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Research Article

Capsule-Bag-Type Sealing Technology for Gas Drainage Boreholes and Its Application

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In gas control, the quality of drilling and sealing plays a key role in the final effect of gas drainage. This paper first studies the mechanism of hole leakage and the stability of the hole sealing section. At the same time, the bag-type grouting hole sealing device and safety pressure limiting valve were developed, and a new grouting hole sealing method for gas extraction was put forward, which could exert active strong support on the hole sealing section. The grouting cement with a high flow state, early strength, good injection ability, and good microexpansibility was prepared by compounding the fast hard sulfoaluminate cement and ordinary Portland cement and adding the appropriate amount of admixture to stimulate its activity. Engineering practice shows that compared with the polyurethane hole sealing method, 97% of the total holes with gas extraction concentration above 60% are extracted by the new grouting hole sealing method under the same conditions. 47% of the total holes were extracted with a gas concentration above 60% in the polyurethane hole sealing method. This shows that the new grouting hole sealing method can keep the stability of the hole sealing section of the borehole, can evade the leakage channel around the borehole, and is beneficial to gas extraction.

1. Introduction

China is a country with coal as its main energy source and has now entered a new stage of high-quality development. With the proposal of carbon peaking and carbon neutrality goals, the construction of a new green and low-carbon cycle energy development pattern should be accelerated. As the basic energy type in China, coal provides a solid guarantee for the smooth operation of the economy [1–5]. The mine is gradually extending to the deep, and the coal seam has the characteristics of high gas, crushing softness, low permeability, and easy outburst [6–9]. The gas problem is becoming more and more serious. The key link of the effect is hole sealing. The quality of hole sealing plays a key role in maintaining the mining replacement cycle and the safe production of the entire mine [10]. At present, much research on hole sealing technology has been carried out at home and abroad. The Ruhr mining area in Germany uses a new type of sealing mixed cement with good fluidity and expansion for sealing. The Donbas mines in Russia use hydraulic expansion sealers, friction sealers, rubber sealers, etc. [11]. With the development of sealing technology, Germany and Japan have comprehensively promoted the application of polyurethane sealing technology. The negative pressure of German extraction reaches 50 kPa, and it is equipped with a pneumatic stirring pressure injection polyurethane pump. The United States uses cement and its supporting mechanical devices to seal holes. British uses resin and rubber ring sealer [12]. Australia adopts the “copper pipe grouting and sealing method” to ensure “high negative pressure, high concentration” gas extraction. At present, the more advanced sealing method abroad is the Bimbal expansion hose sealing device series products produced by the French company Petrometalic [13]. China’s coal seam water injection sealing methods mainly include artificial cement mortar sealing method, different types of water injection hole sealing devices, such as mechanically driven and hydraulically driven, coal seam water injection hole sealing device [14, 15], expansion plug hole sealing device [16], etc. Gas pressure sealing is measured by using yellow mud, cement mortar, rubber ring, capsule, etc. The main processes include manual sealing, grouting sealing, hole sealing device sealing, and rubber ring-pressure mucus sealing. The sealing technologies in gas drainage mainly include cement mortar sealing, mechanical sealing with apron, and clay sealing, but these methods have poor sealing tightness and cumbersome processes. The cement slurry material has high stone body strength, low cost, abundant material sources, convenient slurry preparation, and simple operation [17–20]. But ordinary cement particle size is too large to inject into the soil with a small gap or rock mass with microcracks. Chemical slurries have good injectability and low viscosity and can be injected into fine cracks, but general chemical slurries are toxic and expensive [20–23]. The limitations of the current sealing technology have resulted in many air leakage zones, the length of the sealing section is difficult to guarantee, and the drilling air leakage is difficult to avoid. The gas extraction volume fraction is generally low, which directly affects gas utilization and even causes gas pipeline explosions, threatening the safety of the entire mine [24–27].

Therefore, in view of the problems existing in the conventional plugging method, this paper starts from the source of plugging the leaking gas and conducts an in-depth analysis of the factors that affect the plugging of the leaking gas in the gas drainage borehole. Through the development of new sealing equipment. At the same time, the composite of ordinary Portland cement and sulfoaluminate cement is used, and its activity is stimulated by adding additives to prepare grouting cement with high fluidity, good injectability, and good microexpansion. Finally, its effectiveness is verified by the on-site industry. The research in this paper provides an effective technical approach to improve the problems of serious gas leakage and low extraction volume fraction of existing gas drainage and plugging devices.

2. Study on the Mechanism of Drilling Air Leakage and the Stability of the Sealing Section

2.1. Mechanism of Drilling Air Leakage. When drilling along the coal seam, due to the relatively developed fissures in the coal body, as far as the current sealing method is concerned, even if the hole is tightly sealed, gas leakage will inevitably occur, and the concentration of gas extracted is not high [20], as shown in Figure 1.

Using the bag-type grouting and sealing method, since a grouting pressure is applied by the grouting pump during grouting, the grouting material can be finally set within 2 hours, resulting in a certain strength, which can be produced within one day. The strength of the drill can resist the deformation of the coal wall around the borehole [28], and the supporting force is applied to the borehole in the early stage of sealing to limit the deformation of the borehole and maintain the stability of the borehole. Because the grouting cement has good microexpansion, and the strength of the grouting cement test block is relatively large, the drilling can be kept stable, and there will be no large deformation or even no deformation. Due to the stability of the borehole, during the gas extraction period, no cracks can be formed around the borehole, and no gas leakage channel can be formed, which can keep the gas extraction volume stable, ensure the safety of the coal mine, and also bring huge economic benefits.

The “hole-forming technology” plays an important role in the gas drainage range and drainage efficiency, and whether the problem of “blank area” in the coal mining face can be completely eliminated [29]. It will have a direct impact on the safety and efficiency of coal mining. The “sealing technology” determines the gas drainage negative pressure, drainage effect, and drainage concentration.

The current negative pressure of sealing and drainage is generally low, and the mining industry generally believes that the higher the negative pressure, the lower the gas concentration extracted. The reason is that the higher the negative pressure, the air in the roadway will enter the coal seam along the cracks around the borehole. What is finally extracted is the gas containing a lot of air, which has no utilization value. But in theory, if there is no fracture channel around the gas drainage borehole, the gas concentration should be higher, but in practice, the gas drainage concentration is generally lower. Some sealing techniques can achieve good results in the initial stage, but with the increase of time, coal rheology occurs. Since these seals and materials cannot resist the rheology of the coal body, cracks are generated, and the gas drainage concentration is continuously reduced. Therefore, it can be speculated that if the hole sealing technology is reliable and there is no crack channel around the hole, increasing the negative pressure is beneficial to gas drainage.

2.2. Stability Study of Sealing Section. FLAC3D is an extension of the two-dimensional finite-difference program FLAC2D, which can simulate the mechanical properties of three-dimensional structures of soil, rock, and other materials and analyze plastic flow. At the same time, the software adopts an explicit Lagrangian algorithm and mixed-discrete partitioning technology, which can simulate the plastic failure and large deformation of materials very accurately.

In order to study the change of the coal body around the borehole under different grouting pressures, the FLAC-3D numerical simulation study was carried out on the change of the plastic zone and the displacement of the coal body around the borehole. According to the previous field research and literature review, we set the grouting pressure to 0.8 MPa, 1.0 MPa, and 1.2 MPa for experiments.

2.2.1. Change Law of Plastic Zone. By analyzing the numerical simulation results and theoretical analysis, the change characteristics of the plastic zone can be known. It can be seen from Figure 2 that when the grouting pressure is 0.8 MPa, 1.0 MPa, and 1.2 MPa, the plastic zone range in this area remains basically unchanged, and the plastic zone range is 58.5 mm. Although its plastic zone is the same, its stress

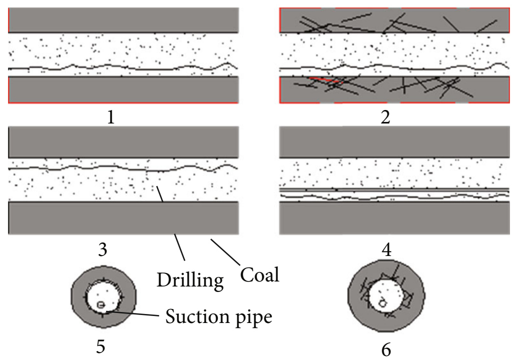


Figure 1: Reasons for air leakage in drilling. 1: air leakage from drilling cuttings; 2: air leakage from fissures; 3: air leakage from the upper part of the filler; 5: pressure relief ring around the hole; 6: rock movement creates new cracks.

level is different, and at different moments, the stress state is also different. When the grouting pressure continues to increase and reaches 1.5 MPa, the plastic zone around the borehole is significantly reduced, and its range is 35.4 mm. Compared with 1.2 MPa, the plastic zone is reduced by 23.2 mm. It can be seen that increasing the grouting pressure within a certain range can reduce the scope of the plastic zone around the borehole, stabilize the periphery of the borehole, and facilitate gas drainage.

