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Research on Clay Mineral Expansion Inhibition in Coalbed Methane Mining Based on XRD Analysis and Drilling Fluid Performance Optimization

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ABSTRACT

Coalbed methane (CBM) is one of the crucial energy sources in China. The swelling of clay mineral components in coal can lead to wellbore instability and reduced coal permeability, posing challenges during drilling operations. To address these issues, analyzing and detecting the mineral components in coal and selecting inhibitors for drilling fluids that can suppress the hydration and swelling of clay minerals are vital. X-ray diffraction (XRD) analysis is employed to determine the mineral composition of coal samples, providing data for reservoir evaluation. Furthermore, coal swelling experiments are conducted to select optimal inhibitors for drilling fluids. The results indicate that potassium chloride effectively inhibits the hydration and swelling of clay minerals in coal. When coal rocks are soaked in drilling fluid containing potassium chloride for 16 hours, the coal swelling rate remains below 0.3%. Therefore, potassium chloride can be used as a drilling fluid additive at drilling sites to enhance coal permeability and achieve efficient CBM extraction.

KEYWORDS

Clay Mineral; Expansion; Inhibitor.

1. INTRODUCTION

China boasts extremely abundant coalbed methane (CBM) resources, with a total volume of up to $30.05\times1012m^3$ at depths shallower than 2000 meters[1]. As one of the significant types of natural gas and with vast reserves in China[2], the development of CBM holds particularly important strategic significance. As a green energy source, the efficient development and utilization of CBM demonstrate significant value in ensuring safe coal mine production and optimizing the national energy structure. Drilling fluids play a crucial role in the extraction process of CBM, known as the "blood" of drilling operations. High-quality drilling fluids can effectively stabilize the wellbore, inhibit formation expansion, and maintain good circulation performance. The mineral composition of coal is complex, primarily classified into clay minerals (such as kaolinite, illite, and montmorillonite), oxide minerals, carbonate minerals, as well as sulfide and sulfate minerals based on mineral types[3]. Among them, clay minerals are prone to hydration and swelling when exposed to water, a phenomenon that not only threatens wellbore stability during drilling operations but also reduces the permeability of coal seams.

Currently, research on inhibiting the hydration and swelling of clay minerals has been conducted worldwide from various perspectives. At the microscopic level, Liang Xiaoqiang[4] believes that due to lattice substitution and other factors, clay particles generally carry a negative charge on their surfaces, causing the adsorption of free cations onto the clay surface under the action of electrostatic forces. However, these adsorbed cations can be replaced by cations of higher valence states, leading to ion exchange adsorption, making cation exchange capacity (CEC) an important parameter for characterizing clay hydration and swelling. Zhu Jianxi et al.[5] also consider the type and concentration of cations as significant factors influencing clay hydration and swelling. Drilling fluids, as carriers of inhibitors, play a crucial role in inhibiting clay mineral swelling. Sun Linlin[6] suggests that cations in drilling fluids are adsorbed onto the negative charges on the clay mineral surface due to electrostatic interactions. The entry of cations reduces the electrostatic repulsion between clay particles, narrowing the interlayer distance and preventing the ingress of water molecules, thereby reducing hydration and swelling. Regarding inhibitors for clay mineral hydration and swelling, Chen et al.[7] studied the impact of KCl on the swelling and mechanical properties of clay minerals, finding that KCl significantly reduces the swelling rate of mudstones and significantly enhances their uniaxial compressive strength and elastic modulus compared to mudstones soaked in water. Li Xiaodong et al.[8] compared and optimized formate drilling fluid systems, proposing that compared to conventional high-density saturated brine sulfonated drilling fluids, formate drilling fluids can reduce the solid phase content of the system, improve thermal stability, maintain more suitable rheological properties, and are suitable for drilling in deep wells, ultra-deep wells, thick composite salt formations, and sub-salt reservoirs. They overcome the challenges of low density adjustment capability, limited temperature and salt resistance, frequent maintenance cycles, and conflicting requirements for inhibition, rheology, and water loss wall-building properties of saturated brine high-density sulfonated drilling fluids. Afshin[9] conducted experimental comparisons of formate drilling fluid systems and systematically evaluated their performance, analyzing the salt contamination resistance of formate drilling fluids and discovering their good compatibility with reservoir rocks, minimizing formation damage.

