drilling fluids from different angles, but they all have certain limitations. For example, the shale swelling experiment can only evaluate the hydration swelling property. However, its applicability on hard and brittle shale is poor. Moreover, this method often obtains opposite experimental results when evaluating the anticollapse effect of polyol [19]. The shale dispersion experiment can simulate the hydration and dispersion of shale and can effectively evaluate anticollapse agents with different inhibition mechanisms. However, there is no standard rock sample at present, and the rock samples of different blocks and different formations are quite different, leading to the evaluation results. The repeatability is poor [20].

According to previous studies, the constructed oil-based drilling fluid functional characteristic evaluation method is used to select high-quality drilling fluids with outstanding



FIGURE 1: Picture of accretion experiment instrument.

effects of inhibiting shale softening and preventing the use of drilling tool mud packs. However, the current conventional drilling fluid evaluation experimental methods are difficult to evaluate and analyze effectively. Therefore, in view of the needs of onsite oil-based drilling fluid characteristic evaluation, it is necessary to explore and establish suitable experimental test methods to further improve the parallelism and experimental comparability of experiments.

**2.2.1. Lubrication and Antiaccretion Test.** Taking the extreme pressure lubrication instrument and the comprehensive lubricity simulation device as a reference, by investigating the adhesion phenomenon of the drilling fluid and the shale rock sample on the simulated experimental steel rod, it can directly reflect the clean and lubricity of the drilling fluid and the antimud package performance. Evaluate the adhesion of drill cuttings on the outer pipe wall of the rotating drill string and use the quality or adhesion rate of the adhered drill cuttings as an inverse correlation evaluation index to further indicate the clean and lubricating characteristics and inhibition of oil-based drilling fluids. The main components include aging tanks and steel bars of different sizes. The bonding tester is shown in Figure 1.

**2.2.2. Slake Durability Test.** According to the shale rolling dispersion experiment, the migration of cuttings in the process of drilling cuttings returning from the wellbore is simulated, and the dynamic collision and screening of cuttings in the hot rolling process are observed [21]. The recovery rate was taken as the positive correlation evaluation index to further evaluate the inhibitory dispersion characteristics of oil-based drilling fluids. The collapse resistance experiment is similar to the shale dispersion experiment. The difference is that the rock sample is placed in an iron cage with a certain diameter for rolling. By simulating the friction between the drill cuttings and the downhole drill string, the inhibition is more truly reflected the ability of the agent to inhibit shale hydration and dispersion. The main components include aging tank, antiaccretion test stand, and screens of different meshes. The slake durability tester is shown in Figure 2.



FIGURE 2: Picture of slake durability tester.



FIGURE 3: Picture of bulk hardness tester.

**2.2.3. Buck Hardness Test.** On the basis of collapse resistance experiment and the principle of mechanics and chemistry of wellbore stability, a simple instrument was designed to evaluate the strength of cuttings possessed or maintained after collapse resistance experiment. With the aid of flexure hardness tester, we can apply appropriate torque and pressure to the rock sample and take the torque tested by the instrument as the positive correlation evaluation index to test the hardness change of mud shale after the action of mud shale and drilling fluid [22]. To a certain extent, it can accurately evaluate and analyze the performance of drilling fluid in inhibiting shale softening. Generally, the hardness of the shale rock sample will change after contacting with the drilling fluid, resulting in softening. The main components of this apparatus include the main test cup, fixing bolts, extrusion pistons, adapters, torque wrenches, supporting bases, and connecting bolts. The buckling hardness tester is shown in Figure 3.

**2.2.4. Microporous Membrane Test.** With “360 mL white oil+3% organic clay+4% main emulsifier+2% auxiliary emulsifier +40mL CaCl<sub>2</sub> brine +2% oil-based lignite” as base slurry, the rheology properties and filtration properties of

