Development of Cement-Based Grouting Material for Reinforcing Narrow Coal Pillars and Engineering Applications

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Abstract: The problem needs to be solved about stability control of small coal pillars along goaf in the coal mining process. In this paper, the effects of water reducer, accelerator and expansion agent on the fluidity, setting time, expansion ratio and stone body strength of grouting materials were analyzed through orthogonal experiments, and the optimal ratio of grouting materials was obtained, and it is applied to the engineering site to obtain the reinforcement effect of the coal pillar grouting material on the coal pillar. The results of the study show that: When the dosage of the accelerating agent is 4%, the amount of water-reducer is 0.3%, and the amount of the expansive agent is 6%, the comprehensive performance of the grouting material is the best. After using the new coal pillar grouting material to strengthen the coal pillars, 30 days of monitoring were conducted to determine the deformation of the surrounding rock of the roadway. The shallow separation layer of the surrounding rock of the roadway was about 39.6~52.5 mm, and the accumulated separation layer of the deep rock was 28.5~29.5 mm, which were kept within the safe control range. The coal pillar grouting material can well fill the surrounding rock fissures and coupling and cement the broken rock mass, improve the bearing capacity of the narrow coal pillar, and enhance the overall stability of the surrounding rock of the roadway. The research results have important reference significance for similar coal pillar grouting.

Keywords: grouting material; orthogonal test; roadway support; setting time; expansion

1. Introduction

Coal resources are non-renewable fossil fuels, and more and more people pay attention to rational development. Traditional technology produces a great waste of resources by setting wide coal pillars [1,2]. The reserved coal pillar is the key technology to replace the working face in the process of coal mining. As the key bearing factor of the stability of the surrounding rock of the goaf, the coal pillar should not only bear the external load and isolate the goaf but also protect the goaf [3–5]. The stability and integrity of the coal pillar directly affect the distribution of surrounding rock pressure and the quality of the support system of a new goaf roadway and directly affect the mine’s production safety [6–9]. As is known to all, the coal pillar is subjected to the disturbance of mining in the upper working face, and its internal integrity may be partially destroyed, resulting in many fissures [10–12]. The water and gas inside the goaf may penetrate into the coal pillar fissures and cause
secondary damage to the damaged coal pillar. Therefore, it is very necessary to protect and repair the coal pillar [13,14].

With the development of grouting technology, the use of grouting to seal the cracks in the coal rock mass is applied in the coal mine production process, and its construction process is simple, easy to operate, low cost and has a remarkable effect. Grouting reinforcement is a technology to consolidate loose crushing surrounding rock, improve the quality of surrounding rock, increase the bearing capacity of surrounding rocks; the slurry can penetrate into the crushing area and fracture the surrounding rock and cement the surrounding coal rock mass during the solidification process. Through this method, loose surrounding rock can be repaired effectively, and the grouting effect depends on not only the grouting process but also the grouting material is particularly critical [15–18]. Traditional grouting materials are difficult to control in terms of the coordination between fluidity and strength and cannot meet the requirements of coal pillar grouting [19–22]. Some scholars have modified the ultra-fine cement and grouted the problem of large mining and high working surfaces, and the effect is remarkable [23–25]. Some scholars have reinforced the coal pillar of the mining roadway by grouting to reduce the deformation of the surrounding rock [26,27]. There are two types of grouting materials: organic and inorganic. Most of the organic grouting materials are organic polymers, some of the toxicity will pollute the water source, the cost is high, and its components will generate a lot of heat when they react, which may cause hidden natural dangers in coal bodies, so the development of inorganic grouting materials has broad application prospects [28,29].