Most methods for inhibiting the hydration and swelling of clay minerals rely heavily on the use of inhibitors. However, comparative studies on the inhibitory effects of potassium chloride (KCl) and sodium formate as inhibitors remain insufficient. KCl, characterized by its low cost, high potassium content, and good solubility, has been widely used as an inhibitor to suppress the hydration and swelling of clay minerals. Sodium formate, on the other hand, offers multiple advantages, including flexible adjustment of drilling fluid density, high cation content, high temperature resistance, non-toxic to humans, and environmental friendliness, while its application fields are also quite extensive. Therefore, conducting in-depth research on the compositional characteristics of clay minerals in coal and analyzing which inhibitor should be selected in drilling fluids to effectively inhibit the hydration and swelling of clay minerals, thereby enhancing coal seam permeability, holds profound significance for the efficient exploitation of coalbed methane resources. Furthermore, although most researchers focus more on the swelling issue of clay minerals in shale formations, this paper argues that inhibiting the hydration and swelling of clay minerals in coal rocks is equally crucial.

Based on this, this paper compares the practical effects of these two inhibitors in inhibiting the hydration and swelling of clay minerals in coal rock formations, selects one of them as the inhibitor in drilling fluids, and verifies its application in actual mining scenarios, aiming to achieve efficient coalbed methane exploitation. This research not only enriches the professional knowledge in the field of geological engineering but also provides powerful technical support for the sustainable development of coalbed methane resources.

2. EXPERIMENTS

2.1. Introduction to the Study Area

This paper focuses on the Baode Mining Area, located on the northeastern margin of the Ordos Basin. This mining area is part of the Hedong Coalfield and constitutes an important component of the largescale coal base in northern Shanxi, covering a total area of 476.46 km^2[10]. The structural morphology of the Baode Mining Area is relatively simple, characterized by a westward-dipping monocline with low levels of fault and fold development. The stratigraphic dip angles range from 1° to 10°. In terms of the hydrological environment, the groundwater in this area mainly originates from atmospheric precipitation and lateral recharge from Ordovician limestone, flowing generally from east to west, categorizing it as a runoff-weak runoff area. The coal seams are buried at depths of 300 to 1200m, with vitrinite reflectance values ranging from 0.71% to 1.22%, indicating low to medium metamorphic bituminous coal. The coal seams have gas contents of 0 to 12.0 m^3/t, permeabilities of 2 to 10mD, and pressure coefficients of 0.65 to 1.10MPa, classifying them as underpressured to normally pressured reservoirs. The coalbed methane reservoirs are self-generated and self-stored, with methane existing in the adsorbed state on the inner surfaces of the coal seam matrix. The gas reservoirs are continuously distributed over a large area without distinct gas, water, or pressure boundaries. Geologically, the coal-bearing strata in the Baode Mining Area are primarily the Lower Permian Shanxi and Taiyuan Formations [11].

2.2. Sample Preparation

In the process of sample preparation, this paper utilizes coal samples from the No. 8 coal seam in the Baode Mining Area as the research subject. Initially, the collected coal samples undergo meticulous processing, employing grinding equipment to reduce them to a fineness of 200 mesh. This step ensures uniform particle size of the coal powder, facilitating the accuracy and reliability of subsequent analyses. Subsequently, the ground coal powder is sieved using a mesh screen to remove potential impurities and particles that do not meet the particle size requirements, further guaranteeing the quality of the samples.

The sieved coal powder undergoes drying to eliminate moisture content. The drying process takes place in a constant temperature drying oven, ensuring that the coal powder reaches a constant weight state at an appropriate temperature and within a specified time frame, thereby avoiding the influence of moisture on subsequent experimental results. The dried coal powder is then packaged into dedicated sample bags, each of which is rigorously labeled with information including the sample's source, processing date, and number, for easy tracing and management in subsequent stages.

Finally, the packaged coal powder samples are stored properly in a dry, cool environment to prevent them from becoming damp or exposed to other adverse factors. These meticulously prepared coal powder samples will be used for subsequent mineral composition analysis and coal rock swelling rate determination experiments, providing reliable data support for in-depth research on the mineralogical characteristics and coalbed methane exploitation potential of the No. 8 coal seam in the Baode Mining Area.

2.3. Experimental Procedure

The finely ground sample powder was poured into the groove of the test specimen and maintained in an even distribution. It was then compressed using a glass slide. Any excess powder outside the groove or above the sample holder was scraped off, and the sample was repressed to ensure that the sample contour was at the same horizontal plane as the edge of the sample holder (Figure 1). An X-ray diffractometer was employed to obtain X-ray diffraction patterns using a continuous scanning mode at room temperature. The mineral components in the coal rocks were analyzed using MDI Jade 6 software.

