

Article

Research on Mechanical Properties and Engineering Applications of Inorganic Cementitious Filling Materials in Coal Mine Abandoned Roadways

Lei Sun, Chong Li *, Zhijun Xu , Lianhai Tai and Yue Cao

School of Mining Engineering, China University of Mining and Technology, Xuzhou 221116, China; tb23020029a41@cumt.edu.cn (L.S.); tb20020034b0@cumt.edu.cn (Z.X.); tb21020024b4@cumt.edu.cn (L.T.); tb1717020002b0@cumt.edu.cn (Y.C.)

* Correspondence: lichongky@163.com

Abstract: To solve the problems of brittleness, high cost, and the complicated construction process of traditional filling materials for filling abandoned roadways, various aspects of the physical and mechanical properties of the materials were studied using laboratory tests and were applied in coal mines. The research shows that the self-developed inorganic cementitious filling material has the advantages of being low cost, easy to cut and wash, and having good filling performance. A foaming agent is a direct factor in controlling the volume expansion of inorganic cementitious filling materials; the increase in the volume of slurry foaming with the addition of a foaming agent initially showed a large and then a small trend with a foaming agent dosage of 100 g. The increase in the volume of slurry foaming is the largest at 56.28%. The effect of the B material (calcium stearate+ J85 rapid-setting agent) on the foaming time and the number of foaming times of the slurry was significant. Foam stabilizers in the B material make the slurry particles uniformly distributed inside the slurry, while quick-setting agents control the initial and final setting time by affecting the slurry setting speed. The water/cement ratio directly affects the foaming times of the slurry but has little effect on the foaming time and setting speed. When the water/cement ratio is less than 1:2, the slurry foaming effect is poor, and the foaming volume remains unchanged. The strength of the material is significantly affected by the proportion of B material and the amount of blowing agent, and the compressive strength of materials with different compositions and ratios varies greatly. A whole set of systems of new inorganic gelatinized abandoned roadway filling materials was researched and applied in coal mines, achieving good results.

Keywords: abandoned roadway; inorganic cementitious materials; physical and mechanical properties; filling process



Citation: Sun, L.; Li, C.; Xu, Z.; Tai, L.; Cao, Y. Research on Mechanical Properties and Engineering Applications of Inorganic Cementitious Filling Materials in Coal Mine Abandoned Roadways. *Appl. Sci.* **2024**, *14*, 4826. <https://doi.org/10.3390/app14114826>

Academic Editor: Andrea Carpinteri

Received: 4 May 2024

Revised: 29 May 2024

Accepted: 29 May 2024

Published: 3 June 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Due to old age and lack of maintenance, the roadway's surrounding rock deformation and damage are serious. During the mining period—especially in the vertical distribution with the working face towards the abandoned roadway—the surrounding rock of the abandoned roadway has difficulty withstanding the influence of the working face over the front support pressure and the phenomenon of roof fracture, which are two types of instability. The working face passes through the abandoned roadway with a large span and for a long time, which is detrimental to its safety and stability [1–6].

At present, domestic and foreign control of the rock surrounding the abandoned roadway mainly involves the use of pillars and wood pallets to support the roof of the abandoned roadway. However, the support strength of the pillars and wood pallets is low and cannot effectively prevent the roof of the abandoned roadway from sinking. By contrast, anchor rods have good support performance, but the cost of support is higher, and they are not conducive to the normal cutting of the face back to the miners. Some

mines set up the working face to bypass the abandoned roadway, use the abandoned roadway as a cutting hole, or use the working face as a cutting hole; however, this makes the working face unsafe and unstable. Therefore, some mines arrange the working face so that it bypasses the abandoned roadway, but this is often restricted by the engineering and geological conditions, coupled with the complexity of relocating the working face. Since it is affected by the existing roadway, the working face cannot be rearranged to bypass the abandoned roadway.

It has been proven in practice that grouting and filling abandoned roadways using filling materials to reinforce the two sides of the road and the top of the broken surrounding rock body can ensure the safety and stability of the working face when crossing the abandoned roadway. At present, mining scholars at home and abroad have been committed to conducting research on filling materials and filling technology for abandoned roadways and have achieved success in mining practice. Research and development of inorganic cementing filling materials are especially gaining increased attention [7–12]. Using abandoned roadway filling technology is an effective way to suppress the deformation and damage of the roadway peripheral rock when the working face passes through the abandoned roadway, which is of great significance for the smooth passage of the coal mining face through the abandoned roadway, the realization of safe and efficient mining of the mine, and the improvement of the extraction rate of coal resources. However, the research and development of filling materials are major problems when filling abandoned roadways.

At present, more representative filling materials mainly include high-water quick-setting materials, Remy filling materials, and inorganic cementitious materials that are mainly based on foamed cement [13,14]. High-water quick-setting materials, such as abandoned roadway filling materials, as a whole, have poor cementing performance and bonding roller, are not easy to wash, and are expensive. With Remy filling materials, due to their brittleness, cutting can easily cause strong vibrations in the coal mining machine, which is not conducive to the safety and stability of the working face [15–18].

Based on the above problems, this paper conducts experimental research on the inorganic cementitious materials that are mainly based on foamed cement, from the independent research and development of materials to the improvement of the filling process and equipment adaptation, forming a complete set of filling systems. The research results have been applied onsite to the filling of the abandoned roadway of the 3122 comprehensive discharge face in the Jingxin Coal Industry; significant results have been achieved. This paper focuses on the physical and mechanical properties of inorganic cementitious filling materials and their application effects in coal mines and verifies the feasibility and advancement of the materials and technologies through engineering cases.

2. Engineering Background

The Jingxin Coal Mine mainly mines the No. 3 coal seam, which is located in the middle and lower part of the Shanxi Group of the Lower Permian System, with a thickness of 5.55–6.55 m and an average thickness of 6.0 m. The coal seam is stable and can be mined in the whole area, with a simple structure and sandy silt sandwiched between, generally containing 0–2 layers of gangue. The bottom plate is black mudstone. Due to the integration of coal resources in the mine, there are a large number of abandoned roadways left in the working face, which are crisscrossed and distributed, destroying the integrity of the coal seam and seriously threatening the safety production of the mine.

A columnar diagram of rock layers in the 3122 working face is shown in Figure 1. The lithology of the top plate of the working face mainly consists of mudstone and sandstone, and the lithology of the bottom plate mainly consists of mudstone and siltstone. As shown in Figure 2, there is an abandoned roadway in the working face near the 3122 transport roadway, which is rectangular in section, 4.5 m wide and 5 m high, and is dug along the bottom plate. The 3122 abandoned roadway is close to the transport roadway and parallel to them is the open-off cut of the working face, which gradually moves away from the

transport roadway with an angle of elevation of 3° along the west 30 m. The width of the coal pillars between the abandoned roadway and the 3122 transport roadway is not more than 20 mm within the range of 70 m from the cutting-off of the working face to the west. The width of the coal pillar between the working face cutting-off and the 3122 haulage trench is not more than 2 m, and the abandoned roadway within 30 m from the end is supported by wooden stacks. The deformation and damage to the peripheral rock are serious, and it needs to be grouted and filled urgently for peripheral rock reinforcement.