Most of the inorganic grouting materials are ordinary cement-based materials, but their volume shrinks and micro-cracks are generated during service, resulting in poor grouting and compaction, affecting the stability and durability of the system. In addition, ordinary cementitious grouting materials have the disadvantages of low early strength, solidification time and fluidity are greatly affected by the water-to-ash ratio. Among the various indicators of grouting materials, improving slurry fluidity, early strength, and micro-expansion are the most critical [30–32]. Some scholars have studied the expansion of grouting material pairs and verified the good effect of expanded grouting materials [33–35]. Some scholars have studied the problems of dry shrinkage, water evolution, poor fluidity and poor strength of cemented coal rock mass of cement slurry [36,37]. In order to achieve engineering adaptability. The improved early strength of grouting materials is necessary, and the accelerating agent is an important material to achieve rapid condensation hardening of the grouting material, which contains chemical substances that affect the hydration rate of the cement, which can effectively reduce the condensation time of the grouting material, promote the formation of numerous prismatic AFt crystals and overlap on the surface of cement particles, and promote the rapid condensation of cement to improve the development rate of early strength [38,39]. Since the 32.38 boring working surface is affected by back-mining disturbance and some areas may be eroded by old kiln water, the degree of surrounding rock damage is further aggravated, and internal fractures are developed. It is necessary to develop a new kind of mining coal pillar grouting material as a means of improving the rock conditions around it. The new grouting material needs to have the following characteristics: Firstly, injectability: the particle size of the grouting material must be kept small, and it can penetrate into the crack to improve the grouting quality; Secondly, rapid coagulation: the solidification time of the grouting material determines the strength improvement speed, considering the rapid construction speed of the roadway excavation, the new grouting material is required to improve the surrounding rock strength in time; and thirdly, micro-expansion: the slurry is subjected to expansion stress during the condensation process, and the slurry spreads to the fissure of the coal rock mass for compression and sealing. Grouting can effectively improve the coal rock mass’s mechanical characteristics, improve the integrity and bearing capacity of the surrounding rock structure, and provide a focus foundation for the support body. Therefore, the admixture is studied in different dosage tests to obtain the optimal dosage and improve the engineering applicability of the new material.
In this paper, the foundation material was ultra-fine cement, and a water-reducer, accelerating agent and expansive agent were added to prepare a new grouting material. We analyze the slurry fluidity, setting time, and mechanical properties and verify the reinforcement applicability of the material through laboratory tests and engineering applications. As a result, the bearing capacity of the coal rock mass is increased during the tunnel excavation process, and the safety of the roadway is guaranteed. The research results have guiding significance for construction and production under other similar engineering conditions.

2. Materials and Methods

2.1. Test Raw Materials

Ultrafine cement: the strength grade is 425 cement, the specific surface area is 630 m²/kg, the fluidity is 230 mm, the median particle size D₅₀ is 10.2 µm, the initial coagulation time is 130 min, and the final coagulation time is 235 min. Its composition is shown in Table 1. and test raw materials are shown in Figure 1.

Table 1. Mineral composition of superfine cement.

| Loss  | MgO | Al₂O₃ | SO₂  | CaO   | Fe₂O₃ | C₃S   | C₃A   | Others |
|-------|-----|-------|------|-------|-------|-------|-------|--------|
| 0.33  | 3.10| 5.57  | 22.52| 31.09 | 3.82  | 28.72 | 2.35  | 2.05   |

Figure 1. Test raw materials (a) Mineral microstructure of superfine cement samples; (b) Particle size distribution of superfine cement; (c) Accelerating agent sample; (d) Water reducer samples.

525 ordinary Portland cement: basic physical properties of the strength level of 525 are shown in Table 2.

Table 2. Basic physical properties of strength level of 52.5.

| Strength Level | Specific Surface Area (m²/kg) | Setting Time (min) | Final Setting Time (min) | Compressive Strength (MPa) | Flexural Strength (MPa) |
|----------------|------------------------------|-------------------|-------------------------|---------------------------|------------------------|
| 52.5           | 385                          | 115               | 180                     | 32(3d)                    | 6.1(3d)                |

Accelerating agent: J85 type rapid-setting agent, powder with a fast-coagulation and fast-hard effect on cement materials and quickly improves the strength of the material after initial coagulation, which has strong adaptability to cement-based materials and good anti-seepage performance.
Water reducer: white powder solid, bulk density 610 kg/m, PH value is 5.5, water loss rate 30.5%, chloride ion content 0.01%, sodium sulfate content 0.24%, total alkali content 0.30%, and no rust on steel bars.

Expanding agent: mainly based on aluminate sulfate, magnesium oxide content of 29%, the total alkali amount of 4.0%, with the purpose of crack resistance, anti-seepage, waterproof, reduces the water excretion rate, and increases the material and ease.

2.2. Raw Material Ratio

Optimize the composition ratio of grouting materials according to the design, fix the amount of ultra-fine cementitious clinker, and mix the material according to the water-ash ratio of 0.75:1. A 3-factor, 3-level orthogonal test was designed by varying the amounts of water reducers, accelerating agents, and expanding agents. The design expanding agent dosage, accelerator agent dosage and water reducer dosage are factors I, II and III. The test is designed according to the ordinary cement slurry mix ratio method, and the orthogonal test method is used for testing. The orthogonal test scheme is shown in Table 3.