2.2.2. Displacement Variation Law. As can be seen from Figure 3, for a single figure, the displacement in the X direction is basically symmetrical on both sides of the borehole, which indicates that a uniform support force is applied to the periphery of the borehole during the grouting process. From the perspective of the entire simulation process, the greater the grouting force applied within a certain range, the greater the support force around the borehole. At the same time, the deformation of the left and right sides of the drilling is smaller. It can be seen that when the grouting pressure is increased from 0.8 MPa to 1.5 MPa, the deformation of the two sides of the drilling is reduced from 2.8 mm to 1.8 mm. From this, it can be inferred that increasing the grouting pressure within a certain range can continue to reduce the deformation of the two sides of the drilling and may no longer produce a plastic zone.

As can be seen from Figure 4, the variable above the borehole is larger in the Z-axis direction. However, as the grouting pressure increases, the difference between the upper and lower deformations gradually decreases. At the same time, from the perspective of the whole process, the deformation of the upper and lower boreholes also decreases continuously with the increase of grouting pressure. When the grouting pressure was increased from 0.8 MPa to 1.5 MPa, the deformation of the upper part of the borehole was reduced from 3.2 mm to 2.0 mm, and the deformation of the lower part was reduced from 2.5 mm to 1.6 mm. It can be seen that as the grouting pressure increases, the deformation of the upper and lower parts of the borehole gradually decreases, but the decrease of the upper deformation is greater than that of the lower part.

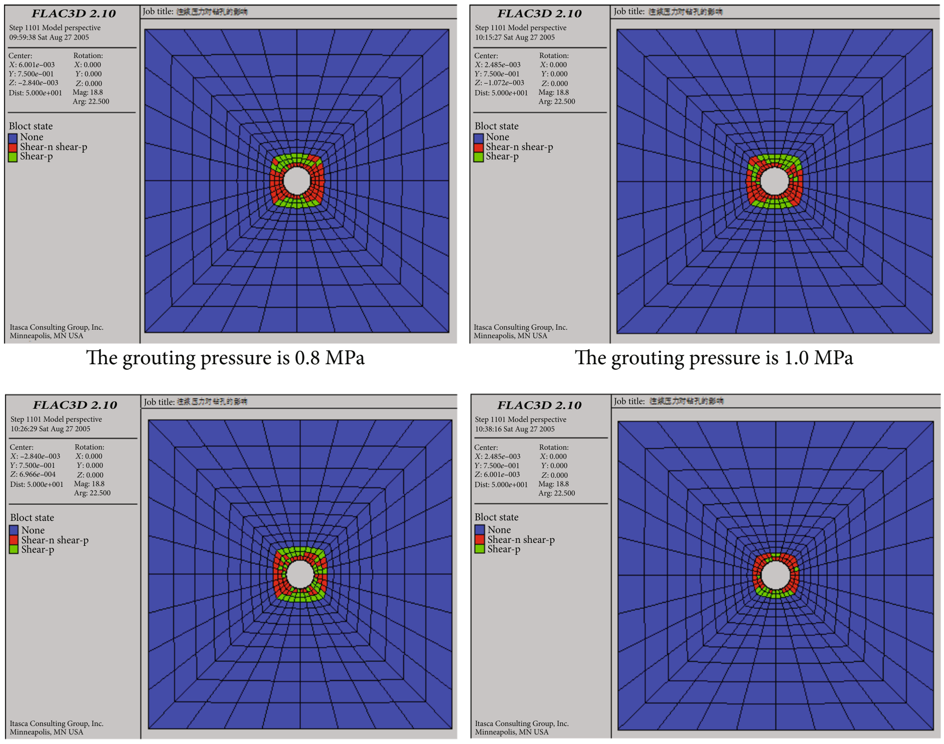
From Figures 3 and 4, it can be seen that with the increase of grouting pressure, the smaller the deformation around the borehole, the more conducive to the stability around the borehole. Due to the limitations of existing equipment and conditions, the maximum grouting pressure used can only reach 1.5 MPa. However, with the further improvement of the sealing device and equipment, the grouting pressure will gradually increase. At the same time, it is inferred that increasing the grouting pressure within a certain range is beneficial to the stability of the periphery of the borehole.

Due to the excavation of the borehole, the original stress balance of the coal body is broken, and the stress in the coal body is redistributed, causing the phenomenon of stress concentration. When the stress value approaches or exceeds the failure strength of the surrounding rock, the coal mass around the borehole will be destroyed. With the intensification of the damage degree of the coal mass, the stress of the coal rock mass is transferred to the deep. In order to control the excessive deformation or instability damage of the coal body around the borehole, and no longer generate new gas leakage channels, the borehole must be supported or dealt with in a timely and effective manner. To achieve a better control effect, a timely and sufficiently large supporting force should be provided to the surrounding rock or the stress state of coal should be changed.

The radius of the coal plastic zone around the borehole and the deformation of the surrounding rock are the main indicators to reflect the stability of the borehole. The larger the radius of the plastic zone, the greater the deformation, the more unstable the roadway, the more cracks generated, and the greater the chance of gas leakage. At present, the more popular method is the foamed polyurethane sealing method, but the strength of the polyurethane is far less than the pressure strength of the coal seam, so it cannot effectively support the drilling and cannot control the deformation of the drilling. The new hole sealing method applies grouting pressure to the periphery of the drilling hole in the early stage, which ensures the stability of the drilling hole in the early stage. At the same time, because the author's self-made cement has good expansiveness, it can exert an active support force in the later stage, interact with the coal body around the borehole, reduce the permeability of the coal seam in the sealing section, and avoid the generation of air leakage channels in the later stage.

3. Development of the Bag-Type Sealing Device

The sealing of underground gas drainage holes in coal mines is divided into permanent sealing and temporary sealing. At present, foamed polyurethane is widely used in the permanent sealing of the coal seam gas drainage drilling holes in China. The early "cement roll sealing device" is no longer used, and the drilling and grouting sealing method is rarely used due to inconvenient operation. Therefore, a new type of sealing device is urgently needed to improve the sealing effect of underground gas drainage holes in coal mines.



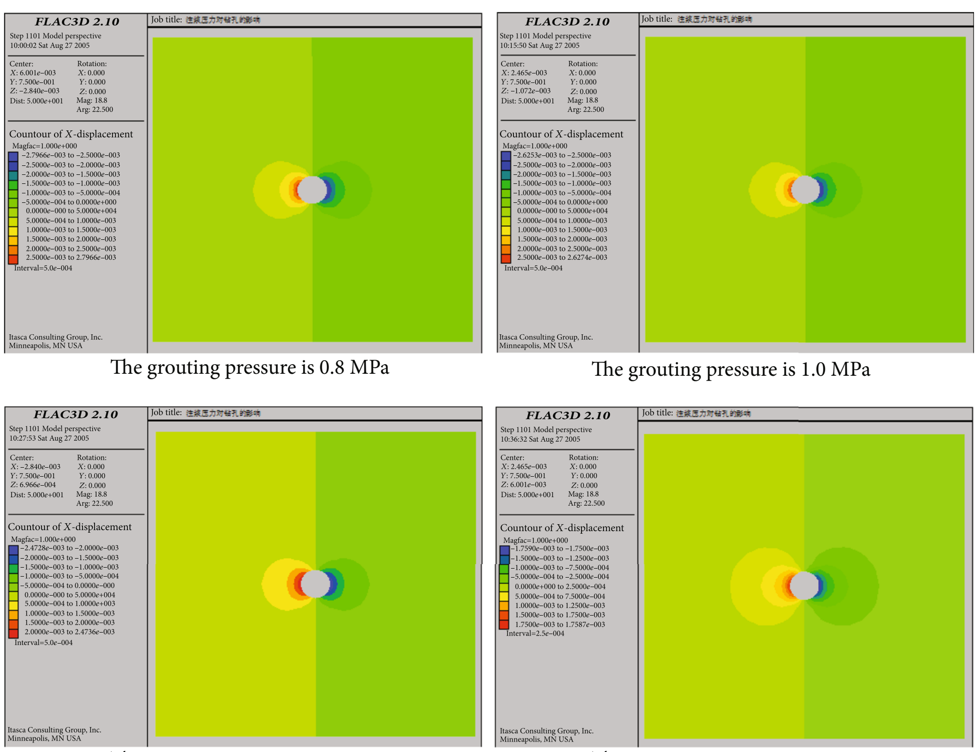
The grouting pressure is 0.8 MPa

The grouting pressure is 1.0 MPa

The grouting pressure is 1.2 MPa

The grouting pressure is 1.5 MPa

FIGURE 2: Distribution map of the plastic zone.