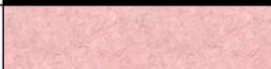
Stratigraphic	Lithology	Columnar	Average thickness of rock layers
Shanxi Formation	sandstone		27.81m
	siltstones or fine sandstones		8.02m
	mudstone		0.59
	3# coal seam		6m
	Mudstone - siltstone		5.63m

Figure 1. Columnar diagram of rock layers in the 3122 working face.

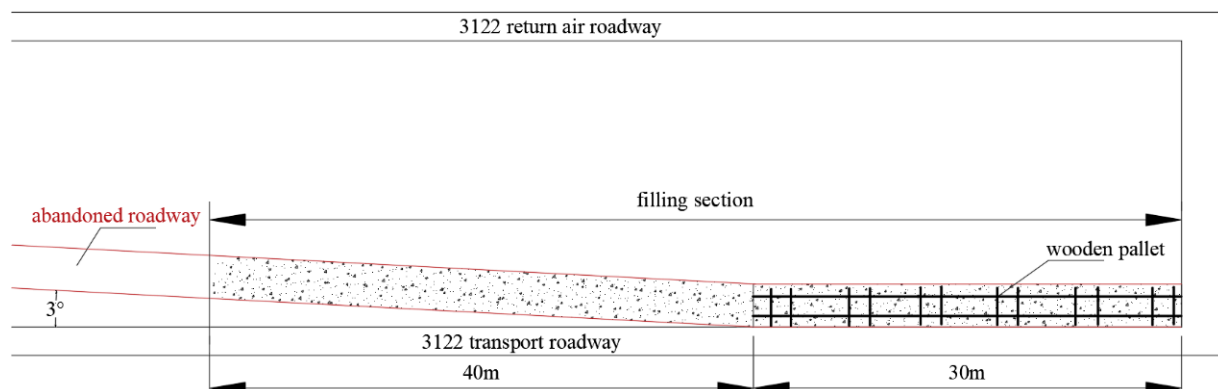


Figure 2. Schematic diagram of the location of the abandoned roadway at the 3122 working face.

Important equipment, such as a power distribution box, pumping station, mobile substation, console, equipment train, etc., is placed in the 3122 transportation tunnels, so the stability of the perimeter rock of the transportation roadway is crucial. At the same time, the 3122 abandoned roadway is located at the end of the working face; due to the large span of the end part and the stress concentration, when the working face pushes through the abandoned roadway, the overhanging area of the roof plate increases, which could easily cause a roof accident. The width of the coal pillar between this empty lane and the 3122 transportation roadway is not more than 2 m. The coal pillar cannot bear the over-supporting stress of the working face and destabilizes and causes damage. The roof plate of the transportation roadway is a cantilever beam; the cantilever length increases when the working face passes through the abandoned roadway, and the roof plate of the transportation roadway is prone to fracture.

Therefore, to reduce the influence of the abandoned roadway during the digging of the transportation roadway, ensure the safety of mechanical and electrical equipment in the transportation roadway, reduce the probability of roof accidents at the end position, and ensure that the working face passes through the abandoned roadway safely, the abandoned roadway within the range of coal pillars less than 2 m wide from the transportation roadway must be reinforced by grouting and filling technology. For the abandoned roadway beyond 70 m west from the cutting-off of the working face, there are enough safe coal pillars between the working face and the transportation roadway, and the deformation of the surrounding rock of the abandoned roadway can be controlled jointly by setting up wooden stacks and replacing the anchor rods (ropes).

3. Test Materials and Methods

3.1. Test Master Material

In foamed cement-based inorganic cementitious filling materials, the primary components are prepared through a combination of materials A and B. Material A consists mainly of Portland cement, fly ash, and lime powder (CaOH_2) mixed in specific proportions. Material B is an additive comprising a foam stabilizer (calcium stearate) and J85 rapid-setting agent. These additives are incorporated to modify the internal structure and enhance stability. Foaming agents are mainly used to increase the foaming multiplier of the filled body. The experimental process involves solidifying various base materials together through cementation and then utilizing the expansion effect of the foaming agent to maximize filling volume in abandoned roadways. Material A plays a crucial role in controlling the molding, bubble hole structure, and strength enhancement of the filling material, with fly ash improving cohesion and shrinkage properties. Material B primarily reduces slurry setting time, promotes early strength development, enhances bubble stability, improves pore structure, and enhances the physical properties of the slurry.

3.2. Test Requirements

The abandoned roadway filling material must provide support for the roof plate, reinforce the fractured surrounding rock of the roadway, and allow the coal mining machine to easily cut through the filling body as it passes the abandoned roadway. Furthermore, the filling material should exhibit economic efficiency by being cost-effective, readily available, and easy to construct. The experimental filling materials should possess the following characteristics:

(1) Filling materials are low cost, widely available, and non-polluting to the environment. Grouting filling materials should have good economic efficiency, the materials should be easy to obtain and create no pollution, to provide convenience for the later grouting construction.

(2) The filling body is easy to cut when the working face is being mined back, and it is convenient to wash the coal after cutting. If the filling material hardness is too great during the workplace mining process to cut the filling body, it is not conducive to the coal mining machine being able to cut it, affecting the normal mining face. At the same time, the filling body should not be easy to hydrate, to make washing convenient later.

(3) A certain compressive strength and support capacity. According to the narrative of relevant references [19], the early strength of the filling material can be calculated by Equation (1), in which 0.03 is the preliminary design self-supporting strength of the material in MPa, which is derived from the preliminary design of the material according to the actual demand of the filling material, as summarized by domestic scholars in the existing formula for the filling material.

$$\sigma_1 = k_1 k_2 (0.03 + \gamma h) \quad (1)$$

where K_1 is the safety coefficient, take 1.5~2;

K_2 is the ratio of the strength determined in the laboratory of the material and the strength of the specimen in the field, taken as 1.1~1.3;

γ is the direct top capacity, KN/m³; and
 h is the direct top thickness, m.

From the safety point of view, K_1 and K_2 are taken as the maximum values, which are 2 and 1.3, respectively. The direct top of the 3122 heddle face of Jingxin Coal Industry is mudstone with a thickness of 0.59 m and a capacitive weight of 1980 KN/m³, and the required early strength of filling material calculated by substituting into Equation (1) should be no less than 0.1 MPa.

The most significant factor influencing the filling effectiveness is the long-term strength of the material, typically assessed after 28 days of cementation and solidification. Once solidified, the abandoned roadway filling body provides support for the overlying rock layer. At the direct top of the 3122 working face in the Jingxin Coal Industry, there are 0.59 m of mudstone, while the old top comprises 8.02 m of siltstone. The material's capacity is 2050 KN/m³. The filling body primarily supports the mudstone and siltstone layers with a combined thickness of 8.61 m. The formula for calculating the bearing strength of the filling body is as follows:

$$\sigma_h = \sum_{i=1}^h \gamma_i h_i = 0.59 \times 0.0198 + 0.0205 \times 8.02 = 0.17 \quad (2)$$

The formula for calculating the late strength σ_2 that the filling material should have, summarized by Dr Yu Yue [19], can be derived as follows:

$$\begin{aligned} \sigma_2 &= K_2(\sigma_1 + K_1\sigma_h) \\ &= 1.3 \times (0.1 + 2 \times 0.17) = 0.57 \end{aligned} \quad (3)$$

The late strength of the filling material calculated by empirical Formulas (1)–(3) should be not less than 0.57 MPa, while the filling material should also have a certain support capacity to ensure that the filling body can be glued to the top plate of the abandoned roadway together to form the top load-bearing layer, which acts as the direct top of the working face.

