Investigation on Pulverized Coal Control Using Calcium Sulfoaluminante Cementitious Proppants in Coalbed Methane Fracturing

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ABSTRACT: Coalbed methane is a type of high-quality clean energy. The development of coalbed methane helps protect the living environment of humans and solves the safety problems in coal mining. However, a large amount of pulverized coal is generated after coalbed methane fracturing, which reduces the production of coalbed methane. Reduction of pulverized coal generation and prevention of pulverized coal migration are important for the development of coalbed methane. This study innovatively mixed calcium sulfoaluminate particles and sand to create a new fracturing proppant. The new proppant was carried by the fracturing fluid into the formation cracks and cured to form a permeable cement stone with a certain compressive strength and permeability at formation temperature and pressure. The permeability and compressive strength of the permeable cement stone were measured at different curing temperatures. Results showed that when the compressive strength of the permeable cement stone was 5.46 MPa, the gas and water permeabilities could reach 2.06 and 0.57 D, respectively. The pore diameter distribution was measured with the semi-permeable diaphragm method. The distribution curve was bimodal, and the range of the variation in pore size was 0.6−300 μm. Blocked pulverized coal size was determined using the seepage theory of particles in porous media and verified through a pulverized coal control experiment. Pulverized coal with a diameter larger than 7.67 μm was blocked by the permeable cement stone. The efficiency of the permeable cement stone in controlling pulverized coal could reach 96%. This study proved that calcium sulfoaluminate cementitious proppants can fix pulverized coal and prevent its migration. It also provided the compressive strength of propping fractures and the high permeability needed for drainage under formation conditions.

1. INTRODUCTION

As an unconventional natural gas, coalbed methane is green and clean energy. The development and utilization of coalbed methane are crucial for improving the energy structure and preventing gas accidents. An effective connecting channel must be established between the coal seam and the wellbore to exploit coalbed methane. The most effective way to create this connecting channel is hydraulic fracturing. However, the flow of the fracturing proppant and fracturing fluid system through the coal seam surface produces pulverized coal,1 which blocks the pores and fracturing cracks in the coal seam.2,3 The blockage affects the seepage of coalbed methane and reduces the gas production. Moreover, the deposition of pulverized coal in the wellbore causes the pump to be buried, and the entrance of accumulated pulverized coal into the production system causes pump jamming, which affects the continuous production of coalbed methane. Pulverized coal has become the major problem that restricts the production of coalbed methane. Pulverized coal blockage reduces the conductivity of fracturing cracks in coal reservoirs and makes it difficult for coalbed methane to reach the expected production. Pulverized coal control is a key problem in coalbed methane development.
Two theoretical guides apply to pulverized coal control. The first one pertains to the theory of limited pulverized coal generation. The migration of coarse particles is limited, and fine particles are carried out through the pore to maintain reservoir permeability. The second one is the theory of preventing pulverized coal migration and stopping pulverized coal from damaging downhole tools and blocking the formation. Pulverized coal control has been implemented in geological prevention, reservoir reconstruction, equipment optimization, production forewarning, drainage control, and process treatment. For geological prevention, geological analysis and geophysical interpretation methods are used to predict and delineate the block with a high incidence of pulverized coal to provide a basis for block selection and well location. For reservoir reconstruction, pulverized coal control measures are mainly worked out in fracturing technology, fracturing fluid composition, and fracturing formation. For equipment optimization, different drainage equipment have different applicability. Horizontal wells require screw pumps with a large powder carrying capacity for drainage. Jet pumps should be used for inclined and horizontal wells with a large amount of water and serious pulverized coal problems. A negative-pressure jet pump cleans the pulverized coal at a high speed to reduce the sedimentation and accumulation of the pulverized coal at the bottom of the well. For production forewarning, pulverized coal concentration monitoring and indicator diagram monitoring are mainly used. Production forewarning is carried out based on the monitored pulverized coal concentration and the limit value of the pulverized coal concentration of the coalbed methane block. For downhole faults caused by coal production, forewarning is given based on indicator diagram monitoring. For drainage control, in accordance with the pulverized coal production, water production, and reservoir pressure of coalbed methane wells, different drainage control measures are applied at different drainage stages to achieve refined drainage. Meanwhile, different well-washing measures are adopted for process management, and a powder-proof tail pipe or a wire-wound screen is connected to the pump suction port. Although different pulverized coal control measures have been proposed, effective prevention and control of the generation and migration of pulverized coal in reservoirs have not been achieved yet. The research on pulverized coal control has focused on pulverized coal production from a formation and wellbore, and limited research has been conducted on preventing the migration of pulverized coal in a formation. The application of pulverized coal control has not been organically combined with the mechanism of pulverized coal migration. The pulverized coal control measures used on-site are blind and one-sided, and no systematic method for pulverized coal control is available.

