Research Article

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The mechanisms of inhibition and lubrication of clean fracturing flowback fluids in water-based drilling fluids

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Abstract: This study presents a novel approach for the reuse of uncontaminated fracturing flowback fluids to improve the inhibitory and lubricating properties of water-based drilling fluids (WBFs), curb environmental pollution arising from flowback fluids, and substantially mitigate the expenses associated with WBFs. The experimental design was optimized using orthogonal experiments and range analyses, whereby the modified rubber powder was set at 2.0%, xanthan gum at 0.15%, and a plant phenol to modified complexing agent ratio of 1:0.01. The assessment of the performance evaluation tests indicated that the use of uncontaminated fracturing flowback fluids as the base water can remarkably enhance the inhibitory and lubricating properties of WBFs. Precisely, this approach reduces the linear expansion rate from 62.31% to 21.25%, the reduction rate of extreme pressure lubrication coefficient by 87.98%, and the reduction rate of mud cake sticking factor by 59.86%. This investigation has established the potential environmental and economic benefits of reusing clean fracturing flowback fluids in WBFs.

Keywords: clean fracturing flowback fluids, cyclic utilization, water-based drilling fluids, shale gas, lubrication

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Nomenclature

AV	apparent viscosity
FL_{API}	API fluid loss
PV	plastic viscosity
DSC	differential scanning calorimeter
KPAM	potassium polyacrylamide
TGA	thermal gravimetric analysis
t_g	lubrication coefficient
XC	xanthate gum
YP	dynamic shear force
YP/PV	dynamic shear force ratio
WBFs	water-based drilling fluids

1 Introduction

Hydraulic fracturing stands as a critically vital technique for augmenting the productivity of oil and gas fields [1–3]. Notably, the gradual growth of hydraulic fracturing in oil and gas fields has led to a marked escalation in the volumes of fracturing flowback fluids. In contrast to other wastewaters emanating from oil and gas fields, the intricate makeup of fracturing flowback fluids renders them highly complex [4–8]. The flowback fluid is comprised of a multitude of chemical additives, sediments, bacteria, heavy metals, and other substances that are present in the formation during the flowback process. As such, fracturing fluid is characterized by a complex composition, high viscosity, strong stability, elevated salinity, and a high content of suspended solids. These factors contribute to the challenges associated with the disposal of fracturing flowback fluids [9,10]. Discharging untreated fracturing fluid directly would result in significant pollution of the soil and surrounding water. Harmless treatment and recycling of fracturing flowback fluids are crucial for solving the pollution caused by fracturing flowback fluids.

The flowback fluids that result from hydraulic fracturing are notably complex in nature, consisting of a multitude of different chemical compounds. In particular, the fundamental constituents of these fluids are heavily concentrated melon gum, various polymers, and a range of other chemical substances [11–14]. Additionally, the flowback fluid contains elements such as S and Fe, as well as some bacteria. Several treatment methods have been developed for the primary components of fracturing flowback fluids. Standard treatment technologies for fracturing flowback fluids comprise physical, chemical, and biological methods [15–20]: The physical method targets suspended contaminants in the fracturing flowback fluids and uses gravity separation, filtration, centrifugal separation, and other physical methods for treatment. Physical treatment offers the advantages of a simple process, low investment, and rapid effect. Lu et al. were the first to use ultrasound to treat fracturing flowback fluids and found that ultrasound treatment was even more effective than chemical treatment in reducing fluids' viscosity. However, the physical method can only treat a small number of contaminants and has limited use for some soluble materials. In the chemical treatment, chemicals are added to the fracturing flowback fluids to react chemically with organic contaminants and cause decomposition or precipitation. The homogeneous Sono-Fenton process decomposes hydroxypropyl guar rubber in fracturing flowback fluids, achieving a COD removal rate of 81.15% [21–23]. However, the treatment effect of this method is easily influenced by various factors, such as field operation and process. The biological method is a process that uses the metabolism of microorganisms to oxidize and decompose organic matter and then performs the conversion of organic matter to stabilize inorganic matter [24–26]. Although good results can be achieved with the biological treatment of fracturing flowback fluids, it is difficult to find suitable microorganisms for fracturing flowback fluids.