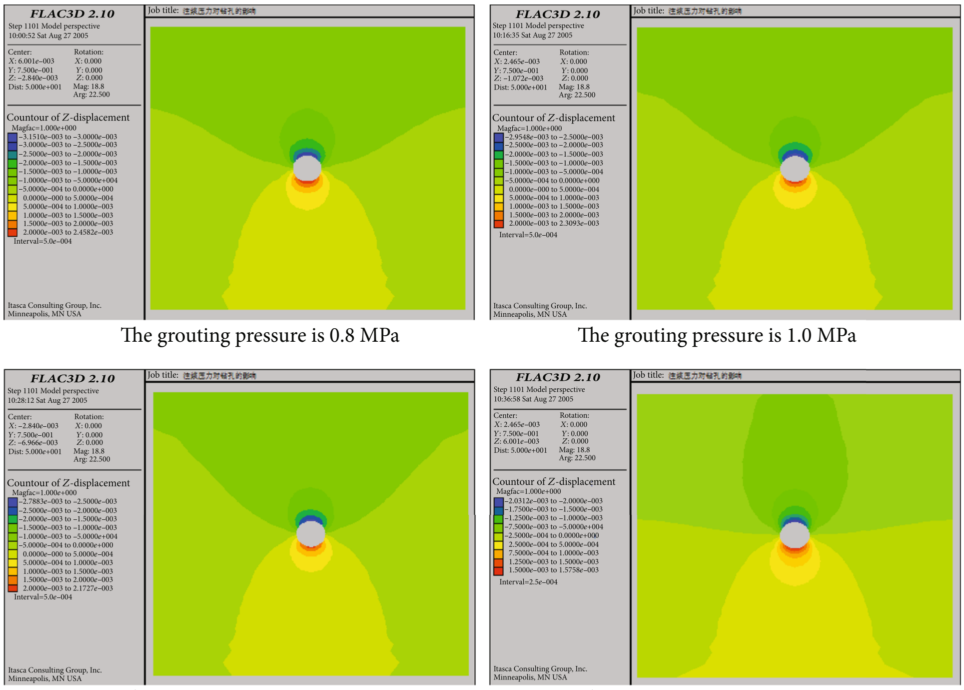
The grouting pressure is 0.8 MPa

The grouting pressure is 1.0 MPa

The grouting pressure is 1.2 MPa

The grouting pressure is 1.5 MPa

FIGURE 3: Displacement distribution in the X direction.



The grouting pressure is 0.8 MPa
The grouting pressure is 1.0 MPa
The grouting pressure is 1.2 MPa
The grouting pressure is 1.5 MPa

FIGURE 4: Displacement distribution in the Z direction.

3.1. Bag-Type Grouting and Sealing Device and Principle. At present, much research on hole sealing technology has been carried out at home and abroad. Australia adopts the "copper pipe grouting and sealing method" to ensure "high negative pressure, high concentration" gas extraction. At present, the more advanced sealing method abroad is the Bimbal expansion hose sealing device series products produced by the French company Petrometalic. In order to improve the sealing effect of gas drainage drilling holes and then realize high negative pressure and high concentration gas drainage, solve the practical problems of gas drainage, and lay a foundation for comprehensive utilization of gas in mining areas. For this reason, the author invented a new type of hole sealing device and method based on the current domestic sealing device and method, that is, "bag-type grouting hole sealing device and hole sealing method", as shown in Figure 5.

At present, there are three main forms of gas leakage in boreholes [30] as follows:

(1) The gas in the borehole leaks out through the pressure relief ring and cracks in the roadway

(2) The gas in the borehole leaks out through the coal in the seal section of the borehole

(3) The gas in the borehole leaks out through the cracks around the borehole and the microcracks between the sealing materials

In theory, the bag-type grouting and sealing device and the method thereof can completely compensate for the above-mentioned three types of gas leakage and increase the gas extraction concentration.

The principle of the bag-type grouting and sealing device and its method is as follows: in the early stage, the self-made grouting cement is filled into the bag-type grouting and sealing device by using a grouting pump. It will be pressed out from the slurry control valve in the middle of the hole sealing device so that the grouting cement will be filled into the cracks around the borehole, and the air leakage channel of the crack formed when the hole is opened will be eliminated, that is, the initial air leakage channel will be eliminated. With the increase of time, the strength of grouting cement is further enhanced. At the same time, the grouting cement has good microexpansion and expands gradually, so that the borehole can be reliably supported and the stability of the borehole can be ensured. Due to the high strength of the cement, the mineral pressure cannot deform the cement column, so that no new cracks and air leakage channels will be created around the borehole. At the same time, the microexpansion of the grouting material is used to exert active strong support on the holes in the sealing section, so that a high-stress area is generated around the holes in the sealing section, and the permeability of the sealing material is improved.

The bag-type grouting and sealing device is composed of a bag, a rear plug, a front plug, middle support, a grouting control valve, and a check valve. A pipe hole is opened on the front plug, and the pipe hole is used to pass through the gas extraction pipe. A sealing device is installed in the pipe hole, and the bag-type hole sealing device is connected with the gas extraction pipe through pins. The pulping control valve is installed on the middle support. The function of the pulping control valve is to control the minimum pulping pressure of the slurry in the bladder bag to the outer pulp of the bladder, so as to ensure that the bladder can be fully expanded and contact the drill before the pulping control

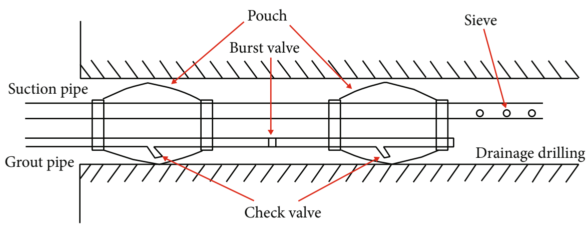


Figure 5: Schematic diagram of the structure of the bag-type grouting device.

valve is discharged. Hole wall. The front plug is provided with a pipe hole and a grouting hole. The pipe hole is used to pierce the extraction pipe. The grouting hole is used to insert the grouting pipe, and a check valve is installed in the grouting hole. The holes are connected by easy-cut grouting pressure control pins. When the grouting pressure reaches the set value, the grouting pressure control pin is automatically cut off, and the grouting pipe is automatically separated from the grouting hole.

3.2. Safety Valve Device and Principle. In the process of grouting and sealing, since the capsule in the grouting device can only withstand a certain pressure, a grouting pressure gauge is installed during the grouting process to prevent the grouting bag from breaking and causing the sealing failure.

During the test, when the pressure gauge was used, the pressure gauge was blocked by cement slurry, which caused damage to the pressure gauge when used for a long time; and it was inconvenient to observe during grouting; therefore, the author made a safety pressure limiting valve to replace the pressure gauge, to facilitate downhole and surface testing.

The safety pressure limiting valve is mainly composed of a valve core, an adjusting nut, a pressure adjusting spring, an O-ring, a sealing gasket, and a valve body, as shown in Figure 6.

The main principle of the safety pressure limiting valve is when the liquid pressure under the safety valve disc exceeds the pressing force of the spring, the disc will be pushed open, and a certain amount of cement slurry will be quickly discharged. Then, when the pressure in the container drops to the allowable value, the valve is automatically closed again, so that the pressure in the container is always lower than the upper limit of the allowable pressure, and the possible device rupture due to overpressure is automatically prevented. The safety valve is also known as the ultimate protection device of the pressure vessel. The force of the spring will overcome the liquid pressure and discharge reaction force acting on the disc, thereby closing the safety valve. The safety valve is used as a part of the hole sealing device. Experiment to increase the pressure in the container to observe whether the equipment is damaged to verify the effectiveness of the safety valve.

3.3. Performance Test of Sealing Device. In order to further study the performance of the new hole sealing device, the author carried out laboratory experiments on each component of the hole sealing device in the laboratory. Mainly through the new sealing device, manual grouting pump, grouting pipe, hard-walled round pipe, and related equipment and materials, the pressure-bearing situation of the device under different grouting pressures are studied. At the same time, the performance of the cooperation and sealing between the components is tested, as shown in Figure 7.