This study mainly investigated the prevention of the migration of pulverized coal in a formation and applied the theory of limited pulverized coal production. A calcium sulfoaluminate cementitious material was mixed with sand in a certain proportion. The fracturing fluid carried the mixture into the fracturing cracks of the coal seam. Under the conditions of formation temperature and pressure, a hydration reaction occurred between the mixture and water and formed a permeable cement stone with a certain compressive strength and permeability. The permeable cement stone filled and supported the fracturing cracks. It acted as a barrier against migrated pulverized coal and could fix the pulverized coal at the location where it was generated. First, the ratio of the calcium sulfoaluminate cementitious material and sand was optimized through tests on compressive strength and gas and water permeability. The mechanism of how the compressive strength and permeability of the permeable cement stone changed with temperature was analyzed. Second, the chemical stability of the permeable cement stone under formation conditions was evaluated. Finally, the pulverized coal control effect and permeability retention rate of the permeable cement stone were simulated through experiments, such as tests on pulverized coal particle size, permeability, and permeable cement stone pore size distributions. The mechanism of how the permeable cement stone prevented pulverized coal migration was studied. This new technology offers a new idea for pulverized coal control methods in coalbed methane development.

2. MATERIALS AND METHODS

2.1. Materials. Calcium sulfoaluminate particles with particle sizes of 0.25–0.6 mm (fine) and 0.6–1.2 mm (coarse) was obtained from Jiahua Special Cement Co., Ltd. Sand with a particle size of 0.381–0.864 mm was provided by Chengde Beiyan New Material Technology Co., Ltd. The water-reducing agent was obtained from Tianjin Kelioi Engineering Material and Technology Co., Ltd. Calcium sulfate dihydrate and sodium gluconate were purchased from Chengdu Kelong Chemical Co., Ltd. All of the chemicals were of analytical grade and used without further purification.

2.2. Preparation of Permeable Cement Stone. Calcium sulfoaluminate particles were selected as the cementitious material, and their particle sizes ranged within 0.25–0.6 mm (fine) and 0.6–1.2 mm (coarse). The calcium sulfoaluminate particles with different particle sizes were mixed with sand in a corrugated agitator at a certain proportion. Then, the fracturing fluid was added and stirred evenly in the corrugated agitator. The mixture was poured into a mold and cured at different temperatures for 72 h to obtain permeable cement stone samples. The sample used for the compressive strength test was a cube (50.8 mm × 50.8 mm × 50.8 mm). The sample used for the permeability test was a cylinder with a diameter of 25 mm and a height of 50 mm.

2.3. XRD, SEM, Particle Size Distribution, and Microscope Test Methods. The permeable cement stone sample was dried and ground into powder and then made to pass through a 60-mesh sieve. The phase composition of the permeable cement stone sample was analyzed using an X-ray diffraction meter (X’Pert MPD PRO, Paneth, Holland) with Cu (Kα) radiation (V = 40 kV, I = 40 mA) at a scanning rate of 2°/min, and the scanning range was 5–70°. The sample to be tested was scattered on conductive tape, and the conductive tape was pasted on a stainless-steel sheet. A thin layer of gold was sprayed on the surface of the test sample because of the non-conductivity of the sample. The morphology of the permeable cement stone sample was observed with a scanning electron microscope (SEM) (Quanta 450, FEI Co., USA) at 20.00 kV. The particle size of the pulverized coal was analyzed and tested using a dry and wet laser particle size analyzer (BZ-2873, Dandong Best Instrument Co., LTD. China) at room temperature with a measurement range of 0.1–1000 μm. The pore structure of the permeable cement stone was tested with an electron microscope (CMM-50, Shanghai Changfang Optical Instrument Co., Ltd.).
2.4. Test of Water/Gas Permeability. The permeable cement stone sample prepared was put into a core holder. The permeability is calculated using Darcy’s law

\[ K = 10^5 \times \frac{Q \times \mu \times L}{A \times \Delta P} \]  

\( K \)—permeability, D; \( Q \)—flux, mL/s; \( \mu \)—viscosity of fluid, Pa·s; \( L \)—sample length, cm; \( A \)—sample cross-sectional area, cm²; and \( \Delta P \)—differential pressure, kPa.