Table 3. Orthogonal test scheme.

| Group | Expanding Agent/% | Accelerating Agent/% | Water-Reducer/% |
|-------|-------------------|----------------------|----------------|
| 1     | 4                 | 2                    | 0.1            |
| 2     | 4                 | 4                    | 0.2            |
| 3     | 4                 | 6                    | 0.3            |
| 4     | 6                 | 4                    | 0.2            |
| 5     | 6                 | 4                    | 0.3            |
| 6     | 6                 | 6                    | 0.1            |
| 7     | 8                 | 2                    | 0.3            |
| 8     | 8                 | 4                    | 0.1            |
| 9     | 8                 | 6                    | 0.2            |

2.3. Test Methods

The grouting is used to repair the loose, broken coal pillar, which requires that the grouting material not only has the characteristics of flow performance, fast setting, early high strength of the stone body and micro expansion performance. The orthogonal test method could realize multi-level and multi-factor interaction analysis. In this study, the fluidity, setting time, limiting expansion force and uniaxial compressive strength of slurry at different ages were studied by test. The test apparatus is displayed in Figure 2.

Figure 2. Test instruments and items.
Slurry fluidity test: According to GB 50119-2013 “Concrete Admixture Homogeneity Test Method,” the cement pure slurry fluidity is tested by a truncated cone with a diameter of 36 mm, a diameter of 60 mm at the lower mouth and a height of 60 mm.

Setting time test: The GB/T1346-2011 test standard “Cement standard consistency, water consumption, coagulation time, stability test method,” the Vicat instrument is used to test the slurry coagulation time.

Expansion test: The expansion of stones is tested according to the provisions of GB 23439-2009 “Expansive agents for concrete.”

Strength test: The samples of 70.7 mm × 70.7 mm × 70.7 mm were prepared and cured for 24 h before demoulding. Then, the compressive strength test was carried out according to the designed age of the test.

3. Results

3.1. Fluidity of Slurry

The initial fluidity of net slurry with different modifier content is shown in Figure 3. From the test data, It can be observed that as the amount of water reducer increases, consequently, the fluidity of the slurry, the amount of water reducer is increased from 0.1% to 0.3%, the flow degree increased from 136 mm to 230 mm, and the flow degree is increased by 94 mm; The expansive agent is increased from 4% to 8%, the flow degree increased from 150 mm to 183 mm, and the flow rate is increased by 33 mm; The dosage of the accelerator agent was increased from 2% to 6%, and the flow rate is reduced by 28 mm. It is clear from the test results that the largest combination of slurry flow rate is $I_{K1}II_{K3}III_{K3}$. The reason is that the incorporation of the superplastic reducer reduces the surface tension of the flocculent structure of the hydration product. Consequently, the breakout energy necessary for particle dispersion is reduced. The cement particles’ same-sex charge and ionization of the hydrophilic group result in an electrical repulsion, which promotes the release of free water, produces a water-reducing lubrication effect, and the fluidity of the slurry decreases with the addition of accelerator agents. Due to the addition of the expanding agent, the cementitious and the expanding agent simultaneously have a water competition phenomenon in the hydration process, which causes a negative effect on the fluidity. The accelerator agent is used mainly to accelerate the hydration reaction of the slurry and promote the development of the early strength of the stone body, so it has an inhibitory effect on the flow of the slurry.

![Figure 3. Test results of fluidity under different factors.](image)

3.2. Setting Time of the Slurry

The slurry solidification time under different modifier dosages is shown in Figure 4. The condensation time determines the speed of the strength improvement of the grouting material, which is an important indicator in the grouting process, and the condensation time should make sure the slurry can fully spread and that it satisfies the requirements of the grouting construction activity. The experimental results demonstrate that with an
increase in the amount of accelerator agent, the coagulation time is gradually shortened. The accelerator agent was raised from 2% to 6%, and the coagulation time was reduced by 71 mins; The water reducer increased from 0.1% to 0.3%, and the slurry coagulation time increased by 9 mins; The expanding agent was increased from 4% to 8%, and the coagulation time is reduced by 8 mins. The degree of influence of the coagulation time: accelerator agent > water reducer > expanding agent. It is evident from the test findings that the largest combination of slurry flow is I\(_K1\)II\(_K3\)III\(_K1\). The amount of accelerator agent mixing plays a pivotal role in the coagulation time of the slurry. When the amount of accelerator agent being mixed rises, the slurry coagulation time is greatly reduced, and the accelerator agent has a noticeable effect; The initial coagulation time of the slurry is less affected by the dosage of the water reducer and expanding agent.

