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Construction and Evaluation of a Degradable Drilling Fluid for Underground Coalbed Methane Extraction Boreholes

Lingrui Kong, Jianxin Tang, Yongjiang Luo,* Fang Yuan, Yuan Lin, and Rui Tao

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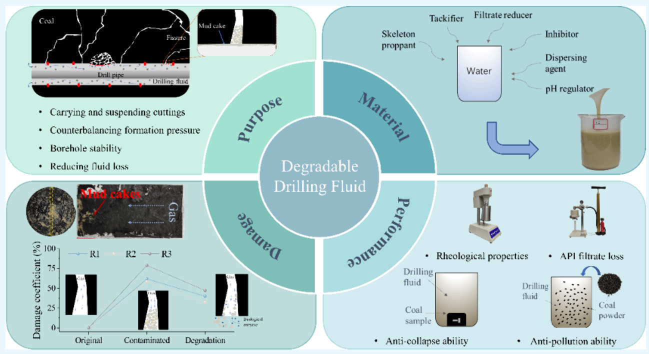
ABSTRACT: Gas drainage with bedding boreholes is an efficient method for preventing gas and achieving coal and gas comining in underground mining engineering. An underground pressurized drilling method is proposed to maintain the borehole stability. However, the presence of natural fractures in coal seams poses challenges during pressurized drilling. Therefore, it is crucial to establish a low-leadage degradable drilling fluid system that minimizes coal seam damage. In this study, a degradable drilling fluid system was developed based on the characteristics of coal seams. The performance and influencing factors of the drilling fluid and the degrading capability of cellulase were examined. Moreover, the damage of the drilling fluid on fractured coal seams was investigated using core flow test methods. The results showed that additives significantly improved the rheology, filtration, and inhibition of the drilling fluid. The drilling fluid system exhibited excellent stability, rheological properties, low filtration, and sealing performance in coal seam environments. However, drilling fluid invasion and mud cake blockage negatively affected gas flow in fractured coal seams, and a higher content of filtrate reducer hindered the recovery of the gas flow rate. Cellulase was used to degrade polymers and alleviate the challenge of mud cake removal after drilling. Research on the influencing factors of cellulase indicates that the degradation efficiency of cellulase enzymes is influenced by the temperature, pH, salinity, and solid-phase content. For polluted coal samples, the gas flow rate significantly recovered after treatment with a cellulase solution. This study provides insights into a degradable drilling fluid system that can enhance underground pressurized drilling methods and minimize reservoir damage.



1. INTRODUCTION

Coalbed methane (CBM) is a valuable clean energy source that is associated with underground mining disasters such as coal and gas outbursts.[1−3] Therefore, as a byproduct gas of coal, efficient extraction of CBM is beneficial for adequate resource utilization, environmental protection, and coal safety production.[4] The use of bedding borehole CBM extraction has become widespread in underground mine gas drainage due to its low cost and high efficiency.[5,6] However, drilling in soft coal seams with CBM accumulation presents challenges due to the developed fractures and complex stresses that increase the probability of accidents such as borehole collapse and shrinkage.[7]

To tackle the drilling issue, we have proposed a pressurized drilling method that ensures smooth drilling of boreholes in coal seams (Figure 1).[8] Unlike surface vertical drilling, underground boreholes are mostly horizontal or inverted holes. These result in insufficient hydrostatic pressure within the borehole to balance the formation stress, and pore pressure, leading to difficulties in overcoming borehole creep and collapse for the present drilling method.[9,10] In the pressurized drilling method, a slush pump and borehole mouth-mounted sealing device are used to increase fluid pressure, preventing gas emission and borehole deformation.

The pressurized drilling method relies on a drilling fluid. During the process, the drilling fluid is responsible for clearing cuttings and stabilizing the borehole wall, as well as suspending the drill pipe and cooling and lubricating the bits.[11,12] There are three main types of drilling fluid: water-based, oil-based, and gas-based.[13−15] Water-based drilling fluid (WBDF) has been extensively researched and used in the field of oil and gas drilling engineering due to its affordability, environmental friendliness, and safety.[16] Initially, WBDF consisted mostly of a base slurry containing water and clay dispersed phases. Bentonite, which possesses good dispersion, adsorption, and mud-forming properties, was widely used as the primary

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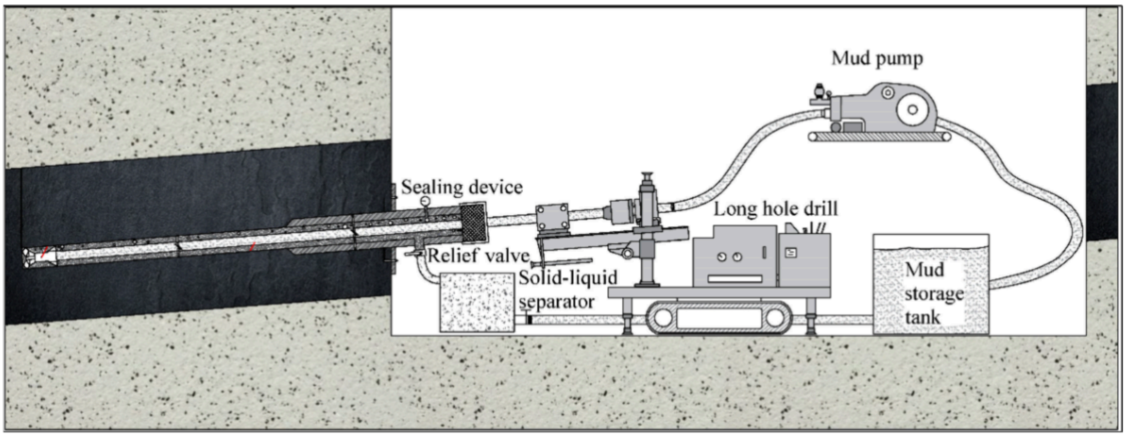

Figure 1. Sketch of the pressurized drilling method.

component.[17] The slurry quickly formed mud cakes during drilling, thereby reducing water filtration and improving the wellbore stability. However, using a base slurry for drilling in complex formations becomes challenging because the high filtration loss and thick mud cake can cause serious reservoir damage and wellbore instability. To address this issue, polymer drilling fluids with different additives, such as polyacrylamide (PAM), have been developed to adapt to complex geological conditions.[18−20] Surfactants and inhibitors can be added to the drilling fluid to improve shale wellbore stability by inhibiting clay hydration and shale swelling.[17,21] Studies have also shown that formate salts and polyglycol can inhibit polymer degradation at high temperatures, leading to the establishment of high-performance drilling fluid systems for extreme temperature conditions.[22] Additionally, a low-temperature drilling fluid system has been developed to enable safe and efficient drilling in frozen soil and natural gas hydrate development.[23]

In recent decades, CBM has received increased attention, and wellbore instability and reservoir damage have become the most challenging issues in CBM drilling.[24,25] The low strength, low matrix permeability, and development of pores and natural fractures in coal formations make them highly susceptible to damage during the drilling process.[26,27] Researchers have used experiments such as core analysis, strength testing, and permeability testing to reveal the characteristics and mechanisms of drilling fluid damage on the strength, permeability, and gas ad/desorption of coal seams.[28−31] Coal seam damage is a result of several factors, including particle and polymer plugging, matrix adsorption expansion, water sensitivity damage, and water locking damage.[32−34] Preventing drilling fluid loss is crucial in reducing damage during the drilling process, and reasonable particles added to the drilling fluid can control drilling fluid loss in fractured reservoirs.[35,36] Nanoparticles have emerged as a new additive with superior performance in drilling fluids, with small amounts able to improve rheological and filtration properties while maintaining excellent stability.[37,38] Fuzzy ball drilling fluids are used to control the wellbore instability in the drilling of CBM wells. These fluids bond with the formation and change the rock's mechanical properties, thereby preventing wellbore collapse.[39,40] Polymer drilling fluids have also been applied in CBM drilling, and their performance and degradation mechanism have been studied.[41,42] Clean water remains the primary flushing medium used in bedding borehole CBM extraction due to its strong cooling capacity and convenience.[43,44] However, it is difficult for water to transport cuttings and maintain fluid pressure in the pressurized drilling method. Positive pressure differential inside the borehole causes water loss, resulting in serious water locking damage and borehole instability. Currently, few researchers pay attention to the drilling fluid used in CBM extraction boreholes, although it is extremely important for underground mining and CBM development.

The study aimed to prepare a degradable polymer drilling fluid system suitable for pressurized drilling in coalbed methane extraction boreholes. To achieve this, we first selected a tackifier, inhibitor, and filtration reducer that were suitable for the demands of the pressurized drilling method. We then tested the properties of these reagents to develop a drilling fluid system. Subsequently, we evaluated the performance of the drilling fluid system and discussed its effects on fractured coal seams by using the core flow test method. Finally, we discussed the degradation efficiency of cellulase.