(4) Condensation time should be moderate. Material setting time should meet the requirements of pipeline transport and project progress; if the initial setting time is short, it is easy to block the pipeline to affect the grouting, and if the initial setting time is long, it affects the filling progress.

(5) Good cementing performance. At the same time, it has a certain mobility and permeability, can pass through the pipeline in a relatively short period, not block the pipe, can effectively penetrate the rock cracks and holes, and does not stick to the drum when the coal mining machine cuts.

3.3. Test Methods

This experiment is based on a variety of ratios of A and B base materials for mixing and stirring, plus a certain amount of blowing agent to obtain several different models of filling cement. Its compressive strength is tested through the press until the conditions meet those of the new inorganic cementitious filling materials. The experimental process is divided into three stages: the first stage is the preparation of the experiment, including the weighing, mixing, and stirring of the A and B base materials and foaming agent; the second stage is the maintenance of the model, including putting the slurry into the mold forming and post-molding maintenance; and the third stage is the strength test, which includes taking molds of the cementitious materials and the test of compressive strength. A schematic diagram of the test process is shown in Figure 3.

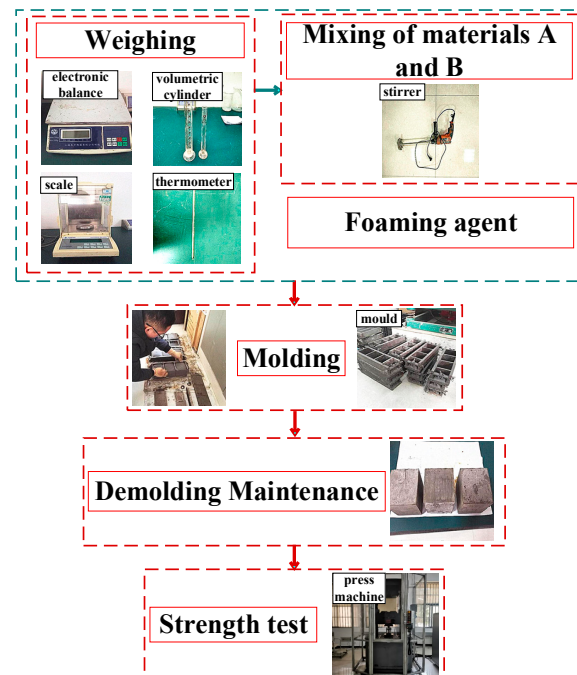


Figure 3. Test flow chart.

According to the narratives of relevant references [20–23], the performance parameters of filling materials during preparation are primarily influenced by the dosage of experimental materials and the water/cement ratio, along with secondary factors such as mixing mode, water temperature, and foaming space. Through a comparative analysis, this experiment focuses on investigating the impact of A and B base material dosage, foaming agent proportion, and water/cement ratio on the performance of inorganic cementitious filling materials. The objective is to identify a new type of inorganic cementitious filling material suitable for filling the abandoned roadway of the 3122 coalface in the Jingxin Coal Industry. The specific experimental groups and objectives are outlined in Table 1.

Table 1. The program of the experiment.

Group Number	Program	Water Content/kg	A Material Content/kg	B Material Content/g	Foaming Agent Content/g	Water-Cement Ratio
Group 1	Program 1	1	1.5	0	50	1:1.5
	Program 2	1	1.5	0	100	1:1.5
	Program 3	1	2.5	0	100	1:2.5
Group 2	Program 1	1	1.5	80	100	1:1.5
	Program 2	1	1.5	120	100	1:1.5
	Program 3	1	1.5	150	100	1:1.5
Group 3	Program 1	1	1.5	130	50	1:1.5
	Program 2	1	1.5	130	100	1:1.5
	Program 3	1	1.5	130	150	1:1.5
Group 4	Program 1	2	2.0	100	140	1:1.0
	Program 2	1	1.5	100	140	1:1.5
	Program 3	1	2.0	100	140	1:2.0

4. Analysis of Test Results

4.1. Test Process and Phenomenon

(1) Initial test phenomenon

Figure 4 shows the effect of slurry foaming at the initial stage of the experiment, as shown in Figure 4. The different program slurries all started foaming at the end of mixing.

In group 1, the foaming process was smooth in programs 1 and 3, and the middle of program 2 slurry was concave. In group 2, there was no fading of the slurry in program 1. The foaming phenomenon was the same in program 2 and program 3, with a more uniform distribution of air holes and larger bubbles. In group 3, none of the slurries subsided, with a uniform distribution of pores and larger bubbles in program 2. In group 4, the overall foaming process of the three programs was smooth, and the distribution of air holes was uniform. The foaming time and initial setting time are shown in Table 2.

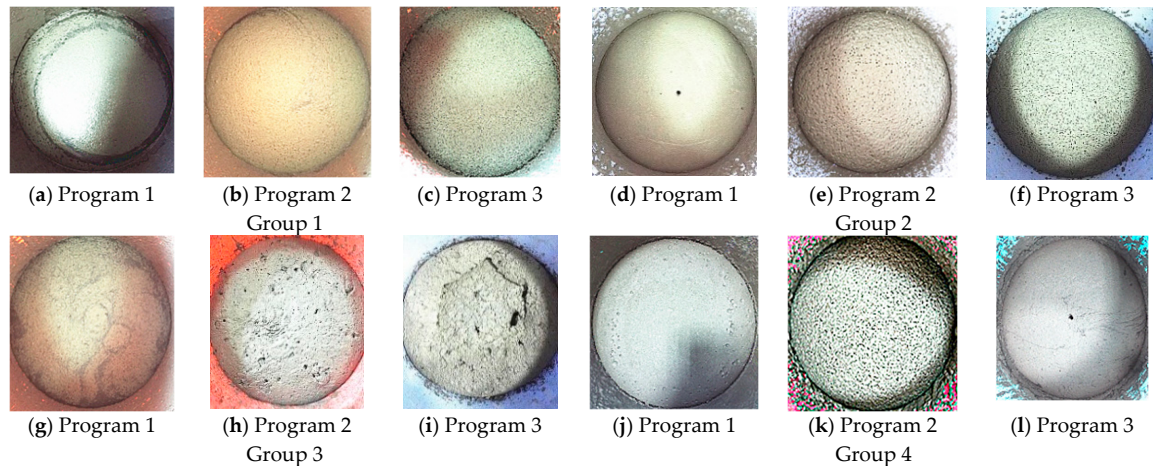


Figure 4. Foaming effect of slurry at the early stage of the test.

Table 2. The foaming time and initial setting time.

Group Number	Program	Foaming Time/min	Initial Setting Time/min	Foam Multiple
Group 1	Program 1	4	20	1.64
	Program 2	6	25	2.83
	Program 3	4	28	2.03
Group 2	Program 1	9	30	2.34
	Program 2	10	20	2.85
	Program 3	12	15	2.94
Group 3	Program 1	6	18	1.83
	Program 2	8	25	2.86
	Program 3	9	28	3.54
Group 4	Program 1	9	27	4.02
	Program 2	10	18	3.21
	Program 3	10	15	2.14

(2) Later experimental phenomenon

The inorganic cementitious filling material was initially mixed in the mixing barrel. For the comparative analysis, a portion of the slurry was extracted and placed in a mold for curing, while the remaining slurry was left in the mixing barrel for natural solidification. As shown in Figure 5, the demolded gel-like filling material displays a smooth, greyish-brown surface. In contrast, the naturally solidified slurry in the mixing barrel forms a cylindrical shape upon removal. A noticeable pore structure is evident on its surface, appearing rough, uneven, porous, greyish-white, and featuring a bulge at the top. This indicates that the mixing barrel offers adequate foaming space for the slurry. Upon curing in the mold, the porous nature of the slurry results in an uneven surface with a bulge at the top, as the limited mold volume restricts full foaming. Following cementation and solidification, the body surface becomes smoother and flat.