During the test, capsules and cloth sleeves were set up to withstand different grouting pressures, and different grouting pressures were set for the whole device. Since the diameters of the hard-walled pipes are the same, capsules with different pipe diameters are used. According to the previous field research and literature review, we set the grouting pressure to 0.8 MPa, 1.0 MPa, 1.2 MPa, and 1.5 MPa for experiments.

In the more than 100 experiments conducted, the various performances and pressures of the sealing device have been comprehensively understood, which provides a strong guide for the downhole sealing test.

In the experiments on the sealed capsules, various grouting pressures ranging from 0 to 1.6 MPa can be controlled by changing the diameter, thickness, and strength of the capsules and cloth sleeves. This proves that the new sealing device is effective. During the experiment, the failure of the capsule under various pressures was at the connection between the end of the rear plug or the front plug and the capsule, which proved that this was the stress concentration area, which was basically consistent with the initial analysis results. Through continuous experimentation and material replacement, the connection problem here was finally resolved, laying the foundation for the successful and industrial testing of the device. The capsule failure form is shown in Figure 8.

The front plug is one of the parts that are easily damaged, and its damage form is relatively simple. On the whole, it is roughly pulled off from one place, which is expressed as a concentrated stress area. Its damage form is shown in Figure 6. Due to the large grouting pressure, the general grouting pipe cannot withstand the pressure, and it also needs antistatic. At the beginning of the test, because the antistatic antihigh pressure grouting pipe was not used, there was little pipe rupture. However, when the antistatic grouting pipe is used, the cracking phenomenon occurs. Among the 11 pipes in the test, 8 of the grouting pipes are broken when the pressure is 1.6 MPa. However, with the combination of manufacturers, continuous improvement has been carried out, and the problem of grouting pipes has also been solved.

In many experiments of equipment such as grouting pressure safety control valve, when the grouting pressure reaches the set value, the equipment will automatically cut off the grouting pressure safety control valve, and the grouting pipe will automatically separate from the grouting hole. This proves the reliability of the device. When the grouting is finished, place it until the grouting cement is finally set, and then saw it with a chainsaw to see the details of the cement in the pipe. In the initial test, there is a platform on the upper part of the round tube, as shown in Figure 9. After analysis, it was caused by the cement not fully hydrating the remaining water, or the gas in the capsule was not completely discharged. After the analysis, a series of

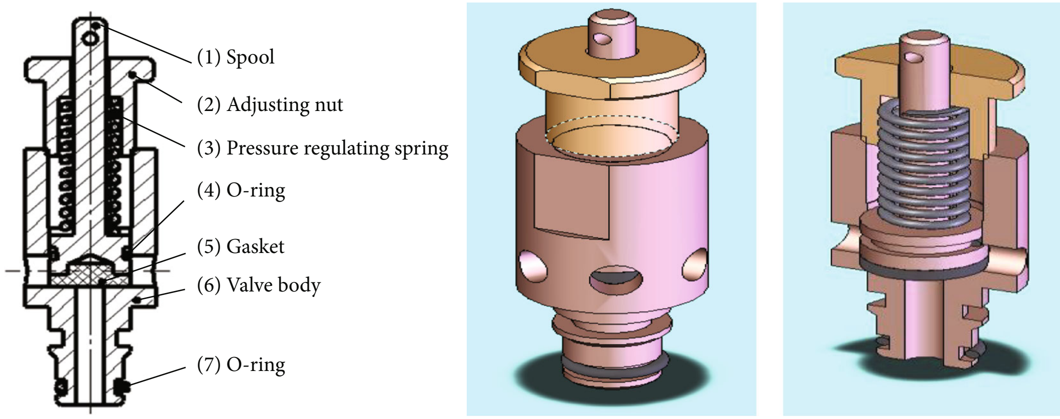


Figure 6: Schematic diagram of the structure of the safety pressure limiting valve.

Figure 7: Test main equipment.

Figure 8: Destruction form of capsule.

measures were taken to ensure that the gas and water that was not fully hydrated could be completely discharged, and the desired effect was achieved, as shown in Figure 10.

4. Development of Modified Cement Sealing Material

When sealing and grouting on-site, the fluidity, setting time, and early strength of grouting materials are the key factors affecting the quality of sealing. In this paper, by exploring the effects of different admixtures and proportions on the fluidity, setting time, and early strength of grouting materials, a reliable sealing grouting material is developed to provide support for on-site sealing construction.

Figure 9: Schematic diagram when the gas and water are not completely discharged.

The raw materials of this experiment are ordinary Portland cement, sulfoaluminate cement, naphthalene-based superplasticizer, high-efficiency expansion agent, retarder, etc. Sulfoaluminate cement has the advantages of early strength, high frost resistance, corrosion resistance, and high penetration resistance. The early-strength grouting cement adopts a composite of sulfoaluminate cement and ordinary Portland cement. Through the optimization of mineral components, it is used as the main component of grouting cement, and then, admixtures such as water-reducing agent and expansion agent are added. The water-cement ratio and different dosages of admixtures are used to prepare grouting cement with early strength, high strength, good injectability, microexpansion, and adjustable setting time.

4.1. Cement Slurry Fluidity Test. By exploring the influence of different dosages of sulfoaluminate cement, water-cement ratio, water-reducing agent, and expansion agent on the fluidity of cement slurry, the optimal cement slurry ratio was selected, and then, grouting for on-site hole sealing provide theoretical support.

The grouting cement needs to maintain good fluidity in the early stage. Once it reaches the setting state, it will quickly lose its fluidity, which is an inevitable characteristic of cement with super early strength. During construction, the proportion of grouting materials must be mastered. Otherwise, the phenomenon of pump blockage and pipe blockage is easy to occur. Due to the relatively high cost of

Horizontal Portrait

FIGURE 10: Schematic diagram when gas and water are completely discharged.

fast-hardening sulfoaluminate cement and its fast setting time, it is not conducive to use. However, on the basis of using composite cement as grouting material, an appropriate amount of fast-hardening sulfoaluminate cement and admixtures can be added to stimulate the activity to meet the requirements of the project. It can also meet its performance requirements on the basis of cost saving.

The fluidity test of the cement slurry uses a flow test die to test its fluidity. The size of the truncated cone die is the inner diameter of the upper part: 360.5 mm, and the inner diameter of the lower part: 610.5 mm. Put the prepared slurry into the truncated cone round mold, level it with a scraper, and immediately lift the truncated cone round mold vertically upwards gently, measure the maximum diameter of the bottom surface of the slurry and the diameter perpendicular to it with a caliper, calculate the average value, and take an integer. Each fluidity test work must be completed within 1 min.

Figure 11 shows the effect of different dosages of sulfoaluminate cement on the fluidity of grouting cement. With the different content of sulfoaluminate cement, its fluidity changes greatly, but the overall fluidity is better. When the content of sulfoaluminate is between 50 and 30%, the fluidity is stable at around 285. When the content of sulfoaluminate is greater than or equal to 50%, the fluidity fluctuates up and down. When the content of sulfoaluminate is less than or equal to 30%, the fluidity also fluctuates greatly, but the fluidity is still above 270 mm, which has little effect on the fluidity.

At the natural temperature of the laboratory, the variation law of fluidity with the amount of superplasticizer is shown in Figure 12. With the increase of the amount of water-reducing agents, the fluidity increases. However, when the content of the superplasticizer reaches more than 1.0%, the fluidity does not increase anymore, and the superplasticizer is precipitated on the surface of the slurry. When the content of the superplasticizer increased, the fluidity increased rapidly, but when it increased to 1.2%, the fluidity decreased with the further increase of the superplasticizer. This shows that the fluidity is not an unlimited increase with the increase of the superplasticizer but has a certain range. At the same time, in the test, when the content of the superplasticizer exceeds 1.0%, the phenomenon of water-reducing occurs.

Figure 13 shows the effect of the water-cement ratio on fluidity at laboratory natural temperature. It can be seen from the figure that the water-cement ratio has a great influence on fluidity. Mobility is positively correlated with the water-cement ratio. It can be seen that the influence of the water-cement ratio on fluidity is regular and stable. With the increase of the water-cement ratio, the fluidity increases.