2.5. Test of the Capillary Pressure Curve. The capillary pressure curve of the permeable cement stone was tested by the semipermeable membrane method. The relationship between capillary pressure and wet saturation was obtained by the test. The capillary pressure is inversely proportional to the capillary radius.

\[ P_c = \frac{2 \times \sigma \times \cos \theta}{r} \]  

\( P_c \)—capillary pressure, kPa; \( \sigma \)—Interfacial tension, mN/m; \( \theta \)—wetting contact angle, °; and \( r \)—capillary radius, μm.

2.6. Experiment on Pulverized Coal Control of Permeable Cement Stone. First, the permeable cement stone was placed in a core holder, and the gas permeability was tested at different gas flow rates. Second, the pulverized coal was added in front of the permeable cement stone, and the gas permeability was tested at different gas flow rates. Finally, the pulverized coal was moved from the core holder, and the gas permeability was tested at different gas flow rates. Each group of experiments was performed three times. The addition of pulverized coal was generated by coalbed methane drainage in the Hancheng block.

3. RESULTS AND DISCUSSION

3.1. Effect of Curing Temperature and Formula of Permeable Cement Stone on Permeability and Compressive Strength. Permeable cement stone can support fracturing cracks and prevent pulverized coal migration. It also can allow water and gas to pass through itself. Water permeability, gas permeability, and compressive strength are the requirements to be considered. The influence of curing temperature on the gas permeability, water permeability, and compressive strength of the permeable cement stone with different proportions was investigated in this study. The results are shown in Figure 1. Figure 1 indicates that curing temperature had a significant influence on the gas permeability, water permeability, and compressive strength of the permeable cement stone with different proportions. The permeable cement stone was made with different mass ratios of fine particles, coarse particles, and sand (4:3:1, 4:2:1, and 4:1:1). The fine particles had a large specific surface area and high reactivity, which improved the consolidation strength of permeable cement stone. The coarse particles ensured that a sufficient pore structure was formed after particle accumulation. Sand ensured the strength of supporting cracks before cement stone consolidation. Figure 1 illustrates that the permeability of the studied permeable cement stone was significantly affected by curing temperature, with the highest permeability observed at the optimal curing temperature.
cement stone decreased and its compressive strength increased with the increase in the proportion of coarse particles. A possible reason is that the fine particles (0.25–0.6 mm) and coarse particles (0.6–1.2 mm) formed a multi-scale solid particle system with a continuous particle size distribution. The particle size ratio of the fine and coarse particles exerted a great influence on packing density. According to binary mixture model packing theory, the packing density of a mixture of two materials depends on the diameter ratio of fine and coarse particles. If the proportion of fine particles is greater than the proportion of coarse particles, the packing density increases with a decrease in the ratio of fine and coarse particles. The higher the packing density is, the higher the compressive strength is and the lower the permeability is.

When the curing temperature increased, the gas and water permeability of the permeable cement stone decreased and then increased, whereas its compressive strength increased and then decreased. The change in curing temperature affected the pore size distribution of the permeable cement stone. In consideration of the compressive strength needed to support the fracturing cracks and the suitable permeability required for gas production, the ratio 4:2:1 was selected for further investigation.

The permeable cement stone was cured at 50 °C. Figure 2 shows that only the characteristic diffraction peaks of ettringite (AFt) (ICDD: 00-041-1451) and aluminum hydroxide (AH₃) (ICDD: 00-031-0018) appeared in the hydration product. The sharp peaks and narrow peak width of the hydration products indicated that AFt and AH₃ had high crystallinity. With the increase in curing temperature, the intensity of the AFt and AH₃ diffraction peaks gradually increased, indicating that the content of AFt and AH₃ in the hydration products gradually increased. The increased temperature was conducive to the hydration reaction, which matched the experimental results on decreased permeability and increased compressive strength of the permeable cement stone in Figure 1. When the curing temperature increased to 65 °C, the diffraction peak intensity of AFt in the XRD spectrum of the permeable cement stone decreased obviously. Moreover, obvious and sharp characteristic diffraction peaks of monosulfoaluminate (AFm) were observed. This result illustrates that AFt had begun to transform to AFm at this temperature. It was one of the reasons for the increase in permeability and decrease in compressive strength of the permeable cement stone shown in Figure 1. When the curing temperature increased to 80 °C, the characteristic diffraction peak of AFt in the XRD spectrum of the permeable cement stone disappeared completely and only the characteristic diffraction peak of AFm appeared. This result indicates that AFt was completely transformed into AFm; the compressive strength of the permeable cement stone continued to decline, and its permeability continued to increase.