Figure 5. Inorganic cementing material appearance.

4.2. Analysis of Test Results

Comparative analysis of four experimental groups reveals a direct relationship between the physical properties of the cementitious materials and variables such as the dosage of materials A and B, the proportion of foaming agent, and the water/cement ratio. The foaming agent directly influences the volume expansion of the inorganic cementitious filling materials, while the water/cement ratio impacts their compressive strength. The ratio of base materials A and B primarily affects the internal structure of the slurry. Additionally, additives play a crucial role in modulating the foaming behavior and setting time of the material, as detailed in Table 2.

From the initial experiment group, it is evident that excluding material B results in a slurry formed solely by mixing material A and the blowing agent. This mixture generally exhibits a longer solidification time, typically around 20–28 min for initial solidification, accompanied by fewer foaming instances. The specific gravity of the blowing agent directly impacts the volume of slurry foaming. Under identical conditions, program 2 utilizes twice the amount of blowing agent compared to program 1, resulting in a volume increase in slurry foaming by 1.64 to 2.83 times. This highlights the blowing agent's direct role in controlling the expansion volume of inorganic cementitious filling material. In program 3, where the specific gravity of material A is increased relative to program 2, foaming instances are reduced. This indicates that the water/cement ratio is another significant factor influencing slurry foaming volume.

Analysis of the second experimental group reveals the significant impact of varying specific gravities of material B under identical conditions on inorganic cementitious filling materials. This impact is primarily observed in the foaming time and frequency of foaming instances in the slurry. The foam stabilizer in the B material can extend the half-life of the slurry foam bursting and increase the viscosity of the slurry by prolonging the foam bursting half-life of the slurry and also improve the slurry porosity structure so that the particles of the slurry can be evenly distributed in the interior of the slurry. The rapid coagulant controls the initial and final coagulation time by influencing the coagulation speed of the slurry. The addition of B material prolongs the foaming time of the slurry, and the larger the specific gravity of B material, the more fully the slurry foams and the foaming volume increase. However, the relative increase in the volume of the slurry is not obvious. In addition to this, through the experimental process of the pore structure characteristics and the receding of the slurry, it can also be seen that the B material can prevent the slurry depression from collapsing and can play a role in shaping it.

From the third set of experiments, it is evident that the quantity of the blowing agent directly influences the effectiveness of slurry foaming. In identical conditions, a higher amount of blowing agent results in a larger volume of slurry foaming. When the blowing agent dosage was 50 g, the volume of slurry foamed 1.83 times; when the blowing agent dosage was 100 g, the volume of slurry foamed 2.86 times, an increase of up to 56.28%. When the blowing agent dosage was 150 g, the volume of slurry foamed 3.54 times, an increase of 23.8%, indicating that increasing the dosage of the blowing agent after the slurry will not cause unlimited foaming but is also subject to the effect of the water-ash ratio.

In the fourth experimental set, it is evident that varying water/cement ratios directly impact the foaming volume of the slurry, with minimal effect on foaming time and setting speed. As can be seen from Figure 6, the larger the water/cement ratio, the larger the corresponding slurry foaming volume. When the water/cement ratio is 1:2.5, the foaming increases by 2.03 times. When the water/cement ratio is 1:2, the foaming is 2.14 times, an increase of 5.42%. When the water/cement ratio is 1:1.5, the foaming is 3.21 times, an increase of 58.12%. When the water/cement ratio is 1:1, the foaming is 4.02 times, an increase of up to 25.23%. When the water/cement ratio is 1:1, the foam is 4.02 times, an increase of 25.23%. Figure 6 can be visualized when the water/cement ratio is less than 1:2—the slurry foaming effect is not obvious, and the foam volume remains unchanged.

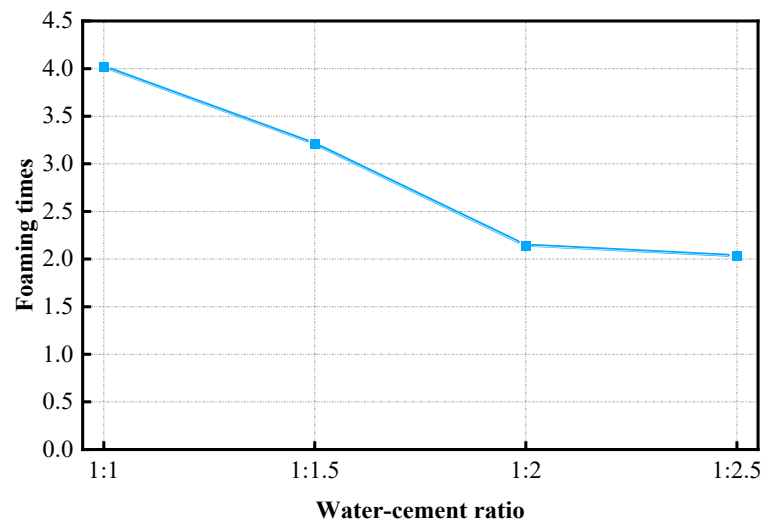


Figure 6. The foaming times vary with the water/cement ratio.

Referring to Figure 7, it is observable that an increase in the amount of foaming agent and the ratio of base materials A and B generally results in a higher number of slurry foaming instances.

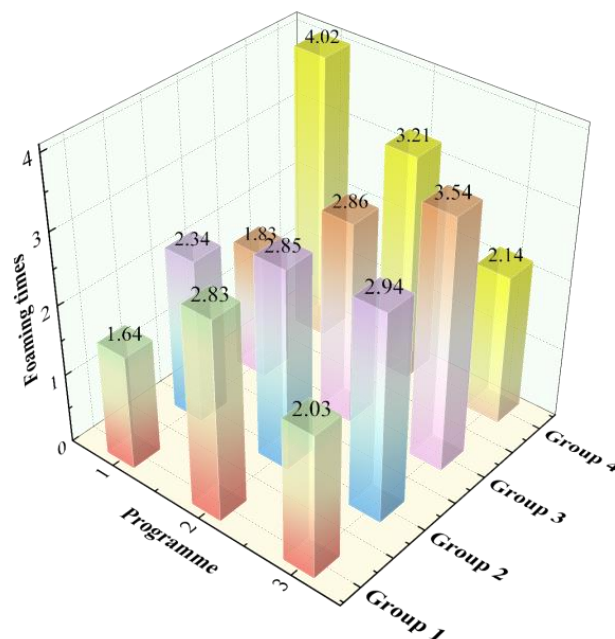


Figure 7. The histogram of the paste foaming multiple.

From Figure 8, it can be seen that the foaming time and initial setting time of the slurry are related to the proportion of B material, and the greater the proportion of B material, the greater the foaming time of the slurry is, and the initial setting time is eased.