2. MATERIALS AND METHODS

2.1. Materials. Complex gas-bearing coal seams are characterized by the development of multiscale pores and fractures, low strength, and low matrix permeability. This means that pressurized drilling requires a drilling fluid system with specific abilities, such as suspending and transporting cuttings to clean the borehole, reducing drilling fluid loss by plugging fractures, and forming thin and compact mud cakes to reduce filtration and protect soft walls. Literature research indicates that the majority of coal seams contain clay minerals, such as kaolinite, illite, illite/smectite mixed clays, montmorillonite, chlorite, etc., which means that some coal seams have a certain water sensitivity.[29,45−50] Hence, the drilling fluid must additionally inhibit the clay hydration dispersion to prevent borehole instability. After drilling, the drilling fluid and mud cake should be easily degraded and removed to reduce damage to the coal seams and restore permeability. The cost and convenience of the drilling fluid system were also be considered. To meet these requirements, the main additives were selected based on polymer drilling fluid system. The materials used in the drilling fluid system included bentonite, guar gum, carboxymethyl cellulose sodium (Na-CMC), potassium polyacrylate (K-PAM), and sodium carbonate (Na_2CO_3), which were purchased from Renqiu Gaoke Chemical Company. M011 cellulase produced by Beijing Hongrun Baoshun Technology Company was chosen as the degrading agent to break down the polymer gel. The primary functions of each additive are listed in Table 1.

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Table 1. Drilling Fluid Additives

composition	primary function	tested drilling fluid components (wt.%)		
		no. 1−10	no. 11−16	no. 17−20
bentonite	rheological modulator and filtrate reducer	3	3	3
guar gum	tackifier			0 to 0.3
Na-CMC	filtrate reducer	0.2 to 2		1.5
K-PAM	inhibitor		0.1 to 2	1
Na_2CO_3	dispersing agent and pH regulator	0.2	0.2	0.2

2.2. Experimental Methodology. *2.2.1. Performance Analysis of Additives.* The rheological properties and filtration loss evolution of a drilling fluid formulated with different additives were tested to optimize its degradability. The first step was adding bentonite and Na_2CO_3 to freshwater and thoroughly stirring to create the base solution. The mixture was then aged at room temperature for 12 h before adding other additives listed in Table 2 to prepare the drilling fluid. The amounts of additives were kept within reasonable limits based on previous research. A 3 wt % concentration of bentonite in the drilling fluid was deemed acceptable. The performance of the drilling fluid was assessed following the American Petroleum Institute (API) methodology.[51] Rheological properties, such as apparent viscosity (AV), plastic viscosity (PV), and yield point (YP), were measured using a ZNN-D6B six-speed rotary viscometer from Qingdao Shande Petroleum Instrument Co., Ltd. Dial readings at different rotational speeds were used to calculate the rheological parameters. The API filtration (AFL) was determined using a ZNS medium-pressure filtration apparatus. In addition, briquette coal samples made from coal powder and an appropriate amount of water were built and placed in various beakers labeled CN1 to CN6. Water and drilling fluids with different K-PAM mass fractions ranging from 0 to 2 wt % were injected into the beakers. The deformation of the coal samples was recorded to assess the inhibitory properties of K-PAM over a period of 24 h.

2.2.2. Characterization of the Degradable Drilling Fluid System. To assess the antipollution ability of the drilling fluid, 60−80 mesh coal cuttings were added to 500 mL of drilling fluid, and the mixture was stirred thoroughly to prepare five drilling fluids containing different coal cuttings contents (ranging from 1 to 5 wt %). The distribution of coal cuttings was observed, and the rheological and filtration properties of each drilling fluid were analyzed. Additionally, rheological and filtration properties of drilling fluids were tested after aging at four temperature gradients ranging from 20 to 80 °C to assess the impact of subsurface temperature variations.

Cellulase solutions with varying concentrations (ranging from 2 to 10 wt %) were prepared by adding cellulase into 10 mL water. Then, these five different cellulase solutions were individually added to 500 mL of the drilling fluid. The viscosity evolution of each drilling fluid over time was measured using a ZNN-D6B six-speed rotary viscometer. The degradability of the mud cake was also tested. First, mud cakes were obtained through AFL tests. Then, 240 mL of water was added to the drilling fluid cup of a medium-pressure filtration apparatus, and the water filtration volume (WFL) of the mud cake was observed within 30 min under a pressure of 0.69 MPa. Afterward, mud cakes were immersed in pure water and a 0.1% cellulase solution for 72 h, and the WFL of these treated mud cakes was tested again after degradation.

The influencing factors of cellulase's degrading capability were also investigated. Drilling fluid containing cellulase was maintained for 12 h under different conditions of temperature, pH, salinity, and solid content. The methods for controlling temperature and solid content were similar to the tests for drilling fluid's antipollution and antitemperature ability. The pH value was adjusted by adding acetic acid and sodium carbonate. The variation in drilling fluid salinity was simulated by changing the amount of added sodium chloride (NaCl). The changes in AV and AFL of the drilling fluid before and after degradation were recorded to assess the cellulase's degradation efficiency.

2.2.3. Gas Flow Test. To evaluate the drilling fluid's effects on the coal seam, coal blocks were collected from Shenmu in Shaanxi Province and processed into a coal pillar measuring 50 mm in diameter and 100 mm in height. The composition of coal was studied using proximate analysis and X-ray diffraction analysis (XRD) (Table 2). The pore distribution of the coal samples was assessed by using nuclear magnetic resonance (NMR) analysis, which revealed that the coal had a porosity of 14.59%. The main types of pores identified were micropores (50.85%), transitional pores (38.15%), and mesopores (10.54%), whereas macropores accounted for only 0.46% of the total pore volume.

The coal samples were subjected to shear loading along the axial direction until they broke into two halves. Finally, the broken coal samples were bonded together to form fractured coal samples, as shown in Figure 2. Coal samples with similar gas permeabilities were carefully selected for testing. Gas flow rates in the fractured coal samples were measured using a self-designed rock seepage device, as shown in Figure 3. The experimental procedure was as follows: First, the coal sample was placed in the core holder and subjected to a confining pressure of 5 MPa. Then, the original gas flow rate in the artificially fractured coal samples was tested. Next, the drilling fluid was injected into one side of the coal sample at a pressure of 2 MPa for 60 min. Finally, gas flow tests were conducted again on the contaminated coal samples. Pure nitrogen gas was used in the experiment, and gas flow rates were measured at eight different gas pressures ranging from 0.2 to 1.6 MPa. In the permeability recovery experiment, gas flow rates were measured and recorded as in the previous experiment. However, after the drilling fluid contaminated the coal samples, they were immersed for 2 h in an aqueous solution containing 0.1 wt % cellulase. Following this, the gas flow rate of the coal sample was measured again. Furthermore, to minimize the impact of the gas pressure, the gas pressure was set to 1 MPa.

Table 2. Proximate Analysis and X-ray Diffraction (XRD) Analysis Results[a]

proximate analysis (%)				XRD analysis (%)						
M_{ad}	A_{ad}	V_{ad}	FC_{ad}	kaolinite	chlorite	illite	quartz	feldspar	calcite	amorphous
6.48	7.60	33.47	52.45	7	1	2	6	2	2	80

[a]Note: M_{ad} is the moisture content, A_{ad} is the ash content, V_{ad} is the volatile content, and FC_{ad} is the fixed carbon content.

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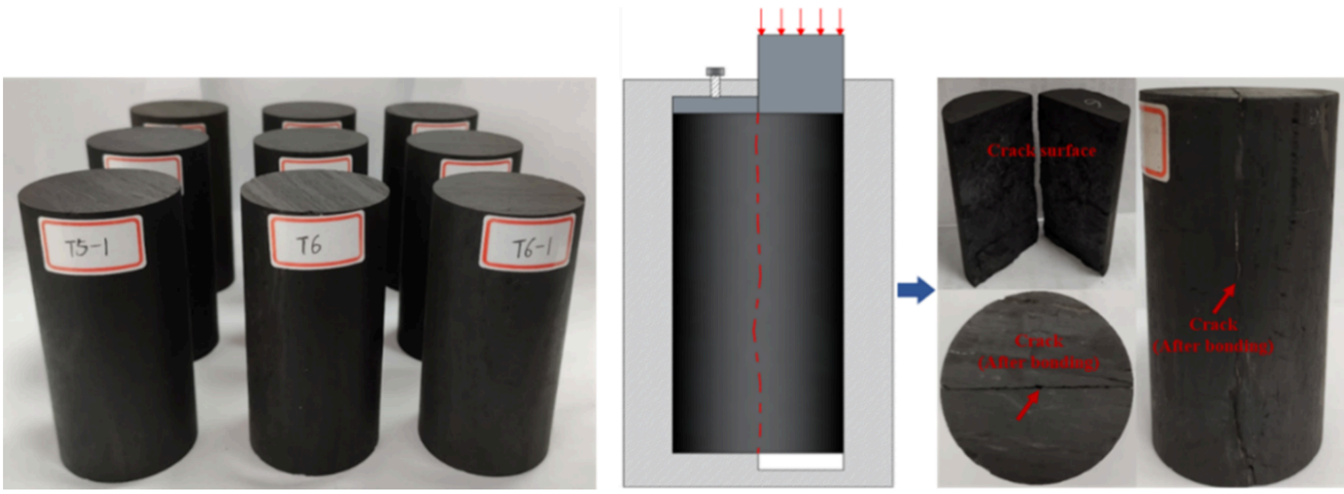

Figure 2. Coal sample preparation.