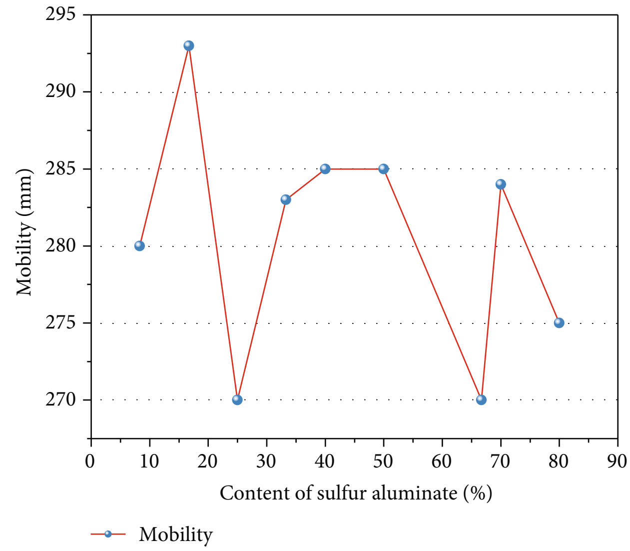


FIGURE 11: Effect of different dosages of sulfoaluminate cement on fluidity.

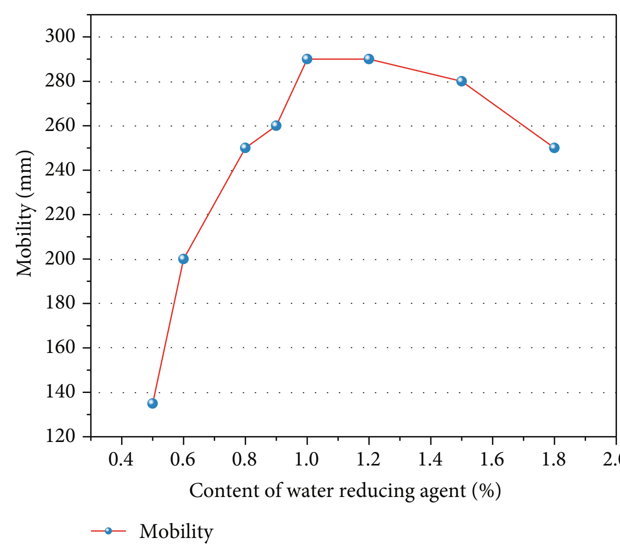


FIGURE 12: Effect of different dosages of superplasticizers on fluidity.

Figure 14 shows the effect of different dosages of borax on the fluidity of grouting cement. With the different content of borax, its fluidity changes greatly, but the overall fluidity is better. When the content of sulfoaluminate is between 0.2 and 0.3%, the fluidity is stable at around 290 and maintains good fluidity.

The appropriate dosage of each component is optimized by conducting experiments on the influence of different dosages of sulfoaluminate cement, water-reducing agent and expansion agent, and different water-cement ratios on the fluidity of cement paste. In addition to the fluidity of the grouting material being a key factor affecting the on-

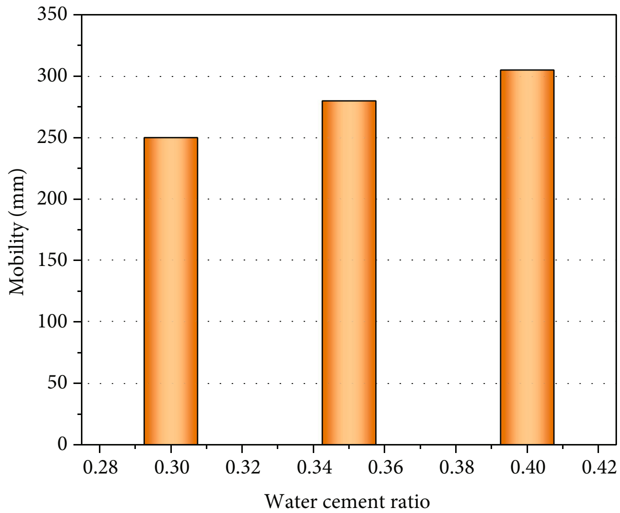


Figure 13: Influence of water-cement ratio on fluidity.

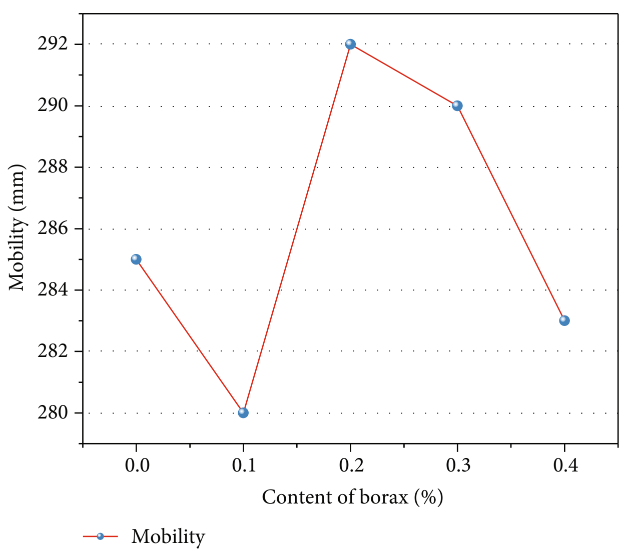


Figure 14: Effect of different dosages of borax on fluidity.

site sealing effect, the setting time of the grouting material also plays an important role in the sealing process.

4.2. Cement Paste Setting Time Test. The setting time of cement is a decisive factor in the cement hardening process. In the absence of admixtures, the setting time of cement determines the speed of cement setting and hardening. If the setting time of the cement is not suitable, the initial setting is too fast, or the final setting is too late, it cannot meet the requirements of hole sealing, which will reduce the workability of the cement. Therefore, in order to ensure that the cement slurry has sufficient time for mixing, transportation, and irrigation, it is necessary to require the cement to have an initial setting time. When the construction is completed, it is hoped that the cement can harden quickly and form early strength as soon as possible, so the cement is required to have a short final setting time.

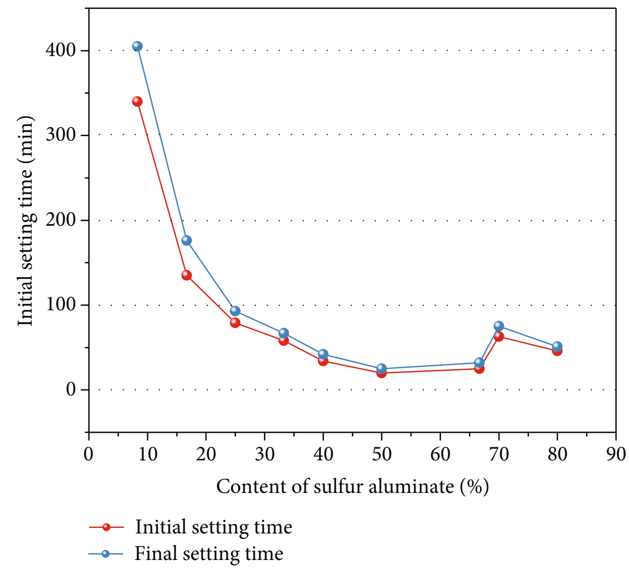


Figure 15: Effects of different dosages of sulfoaluminate cement on setting time.

In this section, by exploring the influence of different dosages of sulfoaluminate cement, water-cement ratio, water-reducing agent, and expansion agent on the setting time of cement slurry, the optimal cement slurry ratio is screened out, and then, it is used for on-site hole sealing. Grouting provides theoretical support. By exploring the range of initial setting time and final setting time of cement, the proportion of cement can be changed according to the needs of the site.

Carry out the setting time test method in GB1346-89 "Water Consumption, Setting Time and Stability Test Method for Standard Consistency of Cement." Prepare the slurry according to the selected water-cement ratio. The prepared slurry is directly injected into the round mold (without vibration), and after being scraped, it is immediately placed on the coagulation time measuring instrument to measure the coagulation time. The time to start adding water was recorded as the initial time for the setting time.

It can be seen from Figure 15 that when the content of sulfoaluminate cement is below 50%, with the increase of the amount of sulfoaluminate cement, the initial setting time and final setting time of cement gradually decrease, and the decrease is very large; when the content of aluminate cement is more than 50%, the initial setting time increases slightly with the increase of sulfoaluminate, but when it increases to more than 70%, there is a decreasing trend. When the content of sulfoaluminate cement exceeds 20%, the difference between the final setting time and the initial setting time is very close. When the content of sulfoaluminate cement is less than 20%, the setting time is prolonged, and the properties of cement slurry are close to those of ordinary Portland cement.