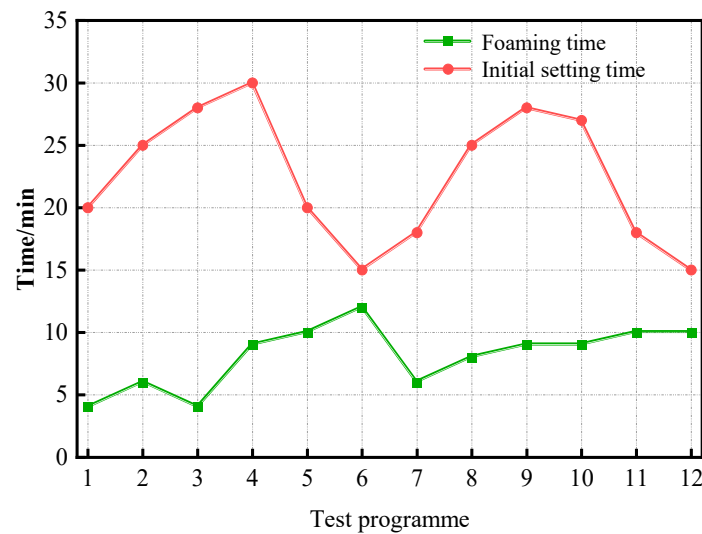


Figure 8. Plasma foaming and coagulation time histogram.

4.3. Strength Performance Analysis

The inorganic cementitious filling material, obtained by mixing and stirring base materials A and B along with the foaming agent, allows for observation and recording of the shape, foaming volume, and condensation time of the cementitious body through physical experiments. However, obtaining the compressive strength of the material requires conducting strength tests. Hence, for inorganic cementitious filling materials with varying ratios, strength tests are necessary. Only materials with a certain strength can effectively control the deformation of the roadway peripheral rock during mining operations.

(1) Strength test analysis of the first group of specimens

Three specimens were taken out from the filling materials obtained from the first group of experiments for compressive strength testing, and the loading method was force loading. The specimens are rectangular; the 1–3 specimen sizes were 5 cm × 6 cm × 6 cm, 5 cm × 6 cm × 6 cm, and 5 cm × 6.8 cm × 6 cm after 30 days of maintenance and measurement of its uniaxial compressive strength. Figure 9 shows the strength test curves of specimen numbers 1–3.

Figure 9 illustrates the peak compressive strength of the specimens: No. 1 at 0.88 MPa, No. 2 at 0.68 MPa, and No. 3 at 0.92 MPa. The load-induced damage process of these specimens encompasses stages of pore compression, density, elasticity, and plasticity damage, stress peaking at the yielding stage, followed by specimen destruction and a rapid reduction of stress to zero. The stress–strain curve of Specimen 1 exhibits a relatively smooth progression with an extended loading time, while Specimens 2 and 3 display notably similar stress–strain curves. Analyzing the deformation and damage characteristics of the specimens leads to the following conclusions: Specimen 1 shows complete cracking at the top, with intertwined transverse and longitudinal cracks on the surface; Specimen 2 features two longitudinal cracks in a ‘Y’ shape pattern along with a short longitudinal crack on the lateral side; Specimen 3 primarily exhibits five longitudinal cracks under the applied pressure.

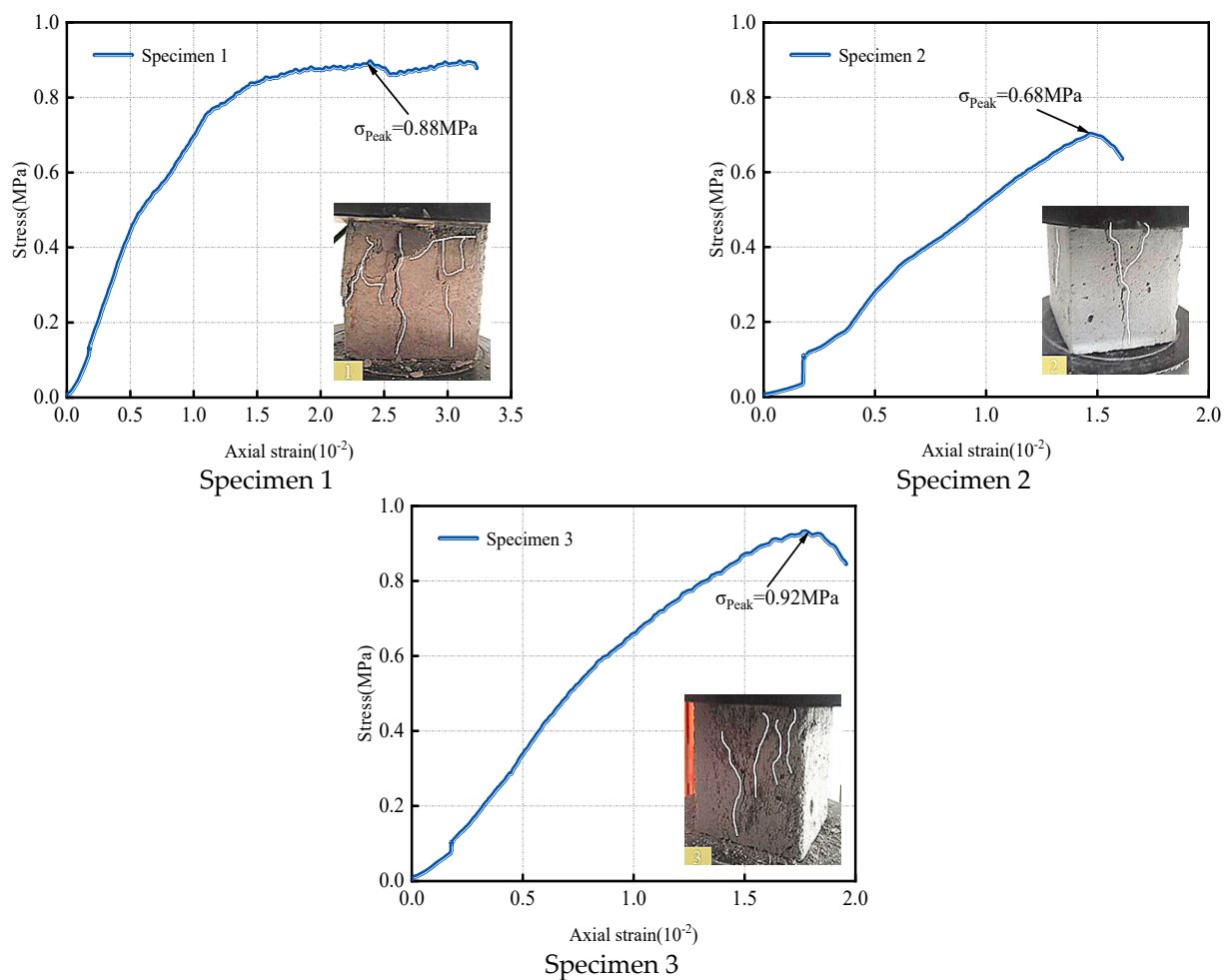


Figure 9. Stress–strain curve of the first group.

(2) Strength test analysis of the second group of specimens

Three specimens were taken out from the filling materials obtained from the second group of experiments for compressive strength testing, and the loading method was force loading. The specimens are rectangular; the sizes of specimens 4–6 are $6 \text{ cm} \times 7 \text{ cm} \times 6 \text{ cm}$, $5 \text{ cm} \times 6.4 \text{ cm} \times 6 \text{ cm}$, and $5 \text{ cm} \times 6 \text{ cm} \times 6 \text{ cm}$, and their uniaxial compressive strength was measured after 30 days of maintenance. Figures 4–7 show the strength test curve of specimen numbers 4–6.