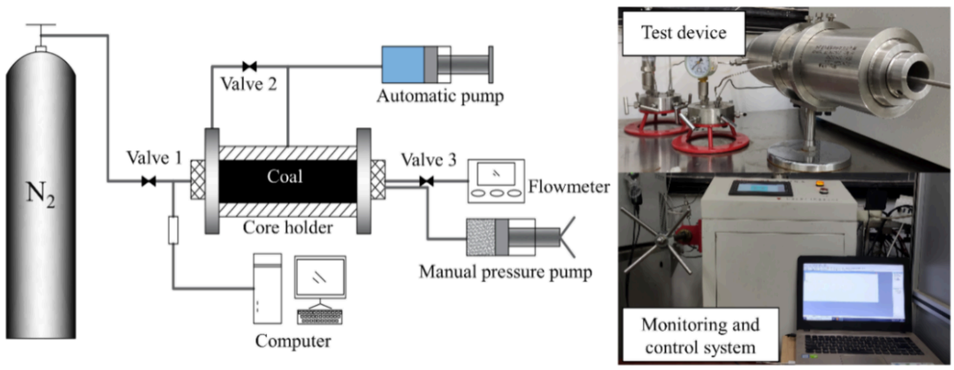

Figure 3. Gas permeability testing diagram.

3. RESULTS AND DISCUSSION

3.1. Optimization of the Degradable Drilling Fluid System. *3.1.1. Depressing Filtration Loss.* Fluid infiltration into coal seams can cause significant damage on the seam by developing micropores. Therefore, it is essential to reduce drilling fluid filtration loss to protect the reservoir. In this study, Na-CMC was added to the original 3 wt % bentonite and 0.2 wt % sodium carbonate drilling fluid to enhance the structural strength of the drilling fluid and decrease filtration loss. AV is the total viscosity exhibited during fluid flow, typically calculated from the dial reading at 600 rpm.

As shown in Figure 4, the AV of the drilling fluid positively correlated with the Na-CMC mass fraction. AFL of the drilling fluid was inversely proportional to the mass fraction of Na-CMC and the AV of the drilling fluid. As the Na-CMC mass fraction increased from 0 to 0.2 wt %, AFL decreased from 31.8 to 17.4 mL, which was 54.72% of the initial AFL. The drilling fluid's filtration rapidly decreased with the increase of Na-CMC content. Subsequently, the AFL of the drilling fluid decreased linearly with the increase in Na-CMC content. Finally, with 2 wt % Na-CMC, the AFL of the drilling fluid was reduced to 9 mL. These results suggest that Na-CMC is useful for forming thin and compact mud cakes, reducing the filtration loss of drilling fluid. Na-CMC connects with bentonite particles to form a network structure, further filled with an increase in Na-CMC content, improving the stability of the network structure, reducing the pore diameter of the network space, and preventing

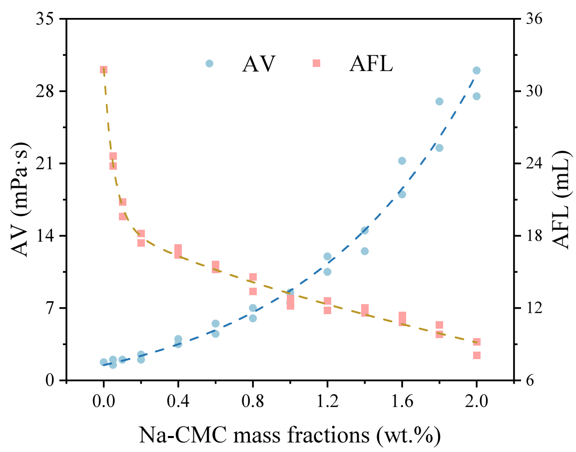

Figure 4. Changes in viscosity and filtration with Na-CMC mass fractions.

the loss of free water.[52] Additionally, the increased viscosity improves the resistance to fluid loss.

3.1.2. Enhanced Inhibition. Clay minerals in coal tend to experience hydration, expansion, and dispersion in water, which can worsen the blockage of seepage channels and weaken the cementation strength of coal.[29] This ultimately leads to damage of the coal seams and borehole instability, particularly in soft coal seams. Therefore, it is necessary to limit the hydration, expansion, and dispersion of clay minerals. Inorganic salt inhibitors are used to compress the diffusion double layer and

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decrease the water molecule activity, thereby inhibiting clay mineral hydration and swelling. Potassium chloride (KCL) is commonly used in water-based drilling fluids, where the strong hydration energy ions in the clay crystal layer are replaced by weak hydration energy potassium ions, reducing the degree of clay mineral hydration expansion.[21] However, the excessive use of KCL is environmentally harmful. Additionally, KCL limits the swelling and dispersion of bentonite and increases the level of drilling fluid filtration.

This study utilized K-PAM as an inhibitor to mitigate the negative effects of additives. Briquette coal samples were immersed in drilling fluids to assess the inhibitory performance of K-PAM. As shown in Figure 5a, coal sample CN1 immediately collapsed after being soaked in water. Correspondingly, the coal sample rapidly failed after experiencing erratic expansion in volume strain (Figure 6a). It is important to note that the volumetric strain of coal sample CN1 was negative due to differences expansion rates. Figure 6b shows the volumetric strain of coal sample CN2 submerged in the base drilling fluid without K-PAM. The volume strain increased rapidly after irregular expansion, and the coal sample collapsed at 36 min. Compared to water, the lower filtration and higher viscosity of the base slurry delayed the water infiltration and restricted coal sample deformation. The volumetric strain of coal samples immersed in drilling fluids with varying K-PAM mass fractions is illustrated in Figures 6c−f. Compared to coal sample CN2, the times from expansion to collapse of coal samples CN3 to CN6 were extended. Coal samples CN4 to CN6 collapsed within 3−4 h but ultimately retained a relatively complete shape (Figure 5b). The results suggest that increasing K-PAM content improved the stability of soft coal. K-PAM forms a protective polymeric membrane on the surface of clay minerals through hydrogen bond adsorption between the amide group and clay. Polymer membranes limit water absorption, inhibit hydration dispersion of clay, and maintain borehole stability.[53] Furthermore, K-PAM has a positive effect on the viscosity and filtration control of the drilling fluid (Figure 7).

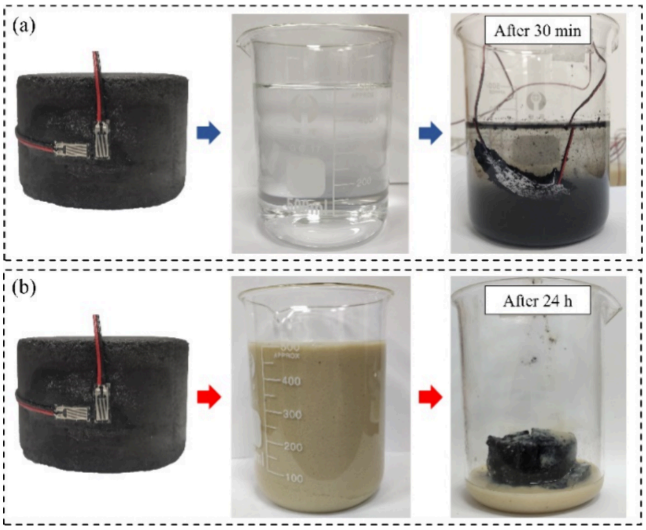

Figure 5. Comparison of coal sample deformation. (a) Coal sample was soaked in water. (b) Coal sample was soaked in drilling fluid.