The changes in the micromorphology of the permeable cement stone at different curing temperatures were determined. Figure 3 shows that the micromorphology differed
significantly at different curing temperatures. When the curing temperature was 50 °C, a large amount of acicular AFt appeared, as shown in Figure 3a. When the curing temperature was increased to 65 °C, the amount of acicular AFt decreased and columnar AFm increased, as shown in Figure 3b, indicating that the increased temperature was conducive to the formation of AFm. When the curing temperature was increased to 80 °C, the hydration product was columnar and flaky AFm (Figure 3c), which was transformed from AFt; the acicular AFt disappeared completely.

The reaction equations are as follows: AFt is generated in the hydration reaction of tricalcium aluminate.

\[
3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{H}_2\text{O} + 3(\text{CaSO}_4 \cdot 2\text{H}_2\text{O}) + 6\text{H}_2\text{O} \\
\rightarrow 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 3\text{CaSO}_4 \cdot 32\text{H}_2\text{O}
\]  \hspace{1cm} (3)

As the temperature increases, AFt is transformed into AFm.

\[
3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 3\text{CaSO}_4 \cdot 32\text{H}_2\text{O} + 2(3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{H}_2\text{O}) \\
\rightarrow 3(3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{CaSO}_4 \cdot 12\text{H}_2\text{O})
\]  \hspace{1cm} (4)

The main chemical composition of calcium sulfoaluminate particles is tricalcium aluminate. The hydration products are mainly AFt, AH3, and AFm.\textsuperscript{21} The reaction of calcium sulfoaluminate hydration is rapid. Large amounts of acicular AFt and AH3 with high strength are generated at the initial stage.\textsuperscript{22} They fill the internal pores of permeable cement stone and refine the pore structure. Permeable cement stone has a certain compressive strength at the initial stage. With the continuous increase in curing temperature, the hydration reaction rate is accelerated, and the generation of AFt and AH3 increases. The permeability of permeable cement stone decreases gradually, but its compressive strength increases gradually.\textsuperscript{23} However, AFt cannot exist stably at high temperatures, and it easily transforms into AFm.\textsuperscript{24,25} The AFm crystal structure is flaky, and the binding energy is lower than that of acicular AFt crystals, which reduces the compressive strength and increases the porosity of hydration products.\textsuperscript{26} The decomposition temperature of AFt is 65 °C and above.\textsuperscript{27} At this stage, AFt loses bound water. When the initial hydration temperature is lower than 65 °C, the hydration product AFt begins to decompose into AFm, the compressive strength of permeable cement decreases, and the gas and water permeabilities increase. This result, which is attributed to the transformation of the hydration product AFt to AFm at high temperatures, is similar to that of other’s research.\textsuperscript{28}

3.2. Effect of Immersion Time on the Gas Permeability and Compressive Strength of Permeable Cement Stone. The long-term stability of permeable cement stone in the high-temperature and high-humidity environment of a formation is crucial. It determines the effectiveness of supporting fractures and coalbed methane development. In this study, a permeable cement stone sample was prepared at a ratio of 4:2:1. It was placed in deionized water, and an aging experiment was performed in a thermostat water bath at 50 °C. The core was taken out and dried every five days, and its gas permeability and compressive strength were measured. The results are shown in Figure 4.

Figure 4 illustrates that the compressive strength of the permeable stone increased to a certain extent with the increase in immersion time. The hydration products of the calcium sulfoaluminate particles were AFt crystals, AH3, and C$-$S$-$H gel.\textsuperscript{31} These hydration products could exist stably at the curing temperature.\textsuperscript{32} With the increase in hydration time, AFt crystals, AH3, and C$-$S$-$H gel were formed in the low-alkalinity medium.\textsuperscript{33} These hydration products filled the pore space of the permeable cement stone, which increased the compressive strength to a certain extent. The gas permeability of the permeable cement stone decreased slightly with the increase in immersion time.

3.3. Experimental Study on Medium Erosion Resistance of Permeable Cement Stone. Permeable cement stones support the fracture cracks and encounter the erosion medium in the formation environment. The long-term effectiveness of permeable cement stones is crucial. In this work, the changes in the gas permeability and compressive strength of the permeable cement stone after immersing in different erosion media at different immersion times were studied. Formation water, oil-well-produced water, 1% HCl solution, and 1% NaOH were the four erosion media. The solution was changed every 3 days to ensure that the
composition of the solution did not change as much as possible. The experimental results are shown in Figure 5.