In Figure 10, the peak compressive strength of the specimens is as follows: No. 4 at 0.71 MPa , No. 5 at 0.87 MPa , and No. 6 at 0.44 MPa . Specimens 4 and 5 initially undergo pore compression and density stages during loading, resulting in a compression-dense and closed internal pore structure. Subsequently, they enter the elastic-plastic stage, reach the yielding point, and ultimately deform and incur damage under peak stress conditions, retaining some residual strength. The loading curve of Specimen 6 exhibits distinct differences, with a relatively short loading damage process and a comparatively lower compressive strength. Notably, when subjected to a 1 kN load, Specimen 6 experiences a steep deformation decline, followed by a short period of stress reduction before slowly rising again until reaching the peak point. This phenomenon is presumed to occur due to the significant addition of B material, altering the internal structure of the specimen. Through the deformation, the damage characteristics of the specimen can be concluded: the upper right corner of the 4th specimen has been cracked, and the surface of the specimen is distributed with several longitudinal cracks of varying lengths, of which the length of the deepest crack is almost the specimen is split in two. Specimen 5's surface is loose and

porous, overall flatter, and the deformation damage that occurred under the action of the press manifested as two longitudinal cracks in a 'Y' shape. The surface of specimen 6 has fewer cracks, and the whole specimen seems to be more intact, with no phenomenon of dropping and breaking, and three cracks are distributed in the shape of an 'X'.

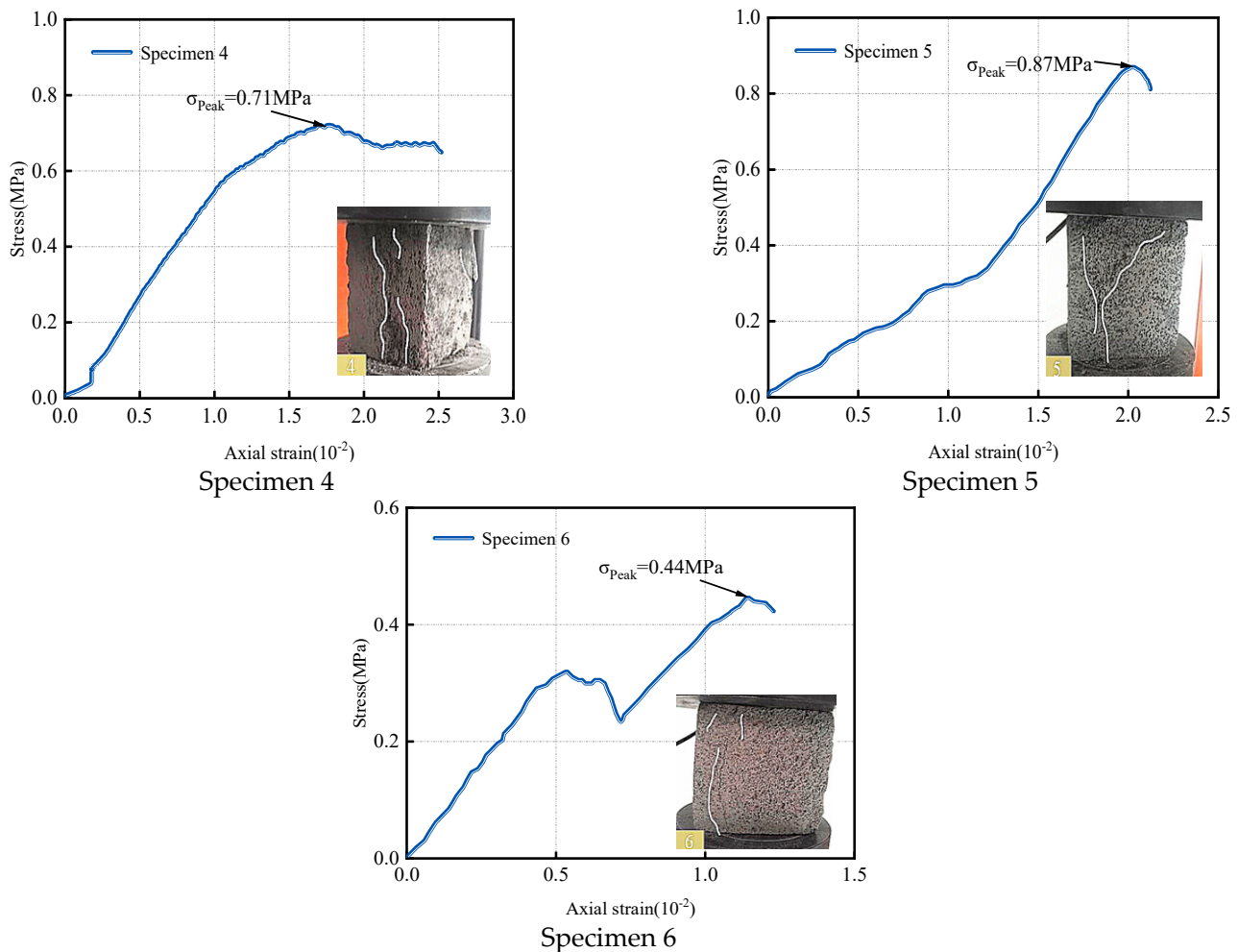


Figure 10. Stress–strain curve of the second group.

(3) Strength test analysis of the third group of specimens

Respectively, the third group of experiments was obtained from the filling material, taking out three pieces of specimens for compressive strength testing, in loading mode for force loading. The specimens are rectangular, and the sizes of specimens 7–9 are $6 \text{ cm} \times 6 \text{ cm} \times 6 \text{ cm}$, $5 \text{ cm} \times 6 \text{ cm} \times 6 \text{ cm}$, and $5 \text{ cm} \times 6 \text{ cm} \times 6 \text{ cm}$, and their uniaxial compressive strength was measured after 30 days of maintenance. Figures 4–8 show the strength test curve of specimens 7–9.

In Figure 11, the peak compressive strengths of the specimens are as follows: No. 7 at 1.01 MPa, No. 8 at 0.88 MPa, and No. 9 at 0.38 MPa. Each specimen initially undergoes a pore compression stage where internal pores are compacted and closed under load. They subsequently progress into the elastic-plastic stage, yielding under increasing load until eventual deformation and failure under peak stress, yet retaining residual strength. Specimen 8 notably exhibits a prolonged decrease in load-carrying capacity after reaching peak stress, contrasting with its shorter time to peak stress compared to other specimens. Specimen 9 experiences a shorter overall loading and destruction process, characterized by lower strength, attributed to the substantial addition of the blowing agent altering its behavior. Through the deformation and damage characteristics of the specimens, it

can be concluded that Specimen 7 is more complete; the crack is short and shallow in the lower left corner of a transverse crack, but the length is not large. Specimen 8 has more serious destruction of the right side of the local slag phenomenon; the surface of the main distribution of the two cracks was an 'X' extension. Specimen 9 has a large depth of longitudinal cracks throughout the entire specimen. The front side of Specimen 9 has a large depth longitudinal crack that runs through the whole specimen, almost splitting the specimen into two.