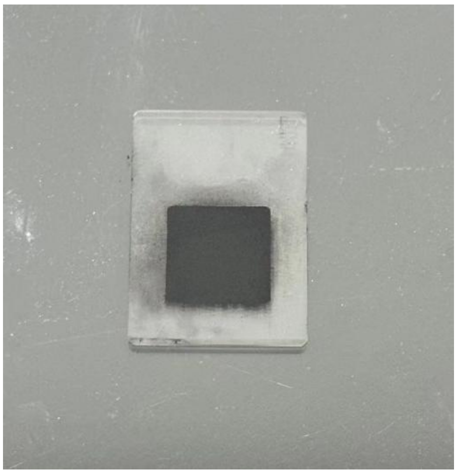

Fig. 1 Preparation of sample

To determine the swelling rate of coal rocks, three samples of raw coal powder, each weighing 10g, were weighed, labeled, and placed in a forced-air oven at a constant temperature of 105°C for 4 hours. The samples were then cooled to room temperature. Subsequently, using a swelling test apparatus (as shown in Figure 2), the coal powder was slowly poured into a measuring cylinder and gently compressed to ensure an even distribution. After placing filter paper at the bottom of the measuring cylinder, the bottom cover was tightened, and the sealing ring of the plunger was installed. The plunger was then inserted into the measuring cylinder.

Before filling with coal powder, a vernier caliper was used to measure and record the total height H1 of the measuring cylinder and plunger assembly (measured at four points in orthogonal directions and averaged). Next, the entire assembly of the measuring cylinder and plunger was placed on a press, and a uniform pressure of 4 MPa was applied for 5 minutes. After stabilizing the pressure, the oil pump valve was opened, the measuring cylinder was removed, and the vernier caliper was used again to measure the total height H2 of the compressed measuring cylinder and plunger assembly (also measured at four points in orthogonal directions and averaged). The difference between H1 and H2 represented the original thickness of the coal column.

Finally, distilled water and drilling fluid were slowly added to different measuring cylinders, and a dial gauge was aligned with the pressure rod. At specified time points, the readings Rt of the dial gauge were recorded. The swelling rate of the coal column at different time points was calculated using the formula $VH = (Rt / (H1 - H2)) \times 100\%$. This experiment not only accurately measured the swelling performance of coal rocks but also provided important data support for assessing the impact of inhibitors in drilling fluids on the swelling behavior of coal rocks.

In the formula:

VH - Linear swelling rate of coal rock at time t, expressed as a percentage (%);

Rt - Linear swelling amount at time t, in millimeters (mm);

H1 - Height of the measuring cylinder before loading the sample powder, in millimeters (mm);

H2 - Height of the measuring cylinder after loading the sample powder, in millimeters (mm).

Figure. 2 Expansion tester

3. ANALYSIS

3.1. Mineral Composition Analysis of Coal Rocks

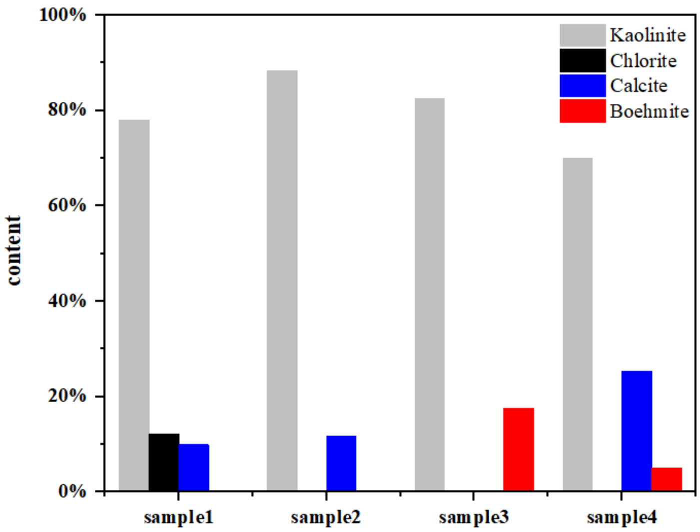

Figure. 3 Histogram of Mineral Composition in Coal Rocks

As depicted in Figure 3, the mineral variety at Baode No. 8 Coal Mine is quite abundant. Through industrial analysis of coal samples, we found that the average proportion of mineral components in coal reaches 8.72%. This proportion not only highlights the significance of mineral components in coal rocks but also provides basic data for further exploring their impact on coalbed methane (CBM) extraction. Among the numerous mineral components, kaolinite and chlorite, as the primary clay minerals, account for an average of 82.7%, making them the most prominent mineral components in Baode coal rocks. These two clay minerals are prone to hydration and swelling, which not only affects the physical and chemical properties of coal rocks but also has a profound impact on the occurrence state and extraction efficiency of CBM.

From the perspective of CBM extraction, the hydration and swelling of clay minerals is an issue that cannot be ignored. When coal seams are intruded by water, clay minerals such as kaolinite and chlorite absorb water and swell, leading to changes in the pore structure of coal rocks and reduced permeability. This process not only increases the difficulty of CBM extraction but may also result in decreased extraction efficiency. Therefore, inhibiting the hydration and swelling of clay minerals in coal rocks is of certain significance for efficient CBM extraction.