The proper disposition of fracturing flowback fluids has gained in importance due to the heightened environmental regulations imposed by governments. There has been a surge in the number of firms and scholars that are delving into the realm of recycling fracturing flowback fluids [1–3,17–20]. Currently, clean fracturing fluids are used in large oil fields because of their environmental friendliness, low viscosity, lower residues, and less damage to the reservoir. However, clean fracturing fluids may contain a variety of surfactants and other additives during the flowback process and cannot be discharged directly. Additionally, large amounts of water are consumed during fracturing, and direct discharge of water resources results in significant waste generation. Therefore, recycling the clean fracturing fluid must be considered. The reflux of the clean fracturing fluid usually contains a large amount of quaternary ammonium salt, inhibiting clay hydration expansion. At the same time, the surfactant components contained in the clean fracturing fluid may have good lubricating properties.

In this study, an assessment was conducted on the feasibility of producing WBFs through the utilization of unadulterated fracturing flowback fluids. Additionally, the optimization of WBFs was achieved through the employment of orthogonal experimental techniques, followed by a comprehensive evaluation of the drilling fluid performance.

2 Materials and methods

2.1 Materials

Sodium-bentonite was purchased from Xi'an Fengyun Chemical Co. Ltd. Polyaluminum chloride was purchased from Yangzhou Runda Oilfield Chemical Co., Ltd. Modified plant phenol was purchased from Lingshi County Hengxing Co., Ltd., Shanxi Province. Xanthan gum and modified gum were from Changqing oilfield site. The clean fracturing flowback fluids were provided by Tangshan Jiyou Ruifeng, Chemical Colimmted Company, Jidong Oilfield, Petro China.

2.2 Clean fracturing flowback fluids preparation of water-based drilling fluid (WBF) method

Complexing agents and modified plant phenol were added to the clean fracturing flowback fluids to make the pH alkaline. Mix water with treated clean fracturing rejection fluid at 1:1, 1:2, 1:3, 1:4, and 1:5. After mixing well, add 4% sodium bentonite to the mixture to prepare the base slurry and age it at room temperature for 12 h before use.

2.3 Determination of the surfactant content

The standard curve was fitted according to the relationship between Abs and the mass concentration of the clean fracturing fluid [27]. The absorbance value (Abs) of standard clean fracturing fluid with different concentrations was determined by UV2802 UV spectrophotometer (Shanghai Dapping Instrument Co., Ltd).

2.4 Component analysis of the clean fracturing flowback fluids

According to the “Oilfield Water Analysis Method” (SY/T 5523-2006) and other industry standards and commonly used experimental test methods to perform the component analysis of clean fracturing flowback water samples.

2.5 Drilling fluid performance test

The drilling fluid was prepared by mixing the clean fracturing flowback fluids with the base mud of different concentrations in a particular ratio with xanthan gum as a sealant [28]. According to the test standard GB/T 16783.1-2014, the apparent viscosity (AV), plastic viscosity (PV), dynamic shear force (YP), dynamic shear force ratio (YP/PV), density (ρ), API fluid loss (FL_{API}), lubrication coefficient (t_g), and other performance parameters of the drilling fluid were determined.