3.1.3. Improvement of Rheological Properties. Based on the above discussion, a drilling fluid containing bentonite (3 wt %), Na-CMC (1.5 wt %), K-PAM (1 wt %), and Na_2CO_3 (0.2 wt %) was used as the base drilling fluid. Guar gum was added to the basic drilling fluid, and the rheological properties of drilling fluid with different guar gum mass fractions were evaluated. As shown in Table 3, the AV, PV, and YP of drilling fluid increased with an increase in guar gum mass fractions. Guar gum enhanced the yield point and plastic viscosity ratio (YP/PV) of drilling fluid. Figure 8 displays the evolution of drilling fluid shear stress with the shear rate. The shear stress positively correlated with the shear rate and guar gum mass fractions, and the shear stress−shear rate curves were fitted by the Herschel−Bulkley model (eq 1).[54] The results suggest that guar gum significantly improved the rheological properties and shear thinning behavior of drilling fluid to efficiently transfer drilling cuttings. Moreover, the AFL of drilling fluid decreased with an increase in guar gum mass fractions, which was attributed to the rise in viscosity.

$$\tau = \tau_0 + K\gamma^n \tag{1}$$

where τ is the shear stress (Pa), τ_0 is the static shear stress (Pa), K is the consistency coefficient (mPa·s^n), and n is the flow behavior index.

3.2. Evaluation of the Drilling Fluid System. A drilling fluid formula for coal seams was established based on multiple experiments and optimizations. The formula includes 3 wt % bentonite, 0.1−1.5 wt % Na-CMC, 0−1 wt % K-PAM, 0−0.3 wt % guar gum, and 0.2 wt % Na_2CO_3. This drilling fluid system offers high viscosity and low filtration loss to clean the borehole and protect the soft wall. To further discuss the applicability of the drilling fluid in coal seams, the performance of the drilling fluid was further evaluated.

3.2.1. Drilling Fluid Performance and Influencing Factors. During the drilling process, the performance of the drilling fluid directly affects the efficiency and safety of the drilling process. The rheological properties of drilling fluids are affected by the temperature, which is closely related to the formation environment and drilling technology. At present, the depth of coal seams mined in China is mostly above −800 m, and the ambient temperature of underground gas extraction boreholes is mostly below 40 °C.[55] However, the drilling process is fraught with uncertainty. In the study, the rheological properties of drilling fluid were evaluated after aging at different temperatures for 16 h. The experimental results are shown in Table 4 and Figure 9.

Table 4 shows that the AV and the PV of the drilling fluid decreased with increasing temperature. On the contrary, the AFL slightly increased. The fluid behavior of drilling fluids aged at different temperatures still conformed to the Herschel-Bulkley model (Figure 9). The increase in the temperature reduces the shear stress of the drilling fluid. This was attributed to the instability of the spatial network structure and the decrease in the mud cake quality caused by the increase in temperature. Specifically, with the increase of temperature, the hydration and dispersion properties of bentonite changed, and the interaction between polymer and bentonite weakened. Second, the enhanced molecular thermal motion resulted in an increase in particle size. Ultimately, it resulted in the destruction of the network structure and a decrease in the quality of mud cake.[22,42,56] As a matter of fact, an increase in the temperature inevitably affected the drilling fluid. However, the evolution of drilling fluid rheology was not significant within the experimental temperature range. The rheological properties of the drilling fluid remained stable under formation temperature conditions. This indicated that the drilling fluid met the requirements for the coal seam temperature and could adapt to drilling operations in certain special temperatures.

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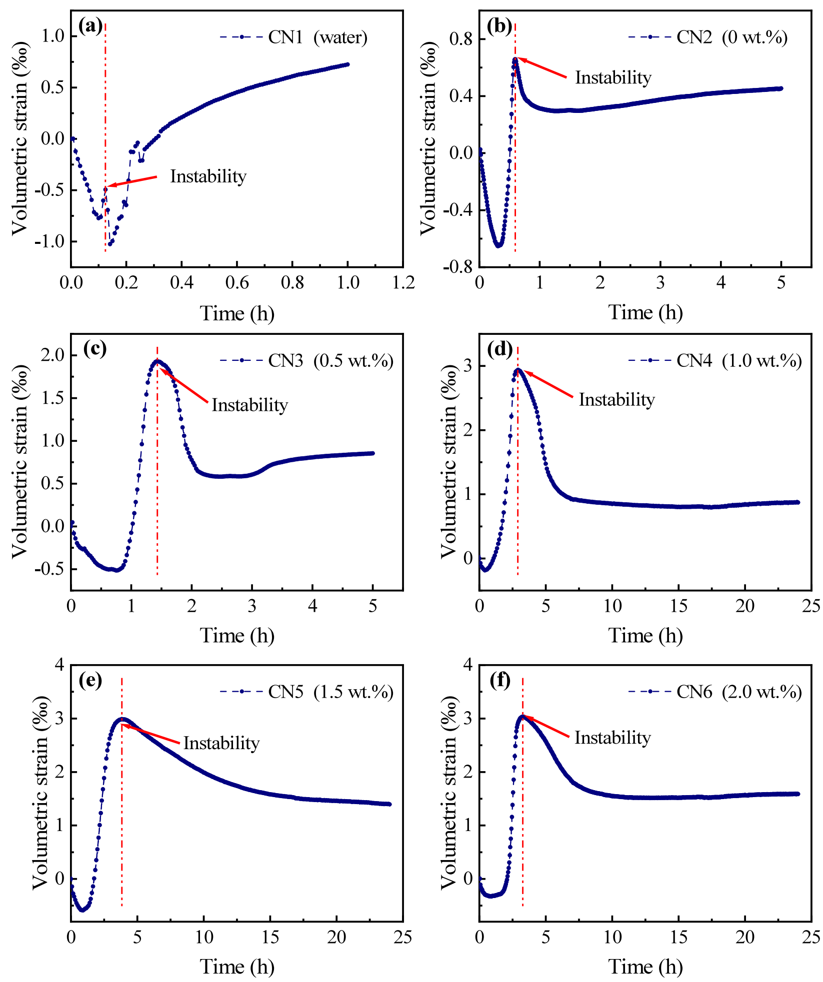

Figure 6. Evolution of volumetric strain of coal samples over time. (a) Coal sample CN1 immersed in water. (b) Coal sample CN2 immersed in drilling fluid with 0 wt % K-PAM. (c) Coal sample CN3 immersed in drilling fluid with 0.5 wt % K-PAM. (d) Coal sample CN4 immersed in drilling fluid with 1.0 wt % K-PAM. (e) Coal sample CN5 immersed in drilling fluid with 1.5 wt % K-PAM. (f) Coal sample CN6 immersed in drilling fluid with 2.0 wt % K-PAM.

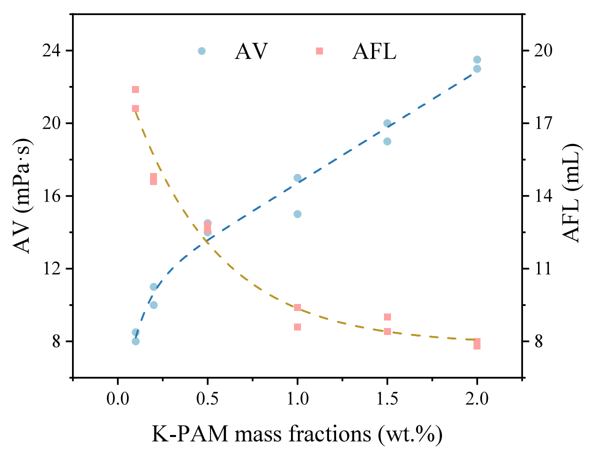

Figure 7. Changes in viscosity and filtration with K-PAM mass fractions.

Coal cuttings are carried by the drilling fluid from the bottom to the outside of the borehole and filtered to recycle and reuse the drilling fluid, which is an economical and environmentally friendly method. However, reprocessing the drilling fluid in an underground pressurized drilling method is challenging. As a result, the content of small coal particles in the drilling fluid increases with each cycle, potentially affecting the performance of the drilling fluid. Thus, the impact of different mass fractions of coal cuttings on the drilling fluid was studied, and as shown in Table 5, the AV and PV of drilling fluid initially decreased and then stabilized with the increase of coal cutting mass fractions. However, the YP of the drilling fluid remained unchanged, indicating that the carrying capacity was not significantly impacted by the cuttings. One possible reason for this phenomenon is that the flocculation ability reduces hydration and dispersion of useless solid phases in the drilling fluid, thereby limiting the influence of solid phases on the drilling fluid's rheological properties. As shown in Figure 10, coal cuttings were observed to be uniformly distributed in the drilling fluid. However, because of flocculation of the drilling fluid, coal cuttings exhibited nondispersibility and agglomeration. This

Table 3. Rheological Properties of Drilling Fluid with Different Guar Gum Mass Fractions

content (wt %)	AV (mPa·s)	PV (mPa·s)	YP (Pa)	YP/PV (Pa/mPa·s)	AFL (mL)
0	23	18	5.11	0.28	9.2
0.1	43	30	13.29	0.44	6.6
0.2	57	40	17.37	0.43	6.0
0.3	80	55	25.55	0.46	5.6

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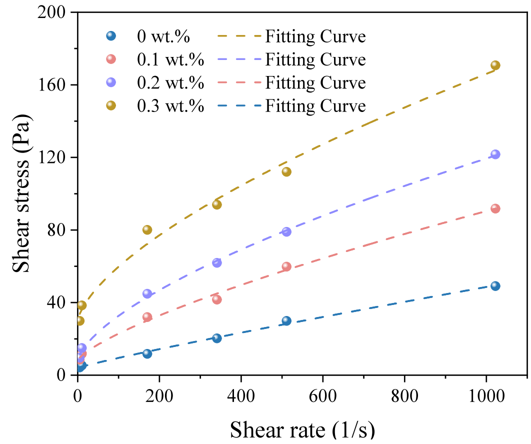

Figure 8. Shear stress evolution of drilling fluid with different guar gum mass fractions.