It can be seen from Figure 16 that the water-reducing agent has a significant effect on prolonging the setting time. With the increase of the mass fraction of the superplasticizer, the initial setting time and final setting time of the cement slurry gradually increased. When the mass fraction of the superplasticizer increased from 0.5% to 1.8%, the initial setting time increased from 74 min to 102 min,

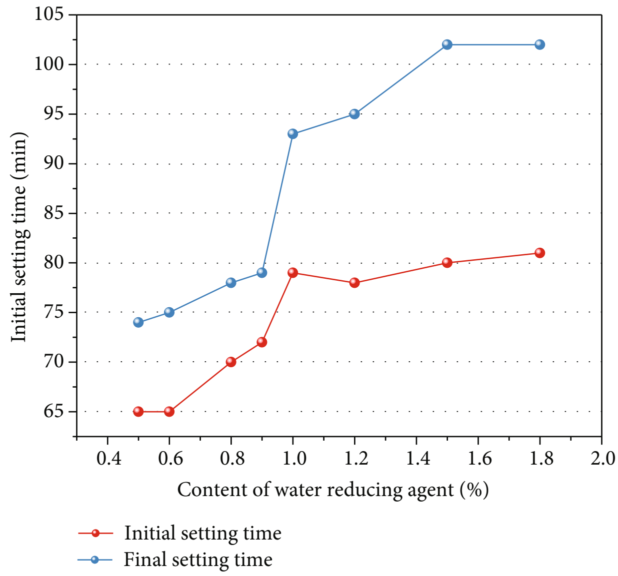


Figure 16: The effect of different dosages of superplasticizer on setting time.

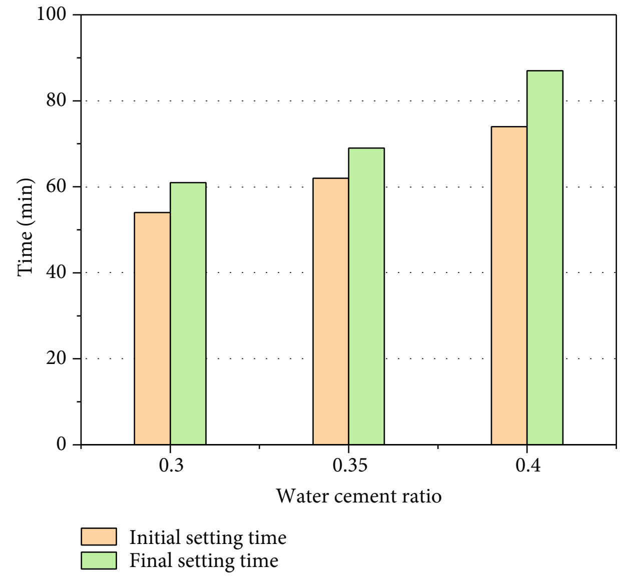


Figure 18: Influence of water-cement ratio on setting time.

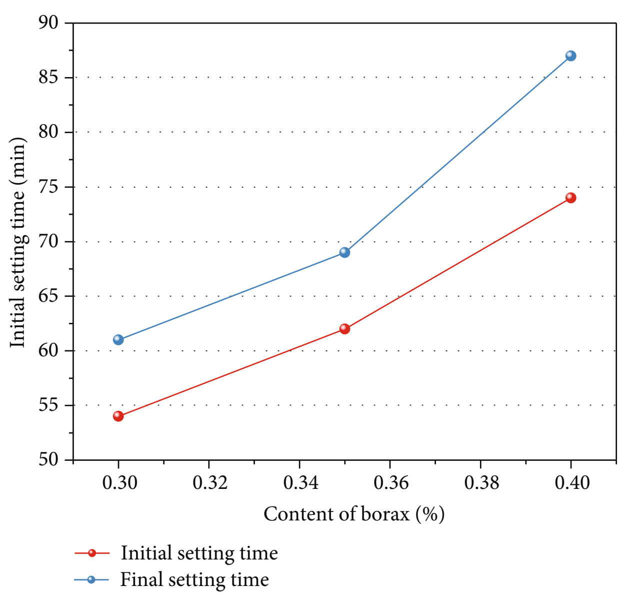


Figure 17: Effect of different dosages of borax on setting time.

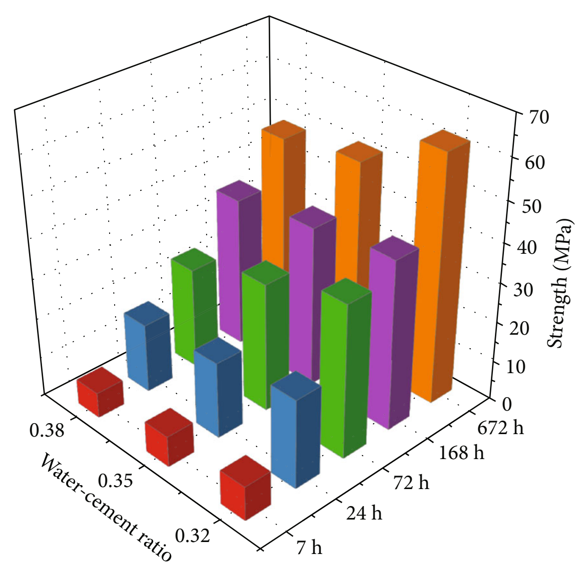


Figure 19: Strength of cement specimen at 28 days.

and the final setting time increased from 74 min to 102 min. The time was increased from 65 min to 81 min. When the mass fraction of the superplasticizer reaches more than 1%, the interval between the initial setting and final setting time increases with the increase of the mass fraction of the superplasticizer.

It can be seen from Figure 17 that borax significantly prolongs the setting time. With the increase of the mass fraction of borax, the initial setting time and final setting time of the cement slurry gradually increased. When the mass fraction of borax increased from 0.0% to 0.4%, the initial setting time increased from 74 minutes to 225 minutes, and the final setting time increased from 77 minutes to 278 min. The retarding effect of borax on the slurry is obvious. Borax has an obvious retarding effect on fluidity. The main reason is that after borax is added to sulfoaluminate water, a layer of small packages is formed on the surface of cement particles, which are the formed calcium borate crystals. Since the formation of the hydration layer wrapped on the surface of the cement particles stabilizes the cement suspension and prevents the cement particles from agglomerating, it can delay the coagulation of the cement. But in the whole stage, the initial setting time and the final setting time interval changed little.

It can be seen from Figure 18 that the water-cement ratio significantly prolongs the setting time. With the increase of the water-cement ratio, the initial setting time and final setting time of cement slurry gradually increased. When

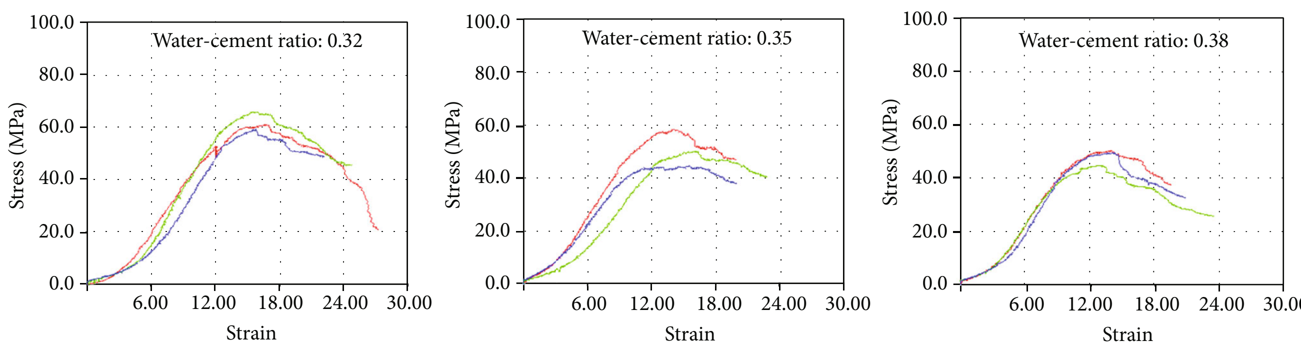


Figure 20: Uniaxial compressive stress-strain curve of new-type sealing cement.

the water-cement ratio increased from 0.3 to 0.4, the initial setting time increased from 54 min to 73 min, and the final setting time increased from 65 min to 87 min. It is very limited to increase the setting time of cement only by increasing the water-cement ratio. The excessive water-cement ratio will cause the settlement of cement slurry, poor thickening performance, slow development of compressive strength, and performance indicators that do not meet the requirements. The hole quality is difficult to guarantee.

4.3. Properties of Cement Stone after Hardening. From Sections 4.1 and 4.2, the effects of different dosages of sulfoaluminate cement, water-cement ratio, water-reducing agent, and expansion agent on the fluidity and setting time of cement are discussed. Referring to the first principle of the fluidity of on-site sealing materials, the corresponding ratio of each material is optimized, and the mechanical strength test of cement stone is carried out. The mechanical strength of the new sealing cement stone was explored compared with the mechanical strength of the traditional foamed polyurethane sealing material.