2.6 Evaluation of drilling fluid inhibition and lubrication

According to the inhibition evaluation standard SY/T6335-1997, the inhibition effect of drilling fluid on clay swelling was evaluated by measuring the change in bentonite swelling data within 2 h. The mass ratio of bentonite to water was 2:1 to produce mud balls of approximately 10 g mass and the mud balls were immersed in the same volume of different treatment agent solutions, and the appearance and morphological changes of the mud balls were recorded by photography after a particular time [29]. The prepared drilling fluid was centrifugally dried, and 5–10 g samples were added to the thermogravimetric analyzer (TGA/DSC1, METTLER TOLEDO, Germany). The N_2 flow rate was set to 10 mL·min^{-1}, the temperature rise rate was set to 10°C·min^{-1}, and the mass changes of the measured samples were recorded. Referring to the enterprise standard Q/SHCG 4-2011 of China Petroleum and Chemical Corporation, the extreme pressure lubrication coefficient of drilling fluid was measured by using an extreme pressure lubrication meter (112-00-01, Osfit Test Equipment Corporation, America).

3 Results

3.1 Detection of surfactant content in clean fracturing flowback fluids

The basis of the clean fracturing fluid is mainly a viscoelastic surfactant system, the main components of which are various surfactants [30]. When using drilling fluids with clean fracturing flowback fluids, the surfactant content in clean fracturing flowback fluids should be measured. The relationship between absorption and surfactant content of clean fracturing fluid was determined by measuring the absorption of standard fluid with different surfactant contents. The standard curve of the clean fracturing fluid is shown in Figure 1.

The fitting equation of the standard curve for clean fracturing fluid is $y = 4.910x - 0.154$, and the linear correlation coefficient $R^2 = 0.99115$. The curve exhibits a good linear relationship and conforms to Beer’s law. If the mass fraction of surfactant in the flowback solution is within the range shown in Figure 1, it can be calculated directly using the fitting equation. If the mass fraction is above this range, it can be measured by dilution conversion.

The clean fracturing flowback fluids are first pretreated at room temperature by natural sedimentation, high-speed centrifugation, and membrane filtration. The effective surfactant content in the pretreated clean fracturing flowback fluids was determined. The experimental results are shown in Table 1. The mean effective mass fraction of surfactant in the clean fracturing flowback

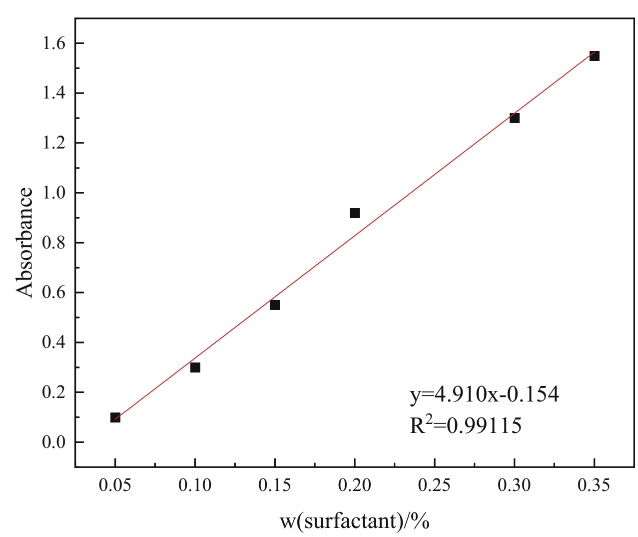

Figure 1: Standard curve of clean fracturing fluid.

Table 1: Determination of surfactant content in clean fracturing flowback fluids

Sample	Absorbance	*w* (surfactant) (%)
1	1.663	0.37
2	1.550	0.35
3	1.368	0.31

fluids was 0.343% after repeated tests on the same batch of samples.

3.2 Components of fracturing flowback fluids

Clean fracturing flowback fluids contain a variety of additives and impurities derived from the formation [31]. Therefore, a water quality analysis should be performed during reuse. The results of the water quality analysis of clean fracturing flowback fluids are shown in Table 2.

The composition and content of fracturing flowback fluids produced in different zones vary widely. The content of sodium ions in the above fracturing flowback fluids is high. This is because sodium chloride is commonly used as a clay stabilizer in fracturing fluids. Sulfate ions in the fracturing flowback fluids come from the formation water and the original fracturing fluid. Iron ions in the fracturing flowback fluids may be due to corrosion in the pipeline. Due to the large number of organics and crude oil in the clean fracturing flowback fluids and the complex formation environment, the level of chemical oxygen demand and suspended solids in the clean fracturing flowback fluids is high. The salt content and total dissolved solids in the fracturing flowback fluids are high, so it is necessary to treat various harmful salt ions in the flowback fluids.