Table 4. Rheological Properties of Drilling Fluid at Different Temperatures[a]

temperature (°C)	AV (mPa·s)	PV (mPa·s)	YP (Pa)	YP/PV (Pa/mPa·s)	AFL (mL)
20	45	30	15.33	0.51	6.4
40	41	26	15.33	0.59	7
60	34	19	15.33	0.81	8.9
80	32.5	19	13.80	0.73	9.1

[a]Note: The drilling fluid formula in this section is 3 wt % bentonite + 1.5 wt % Na-CMC + 1 wt % K-PAM + 0.1 wt % guar gum + 0.2 wt % Na_2CO_3.

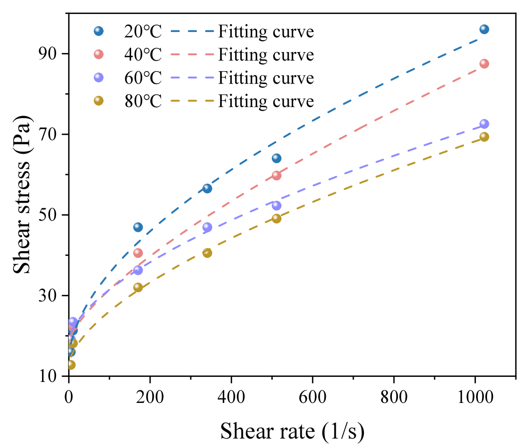

Figure 9. Shear stress evolution of drilling fluid at different temperatures.

Table 5. Rheological Properties of Drilling Fluid with Different Coal Particle Mass Fractions

content (wt %)	AV (mPa·s)	PV (mPa·s)	YP (Pa)	YP/PV (Pa/mPa·s)	AFL (mL)
0	43	30	13.29	0.44	6.6
1	40	27	13.28	0.49	6.8
2	35.5	22	13.80	0.63	8.4
3	32	18	14.31	0.79	10.2
4	32.5	19	13.797	0.73	11.2
5	32	21	11.24	0.54	12.8

made it difficult for coal particles to connect with Na-CMC and polymers to form a network structure, leading to a decrease in the density of the mud cake and an increase in the AFL and thickness.

The results showed that the drilling fluid has excellent antipollution ability to maintain adequate viscosity and carrying capacity due to the flocculation effect of the drilling fluid. However, the filtration loss of drilling fluid increases with the increase in useless solid content, leading to coal seam damage and wellbore instability. Additionally, there is concern regarding the aggravation of equipment abrasion. Therefore, it is necessary to replace or dilute drilling fluid with a high solid content. Generally, a solid content of less than 5% is considered acceptable.

3.2.2. Fracture Plugging and Coal Seam Damage by Drilling Fluid. In this section, we aimed to analyze the effects of drilling fluid on fractured coal seams. Pressure maintaining drilling increases the pressure difference between the drilling fluid and formation fluid, making it easier for the drilling fluid to enter coal seams. Therefore, drilling fluid should not only have good cutting transportation abilities but also be able to plug fractures and depress filtration loss. A filter reducer was added to the drilling fluid to reduce the fluid loss. However, the mud cake and drilling fluid blocked the flow channels after drilling, reducing the permeability of the coal seam and gas drainage efficiency.

Figure 11 displays the gas flow rate of coal samples at a 1 MPa gas pressure. The gas flow rate of the contaminated coal sample was considerably lower than that of the original coal sample, likely due to the blockage of flow channels in the coal sample by water, bentonite, and polymer molecules, particularly blocking the flow channel inlet by forming mud cake (Figure 12). To describe the decrease in the gas flow rate, K was defined as the damage coefficient. Because of the fact that the permeability of the coal matrix (approximately 0.03×10^{-3} μm^2 under 1 MPa gas pressure and 5 MPa confining pressure) is much lower than that of fractures (about 4.75×10^{-3} μm^2 with the same conditions), the damage coefficient was also used to assess the plugging degree of the fracture, which can be calculated as

$$K = \frac{Q_0 - Q}{Q_0} \times 100\%/ \tag{2}$$

where K is the damage coefficient (%) and Q_0 and Q are the initial and current gas flow rate of coal samples (cm^3/s).

The damage coefficient increased gradually as the mass fraction of the Na-CMC content in the drilling fluid increased. Specifically, as the Na-CMC content increased from 0.5 to 1.5 wt %, the damage coefficient increased from 36.67 to 66.53%. These results suggest that there is a positive correlation between the ability of the drilling fluid to plug fractures and the mass fraction of Na-CMC. This correlation can be attributed to the increase in the content of the filtrate reducer, which improves the density of the mud cake and fills the network structure space. As a result, the permeability of the mud cake decreases with an increasing filtrate reducer content, resulting in a decrease in gas flow rate after the flow channel is blocked by the mud cake.

In Figure 13, the gas flow rate demonstrated a positive correlation with the gas pressure. Conversely, the damage coefficient of contaminated coal samples decreased as gas pressure increased. This phenomenon can be attributed to the reopening of the flow channels previously blocked by the mud cakes. The evolution of the damage coefficient was divided into two stages: slow decline and rapid decline. In the slow decline stage, lower gas pressures were unable to break through the

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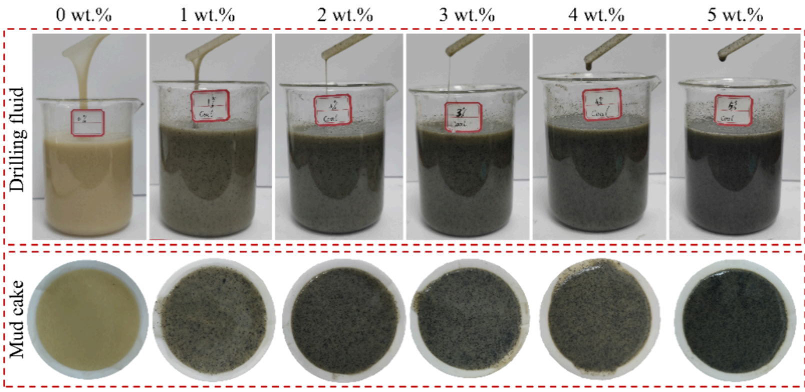

Figure 10. Mud cakes with different coal cutting mass fractions.

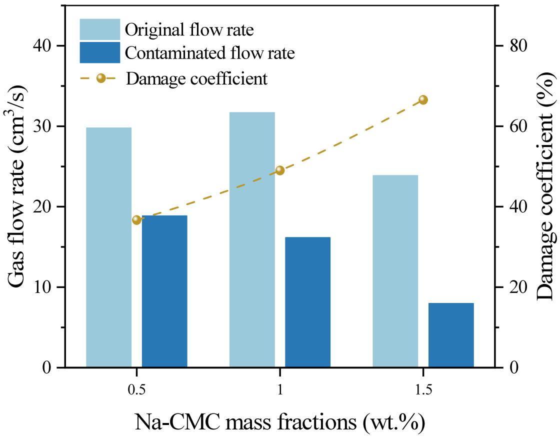

Figure 11. Gas flow rate and damage coefficient of coal samples.