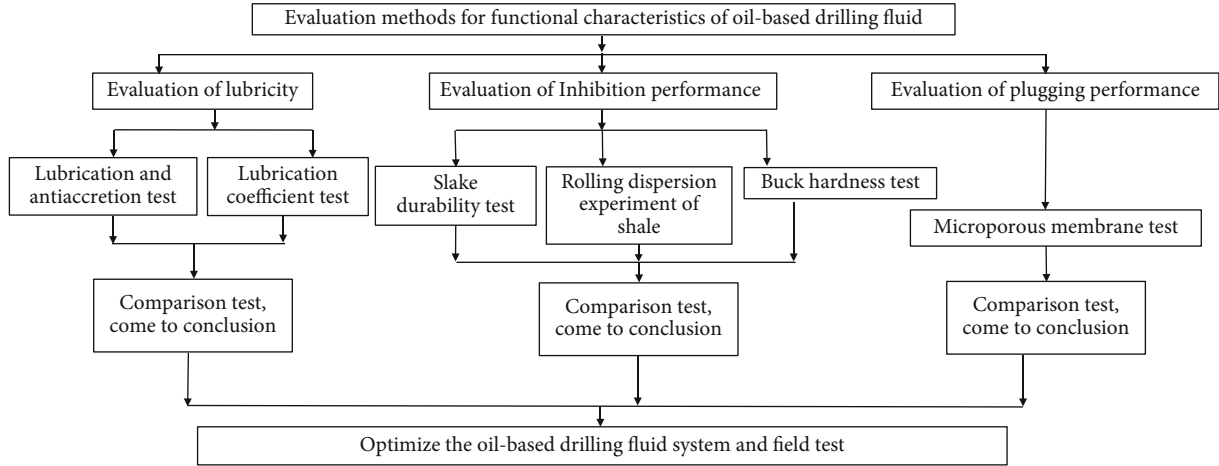


FIGURE 4: A flow chart about the evaluation methods for functional characteristics.

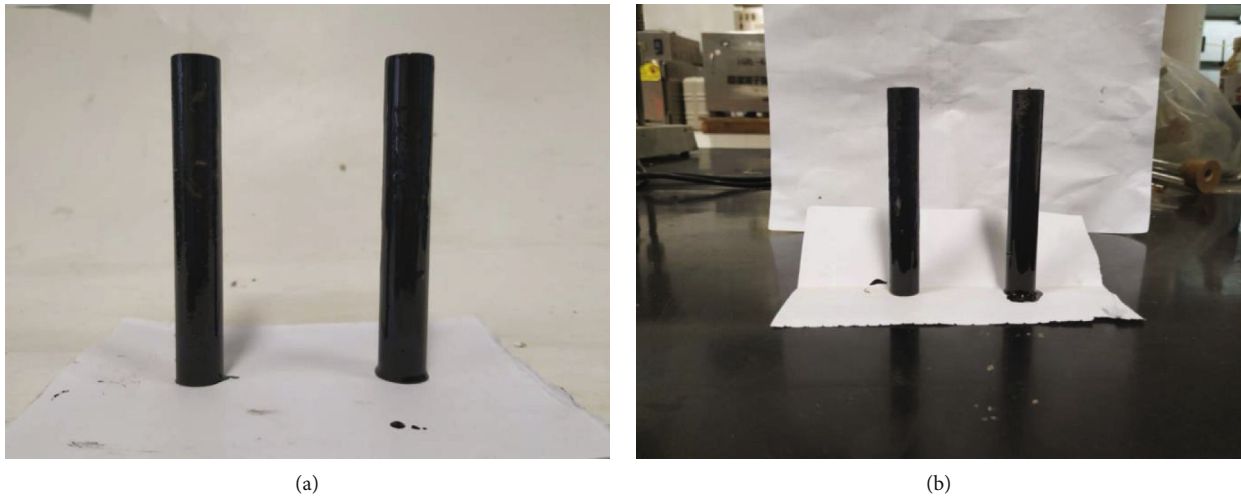


FIGURE 5: Picture of accretion on steel bar for the accretion test, Note: (a) CN209H2 and CN209H1 from left to right; (b) from left to right, and it is CN216H1 and CN209H3.

TABLE 1: Lubrication and anti-accretion test results.

Sampled well number	Test the lubrication coefficient with extreme pressure lubricator	Quality of artificial rock samples adhered to steel columns/g
CN216H1	0.032	0.82
CN209H1	0.043	0.50
CN209H2	0.043	0.41
CN209H3	0.043	0.91

5% plugging and antisloughing agents aged at 125°C/16 h in base slurry were compared, including polysiloxane fiber S, amphiphilic pressure-bearing plugging agent, YX1200 plugging agent, and YX400 taking the bearing capacity of aging fractured plugging as the main index. The plugging agent with better comprehensive performance was evaluated by using microporous membrane experiment method.