According to the cement strength test standard, the cement was poured into a test block with a size of 70.7 mm × 70.7 mm × 70.7 mm. Under natural curing conditions, the strength of 7 h, 24 h, 3 d, 7 d, and 28 d was measured. The strength test of cement is carried out according to the "Cement Mortar Strength Test Method." The DZE-300B flexural and compressive testing machine produced by Wuxi Shuangniu Building Materials Equipment Factory was used.

It can be seen from Figure 19 that the cement strength decreases with the increase of the water-cement ratio. It can be seen from Figures 20 and 21 that the uniaxial compressive strength of polyurethane is only 0.143 MPa, while the minimum strength of the cement specimen for 28 days is 48.02 MPa, which is far greater than that of polyurethane. Because the strength of the cement sample is relatively high, it can resist the deformation of the drilling hole and reduce the deformation of the drilling hole. At the same time, the new grouting material developed in this paper has good fluidity and microexpansion and can enter into the cracks of the drilled hole and then plug it. This prevents the borehole from generating leakage channels due to deformation around the borehole so that the borehole is stabilized and the gas drainage concentration can be increased. However, polyurethane has very little strength and cannot guarantee

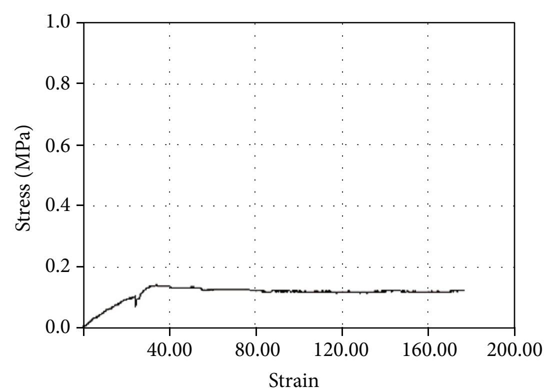


Figure 21: Uniaxial compressive stress-strain curve of foamed polyurethane.

the stability of drilling holes, so a gas leakage channel is generated and the gas drainage concentration is reduced.

5. Field Application

5.1. Test Overview. The field test is located in the 3209 roadway of the Chengzhuang Mine of Jinmei Group, with a roadway depth of 300-350 m. After the drilling is completed, the sealing arrangement begins. A comparative test is carried out in the transport lane of 3209 working face. There is a comparison of the sealing effect of the current sealing method and the new sealing method on the mine. In the newly drilled holes, every ten holes are rotated, and then, the gas concentration test is carried out by a gas analyzer.

A total of 20 holes were sealed in the test. Drill holes No. 452 to 461 (except No. 455) and No. 474 to 484 used new sealing grouting materials, and holes No. 455 and No. 462 to 473 were the current polyurethane sealing holes. The authors randomly selected 9 groups of data. For the hole sealing using the new sealing grouting material, HSY, JSY, and BSY are used instead due to different sealing methods. Three types of sealing methods are selected for each model, while the mine only adopts one method of polyurethane sealing, which is represented by XX, and then makes an overall comparison of the average value. The effectiveness of grouting and sealing materials was measured by comparing the proportion and change of the average concentration of gas drainage in each group.

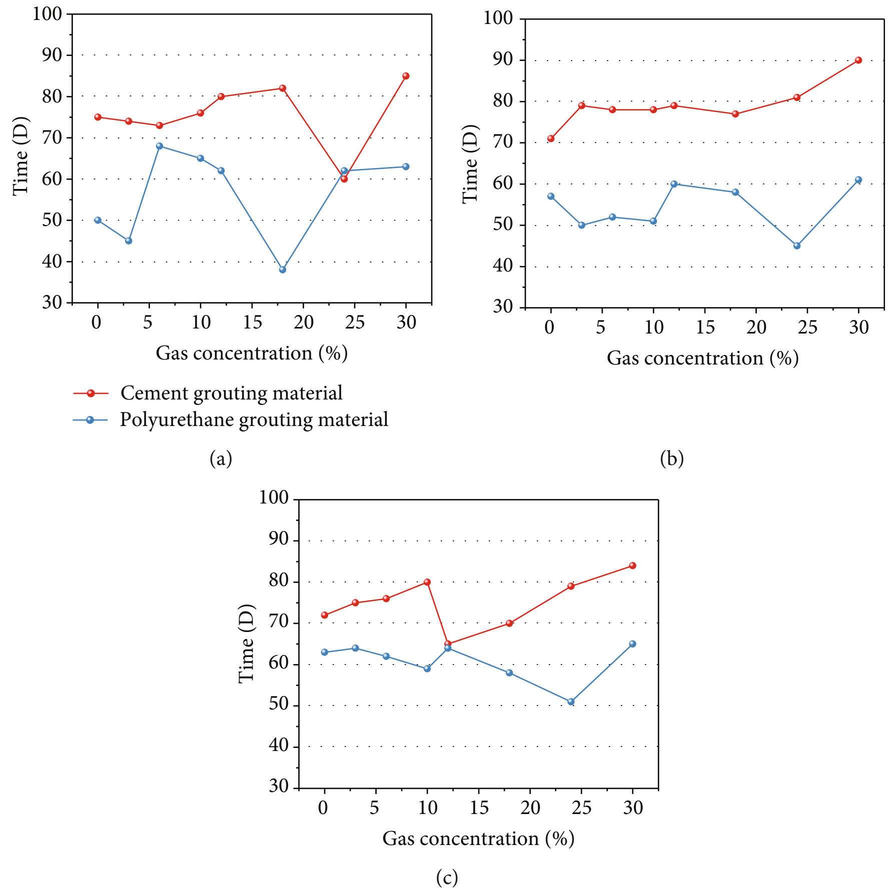


Figure 22: (a) The first group, (b) the second group, and (c) the third group: the comparison of the average concentration of gas drainage.

5.2. Data Testing and Comparative Analysis. Analysis of the measurement data of one month in the field. The sampling data is shown in Figure 22. The comparison of the three sets of data shows that the gas drainage concentration of the three methods of cement grouting and sealing is higher than that of the polyurethane sealing. A total of 71 data were measured for sealing with the new sealing grouting material, and 72 data were measured for the mine-side polyurethane sealing. Among them, the concentration distribution of cement grouting and sealing gas drainage is 3 holes above 90%, 26 holes between 80% and 89%, 30 holes between 70% and 79%, and 10 holes between 60% and 69%. One hole and 2 holes below 60% account for 4.2%, 36.62%, 42.25%, 14.08%, and 2.81% of the total number of holes, respectively. The concentration distribution of urethane sealing gas drainage is 1 hole above 90%, 8 holes between 80% and 89%, 13 holes between 70% and 79%, and 12 holes between 60% and 69%. 38 holes below 60% account for 1.39%, 11.11%, 18.06%, 16.7%, and 52.78% of the total number of holes, respectively. It can be seen that the gas drainage concentration of cement grouting sealing holes is generally high, and the drilling holes with a concentration of more than 70% account for more than 83% of the total drilling holes. However, the gas concentration of polyurethane sealing holes is generally low. The drilling holes with a concentration of more than 70% only account for 30% of the total drilling holes, while the concentration of less than 60% exceeds 50%. The above shows that the cement grouting sealing has achieved a good sealing effect.

From the analysis of the above figure, it can be seen that the polyurethane sealing hole also has relatively high data and the concentration of No. XX469 hole is also high, and the single hole concentration is up to 94%. High, the pore-forming effect is better, so the concentration of individual pores may be higher. But the concentration of more than 50% of its pores is below 60%. The grouting and sealing with the new sealing grouting material also have some cases where the extraction concentration is low. The reasons are analyzed: the operator's level of operation and the use of optical gas measuring instrument are the reasons for the error; the drainage hole contains a certain amount of water, the perforation in the roadway, the crack of the anchor cable, and so on. It can be seen that when the new type of bag-type grouting method is used to seal the hole, the gas drainage concentration tends to increase as a whole with the increase of time, which shows that the expansion of the expansion cement grouting maintains the stability of the drilling hole, which is beneficial to increase in the concentration of extracted gas.

6. Conclusions

In view of the problems existing in gas drainage drilling and sealing, a new type of bag-type grouting sealing device and safety pressure limiting valve is developed in this paper. At the same time, a sealing material with high fluidity, good injectability, and good microexpansion has been developed. Finally, the feasibility of this sealing method is clarified in combination with the field industrial test.