![Figure 4](image.png)

**Figure 4.** Test results of setting time under different factors.

3.3. **Swelling of the Consolidation Strength**

The expansion performance test curve under different modifier dosages is shown in Figure 5. In the extreme analysis of the parameters with the limiting expansion force as the target parameter, wherein the amount of expanding agent doping plays a pivotal role in the limiting expansion force of the slurry, with a ramp-up in the amount of expanding agent, the slurry limiting expansion force is greatly improved, indicating that some of the materials in the expander and the Ca(OH)\(_2\) produced during cement hydration are combined to form calcium thionate-calcium aluminite hydrated. From the test data, it could be seen that the limiting expansion force increases with the increase of the expansion agent, but the increment tends to decrease. As can be seen from Figure 5, the expansion agent has the greatest influence on the expansion rate of the material. The expansion rate increases by 0.158% from 0.082%. When the dosage of the accelerator agent increased from 4% to 8%, the expansion rate increased from 0.105% to 0.131%. The impact of each factor on the slurry limiting expansion force is as follows: expansion agent > accelerator agent > water reducer, and the test results demonstrate that the largest combination of slurry fluidity is I\(_K3\)II\(_K3\)III\(_K1\). The amount of accelerator agent and water reducer has less effect on the slurry limiting expansion force.
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Figure 5. Test results of expansion rate under different factors.

3.4. Consolidation Strength

The compressive strength of 3d and 7d grouting materials is shown in Figure 6. In the extreme analysis of the 3d and 7d uniaxial compressive strength as the target parameters, the 3d strength increased by 11.14% and 5.05%, respectively, when the accelerator agent content increased from 2% to 6% with the gradual increase of the dosage of the accelerator agent. The 7d strength increased by 8.55% and 2.84%, respectively; Experimental data show that the accelerator agent improves the early strength of the stone body; When the expanding agent content is 2–4% and 4–6%, the 3d strength is increased by 2.59% and 1.54%. The 7d strength increased by 8.24% and −1.72%, respectively, and the experimental data demonstrated that the compressive strength of the expander on the stone body was significantly improved, mainly due to the expansion inside the stone body and the enhancement of internal compactness. The effect of the amount of superplastic agent on the compressive strength of slurry stones was relatively obvious, and the water reducer content increased by 32.5% and 4.64%, respectively, from 0.2% to 0.3% and 0.3% to 0.4%. The 7d strength increased by 31.63% and 3.57%, respectively, and the experimental data showed that the 0.3% of the water reducer increased the strength of the stone body significantly, and the 0.4% dosage did not increase the strength of the stone body significantly, mainly because the excessive amount of the water reducer would lead to slurry segregation and water secretion, and reduce the compressive strength of the specimen. From the test results, it is apparent that the 3d maximum compressive strength combination is I\text{K3} II\text{K2} III\text{K3}; The 7d maximum compressive strength combination is I\text{K3} II\text{K3} III\text{K3}.

Figure 6. Results of compression strength tests under different factors of 3d and 7d. (a) Compressive strength on day 3, (b) Compressive strength on day 7.

Through the comprehensive balance of the optimal conditions for the four indexes of fluidity, setting time, expansion rate and compressive strength, the conditions that take into account the main influencing factors of each index are found, and the slurry mixture...
ratio that is most conducive to the four indexes is proposed, and we could recommend the slurry mix ratio that benefited these four indications the most. Considering the various properties of the materials, it is concluded that the ratio of the new mining coal pillar grouting materials is 4%, the amount of water reducer is 0.3%, and the best amount of expansion agent is 6%.