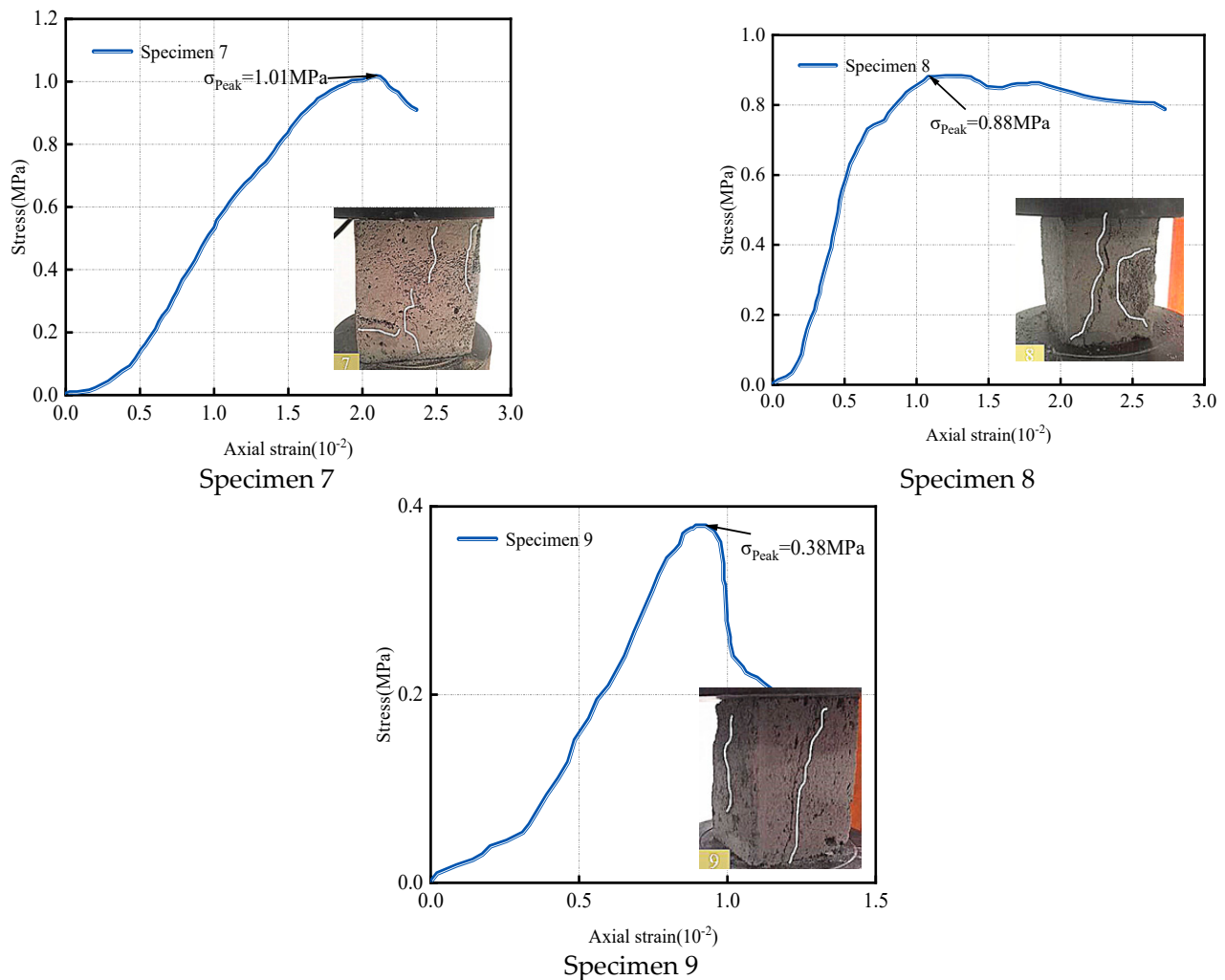


Figure 11. Stress–strain curve of the third group.

(4) Strength test analysis of the fourth group of specimens

Respectively, from the fourth group of experiments obtained from the filling material, taking out three pieces of specimens for compressive strength testing in loading mode for force loading, specimens 10–12 were rectangular, and their sizes were $5 \text{ cm} \times 6 \text{ cm} \times 6 \text{ cm}$, $5 \text{ cm} \times 6 \text{ cm} \times 6 \text{ cm}$, and $6.2 \text{ cm} \times 6.5 \text{ cm} \times 6 \text{ cm}$, after 30 days of maintenance and measurement of their uniaxial compressive strength. Figures 4–9 show the specimen strength test curve.

Figure 12 illustrates the peak compressive strengths of the specimens: No. 10 at 0.41 MPa, No. 11 at 0.51 MPa, and No. 12 at 0.90 MPa. Initially elastic during the pore compression stage, the specimens contain numerous air holes and pores that close under load, leading to gradual deformation with increasing load and a transition to the elastic-plastic stage. Upon final destruction, the stress peaks before a sharp decline, indicating residual load-bearing capacity. Specimens 10 and 11 exhibit shorter loading processes

and lower compressive strength than Specimen 12, whose force-deformation curve displays clear serrations suggesting intermittent load-bearing capacity. Specimen 12 further shows a sawtooth shape, indicating internal structural instability resulting in fluctuating stresses but retaining some load-bearing capacity post-destruction. Examination of the specimens' deformation and damage reveals distinct characteristics: Specimen 10 displays three varying-length cracks, Specimen 11 features large transverse and longitudinal cracks intertwining vertically, while Specimen 12 presents longitudinal cracks at the corners without significant surface cracks elsewhere.