![Figure 5](image-url)

**Figure 5.** Effect of erosion medium on compressive strength and gas permeability of permeable cement stone.

The experimental results are shown in Figure 5. Figure 5 indicates that when the permeable cement stone samples were immersed in formation water and oil well-produced water for 20 days, the gas permeability and compressive strength were basically unchanged. The hydration process of the permeable cement stone was not affected by the formation water and oil well-produced water, and the hydration products were not eroded. The permeable cement stone could maintain its stable performance for a long time in this environment.

When permeable cement stone samples were immersed in 1% HCl solution or 1% NaOH solution for 20 days, the compressive strength decreased to a certain extent. H⁺ or OH⁻ penetrated the permeable cement stone and affected the hydration process. It destroyed the structure of the hydration product and reduced the compressive strength. However, the compressive strength of the permeable cement stone did not decrease significantly, and it could still support formation cracks. In addition, the gas permeability of the permeable cement stone increased because of the erosion of H⁺ or OH⁻, and it was easy for coalbed methane to be recovered from the formation. If the gas production is not as good as expected after fracturing with the calcium sulfoaluminate cementitious proppant, a dilute hydrochloric acid or dilute alkali solution can be used to treat the permeable cement stone in the formation and increase its permeability.

### 3.4. Experimental Study on Pulverized Coal Control with Permeable Cement Stone

The effect of pulverized coal control with permeable cement stone determines whether it can be used in downhole operations. The gas permeability of permeable cement stone was tested in the condition of pulverized coal migration. The permeable cement stone was prepared according to the ratio 4:2:1.

The particle size distribution of on-site pulverized coal was measured with a Malvern laser particle size analyzer. Figure 6 shows that the distribution curve was bimodal, and the variation range of particle size was 0.2–1000 μm. The main peak appeared at 10–100 μm, and the secondary peak appeared at 300–1000 μm. The cumulative particle size distributions of pulverized coal less than 1 μm, less than 8 μm, less than 10 μm, and less than 100 μm were 1.02, 5.4, 6.1, and 59.8%, respectively.

Gas permeability was tested under the condition with no pulverized coal, with added pulverized coal, and with cleaned pulverized coal to verify the pulverized coal control performance of the permeable cement stone and sand. Figure 7a shows that the gas permeability of the permeable cement stone decreased with the increase in the gas flow rate. The “gas slippage effect” occurs when gas molecules flow in pores. The greater the gas pressure is, the lower the measured permeability is. When the pulverized coal was added to the front of the permeable cement stone core in this study, the gas permeability decreased significantly. The average gas permeability loss rate was 28.4%. The decrease in gas permeability may be due to the fact that pulverized coal entered the pore structure of the permeable cement stone during the displacement process, thereby forming a bridge plug and causing a decrease in gas permeability. After removing the pulverized coal from the core holder, the gas permeability of the

![Figure 6](image-url)

**Figure 6.** Particle size distribution curve of on-site pulverized coal particles.
permeable cement stone was tested again. A significant recovery in gas permeability was observed. The average gas permeability recovery rate was 118.5%. These results indicate that the pulverized coal was mainly blocked on the surface of the permeable cement stone.

![Figure 7. Effect of gas velocity on pulverized coal displacement.](image1)

![Figure 8. (a) Capillary pressure curve of permeable cement stone, (b) pore size distribution curve of permeable cement stone, and (c) micrograph of a section of permeable cement stone (×100).](image2)
The semi-permeable diaphragm method was used to analyze the pulverized coal control mechanism. The capillary pressure curve was tested, and the pore size distribution curve was calculated. The semi-permeable diaphragm method has a high measurement accuracy and a simple operation. The semi-permeable diaphragm only allows the wet-phase fluid to pass through and blocks the non-wet-phase fluid within a certain pressure range. The relationship curve between capillary pressure and wet-phase saturation was obtained with the semi-permeable diaphragm method in this study. The capillary pressure curve and pore size distribution of the permeable cement stone are shown in Figure 8a.

The capillary pressure curve was divided into initial, middle gentle, and end upturned sections. Figure 8a illustrates the capillary pressure curve of permeable cement stone measured by the semi-permeable diaphragm method. At the initial stage of displacement, the water saturation decreased slowly with the increase in capillary pressure. This decrease did not mean that the gas had entered the permeable cement stone; it might mean that the gas drove out the water in different concave–convex parts of the core surface. With the increase in capillary pressure, the water saturation continued to decline and entered the middle gentle section. At this stage, the water phase was largely carried out from the permeable cement stone by the gas phase. The water saturation decreased rapidly, and the capillary pressure change was small. The closer it was to the saturation axis, the larger the pore radius of the permeable cement stone was. In the end upturned section, the capillary curve was nearly parallel to the capillary pressure axis. With the increase in pressure, the water saturation remained unchanged, showing that the water saturation of the permeable cement stone had reached irreducible water saturation. Figure 8a illustrates that the water saturation did not change when the capillary pressure reached 150 kPa. The curve was nearly parallel to that of the capillary pressure, and the irreducible water saturation of the permeable cement stone was 27.8%. The median saturation pressure was 12.5 kPa when the water saturation was 50%. According to the calculation formula of the median pore throat radius, the calculated median pore throat radius was 11.5 μm. The median pore size was 23 μm, which was twice the median pore throat radius.