According to the above four evaluation methods, the flow chart of evaluation methods for functional characteristics of oil-based drilling fluid is sorted out, as shown in Figure 4.

### 3. Results and Discussion

**3.1. Lubrication and Antiaccretion Test.** CN216H1, CN209H1, CN209H2, and CN209H3 well slurries were selected. And their lubricating properties were evaluated according to the adhesion test method. Submerge steel bars into these base slurry samples while rolling them for 2 h at room temperature. Then, take out these steel bars to observe the mud bags. The results are shown in Figure 5 and Table 1.

As shown in Figure 5 and Table 1, the lubrication coefficient of each well slurry measured by extreme pressure lubricator is 0.032, which indicates that the lubrication performance is good, while that of other wells is 0.043, which is poor. In the field drilling process, well CN216H1 still has problems such as downhole sticking and large friction. The



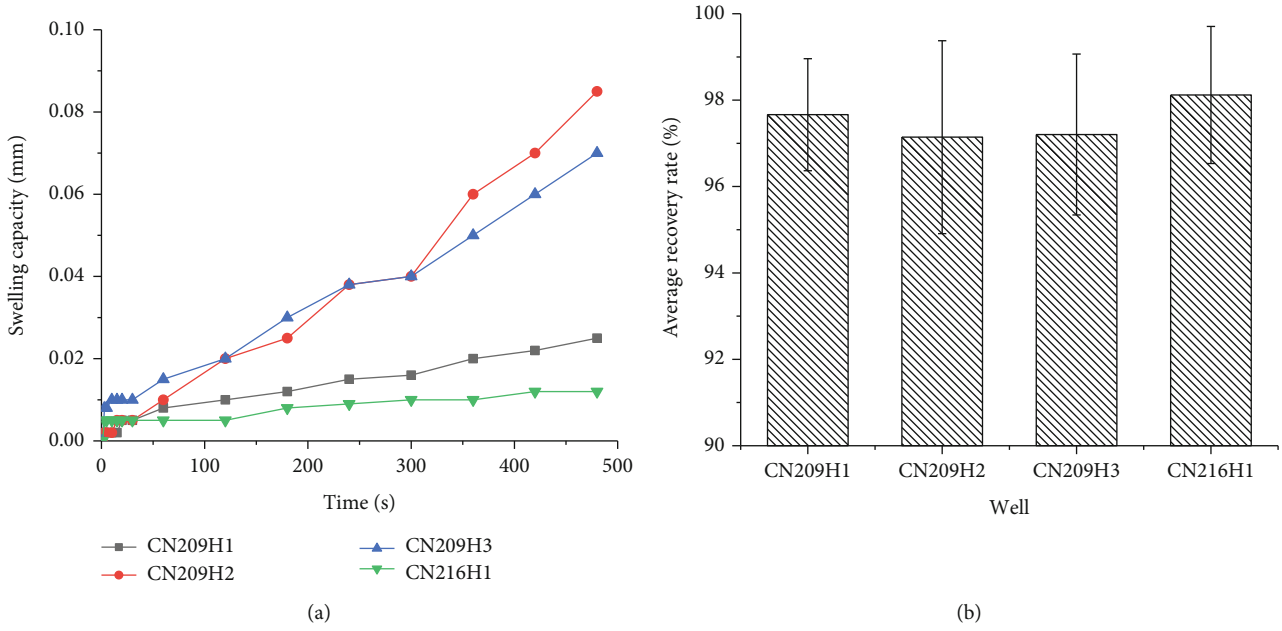


FIGURE 6: Drilling fluid hydration expansion experiment.

TABLE 2: Experimental evaluation results of drilling fluid dispersion and slake durability.

Sampled well number	Rolling dispersion experiment of shale			Anti-accretion experiment		
	Recovery quality/g	Recovery quality/g	Average recovery rate/%	Recovery quality/g	Recovery rate/%	
CN216H1	30.53	30.10	29.73	97.66	25.71	85.70
CN209H3	29.85	29.35	28.52	97.14	22.06	73.53
CN209H1	30.68	29.72	29.65	97.20	26.31	87.70
CN209H2	30.22	29.26	29.71	98.12	20.22	67.40

lubrication and antiadhesion test was used to evaluate the above slurry, and the mass of the artificial rock sample adhered to the steel column of well CN209H2 was 0.41 g, which showed that the drilling fluid of well CN209H2 could effectively inhibit the hydration and dispersion of clay, and at the same time, play a better role in preventing mud bag and lubrication.