Table 2: Analysis of fracture flowback fluids components

Type	Result
pH	6.0
Cl^- ($mg\cdot L^{-1}$)	8,421
SO_4^2 ($mg\cdot L^{-1}$)	214
Ca^{2+} ($mg\cdot L^{-1}$)	952
Mg^{2+} ($mg\cdot L^{-1}$)	19
Na^+ ($mg\cdot L^{-1}$)	3,246
K^+ ($mg\cdot L^{-1}$)	126
Fe^{2+} and Fe^{3+} ($mg\cdot L^{-1}$)	30
Ba^{2+} ($mg\cdot L^{-1}$)	25
Total mineralization	13,464
Oil ($mg\cdot L^{-1}$)	300
Suspended matter content (SS, $mg\cdot L^{-1}$)	597
Chemical oxygen demand (COD, $mg\cdot L^{-1}$)	5,000
Total dissolved solid (TDS, $mg\cdot L^{-1}$)	60,000
Turbidity (NTU, $mg\cdot L^{-1}$)	367
Viscosity (MPa·s)	5.0

3.3 Screening of mixing ratio between clean fracturing flowback fluids and base mud

According to the method in Section 2.2, fracturing flowback fluids was mixed with base mud at different concentrations and proportions to produce a drilling fluid. The properties of the drilling fluid were investigated, and the experimental results are shown in Table 3.

According to Table 3, the filtration loss of the drilling fluid prepared by mixing water with clean fracture rejection fluid at 1:3 was 17.2 mL. The dynamic–plastic ratio of the drilling fluid prepared at this mixing ratio is 0.36, indicating that the drilling fluid has suitable shear dilution. The friction of the cake is reduced to 0.1975, indicating that the lubrication performance is relatively good. To ensure that the drilling fluid configured with fracturing flowback fluids has good inhibition performance and lubrication, the following experiments are conducted by this ratio.

3.4 Drilling fluid formulation optimization

The main component of the clean fracturing fluid is quaternary ammonium salt, which strongly inhibits the hydration expansion of clay and cannot be directly used to prepare drilling fluids [32]. Therefore, when cleaning fracturing flowback fluids to prepare drilling fluid, it is necessary to add a colloid protection reagent to maintain the stability of the drilling fluid. XC (xanthan gum) and modified gum powder were used as protective agents to adjust the mixing ratio of plant phenol and complexing agent. An orthogonal test was conducted to optimize the drilling fluid formula. The table of the orthogonal experimental design is shown in Table 4. The test results of the drilling fluid are shown in Table 5.

According to the data in Table 5, the range method was used to analyze the experimental results and optimize the reaction conditions. The corresponding mean values of AV and PV in the orthogonal test are shown in Tables 6 and 7.

From the orthogonal test orthogonal tests and range analysis, modified gum powder is the main influencing factor for AV and PV on drilling fluid properties, as shown

Table 3: Performance evaluation of drilling fluids formulated with a mixture of water and different ratios of clean fracturing rejection fluid

Ratio	AV (mPa·s)	PV (mPa·s)	YP (Pa)	YP/PV	pH	ρ (g·cm^{-3})	t_g	FL_{API} (mL)
1:1	18.5	7.6	1.9	0.25	9.35	1.027	0.2024	22.6
1:2	17.8	7.2	2.2	0.31	9.26	1.036	0.2358	21.8
1:3	16.7	5.8	2.0	0.36	9.14	1.039	0.1975	17.2
1:4	14.9	3.6	1.0	0.29	9.25	1.042	0.2257	19.9
1:5	15.3	4.5	1.2	0.27	9.38	1.047	0.2261	23.4