4. Briquette Tests of Different Materials
4.1. Briquette Sample Production

Due to the loose fragmentation of the coal rock mass at the project site and the development of the fracture layer, it is difficult to take the molding standard specimen for the grouting test. Therefore, research by making molded coal sample specimens has become an effective way [40,41]. The samples of coal utilized in the test were from the fresh coal body of the 3238 tunneling workplace and returned to the laboratory for crushing by a crusher, sieved and screened, and the selected particle sizes were 0.25–0.5 mm, 0.5–1.0 mm, and 1.0–2.0 mm. According to a certain proportion (the particle size 0.25–0.5 mm accounted for 60%, the particle size of 0.5–1.0 mm accounted for 30%, and the particle size of 1.0–2.0 mm accounted for 10%) for gradation, in the pulverized coal particles add different types, different content of materials and water to mix, the mixed mixture is poured into the mold, and then the coal particles are pressed into 50 mm × 100 mm briquette test pieces under 4.0 MPa molding pressure conditions. The grouting materials used this time are strength grade 425 cement, strength grade 525 cement and new coal pillar grouting materials. The pulverized coal with different particle sizes is shown in Figure 7. The briquette production process is shown in Figure 8. The briquette is made using different grouting materials, and the molded coal sample is maintained for 3 days for a compressive strength test.

Figure 7. Pulverized coal with different particle sizes after screening.

Figure 8. Production process and specimen.
4.2. Test Equipment and results

This experiment utilizes the WAW-2000 universal electro-hydraulic servo testing machine, and the instrument is composed of a loading module, control module, servo-hydraulic module, force, deformation, displacement measurement unit, calculation unit and control unit. After the specimen was completely in contact with the experimental machine, the loading was carried out by displacement control method with the loading rate of 0.01 mm/s until the specimen was damaged and the experiment was finished. The briquette strength test curve under different materials is shown in Figure 9.

![Figure 9](image-url)

Figure 9. Strength experiment of briquette with different materials.

The experimental results of the briquette strength of different materials are shown in Figure 9. The test curve demonstrates that when the coal body P.O 425 is used as a cementitious material to make briquettes, the uniaxial compressive strength of the briquette is 0.34 MPa, and the strength of the coal body after adding P.O 525 material is 0.56 MPa, which is 1.65 times the uniaxial compressive strength of P.O 425 briquette; the compressive strength of the coal sample after adding the modified material is 1.12 MPa, which is 2.0 times the strength of ordinary silicate injection P.O 525 briquette, which is 3.29 times the P.O 425 grouting material.

4.3. Analysis of Grouting Reinforcement Machine

Experimental data show that the new mining coal pillar grouting material has an obvious effect on the strength of the coal body. The main reason is that in the process of roadway excavation. It is easy to lead to stress release of coal and rock mass without taking any advance support measures. Due to the physical and mechanical properties of coal and rock mass, when the original structure is damaged, it cannot produce self-stability, so collapse, and roof collapse accidents often occur, which is easy to cause safety hazards. Therefore, the grouting reinforcement of the coal pillar can not only fill the cracks but also the expansion force generated by the grouting material itself can consolidate the coal and rock mass into a whole, improve the physical and mechanical parameters of the coal pillar and increase the safety factor in the process of excavation. The schematic diagram of coal grouting reinforcement mechanism is shown in Figure 10. Cement-based material grouting reinforcement mainly through the process of penetration, filling and compaction to achieve the purpose of reinforcement, and substances in cement-based materials can interact with fracture contact surfaces through chemical cementation. After the grout condenses in the rock mass structure surface, it fills and reinforces the structure surface, which improves the cohesion force and internal friction angle of the structure surface, and enhances the ability of engineering rock mass to resist external force damage. It is applied to the grouting reinforcement of the surrounding rock of the roadway to improve the mechanical properties of the coal pillar and enhance the bearing capacity of the coal pillar.
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Figure 10. Schematic diagram of coal grouting reinforcement mechanism.

5. Engineering Application

5.1. Engineering Background

The 3238 working surface of a mine in the Bozhou Mining area is located in the fourth section of the north wing of the lower mountain of the II level 33 mining area, and the working surface has an oblique length of 238.5 m, an average walking length of 1702 m, a coal seam burial depth of 600 m, and a primary rock stress of about 14.5 MPa. The average thickness of the coal seam on the working surface is about 3.10 m; the coal seam is generally in a north-south direction, and the inclination of the coal seam’s angle is about 20°; The coal seam is relatively stable and complex in structure, and the main structure is a fracture structure. The top and bottom slate lithology of the coal seam, as shown in Table 4.