(1) It is proved theoretically that the bag-type grouting and sealing method can apply support force to the borehole during the support process, which can ensure the stability of the borehole and improve the gas drainage rate. The reasons for air leakage in the borehole are analyzed, and the new type of bag-type grouting sealing method provides an active support force for the borehole in the early stage of sealing so that there will be no large deformation around the borehole, and the hole is maintained. Drilling stability. With the increase of grouting pressure, the plastic zone and deformation around the borehole decrease continuously. From this, it can be inferred that increasing the grouting pressure within a certain range will be beneficial to the stability of the borehole

(2) A new type of bag-type sealing device and safety pressure limiting valve was developed, and their principles were studied: on the one hand, the slurry was used to fill the cracks around the hole in the sealing section. On the other hand, the microexpansion of the grouting material is used to exert active strong support on the drilling in the sealing section and reduce the permeability of the coal body around the drilling in the sealing section. At the same time, fast-hardening sulfoaluminate cement and ordinary Portland cement are used for compounding, and their activity is stimulated by adding an appropriate amount of admixture to prepare grouting with high fluidity, early strength, good injectability, and good microexpansion. Cement. It provides theoretical support for the preparation of on-site grouting and sealing materials

(3) Through the comparison of industrial experiments, it is proved that the gas drainage concentration of the sealed hole using the new cement grouting method is higher than that of the current polyurethane sealing hole. The gas drainage concentration of the new type of cement grouting sealing is above 60%, accounting for 97% of the total number of holes, while the gas drainage concentration of the polyurethane sealing hole is more than 60%, accounting for 47% of the total number of holes. It shows that the new type of cement grouting has a good drainage effect. The concentration data proves that the new type of cement grouting can maintain the stability of the borehole, can avoid air leakage around the borehole, and is conducive to gas drainage

Data Availability

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

Conflicts of Interest

The authors declare that they have no conflicts of interest in this work. We declare that we do not have any commercial or associated interests that represent conflicts of interest in connection with the work submitted.

Acknowledgments

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References

[1] D. H. Diering, "Ultra-deep level mining future requirements," *Journal of the South African Institute of Mining and Metallurgy*, vol. 97, no. 6, pp. 249–255, 1997.

[2] M. C. He, H. P. Xie, S. P. Peng et al., "Study on deep mining rock mechanics and engineering disaster control," *Coal Mine Support*, vol. 30, no. 6, pp. 47-48, 2007.

[3] Z. M. Zhang and Y. G. Zhang, "Investigation into coal gas outburst occurred in Daping coal mine by using theories of gas-geology," *Journal of China Coal Society*, vol. 30, no. 2, pp. 137–140, 2005.

[4] L. Wang, Y. P. Cheng, F. R. Li, H. F. Wang, and H. B. Liu, "Fracture evolution and pressure relief gas drainage from distant protected coal seams under an extremely thick key stratum," *Journal of Coal Science & Engineering (China)*, vol. 18, no. 2, pp. 182–186, 2008.

[5] Y. L. Chen, J. P. Zuo, D. J. Liu, Y. J. Li, and Z. B. Wang, "Experimental and numerical study of coal-rock bimaterial composite bodies under triaxial compression," *International Journal of Coal Scencei & Technology*, vol. 8, no. 5, pp. 908–924, 2021.

[6] K. Noack, "Control of gas emissions in underground coal mines," *International Journal of Coal Geology*, vol. 35, no. 1-4, pp. 57–82, 1998.

[7] Q. L. Zou, H. Liu, Y. J. Zhang, Q. M. Li, J. W. Fu, and Q. T. Hu, "Rationality evaluation of production deployment of outburst-prone coal mines: a case study of Nantong coal mine in Chongqing, China," *Safety Science*, vol. 122, article 104515, 2020.

[8] X. Wang, Z. M. Xu, Y. J. Sun, J. M. Zheng, C. H. Zhang, and Z. W. Duan, "Construction of multi-factor identification model for real-time monitoring and early warning of mine water inrush," *International Journal of Mining Science & Technology*, vol. 31, no. 5, pp. 853–866, 2021.

[9] M. Colwell and R. Frith, "Utilising the scientific method to demonstrate that slender beam/column behaviour is the dominant behavioural mechanism leading to roof/rib failure,"

International Journal of Mining Science and Technology, vol. 31, no. 5, pp. 867–887, 2021.

[10] Z. H. Le, Q. L. Yu, W. C. Zhu, H. Y. Liu, and T. H. Yang, "Experimental study on the effect of granular backfill with various gradations on the mechanical behavior of rock," *International Journal of Mining Science & Technology*, vol. 31, no. 5, pp. 889–899, 2021.

[11] B. Q. Lin and X. Q. He, "Coal permeability and its affect to coal and gas outburst," *Coal Science and Technology*, vol. 19, no. 4, pp. 50–53, 1991.

[12] H. X. Zhou, Y. P. Cheng, and H. Y. Liu, "Permeability improvement technology of array crossing boreholes and its application in outburst coal seam," *Journal of China Coal Society*, vol. 36, no. 9, pp. 1515–1518, 2011.

[13] Y. B. Yao, D. M. Liu, W. H. Huang, and D. Z. T. S. H. Tang, "Research on the pore-fractures system properties of coal bed methane reservoirs and recovery in Huainan and Huaibei coal-fields," *Journal of China Coal Society*, vol. 31, no. 2, pp. 163–168, 2006.

[14] B. Q. Lin, H. J. Wu, L. J. Zhang, H. L. Lu, H. B. Zhang, and F. W. Meng, "Integrative outburst prevention technique of high pressure jet of abrasive drillings lotting," *Procedia Earth and Planetary Science*, vol. 1, no. 1, pp. 27–34, 2009.

[15] B. Q. Lin, Y. C. Lv, B. Y. Li, and Z. Cheng, "High pressure abrasive hydraulic cutting seam technology and its application in outbursts prevention," *Journal of China Coal Society*, vol. 32, no. 9, pp. 959–963, 2007.

[16] Q. L. Zou, B. Q. Lin, C. S. Zheng et al., "Novel integrated techniques of drilling-slotting-separation-sealing for enhanced coal bed methane recovery in underground coal mines," *Journal of Natural Gas Science and Engineering*, vol. 26, pp. 960–973, 2015.

[17] L. Z. Jin, *Mine Dust Control*, Coal Industry Press, Beijing, 1993.

[18] T. G. Zhang, *Mine Gas Comprehensive Control Technology*, Coal Industry Press, Beijing, 2001.

[19] S. S. Hu, B. S. Li, and X. Y. Liu, *Application of High Technology in Coal Mines*, China University of Mining and Technology Press, Xuzhou, 1996.

[20] J. Chen, *Research and application of sealing technology in mine safety production, [M.S. thesis]*, University of Science and Technology Beijing, Beijing, 2004.

[21] D. J. Xue, L. L. Lu, J. Zhou, L. Lu, and Y. T. Liu, "Cluster modeling of the short-range correlation of acoustically emitted scattering signals," *International Journal of Coal & Science Technology*, vol. 8, no. 4, pp. 575–589, 2021.

[22] H. C. Zhou, *Research on the stability of boreholes in gas drainage and sealing section, [M.S. thesis]*, Henan University of Technology, Jiaozuo, 2006.

[23] Z. Y. Ye, *Mine Dust Control*, China University of Mining and Technology Press, Xuzhou, 1991.

[24] L. Yuan, *Theory and Technology of Gas Drainage in Soft and Low Permeability Coal Seam Group*, Coal Industry Press, Beijing, 2004.

[25] Q. L. Zou, T. C. Zhang, Z. H. Cheng, Z. B. Jiang, and S. X. Tian, "A method for selection rationality evaluation of the first-mining seam in multi-seam mining," *Geomechanics and Geophysics for Geo-Energy and Geo-Resources*, vol. 8, no. 1, p. 17, 2022.

[26] B. F. Yu and Y. A. Wang, *Technical Manual for Mine Gas Disaster Prevention and Utilization*, Coal Industry Press, Beijing, 2000.

[27] Y. P. Cheng, J. H. Fu, and Q. X. Yu, "Development of gas extraction technology in coal mines of China," *Journal of Mining & Safety Engineering*, vol. 26, no. 2, pp. 127–139, 2009.

[28] Q. L. Zou, H. Liu, Z. B. Jiang, and X. A. Wu, "Gas flow laws in coal subjected to hydraulic slotting and a prediction model for its permeability-enhancing effect," in *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, Taylor & Francis, 2021.

[29] S. N. Zhou and B. Q. Lin, *Coal Seam Gas Occurrence and Flow Theory*, Coal Industry Press, Beijing, 1997.

[30] M. Piotr, N. Zbigniew, and B. Tafida, "A statistical analysis of geomechanical data and its effect on rock mass numerical modeling: a case study," *International Journal of Coal & Science Technology*, vol. 8, no. 2, pp. 312–323, 2021.