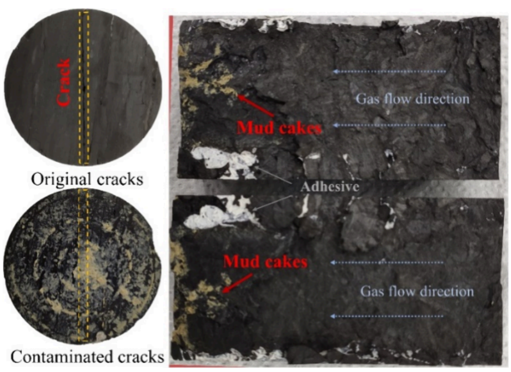

Figure 12. Contaminated cracks of the coal sample.

plugging caused by the drilling fluid. Once the gas pressure reached a critical value, gas flow in the contaminated fractures recovered, as more flow channels reopened. This led to a rapid decrease in the damage coefficient with an increase in gas pressure (rapid decline stage). The critical values of different contaminated coal samples varied and were closely related to the degree of fracture blockage. These values improved with an increase in the filtrate reducer content in the drilling fluid. As a result, a gas breakthrough pressure (P_b) was defined to quantitatively analyze the blockage of the fracture.[57]

Gas breakthrough pressure is a vital parameter that correlates with the shape and connectivity of pores and fissures in coal. Once the gas pressure reaches the gas breakthrough pressure, the gas forms a continuous flow through the cracks. Subsequently, the evolution curves of the gas flow rate gradually change from a nonlinear concave curve to a linear curve with an increase in gas pressure.[58,59] As shown in Figure 13, the linear fitting method was used to fit the linear growth segment of the curve. The breakthrough pressure was defined as the gas pressure calculated by the fitting equation at the flow rate of 0 mL/s.[60] For instance, the breakthrough pressure of coal sample F1 increased from 0.62 to 0.70 MPa, corresponding to an increase of 0.08 MPa in breakthrough pressure. It can be inferred that the increase in breakthrough pressure was caused by the blockage of fractures. Similarly, the breakthrough pressures of contaminated coal samples F2 and F3 increased by 0.2 and 0.51 MPa, respectively. These results indicate that the drilling fluid has an excellent ability to plug fractures and that the plugging ability improves with an increase in filtrate reducer content. This reduction in leakage of drilling fluid in the pressurized drilling method suggests improved performance.

It is worth noting that the increase in the filtrate reducer content in the drilling fluid exacerbated the damage to the coal seams. Additionally, it is difficult to restore the gas flow rate of a contaminated coal seam through backflow after completing the drilling. The degree of damage of coal seams can recover only with a decrease in gas pressure during the gas drainage process. Therefore, it is essential to remove residual drilling fluid and mud cake to alleviate the blockage of the gas flow channels.

3.2.3. Biodegradability of Drilling Fluid. Polymer molecules can be decomposed into low degrees of polymerization molecules or even monomers by corresponding biological enzymes.[52,61] This decomposition leads to a decrease in the viscosity of the drilling fluid, and the structure of the mud cake is broken down, making it easier to remove the drilling fluid residues. Cellulase is an effective enzyme that can degrade Na-CMC, guar gum, and K-PAM in drilling fluid systems. Therefore, cellulase was chosen as the primary degradation agent. To test the effectiveness of cellulase, various samples of cellulase with different mass fractions were added to the drilling fluids. The drilling fluid formula consisted of 3 wt % bentonite, 1.5 wt % Na-CMC, 1 wt % K-PAM, 0.3 wt % guar gum, and 0.2 wt % Na_2CO_3. The viscosity of the drilling fluid decreased after polymer degradation. This decrease in viscosity indicates successful polymer degradation. The evolution of the drilling fluid AV with time is depicted in Figure 14.

During the 100 h test, mud 1 (original drilling fluid) maintained a stable AV, indicating that the drilling fluid system was stable and would not self-degrade. When cellulase was added to the drilling fluids, the AV significantly decreased with time. The rate of decrease was faster in the first 2 h. For instance,

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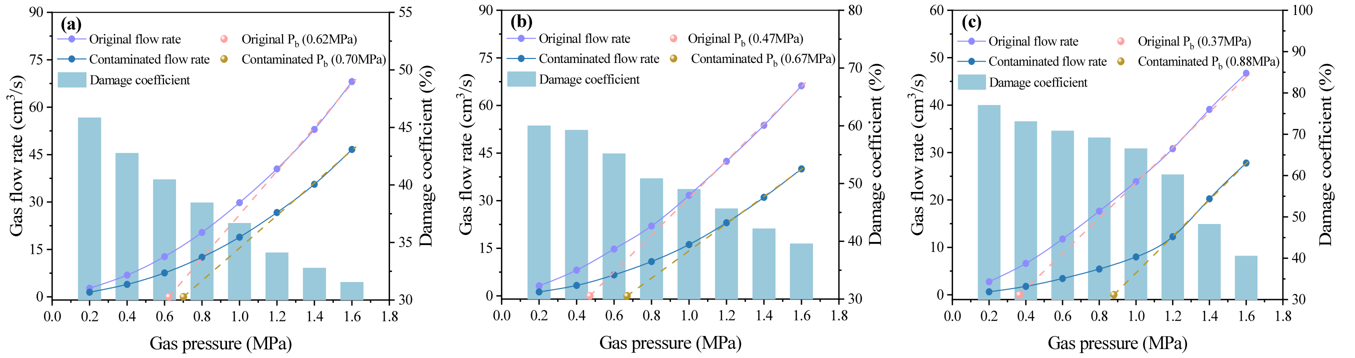

Figure 13. Evolutions of gas flow rate, damage coefficient, and gas breakthrough pressure in coal sample. (a) Coal sample F1 contaminated with drilling fluid containing 0.5 wt % CMC. (b) Coal sample F2 contaminated with drilling fluid containing 1 wt % CMC. (c) Coal sample F3 contaminated with drilling fluid containing 1.5 wt % CMC.

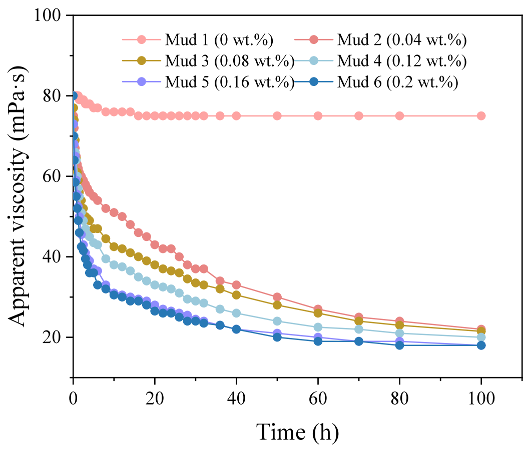

Figure 14. Evolution of drilling fluid AV with time.

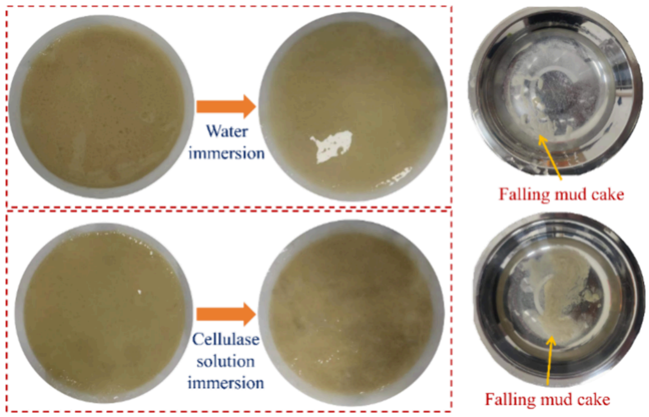

Figure 15. Degradation and removal of the mud cake.

the AV of the drilling fluid containing 0.04% cellulase decreased from 80 to 60 mPa·s within 2 h, corresponding to a relative decrease of 25%. Similarly, the AV of the drilling fluid with 0.2% cellulase decreased by 46.88% within 2 h. The degradation efficiency of cellulase was found to be directly proportional to the cellulase content. However, all drilling fluids ultimately reduced their AV to around 20 mPa·s, corresponding to a decrease of 75%. This suggests that although the cellulase content is closely related to the degradation rate, its impact on the ultimate degradation effect is limited. In effect, even a small amount of cellulase can effectively degrade the drilling fluid and reduce its the AV.

The effect of cellulase on mud cake was analyzed using a WFL (water filtration loss) test. Mud cakes were immersed in water and 0.1 wt % cellulase solution for 72 h, respectively. The WFL of the mud cakes was tested before and after immersion. The WFL of mud cake 1 immersed in pure water increased from 10.8 to 11.2 mL, whereas the WFL of mud cake 2 immersed in cellulase solution increased from 10.4 to 48 mL. The filtration loss of the degraded mud cake significantly increased, which can be attributed to the destruction of the mud cake caused by cellulase degradation. Figure 15 compares the mud cakes in different solutions, with the mud cake immersed in pure water remaining intact. Conversely, due to the degradation of cellulase damaging the network structure of the mud cake, the mud cakes immersed in cellulase solution naturally fell off the filter paper. This is beneficial for the recovery of the coal seam permeability.