**3.2. Slake Durability Test.** Figure 6 shows the analysis results of hydration properties of the selected rock samples. From Figure 6(a), it can be concluded that the swelling rate of the selected formation rock samples is between 0.10% and 1.00%, and the swelling rate of drilling fluid in well CN209H2 reached the highest value as 0.09 mm. The lowest swelling rate of drilling fluid in well CN216H1 is 0.012 mm. It can be seen from Figure 6(b) that the recovery rate of rock samples in the Changning area is relatively, the average recovery rate is 99.06%, and the drilling fluid has good hydration and dispersion resistance.

CN216H1, CN209H1, CN209H2, and CN209H3 well slurries were selected, and different inhibitors were evaluated by the antiaccretion test and shale rolling dispersion test: test solution: 280 mL tap water + different amounts of inhibitors. The amount of artificial cuttings is 40 g.

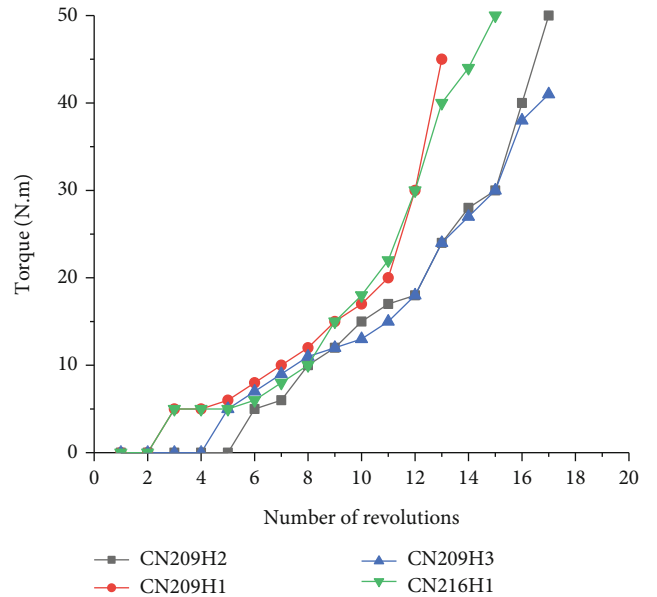


FIGURE 7: Evaluation results of field drilling fluid buckling hardness.

TABLE 3: Optimal experimental results of plugging agents.

System	Condition	AV (mPa·s)	PV (mPa·s)	YP (Pa·s)	Gel10''/Gel10' (Pa/Pa)	Yield point and plastic viscosity ratio Pa/(mPa·s)	FL <sub>API</sub> (mL)	FL <sub>filter membrane</sub> (mL)	
								22 $\mu$ m	45 $\mu$ m
Base slurry	After aging	12.5	10	2.5	2.044/1.533	0.250	12.5	24	24
Slurry 1	After aging	9.5	8	1.5	1.533/1.022	0.188	8	14.8	14.8
Slurry 2	After aging	12	11	1	1.533/1.022	0.091	5.6	18	18
Slurry 3	After aging	12.5	11	1.5	1.533/1.022	0.136	5.6	10	9.6
Slurry 4	After aging	12.5	9	3.5	1.533/1.022	0.389	6.4	12.8	11.2

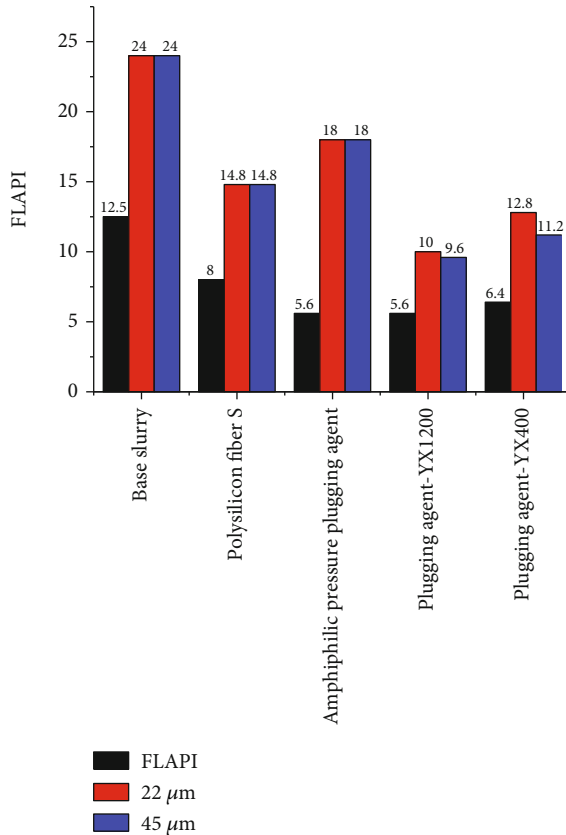


FIGURE 8: Comparison chart of API and microporous membrane filter loss after aging.