Table 4: L9 (33) orthogonal experimental design

Number	Modified rubber powder	XC (%)	Plant phenol and complexing agent
1	0.5	0.05	1:0.01
2	0.5	0.10	1:0.02
3	0.5	0.15	1:0.03
4	1.0	0.05	1:0.02
5	1.0	0.10	1:0.03
6	1.0	0.15	1:0.01
7	1.5	0.05	1:0.03
8	1.5	0.10	1:0.01
9	1.5	0.15	1:0.02

in Tables 6 and 7. The ratio of xanthan gum and plant phenol complexing agent had little effect. Therefore, in the following experiment, the concentration of xanthan gum was set at 0.05%, and the mixing ratio of plant phenol to complexing agent was set at 1:0.01 to investigate the effects of the concentration of the modified gum powder on the properties of the drilling fluid. The experimental results are shown in Table 8.

As shown in Table 8, AV and PV are significantly affected by the concentration of the modified rubber powder. When the concentration of modified rubber powder was increased to 2.0%, the PV and AV of the drilling fluid were more suitable and exhibited good shear thinning. At this concentration, the fluid loss was reduced to 10.3 mL. Therefore, the optimum dosage of modified rubber powder is 2.0%.

Table 6: Mean corresponding table of AV

Level	Modified rubber powder	XC	Plant phenoll and complexing agent
1	18.967	22.033	21.967
2	20.600	20.633	21.900
3	23.733	20.633	19.533
Range	4.766	1.400	1.367
SupRank	1	2	3

Table 7: Mean corresponding table of PV

Level	Modified rubber powder	XC	Plant phenol and complexing agent
1	17.400	17.900	17.967
2	15.367	16.933	16.933
3	18.200	16.133	16.667
Range	2.833	1.767	1.634
SupRank	1	2	3

Orthogonal tests and range analyses were conducted to investigate the effects of each material on t_g and FL_{API} in the drilling fluid formulation. The corresponding mean values of AV and PV in the orthogonal test are shown in Tables 9 and 10.

Table 9 shows that modified rubber powder in the drilling fluid formulation is the main factor affecting t_g.

Table 5: The performance of drilling fluid

Number	AV (mPa·s)	PV (mPa·s)	YP (Pa)	YP/PV	pH	ρ (g·cm^{-3})	t_g	FL_{API} (mL)
1	21.4	19.4	6.0	0.31	9.14	1.031	0.1125	13.6
2	18.8	17.6	5.1	0.29	9.26	1.044	0.1263	14.9
3	16.7	14.3	5.4	0.38	9.23	1.035	0.0957	18.6
4	19.4	14.9	4.7	0.32	9.02	1.042	0.1123	15.4
5	23.6	16.3	6.0	0.37	8.86	1.041	0.1354	14.6
6	26.8	17.6	5.1	0.29	8.79	1.038	0.1268	13.2
7	25.3	19.4	6.0	0.31	8.64	1.046	0.1397	12.9
8	32.5	16.9	3.4	0.20	8.82	1.038	0.1428	14.5
9	33.4	16.5	3.9	0.24	8.74	1.044	0.1385	15.8

Table 8: Effect of modified rubber powder concentration on drilling fluid properties

Concentration (%)	AV (mPa·s)	PV (mPa·s)	YP (Pa)	YP/PV	pH	ρ (g·cm^{-3})	t_g	FL_{API} (mL)
0.5	23.2	11.4	1.4	0.12	8.56	1.022	0.1254	12.6
1.0	25.6	13.3	2.1	0.16	8.48	1.031	0.1348	13.5
1.5	27.6	15.7	4.1	0.26	8.96	1.053	0.1025	11.8
2.0	33.5	16.8	5.2	0.31	9.10	1.041	0.1261	10.3
2.5	38.2	26.3	7.6	0.29	8.23	1.039	0.1358	11.4