3.2.4. Evaluation of Degradability. The drilling process is fraught with uncertainties, such as temperature, salinity, pH value, and solid content of drilling fluid, which vary depending on the environment and drilling technology. These factors influence the performance of cellulase.[52,62] It is imperative to assess the capacity of cellulase to degrade drilling fluids in different environments. The cellulase's efficacy was evaluated by comparing the AV and AFL before and after degradation of drilling fluid within 12 h. The drilling fluid formulation remained consistent with that shown in Section 3.2.1. The experimental results are shown in Figures 16−19. There was a negative correlation between AFL apparent viscosity AV. In comparison to the predegradation state, the cellulase degraded drilling fluid exhibited an increase in AV and a decrease in AFL. These changes were closely associated with the experimental conditions. Evidently, the magnitude of changes in AV and AFL after degradation reflected the cellulase degradation capability. The change percentage is defined as the ratio of the magnitude of change to the predegradation value, serving as a quantitative representation of the degradative efficacy of cellulase.

From Figure 16, it was evident that the optimal temperature for cellulase was around 40 °C. Deviations from this temperature, either too high or too low, resulted in a reduction in cellulase degradation efficiency, with higher temperatures exerting a more pronounced impact. This is attributed to lower temperatures causing a decrease in enzymatic activity and a slower degradation rate. Higher temperatures induce enzyme denaturation and inactivation, significantly diminishing the degradability of cellulase. The test results under different pH

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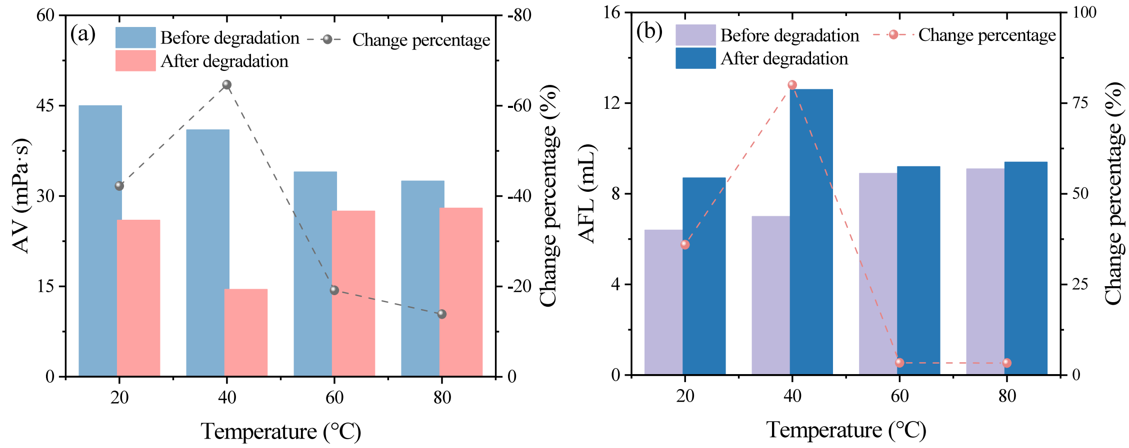

Figure 16. Evaluation of cellulase degradation ability at different temperatures. (a) Changes in AV of drilling fluid before and after degradation. (b) Changes in AFL of drilling fluid before and after degradation.

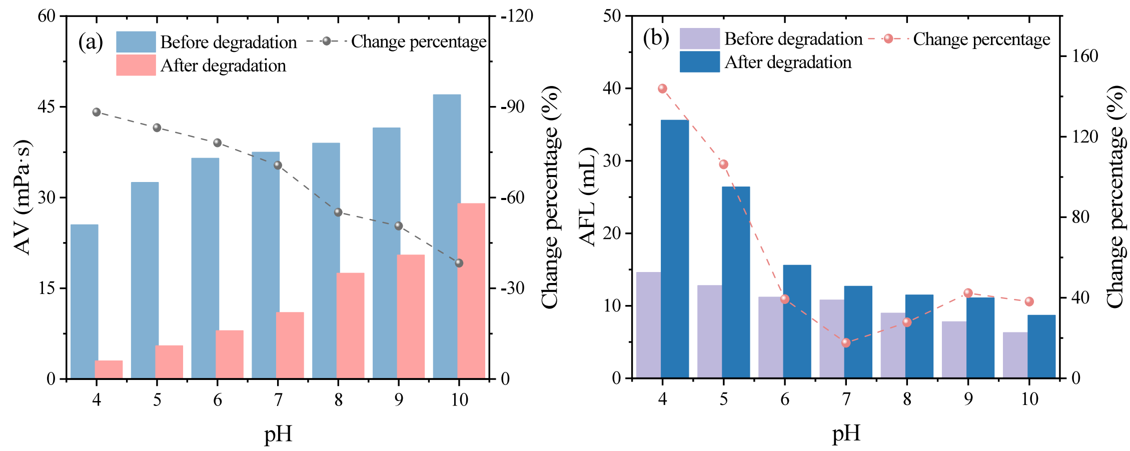

Figure 17. Evaluation of cellulase degradation ability at different pH values. (a) Changes in AV of drilling fluid before and after degradation. (b) Changes in AFL of drilling fluid before and after degradation.

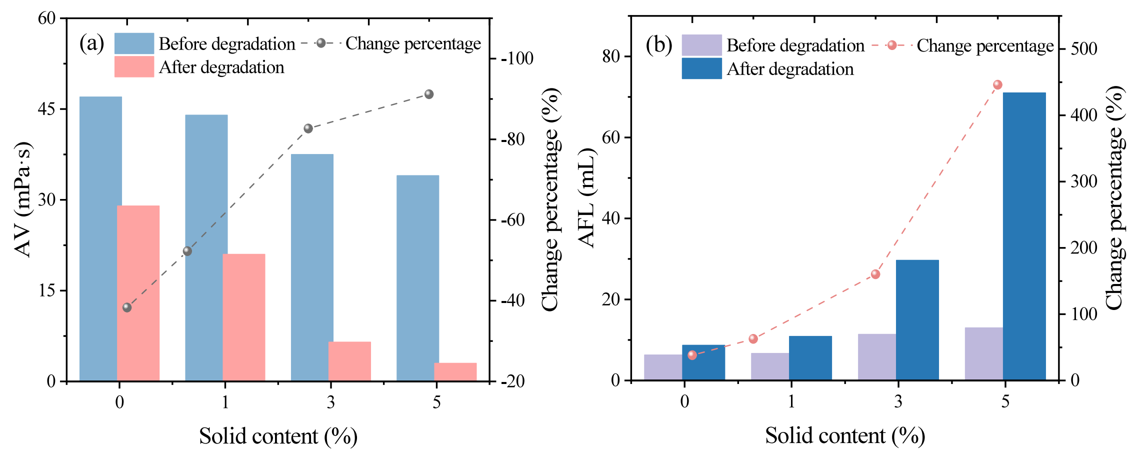

Figure 18. Evaluation of cellulase degradation ability at different salinity. (a) Changes in AV of drilling fluid before and after degradation. (b) Changes in AFL of drilling fluid before and after degradation.

conditions indicated that a slightly acidic environment promoted the degradation efficiency of cellulase, whereas the degrading capability remained relatively stable in alkaline environments (Figure 17). This is due to the common cellulase enzyme having an optimal pH range between 4 and 6, where the degradation efficiency is maximized. In Figure 18, a comparison of the degradation effects on drilling fluids with different solid contents revealed a significant decrease in AV and a notable increase in AFL as the solid-phase content increased. This indicates a substantial enhancement in the degradation efficiency of cellulase in drilling fluids with a high solid content. This is attributed to two factors: the coal powder promotes the

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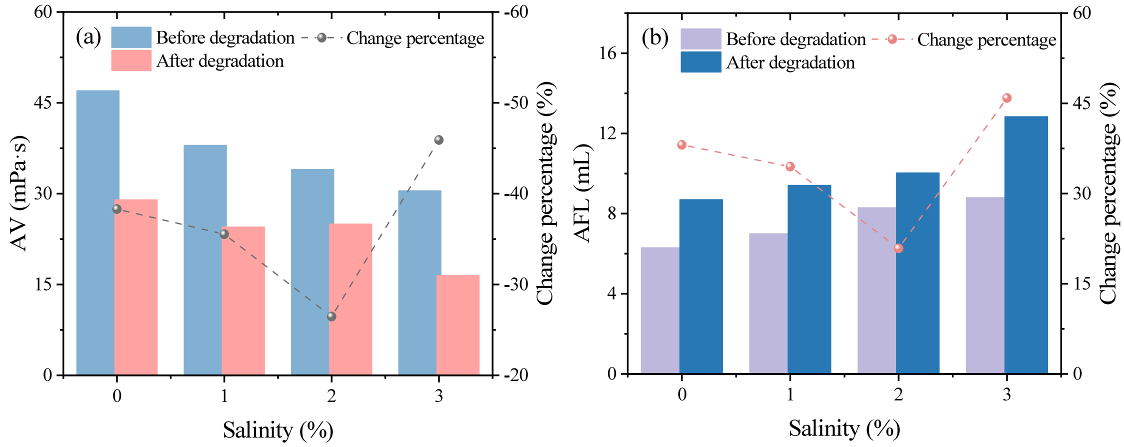