Figure 8b presents the pore size distribution of permeable cement stone calculated using eq 2. The cumulative distribution less than 42 μm was 35%. The cumulative distribution greater than 42 μm but less than 148 μm was 62.8%. The cumulative distribution greater than 148 μm but less than 178 μm was 2.2%. The presence of large pores allowed the permeable cement stone to maintain a high gas permeability. According to the research on the seepage of suspended solids in porous media, particles with a diameter greater than or equal to one-third of the median pore size of the core can serve as a bridge in the pores. In this study, the pulverized coal with a diameter greater than 7.67 μm could serve as a bridge in the pores of the permeable cement stone.

As shown in Figure 6, the cumulative particle size distribution of pulverized coal less than 7.67 μm was about 5%. This result is in good agreement with the pulverized coal loss rate measured in the pulverized coal control experiment (4.09%). However, several differences still exist. The main reason could be that the pulverized coal with a small particle size easily entered the pores, resulting in plugging. It reduced the gas permeability of the permeable cement stone to a certain extent, as verified by the test results on gas permeability in the pulverized coal control experiment. Pulverized coal easily entered the large pores, which reduced the pore diameter and blocked the entry of pulverized coal with a matching original particle size. The pulverized coal with a matching particle size was blocked outside the permeable stone; thus, the test results showed that the loss rate of pulverized coal was only 4.09%.

Figure 8c illustrates the section morphology of permeable cement stone observed with a microscope. The microscope photographs show the pore size distribution in the permeable cement stone. Pores of different sizes were present in the permeable cement stone, and they were similar to the pore size distribution measured with the semi-permeable diaphragm method. These pores of different sizes could ensure a proper compressive strength and permeability of the permeable cement stone while effectively preventing the migration of pulverized coal in the formation.

3.5. Possible Mechanisms. Figure 9 shows that when the particle size of pulverized coal is greater than one-third of the...
pore diameter, the pulverized coal is stuck in the pores and forms a stable triangular structure by bridging and blocking the pores and preventing the subsequent pulverized coal from entering. When the particle size of pulverized coal is less than one-third of the pore diameter, unstable accumulation is formed. The flow impulse can easily disperse the bridge, and no blockage is formed.

The principle of selecting the particle size of calcium sulfoaluminate cement to prevent pulverized coal blockage is as follows. On one hand, it prevents pulverized coal from being generated and entering the permeable cement stone. On the other hand, it ensures that the output of the pulverized coal enters the permeable cement stone and prevents it from getting stuck in the pores and forming particle blockage.

4. CONCLUSIONS

A new calcium sulfoaluminate cementitious proppant was investigated to solve the problem of pulverized coal migration. The following conclusions were obtained.

(1) With the increase in temperature, the permeability of permeable cement stone decreases and then increases. On the contrary, with the increase in temperature, the compressive strength of the permeable cement stone increases and then decreases. The formula of permeable cement stone can be adjusted according to geological conditions to meet the needs of fracturing construction.

(2) The gas permeability and compressive strength of permeable cement stone can be kept stable in the formation and unaffected by the erosion of the formation medium. If the permeability of permeable cement stone is relatively low after hydraulic fracturing, dilute hydrochloric acid or dilute alkali solution can be used to treat the permeable cement and increase its permeability.

(3) Permeable cement stone can block and fix pulverized coal with a particle size larger than one-third of its average pore diameter in the formation. Small pulverized coal can migrate out of the formation through the pores of permeable cement stone. Moderate pulverized coal production can ensure the continuity of coalbed methane production. Permeable cement stone not only reduces the damage of pulverized coal on the formation but also ensures the continuity of coalbed methane production.