3.2. Experimental Analysis of Coal Rock Swelling

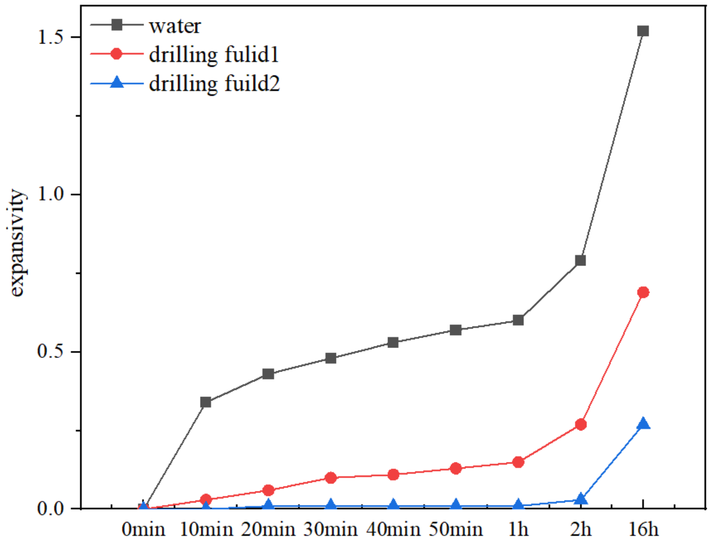

Figure. 4 Line Chart for Coal Rock Swelling Rate Experiment

As shown in Figure 4, when coal rocks are soaked in distilled water, the swelling rate at Baode Coal Mine is relatively high, reaching 0.79% at 2 hours and 1.52% at 16 hours, indicating a tendency for coal rocks to swell easily. Therefore, inhibitors need to be added to the drilling fluid to suppress coal rock swelling. The swelling rate caused by soaking coal rocks in drilling fluid with sodium formate as the inhibitor is 0.27% at 2 hours, while the swelling rate caused by soaking coal rocks in drilling fluid with potassium chloride as the inhibitor is 0.03% at 2 hours. It can be observed that potassium chloride exhibits better inhibitory effects compared to sodium formate. This paper conducts an in-depth discussion on the superiority of potassium chloride inhibitors over sodium formate inhibitors: Firstly, from the perspective of ionic inhibition, potassium ions in potassium chloride have a stronger ability to inhibit coal rock swelling compared to sodium ions in sodium formate. Additionally, chloride ions in potassium chloride also possess certain swelling inhibition properties, which further enhances the effectiveness of potassium chloride inhibitors. Moreover, at the same concentration, the number of cations in potassium chloride is greater than that in sodium formate, providing strong support for the superior performance of potassium chloride inhibitors.

4. CONCLUSIONS

This paper conducted in-depth experimental investigations into the mineral composition characteristics of Coal No. 8 from the Baode mining area and the impact of clay minerals on coal seam permeability. Based on these investigations, the inhibitory effects of two additives, potassium chloride and sodium formate, on the hydration and swelling of clay minerals in coal samples were evaluated.

(1) Firstly, the mineral analysis experimental results revealed that Coal No. 8 from the Baode mining area exhibits a diverse range of mineral types, with clay minerals accounting for a significant proportion. The hydration and swelling characteristics of clay minerals not only lead to the destruction of coal rock structures but also significantly reduce the permeability of coal seams, adversely affecting the efficiency of coalbed methane (CBM) extraction. Therefore, inhibiting the hydration and swelling of clay minerals in coal rocks is of significant research importance.

(2) Through data analysis of coal rock swelling experiments, it is clearly evident that potassium chloride exhibits a more significant inhibitory effect on the hydration and swelling of clay minerals in Baode coal samples compared to sodium formate additives. Within a 2-hour experimental period,

the swelling rate of coal samples with potassium chloride additives was only 0.03%, fully demonstrating the superiority of potassium chloride additives in inhibiting the hydration and swelling of clay minerals.

(3) Additionally, experimental tests were conducted on the performance of two types of drilling fluids, and comparative analyses were performed in conjunction with the actual operating conditions of the Baode mining area. The experimental results showed that drilling fluids with potassium chloride additives exhibited better adaptability in terms of various performance indicators and were more suitable for the field conditions of the Baode mining area. To further verify the practical application effects of the drilling fluids, they were field-tested in the Baode mining area and received positive feedback. They not only effectively inhibited the hydration and swelling of coal rocks but also maintained wellbore stability, enhancing the safety and efficiency of drilling operations.

In summary, this study revealed the mineral composition characteristics of Coal No. 8 from the Baode mining area and their impact on coal seam permeability through systematic experimental analysis. More effective potassium chloride additives were screened out and their practical application effects in the Baode mining area were verified. These research findings not only provide important theoretical and technical support for drilling operations during CBM extraction but also offer new ideas and methods for subsequent research and applications aimed at inhibiting the hydration and swelling of clay minerals and improving coal seam permeability.

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