Table 9: Mean corresponding table of t_g

Level	Modified rubber powder	XC	Plant phenol and complexing agent
1	0.112	0.121	0.127
2	0.125	0.135	0.126
3	0.140	0.120	0.124
Range	0.028	0.015	0.014
SupRank	1	2	3

Table 10: Mean corresponding table of FL_{API}

Level	Modified rubber powder	XC	Plant phenol and complexing agent
1	9.700	7.967	7.767
2	8.400	8.667	9.367
3	8.400	9.867	9.367
Range	1.300	1.900	1.600
SupRank	3	1	2

According to Table 8, the optimum formula of drilling fluid with modified gum powder 2.0%, xanthan gum 0.1%, and plant phenol:complexing agent = 1:0.01 was determined. Table 10 shows that xanthine has the most apparent effect on FL_{API} in the drilling fluid formulation. Therefore, the modified gum powder content of 2.0% and plant phenol: complexing agent = 1:0.01 were used in the solid drilling fluid formulation to investigate the effect of the content of XC on fluid loss performance. The experimental results are shown in Table 11.

As shown in Table 11, it can be seen that AV and PY showed an increasing trend with the increase of xanthan content. When the xanthan content increased to 0.15%, the fluid loss decreased to 7.0 mL. Under these conditions, the rheological properties of the drilling fluid can be well maintained. The t_g value (filter cake friction) was reduced to 0.0842, indicating good lubrication performance. Therefore, the formula for the drilling fluid was set as follows: modified gum powder 2.0%, xanthan gum 0.15%, plant phenol: modified complexing agent = 1:0.01. This formula was used for the subsequent tests.

3.5 Effect of temperature on properties of drilling fluids treated with fracturing flowback fluids

The effect of temperature on the performance of the drilling fluid is shown in Table 12. As temperature increases, the AV of the drilling fluid first increases and then decreases while the PV decreases. When the temperature increased to 150°C, the drilling fluid with xanthan gum as the colloid protection reagent still performed well. When the temperature rose to 180°C, the filtration loss of the drilling fluid reached 22.6 mL, which could no longer meet the standard drilling requirements.

Table 11: Effect of XC concentration on drilling fluid properties

Concentration (%)	AV (mPa·s)	PV (mPa·s)	YP (Pa)	YP/PV	pH	ρ (g·cm^{-3})	t_g	FL_{API} (mL)
0.05	20.2	9.0	1.4	0.22	8.67	1.027	0.1053	8.5
0.10	23.5	11.1	2.1	0.30	8.51	1.045	0.1526	8.2
0.15	28.2	15.3	4.1	0.34	8.85	1.033	0.0842	7.0
0.20	33.6	18.6	5.2	0.26	8.12	1.052	0.1268	7.3
0.25	32.1	25.3	7.6	0.32	9.35	1.046	0.1324	9.8

Table 12: Effect of temperature on drilling fluid properties

Temperature (°C)	AV (mPa·s)	PV (mPa·s)	YP (Pa)	YP/PV	pH	ρ (g·cm^{-3})	t_g	FL_{API} (mL)
30	28.2	15.3	4.1	0.34	8.85	1.033	0.0842	7.0
90	19.5	10.6	2.6	0.25	8.12	1.024	0.1365	9.8
120	17.2	9.2	2.2	0.24	7.46	1.018	0.1563	10.3
150	13.3	8.3	1.7	0.21	7.24	1.023	0.1829	12.0
180	7.6	6.5	1.0	0.15	8.35	1.031	0.1721	22.6

3.6 Evaluation of inhibition of drilling fluids produced with clean fracturing flowback fluids

3.6.1 Linear expansion ratio

The linear expansion ratio of the drilling fluid and the supernatant prepared with the best formula was measured to evaluate the inhibition of clay. The experimental results are shown in Figure 2.