Table 4. Working face top and bottom.

| Rock Formation | Thickness/m | Lithology               | Lithologic Character                                      |
|----------------|-------------|-------------------------|-----------------------------------------------------------|
| Upper roof     | 1.30~5.15   | Fine sandstone and mudstone | Grey, thin lamellar, fine-grained structure, calccareous cementation, is a stable rock mass |
| mediate roof   | 3.61~9.90   | Mudstone                | Dark gray, medium-thick layered, argillaceous structure    |
| False roof     | 0.3~0.45    | Carbonaceous mudstone and siltstone | Thin thickness and poor stability, with coal seam mining and fall, is an unstable rock mass |
| Immediate bottom | 2.89~5.64  | Siltstone               | Light gray, thick layer, block, for poor stability rock mass |

The 3238 working surface wind lane is along the empty roadway, its high gang side adjacent to the 3236 goaf area, the goaf area left in the old kiln water, and the working surface layout diagram is shown in Figure 11. Due to the pressure intrusion of the coal pillar during the recovery process of the 3236 mining face, the fracture development inside the surrounding rock, and the anchor support failure during the construction. The deformation of the coal pillar of the roadway is severe, resulting in safety accidents such as construction water seepage, and the support section is shown in Figure 12.
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Figure 11. Schematic diagram of the 3_238 tunneling face.

Figure 12. Roadway support drawing.

5.2. Selection of Grouting Parameters

(1) Grouting depth: The grouting depth can be according to the theory of the surrounding rock loose coil, and the calculation formula is as follows:

\[
R = r \left[ \frac{(C \cot \varphi + P)(1 - \sin \varphi)}{P_s + C \cot \varphi} \right]^{\frac{1}{1 - \sin \varphi}} \quad (1)
\]

In the formula: \( r \) is the roadway radius, m; \( P \) is the pressure on the roadway; \( \varphi \) is the friction angle of the coal body in the coal pillar; \( C \) is the coal pillar cohesion; \( P_s \) provides supporting reactions for coal pillars. Due to the small width of the small coal pillar of the guard lane, if the grouting depth is too large, it may lead to the side of the roadway and the goaf, which will affect the safety production, combined with the actual situation, the grouting drilling depth is determined to be 2 m;

(2) Grouting pressure: According to the principle that the slurry can penetrate into the surrounding rock fissures without causing the coal body to be split by the slurry due to excessive pressure, combined with the coal body strength and the development of surrounding rock fissures, the grouting pressure is comprehensively determined to be 1–1.5 MPa;

(3) Grouting drilling design: three grouting holes are arranged in each section of the coal pillar side of the wind lane, and the distance from the top plate is 300, 1800, 3300 mm,
the drilling diameter is 42 mm, the hole depth is 2 m, and the interval spacing is 2 m. A schematic diagram of grout reinforcement for each section is shown in Figure 11.

The experimental site was selected at 3238 wind lane 80 m from the excavation head to start the pressure grouting reinforcement of the coal pillar, the grouting material was selected from the new mining coal pillar grouting material, and the pipeline should be tested before the grouting construction, and the final pressure standard of the injection pressure $P = 1.5$ MPa was used; Check the tightness of the grouting pump and pipeline before grouting, that is, no leakage occurs in the grouting pipeline within 10–15 min. It can ensure that the slurry penetrates into the fractures of the surrounding rock as much as possible, better exerts the performance of the grouting material and enhances the integrity of the surrounding rock. The progress of grouting construction is consistent with the tunnel boring speed.

5.3. Evaluation of Grouting Reinforcement Effect

5.3.1. Roof Discrete Instrument

As an instrument that effectively detects the relative displacement change between the rock mass and the surface in the overlay area of the top plate of the surrounding rock within a certain range. The physical object is shown in Figure 13. The installation method is 6 m for the deep base point and 3 m for the shallow base point, and 2 measuring stations are arranged.