Figure 19. Evaluation of cellulase degradation ability at different salinity. (a) Changes in AV of drilling fluid before and after degradation. (b) Changes in AFL of drilling fluid before and after degradation.

enzymatic activity, and degradation weakens the flocculation ability of drilling fluids. The coal powder is further dispersed in the drilling fluid, disrupting the network structure and reducing the mud cake quality. Ultimately, this manifests as a significant decline in the performance of the degraded drilling fluid. Drilling fluids with varying NaCl contents were degraded to assess the impact of salinity on the efficiency of cellulase degradation (Figure 19). At NaCl levels below 2%, the degrading capability of cellulase enzymes diminished with increasing salinity. This indicates a reduction in degradation efficiency owing to the inhibitory effect of high salinity on the enzyme activity. It is worth noting that the considerable increase in the rate of AV reduction and AFL growth in the drilling fluid was observed at a NaCl content of 3%. One possible explanation for this phenomenon is that an increase in salinity could disrupt the hydration of bentonite, consequently reducing the stability of the drilling fluid. This makes the drilling fluid more susceptible to decomposition by cellulase. In summary, the optimal conditions for cellulase performance are around 40 °C with a pH level of 4−6, and this correlates positively with solid-phase content. Increased salinity inhibits enzyme activity, but higher salinity accelerates the decomposition of the drilling fluid.

To evaluate the efficacy of cellulase in minimizing damage to coal seams, we conducted tests to monitor gas flow rate fluctuations in three contaminated coal samples labeled R1, R2, and R3. As illustrated in Figure 20, the initial gas flow rate of fractured coal samples ranged between 28.65 and 33.69 cm^3/s. However, after exposure to drilling fluid, the coal sample's gas flow rate decreased significantly to a range of 6.97 to 12.88 cm^3/s. The maximum damage coefficient of the coal sample recorded was at 78.88%. Thereafter, we subjected the contaminated coal samples to a cellulase aqueous solution for approximately 2 h. Consequently, the gas flow rate range for the treated coal samples increased from 17.42 to 20.21 cm^3/s. We also noted a significant drop in the damage coefficient to 32.55−47.21%. Treatment with cellulase solution helped in the degradation of the polymer and removal of mud cakes, contributing to the revival of gas flow rates within the fractured coal samples. However, complete elimination of the drilling fluid in the fracture proved challenging, resulting in the incomplete recovery of the gas flow rate in the fractured coal sample (Figure 21).

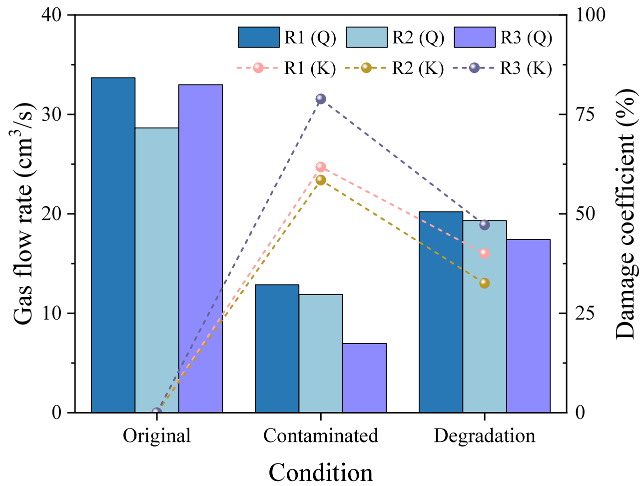

Figure 20. Gas flow rates in different coal samples.

6. CONCLUSIONS

The aim of this study is to develop a drilling fluid system suitable for underground pressurized drilling and to evaluate its properties. We experimented with different reagents to determine their effects on the rheological, filtration, and inhibitory properties of the drilling fluids. Additionally, we assessed the drilling fluid's antipollution capability, fracture plugging ability, coal seam damage, and biodegradability. The research findings are summarized below:

(1) Within the drilling fluid system, the interaction between Na-CMC and bentonite particles created a network structure that reduced the filtration of the drilling fluid. K-PAM was found to enhance the stability of soft coal by preventing clay hydration. Guar gum was added in the drilling fluid to improve its rheological properties and rock carrying capacity.

(2) The performance of the drilling fluid is influenced by temperature and useless solid content. As temperature and solid content increase, the AV decreases and the AFL increases. Despite the variation in AV and AFL, the rheological properties and carrying capacity of drilling fluid are adequate, indicating its ability to withstand temperature variations and solid contamination in the coal seam.

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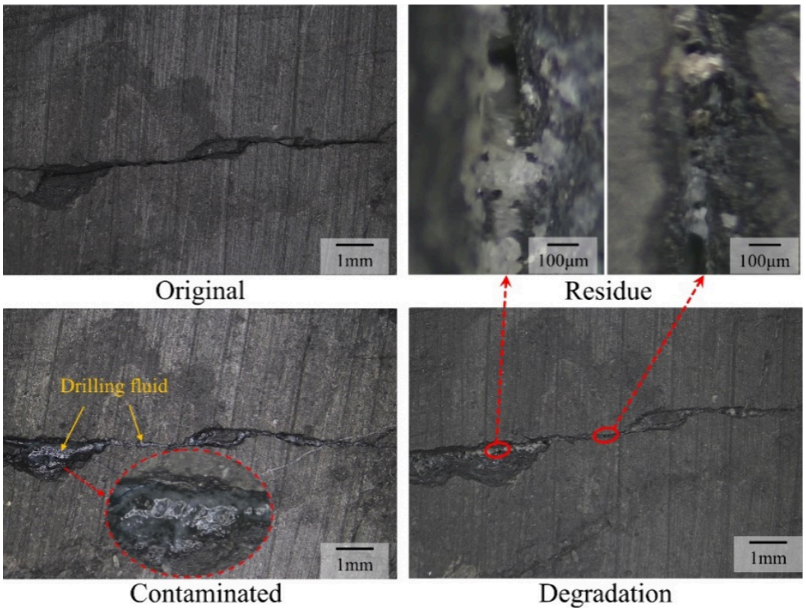

Figure 21. Degradation of the drilling fluid in fractures.

(3) The drilling fluid's fracture plugging ability rose with an increase in filtrate reducer content. However, residual mud cake formation could reduce the gas flow rate after drilling, leading to an increased damage coefficient and breakthrough pressure with a rise in filtrate reducer content.

(4) The use of cellulase resulted in the degradation of polymers within the drilling fluid, ultimately reducing the fluid's viscosity and mud cake cleaning difficulty. Cellulase activity is higher at 40 °C and a pH of 4. An increase in salinity inhibits the activity of enzymes. The solid content has a positive effect on the degradation of drilling fluid. Furthermore, contaminated coal samples showed a significant restoration of gas flow rates following treatment with cellulase solution.

■ AUTHOR INFORMATION

Corresponding Author

Yongjiang Luo − *Chongqing University state key laboratory of coal mine disaster dynamics and control and Chongqing University school of resources and safety engineering, Chongqing University, Chongqing 400044, China;* orcid.org/0000-0003-1643-7015; Phone: +86 17783357321; Email: luoyj16@cqu.edu.cn; Fax: 023-65111826

Authors

Lingrui Kong − *Chongqing University state key laboratory of coal mine disaster dynamics and control and Chongqing University school of resources and safety engineering, Chongqing University, Chongqing 400044, China*

Jianxin Tang − *Chongqing University state key laboratory of coal mine disaster dynamics and control and Chongqing University school of resources and safety engineering, Chongqing University, Chongqing 400044, China*

Fang Yuan − *Chongqing University state key laboratory of coal mine disaster dynamics and control and Chongqing University school of resources and safety engineering, Chongqing University, Chongqing 400044, China*

Yuan Lin − *Chongqing University state key laboratory of coal mine disaster dynamics and control and Chongqing University school of resources and safety engineering, Chongqing University, Chongqing 400044, China*

Rui Tao − *Ningxia Institute of Mineral Geological Survey(Autonomous Region Institute of Mineral Geology), Yinchuan City 750000, China*

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.3c08457

Author Contributions

Lingrui Kong: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing − original draft. Jianxin Tang: Supervision, Funding acquisition, Conceptualization, Methodology, Project administration. Yongjiang Luo: Resources, Conceptualization, Formal analysis, Writing − review and editing. Fang Yuan: Methodology, Investigation, Formal analysis. Yuan Lin: Methodology, Investigation.

Notes

The authors declare no competing financial interest.

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