The experimental results are shown in Table 2.

The experimental results in Table 2 show that the highest recovery rate of drilling fluid in well CN209H1 is 87.70%, the lowest recovery rate of drilling fluid in well CN209H2 is 67.40%, and the average recovery rate against collapse is 78.54%. Through shale rolling dispersion experiment analysis, it can be seen that each well has good hydration and dispersion performance, but there is a problem of poor inhibition during field construction, which indicates that drilling fluid with strong adaptability cannot be optimized through shale dispersion experiment. The antiaccretion experiment can better simulate the dynamic collision and screening of drilling cuttings in the process of deteriorating hot rolling. Although the recovery rate of drilling fluid in well

CN209H2 is high in rolling recovery experiment, the recovery rate of antiaccretion experiment is low, which indicates that the drilling fluid in well CN209H2 cannot maintain the strength of rock samples, resulting in the decrease of the antiaccretion recovery rate.

**3.3. Buck Hardness Test.** It can be seen from the experimental results in Figure 7 that the oil-based drilling fluid can keep the integrity and strength of cuttings. During the torque application, no cuttings are squeezed out of the orifice plate, and the torque increases rapidly with the increase of rotation speed. The final torque of drilling fluids in well CN209H2 and CN216H1 was up to 50 N·m, higher than that of 45 N·m and 41 N·m of drilling fluids in well CN209H1 and CN209H3, indicating that the inhibition performance of drilling fluids in well CN209H2 and CN216H1 was better than that of drilling fluids in well CN209H1 and CN209H3.

**3.4. Microporous Membrane Test.** The experimental results are as follows.

It can be seen from Table 3 and Figure 8 that after the experimental evaluation of microporous membrane, the API filtration loss of experimental slurry with YX1200 plugging agent is 5.6 mL, and the filtration loss through microporous membrane with pore diameter of 22  $\mu$ m and 45  $\mu$ m is 10 mL and 9.6 mL, respectively. Compared with other plugging agents, the filtration loss is the lowest, and the plugging effect is the best; so, oil-based drilling fluid can be selected as plugging agent.

**3.5. Filed Test**

**3.5.1. Application Situation.** In Changning, Zhaotong, 29 wells were drilled in the horizontal section, and erosive block loss was common in the downhole, all of which were stuck in different degrees. There were 4 wells and 6 wells with more serious stuck time, with a total loss of 144.66 days. The analysis found that the main reasons for the sticking are as follows: (1) geologically, the drilling encounters a thin formation, large changes, broken zones, and high content of brittle minerals; (2) engineering tool combination, joint outer diameter, wellbore trajectory design, and drilling, The hydraulic parameters need to be further optimized. The "360mL white oil+3% organic soil+4% primary emulsifier+2% secondary emulsifier+40mL CaCl<sub>2</sub> brine+2% oil-based lignite+5% YX1200+1.5% solid lubricant" oil was selected by the functional characteristic evaluation method. The base