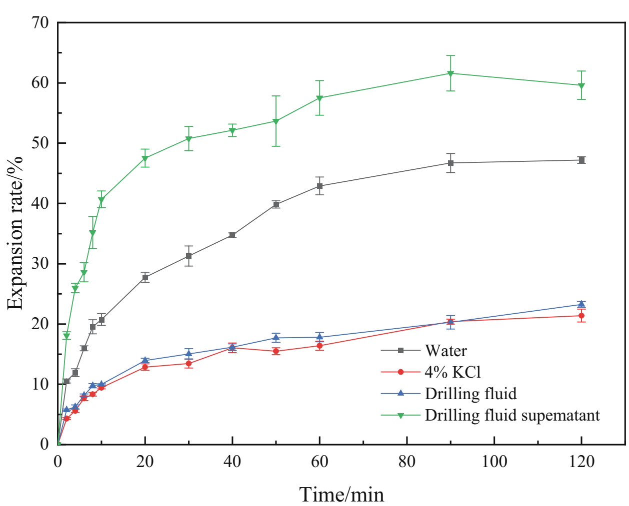

Figure 2: Effect of drilling fluid on the linear expansion rate of clay.

As shown in Figure 2, the drilling fluid and supernatant produced by clean fracturing flowback fluids have an excellent inhibition effect on the hydration expansion of clay. After 120 min, the expansion rate of the drilling fluid-treated clay is only 21.25%, which is better than that of the 4% KCl solution. When linear swelling experiments were performed using drilling fluid supernatant, the swelling of the clay was reduced from 62.31% to 23.64%. The reason is that the polar groups of quaternary ammonium salt contained in the clean fracturing flowback fluids can efficiently adsorb the clay, forming an adsorption layer. This creates an adsorption layer on the clay surface that further slows the flow of water molecules into the shale. Modified rubber powder prevents the penetration of free water into the clay by hydrogen bonds formed by a large number of hydroxyl groups in the molecular chain.

3.6.2 Mud ball tests

The inhibitory effect of the drilling fluid was tested by a mud ball test. The experimental results are shown in Figure 3. As shown in Figure 3a, the mud ball collapsed after it was soaked in tap water. The mud ball's surface, soaked with the drilling fluid's supernatant, remains intact and smooth. This indicates that the fluid prepared with fracturing flowback fluids can significantly inhibit the hydration expansion of the clay. The drilling fluid under

(a) (b) (c) (d)

Figure 3: The mud balls are soaked in different treating agents for 24 h: (a) water, (b) 3% KCl, (c) 1% KPAM, and (d) the drilling fluid.

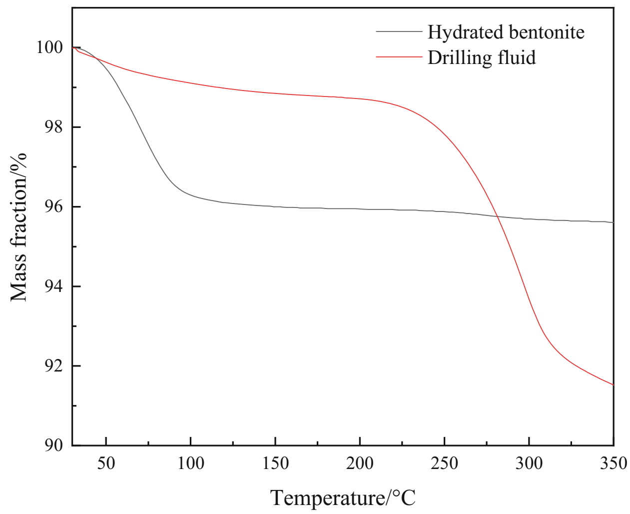

Figure 4: Thermogravimetric curve of clay in drilling fluid prepared with fracturing flowback fluids.