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REFERENCES

(1) Massarotto, P.; Iyer, R. S.; Elma, M.; Nicholson, T. An Experimental Study on Characterizing Coal Bed Methane (CBM) Fines Production and Migration of Mineral Matter in Coal Beds. Energy Fuels 2014, 28, 766–773.
(2) Guo, Z.; Vu, P. N. H.; Hussain, F. A Laboratory Study of the Effect of Creep and Fines Migration on Coal Permeability during Single-Phase Flow. Int. J. Coal Geol. 2018, 200, 61–76.
(3) Hu, S.; Chen, Y.; Hao, Y.; Chen, Z.; Feng, G.; Li, G.; Guan, S.; Zhang, X.; Li, S. Experimental Study of the Effects of Fine Retention on Fracturing Proppant Permeability in Coalbed Methane Reservoirs. J. Nat. Gas Sci. Eng. 2020, 83, 103604.
(4) Han, W.; Wang, Y.; Fan, J.; Li, Y.; Wu, X.; Yu, Y. An Experimental Study on Coal Fines Migration during Single Phase Water Flow. GeoFluids 2020, 2020, 1–13.
(5) Khilar, K. C.; Fogler, H. S. Migrations of Fines in Porous Media; Theory and Applications of Transport in Porous Media; Bear, J., Series, Eds.; Springer: Netherlands, Dordrecht, 1998; Vol. 12.
(6) Guo, Z.; Hussain, F.; Cinar, Y. Permeability Variation Associated with Fines Production from Anthracite Coal during Water Injection. Int. J. Coal Geol. 2015, 147, 148–157.
(7) Han, G.; Ling, K.; Wu, H.; Gao, F.; Zhu, F.; Zhang, M. An Experimental Study of Coal-Fines Migration in Coalbed-Methane Production Wells. J. Nat. Gas Sci. Eng. 2015, 26, 1542–1548.
(8) Zhao, X.; Liu, S.; Sang, S.; Pan, Z.; Zhao, W.; Yang, Y.; Hu, Q.; Yang, Y. Characteristics and Generation Mechanisms of Coal Fines in Coalbed Methane Wells in the Southern Qinshui Basin, China. J. Nat. Gas Sci. Eng. 2016, 34, 849–863.
(9) Yao, Z.; Cao, D.; Wei, Y.; Li, X.; Wang, X.; Zhang, X. Experimental Analysis on the Effect of Tectonically Deformed Coal Types on Fines Generation Characteristics. J. Pet. Sci. Eng. 2016, 146, 350–359.
(10) Zhang, A.; Cao, D.; Wei, Y.; Rufford, T. E. Characterization of Fines Produced during Drainage of Coalbed Methane Reservoirs in the Linfen Block, Ordos Basin. Energy Explor. Exploit. 2020, 38, 1664–1679.
(11) Ogolo, N.; Olafuyi, O.; Onyekonwu, M. Effect of Nanoparticles on Migrating Fines in Formations. All Days; SPE: Noordwijk, The Netherlands, 2012. p SPE-155213-MS.
(12) Palmer, I.; Technologies, H.; Moschovidis, Z.; Cameron, J.; Technical, P. Coal Failure and Consequences for Coalbed Methane Wells, 2005; p 11.
(13) Wei, Y.; Li, C.; Cao, D.; Wang, A.; Zhang, A.; Yao, Z. The Effects of Particle Size and Inorganic Mineral Content on Fines Migration in Fracturing Proppant during Coalbed Methane Production. J. Pet. Sci. Eng. 2019, 182, 106355.

(14) Bai, T.; Chen, Z.; Aminossadati, S. M.; Rufford, T. E.; Li, L. Experimental Investigation on the Impact of Coal Fines Generation and Migration on Coal Permeability. J. Pet. Sci. Eng. 2017, 159, 257–266.

(15) Gao, D.; Liu, Y.; Wang, T.; Wang, D. Experimental Investigation of the Impact of Coal Fines Migration on Coal Core Water Flooding. Sustainability 2018, 10, 4102.

(16) Tao, S.; Tang, D.; Xu, H.; Li, S.; Geng, Y.; Zhao, J.; Wu, S.; Meng, Q.; Kou, X.; Yang, S.; Yi, C. Fluid Velocity Sensitivity of Coal Reservoir and Its Effect on Coalbed Methane Well Productivity: A Case of Baode Block, Northeastern Ordos Basin, China. J. Pet. Sci. Eng. 2017, 152, 229–237.

(17) Zhu, S.-Y.; Peng, X.-L.; Du, Z.-M.; Wang, C.-W.; Deng, P.; Mo, F.; Lei, Y.; Wang, M. Modeling of Coal Fine Migration During CBM Production in High-Rank Coal. Transport Porous Media 2017, 118, 65–83.

(18) Furnas, C. C. Grading Aggregates-I: Mathematical Relations for Beds of Broken Solids of Maximum Density. Ind. Eng. Chem. 1931, 23, 1052–1058.