![Figure 13. Physical diagram of the instrument.](image)

The change curve of the roof separation layer is shown in Figure 14. The 1# and 2# measurement points are within 1–8 d, the delayer speed is faster, the value of the delayer is also larger, and the delayer value detected by the 1# measuring station is about 20 mm; The stratification value of the 2# test station is about 23 mm. The delamination trend of rock formations in the monitored area for 8–30 d gradually slowed down and was basically stable on 22d. During the 30d monitoring period, the maximum delamination of the 1# station is about 39.6 mm in the shallow part, and the cumulative delamination in depth is 28.5 mm; the cumulative delamination of the 2# station is about 52.5 mm, and the cumulative depth separation is 29.5 mm. The delamination change trend indicates that the surrounding rock changes greatly in the early stage of roadway excavation, and after grouting and reinforcement, the deformation of the surrounding rock gradually shifts to the deep, and the deep surrounding rock pellet is also maintained in safety, ensuring safe and efficient roadway construction. The loose coil’s stability is increased, the small coal pillar’s bearing capacity is ensured, the stability issue of the tiny coal pillar after excavation is avoided, and it is then repaired thanks to the grouting reinforcement of the surrounding rock of the roadway, and ensures the shape and size requirements of the roadway section.
is also larger, and the delayer value detected by the 1# measuring station is about 20 mm; the cumulative depth separation is 29.5 mm. The delamination change trend indicates that the deformation of the roadway surrounding rock is avoided, and it is then repaired thanks to the grouting reinforcement of the surrounding rock of the roadway, and ensures the shape and size requirements of the roadway construction. The loose coal's stability is increased, the small coal pillar side, solid coal side, roof and floor of 2# measuring point is stable at 107 mm, 62 mm and 46 mm, and the maximum moving rates are 10 mm/d, 5 mm/d, and 6 mm/d. The deformation of the pillar side is greater than that of the solid coal side.

Figure 14. Roof separation change curve.

5.3.2. Roadway Surrounding Rock Deformation Monitoring

The deformation curve of the surrounding rock of the roadway is shown in Figure 15. The overall convergence deformation of the surrounding rock is significant 1~12 days after excavation, and from 12 to 30 days, the deformation of the surrounding rock decreases and gradually becomes stable. The final deformation of the pillar side, solid coal side, roof and floor of 1# measuring point is stable at 130, 58 and 39 mm, and the maximum moving rates are 15, 10 and 6 mm/d. The final deformation of the pillar side, solid coal side, roof and floor of 2# measuring point is stable at 107, 62 and 46 mm, and the maximum moving rates are 10, 5, and 6 mm/d. The deformation of the pillar side is greater than that of the solid coal side.

Figure 15. Deformation curve of the roadway’s surrounding rock.

The comprehensive analysis shows that the coal pillar reinforced by grouting can withstand the mining pressure during the roadway excavation; it improves the bearing capacity of the narrow coal pillar and effectively improves the bearing structure of the roadway surrounding rock. The mechanism of action is as follows: the grouting with pressure can make the slurry penetrate into the micro-cracks of the coal and rock mass, block the cracks of the coal and rock mass, isolate the penetration path of air and water, avoid the deterioration effect of the coal and rock mass, and maintain the strength of the coal and rock mass. The grouting slurry penetrates into the micro-cracks, solidifies the loose, broken coal and rock mass into a new overall structure, changes the mechanical properties of the original surrounding rock, improves the overall cohesion and strength, and effectively improves the stress environment of the supporting structure.

By using the modified material to grout the coal pillar, the damaged surrounding rock can be repaired, the bolt support effect can be improved, the axial restraint of the support on the surrounding rock can be increased, and the overall bearing capacity of the surrounding rock can be enhanced.

6. Conclusions

(1) Through orthogonal test and comprehensive equilibrium analysis, it is concluded that the best ratio of the coal pillar grouting material for mine is the dosage of accelerating agent is 4%, the dosage of water reducing agent is 0.2%, and the dosage of expanding agent is 6%;
(2) Through the briquette test of different grouting materials, it is concluded that the briquette compressive strength strengthened by the coal column grouting material reaches 1.12 MPa, which is 2.0 times the strength of ordinary silicate injection P.425 briquette, and 3.29 times of the strength of P.525 grouting material. It shows that the grouting material of coal pillars has an obvious effect on the strength improvement of coal samples;

(3) The field testing shows that the roadway surrounding rock is basically in a stable state after 30 days of roadway excavation after the use of coal pillar grouting materials for reinforcement. The grouting with pressure can make the grout infiltrate into the micro-cracks of coal and rock mass, seal the cracks of coal and rock mass, avoid the deterioration effect of coal and rock mass, change the mechanical properties of the original surrounding rock, improve the overall cohesion and strength, increase the bearing capacity of the core area of small coal pillar, and ensure the safe and fast tunneling of roadway construction.

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