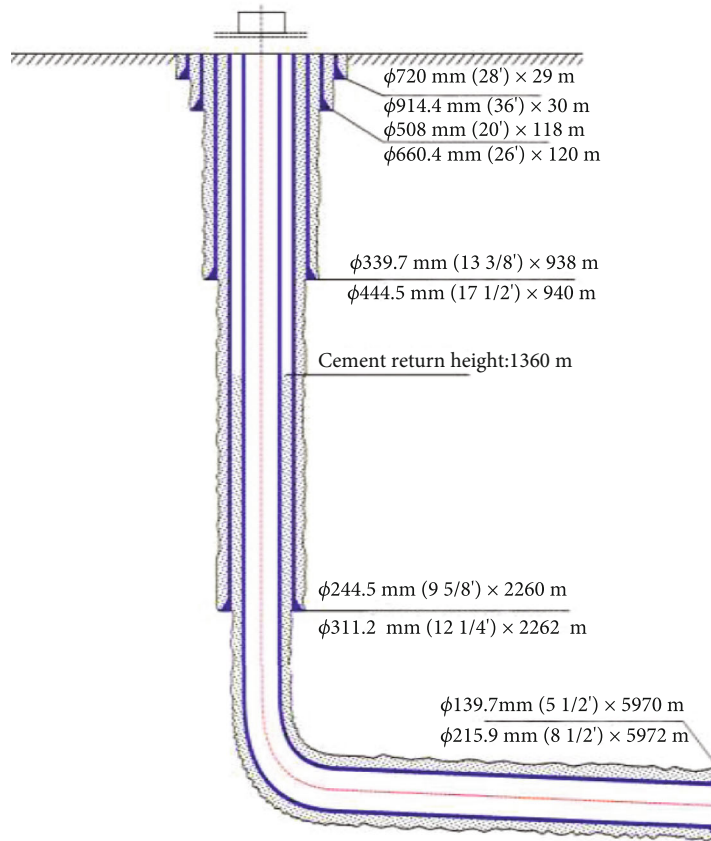


FIGURE 9: Chart of casing program of well CN209H5.

TABLE 4: Comparison of performance indicators of oil-based drilling fluids evaluated by functional characteristics methods.

Performance indicators	Recovery rate/%	FL <sub>API</sub> /mL	Quality of adhesive rock sample/g	Caliper expansion rate/%	Average drilling speed/(m/h)
Field drilling fluid system	78.54	12.5	5.57	92.59	7.79
Preferred postdrilling fluid system	95.48	5.6	0.41	4.75	10.68

drilling fluid system has been tested and applied in more than 10 wells in the Changning block, effectively solving the problem of poor inhibition and unstable performance of onsite oil-based drilling fluids [23–25]. Compared with the evaluation method of unused functional characteristics in the same block, the recovery rate is 95.48%, the API fluid loss of the entire formation section is controlled below 6 mL, and the HTHP fluid loss is controlled below 12 mL. The inhibition and lubrication performance are significantly improved. The maintenance of the base drilling fluid provides a basis.

**3.5.2. The Application Effect in CN209H5 Well.** Block CN209 is located at the edge of the Sichuan Basin, that is, at the junction of the southern Sichuan Fold Belt and the Loushan Fault Fold Belt in the Sichuan Basin. The north is affected by the west extension of the East Sichuan Fold and Thrust Belt, and the south is controlled by the evolution of the Loushan Fold Belt. Its structural feature is a

tectonic complex integrating the two. The block structure can be roughly divided into three major structural layers in the vertical direction; the shallow layer is the Upper Triassic and above layers, of which the structural form is represented by the Xudi; the middle layer is composed of the Middle, Lower Triassic, and Permian. The structural form is represented by the “Upper Permian bottom”; the deep layer is represented by the layers below the Permian, and the structural form is represented by the “cold bottom.” The development of faults and variable strike is one of the geological structural features of this block. Well CN209H5 is a development well in this block. The designed well depth is 5970 m. The target layer is the Paleozoic Longmaxi Formation. The well depth structure is shown in Figure 9. During the drilling process of this well, complex problems such as wall falling, lost circulation, and gas intrusion occurred. The newly proposed functional characteristic method was used to evaluate the