(19) Frigione, G.; Marra, S. Relationship Between Particle Size Distribution and Compressive Strength in Portland C−L. Cement Concr. Res. 1976, 6, 113.

(20) Stovall, T.; de Larrard, F.; Buil, M. Linear Packing Density Model of Grain Mixtures. Powder Technol. 1986, 48, 1–12.

(21) Tellesca, A.; Marrocchini, M.; Pace, M. L.; Tomasulo, M.; Valenti, G. L.; Monteiro, P. J. M. A Hydration Study of Various Calcium Sulfoaluminate Cements. Cem. Concr. Compos. 2014, 53, 224–232.

(22) Zhang, L.; Glasser, F. P. Hydration of Calcium Sulfoaluminate Cement at Less than 24 h. Adv. Cem. Res. 2002, 14, 141.

(23) Borišnár, M.; Danue, N.; Dolenc, S. Phase Development and Hydration Kinetics of Belite-Calcium Sulfoaluminate Cements at Different Curing Temperatures. Ceram. Int. 2020, 46, 29421–29428.

(24) Satava, V.; Veprek, O. Thermal Decomposition of Ettringite Under Hydrothermal Conditions. J. Am. Ceram. Soc. 1975, 58, 357–359.

(25) Hall, C.; Billimore, A. D.; Barnes, P. Thermal Decomposition of Ettringite Ca6[Al(OH)6]2(SO4)3·26H2O. J. Chem. Soc., Faraday Trans. 1996, 92, 2125.

(26) Taylor, H. F. W. Cement Chemistry, 2nd ed.; T. Telford: London, 1997.

(27) Deschner, F.; Lothenbach, B.; Winningfeld, F.; Neubauer, J. Effect of Temperature on the Hydration of Portland Cement Blended with Siliceous Fly Ash. Cem. Concr. Res. 2013, 52, 169–181.

(28) Li, L.; Wang, R.; Zhang, S. Effect of Curing Temperature and Relative Humidity on the Hydrates and Porosity of Calcium Sulfoaluminate Cement. Constr. Build. Mater. 2019, 213, 627–636.

(29) Rastrop, E. Heat of Hydration in Concrete. Mag. Concr. Res. 1954, 6, 79–92.

(30) Kaufmann, J.; Winningfeld, F.; Lothenbach, B. Stability of Ettringite in CSA Cement at Elevated Temperatures. Adv. Cem. Res. 2016, 28, 251–261.

(31) Baur, I.; Keller, P.; Mavrocordatos, D.; Wehrli, B.; Johnson, C. A. Dissolution-Precipitation Behaviour of Ettringite, Monosulphate, and Calcium Silicate Hydrate. Cem. Concr. Res. 2004, 34, 341–348.

(32) Berger, S.; Aouad, G.; Coumes, C.; Bescop, P.; Damidot, D. Leaching of Calcium Sulfoaluminate Cement Pastes by Water at Regulated PH and Temperature: Experimental Investigation and Modeling. Cem. Concr. Res. 2013, 53, 211–220.

(33) Tambara, L. U. D.; Cheriaf, M.; Rocha, J. C.; Palomo, A.; Fernández-Jiménez, A. Effect of Alkalis Content on Calcium Sulfoaluminate (CSA) Cement Hydration. Cem. Concr. Res. 2020, 128, 105953.

(34) Pastore, T.; Cabrini, M.; Coppola, L.; Lorenzi, S.; Marcassoli, P.; Buoso, A. Evaluation of the Corrosion Inhibition of Salts of Organic Acids in Alkaline Solutions and Chloride Contaminated Concrete: Organic Inhibitors for Chloride Contaminated Concrete. Mater. Corros. 2011, 62, 187–195.

(35) Chen, M.-C.; Wang, K.; Xie, L. Deterioration Mechanism of Cementitious Materials under Acid Rain Attack. Eng. Fail. Anal. 2013, 27, 272–285.

(36) Tang, G. H.; Tao, W. Q.; He, Y. L. Gas Slippage Effect on Microscale Porous Flow Using the Lattice Boltzmann Method. Phys. Rev. E: Stat., Nonlinear, Soft Matter Phys. 2005, 72, 056301.

(37) Barkman, J. H.; Davidson, D. H. Measuring Water Quality and Predicting Well Impairment. J. Pet. Technol. 1972, 24, 865–873.

(38) Abrams, A. Mud Design to Minimize Rock Impairment Due to Particle Invasion. J. Pet. Technol. 1977, 29, 586–592.