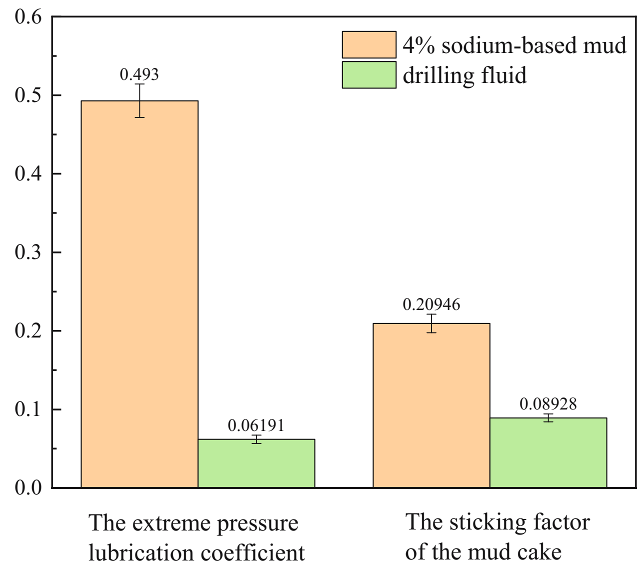

Figure 5: Lubrication performance evaluation of drilling fluid prepared with fracturing flowback fluids.

this formulation can effectively inhibit water molecules from entering inside the mud ball, and its inhibition effect is better than 3% KCl and 1% KPAM.

3.6.3 Thermogravimetric analysis

The bentonite in the drilling fluid was centrifuged and dried for thermogravimetric analysis. The experimental results are shown in Figure 4. As the temperature increases, the clay particles become weightless to a certain extent. When the temperature increased to 100°C, the mass loss rate of the bentonite hydrated with tap water reached 3.73%. At the same temperature, the mass loss rate of the fracturing flowback fluids was only 0.99%. The main reason for this is that the quaternary ammonium salts contained in the clean fracturing flowback fluids effectively slow down the penetration of water molecules into the clay layer. When the temperature rises to 300°C, the mass fraction of clay decreases significantly. This may be due to the thermal decomposition of surfactant components, xanthan gum, and modified guar gum in the drilling fluid.

3.7 Evaluation of lubrication of drilling fluids produced with clean fracturing flowback fluids

The surfactants in clean fracturing flowback fluids ensure that the drilling fluid is prepared with lubrication. Therefore, the extreme pressure lubrication coefficient of the drilling fluid prepared with fracturing flowback fluids was measured to evaluate the lubrication performance. The experimental results are shown in Figure 5.

At room temperature, the extreme pressure lubrication coefficient of 4% sodium-based mud is 0.5100. The extreme pressure lubrication coefficient of drilling fluid prepared with clean fracturing flowback fluids was 0.0613, and the extreme pressure lubrication coefficient reduction rate was 87.98%. The sticking factor of the mud cake decreased from 0.2152 to 0.0864, and the sticking factor of the mud cake decreased by 59.86%. The extreme pressure lubrication coefficient of the drilling fluid decreases significantly and has good lubrication performance.

4 Conclusions

This study delved into the possible impeding and smoothing outcomes of purified fracturing flowback fluids in WBFs. The formula was optimized through a series of tests including orthogonal, range, and single-factor testing. The resulting optimized formula consists of 2.0% modified gum powder, 0.15% xanthan gum, and a plant phenol to modified complexing agent ratio of 1:0.01. The experimental findings indicate that utilizing purified fracturing flowback fluids as the fundamental water source can enhance the impeding and smoothing properties of the WBFs. Specifically, it leads to a reduction in linear expansion rate from 62.31% to 21.25%, an 87.98% decrease in the reduction rate of extreme pressure lubrication coefficient, and a 59.86% decrease in the reduction rate of mud cake sticking factor. The organic salts and surfactants found in clean fracturing flowback fluids possess active components that are capable of enhancing the inhibition and lubrication characteristics of WBFs. Furthermore, there exists the possibility of potential environmental and economic benefits when clean fracturing flowback fluids are reused.

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Conflicts of interest: The authors state no conflict of interest.

Data availability statement: All data generated or analysed during this study are included in this published article [and its supplementary information files].

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