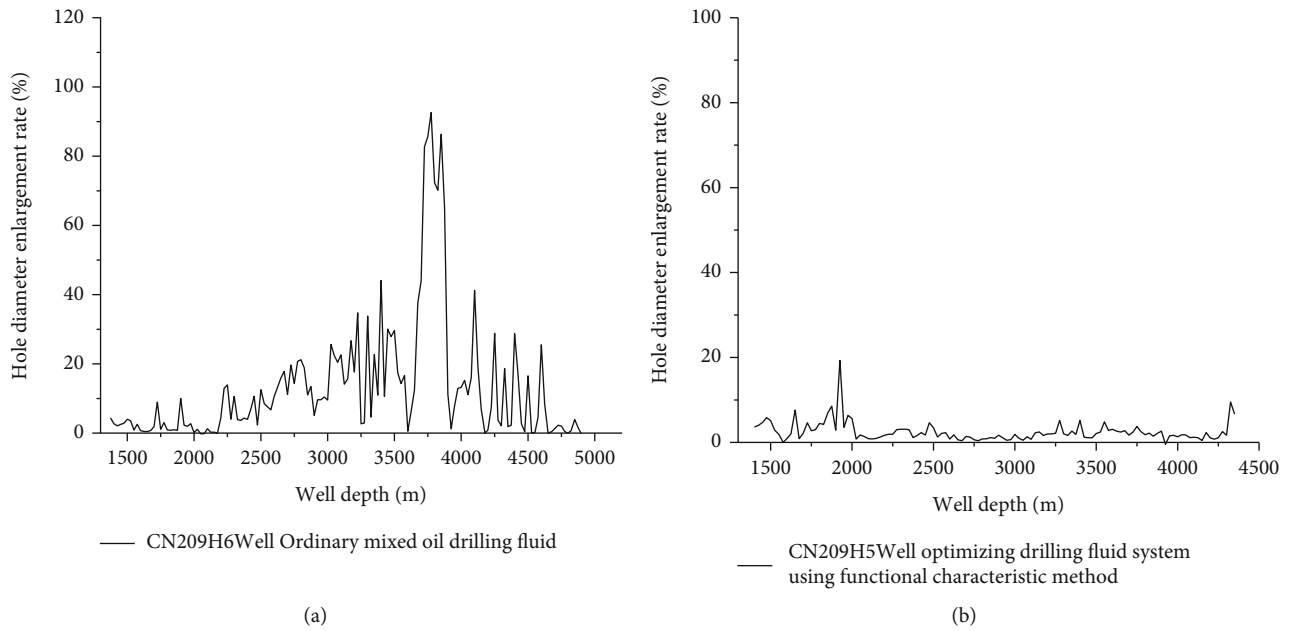


FIGURE 10: Comparison of the caliper expansion rate of field application wells.

onsite drilling fluid and found that the original drilling fluid system had a low recovery rate of only 78.54%. The API filtration loss is large, reaching 12.5 mL, indicating that the system has poor inhibition and lubricity.

The oil-based drilling fluid system of “360mL white oil +3% organic clay +4% primary emulsifier +2% secondary emulsifier +40 ml  $\text{CaCl}_2$  brine +2% oil-based lignite +5% YX1200 +1.5% solid lubricant” was optimized by using the functional characteristic methods. After applying the system to well CN209H5, it was evaluated again and found that the quality of the artificial rock sample adhered to the steel column was 0.28 g, and the lubrication performance was increased by 44%; the recovery rate was increased by 16.94% to 95.48%. The relevant indicators are shown in Table 4. As shown in Figure 10, the average diameter expansion rate of CN209H6 well formation (1400-4350 m) is 25.62%, and the maximum well diameter expansion rate is 92.59%; the average well diameter expansion rate of CN209H5 formation (1500-4900 m) is 4.75%, indicating that the new method is used to optimize oil. The base drilling fluid system has good lubrication performance, strong suppression and anticollapse, and no lost circulation or stuck drill occurred during the drilling process.

#### 4. Conclusions

- (1) Experiments have proved that the constructed buckling hardness, collapse resistance and lubrication, and anticaking experiments can better evaluate the lubricity and inhibition of the shale gas oil-based drilling fluid in the Changing block. Compared with the hot rolling dispersion experiment, the wear performance has been greatly improved in accuracy by simulating the dynamic collision and screening of the

drill cuttings during the deteriorating hot rolling process, with a certain repeatability

- (2) Through the microporous membrane experiment, the YX1200 plugging agent was selected. The filtration loss through the microporous membrane with pore size of 22  $\mu\text{m}$  and 45  $\mu\text{m}$  is 10 mL and 9.6 mL, respectively, which is the lowest compared with other plugging agents. The blocking effect is significant
- (3) The oil-based drilling fluid system optimized by the new method has been successfully applied in well CN209H5 with the lubrication performance increased by 44%, and the recovery rate reached 95.48%. It has good inhibition and collapse resistance. No downhole complications occurred during the construction process. According to this method, the performance of oil-based drilling fluid can be maintained and adjusted

#### Data Availability

The data used to support the findings of this study are included within the article.

#### Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

#### Acknowledgments

This work was financially supported by the National Natural Science Foundation of China (No. 51974351; No. 51704322; Major Program, No. 51991361), the National Science and



Technology Major Project of China (No. 2016ZX05040-005), and PCSIRT (IRT\_14R58).

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