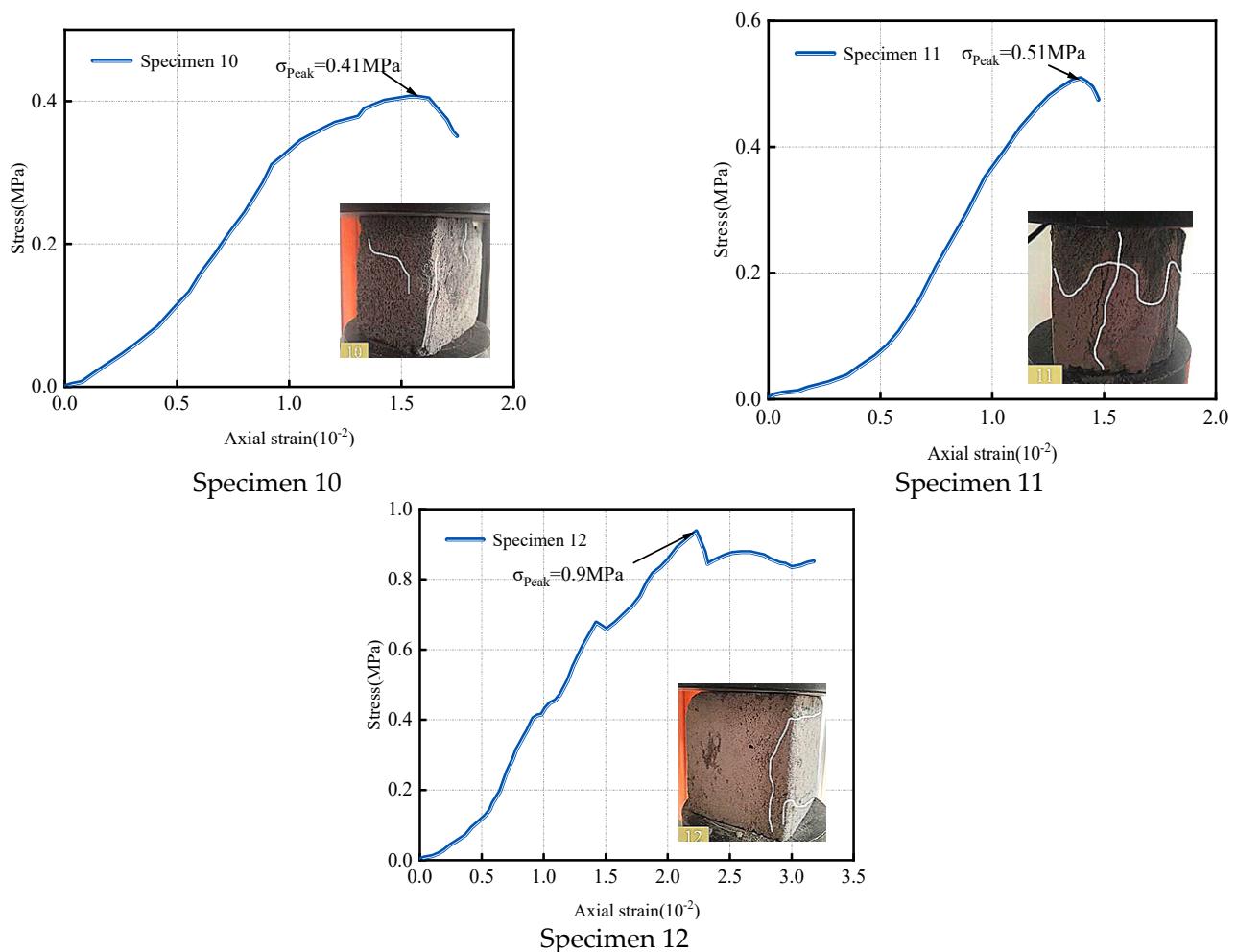


Figure 12. Stress–strain curve of the fourth group.

Table 3 is the strength of four groups of specimen test data; the analysis shows that the compressive strength of the inorganic cementitious filling materials and the proportion of B material, the amount of blowing agent, and the water/cement ratio are related to the highest compressive strength of the material obtained by the experiment, which was 1.01 MPa. The lowest was 0.38 MPa, and the visible composition of the material and the ratio correspond to a greater disparity between the compressive strength.

In Figure 13, it is evident that a higher water/cement ratio correlates with lower compressive strength of the filling material. Similarly, increased blowing agent quantity results in decreased compressive strength, while a higher proportion of B material enhances compressive strength, though diminishing returns occur beyond a certain threshold. Therefore, when preparing inorganic cementitious filling materials, it is crucial to balance foaming times for economic efficiency, control the water/cement ratio for adequate strength, and optimize material ratios to ensure desired properties.

Table 3. Specimen strength test data.

Group Number	Program	Contact Area/cm ²	Peak Force/KN	Peak Compressive Strength/MPa	Deformation/mm
Group 1	Programme 1	30	2.64	0.88	3.24
	Programme 2	30	2.04	0.68	2.01
	Programme 3	34	3.14	0.92	1.91
Group 2	Programme 4	42	3.01	0.71	2.50
	Programme 5	32	2.78	0.87	2.11
	Programme 6	30	1.32	0.44	1.21
Group 3	Programme 7	36	3.66	1.01	2.34
	Programme 8	30	2.64	0.88	2.70
	Programme 9	30	1.13	0.38	1.32
Group 4	Programme10	30	1.23	0.41	1.72
	Programme11	30	1.54	0.51	1.44
	Programme12	40	3.60	0.90	3.19

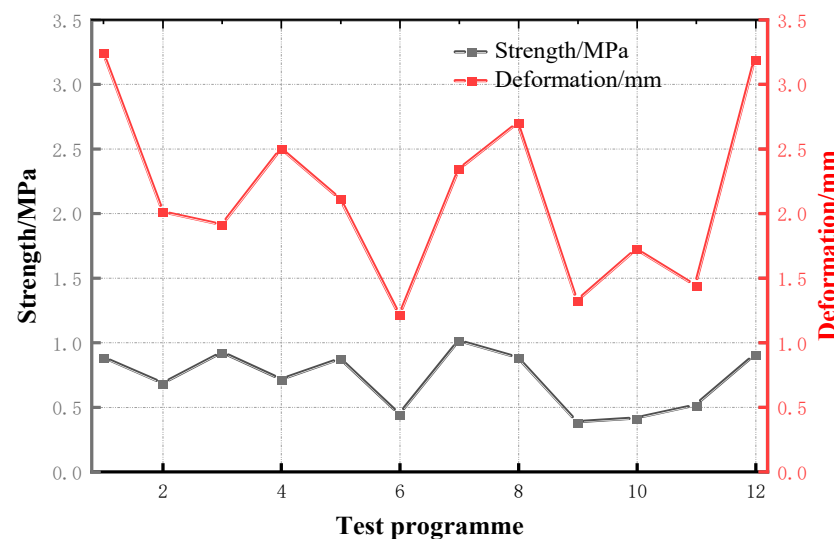


Figure 13. Intensity distribution histogram of samples.

From the economic benefit point of view, the higher the foaming times of the filling material, the larger the volume of the abandoned roadway that can be filled by the unit quality of the cementitious material, and the lower the corresponding economic cost. From the point of view of the compressive strength of the material, the smaller the water/cement ratio, the greater the strength of the filling material. However, with the preparation of materials A and B, material consumption increases, the foaming times also reduce, and the corresponding economic costs rise steeply. Therefore, controlling the water/cement ratio and foaming times to determine a reasonable material ratio is the key factor in the preparation of inorganic cementitious filling materials.

From the four groups of experimental results, program 10 has the largest number of foaming times at 4.02, but its compressive strength is low, only 0.41 MPa. Program 1 has the lowest foaming times at only 1.64 times, but the compressive strength is larger, at 0.88 MPa. Program 7's compressive strength is the largest, 1.01 MPa, but only foams 1.83 times. Program 9's compressive strength is the smallest, at only 0.38 MPa, but with foaming times of 3.54. Programs 3 and 12's strength and foaming times are more satisfactory, but with a water/cement ratio of 1:2 under the same conditions, the consumables are large, and the cost is high. The material properties obtained by these six schemes are more one-sided, failing to take into account the dual requirements of the economy and strength. According to the aforementioned analysis, through the empirical formula calculated by

the Jingxin Coal Industry, the 3122 comprehensive discharge face abandoned roadway filling material requires a strength of not less than 0.57 MPa, the best choice is the water/cement ratio of program 4, program 5, and program 8 of 1:1.5, with foaming multiples of 2–3 times, and a strength of 0.7 to 0.9 MPa—basically the characteristics of being low-cost and high-strength are the best choice for the abandoned roadway filling material. When preparing the material on site, it can be prepared according to the material proportion of program V, i.e., water:material A:material B:foaming agent = 1:1.5:0.12:0.1, a foaming time of 8–10 min, and an initial setting time of 15–25 min.

5. Working Face Abandoned Roadway Filling Technology Process

5.1. Conveying and Filling Process

The new inorganic cementitious filling material comprises three components: A material, B material, and foaming agent. During slurry preparation, both A and B materials are mixed thoroughly with the foaming agent. The slurry is pressurized using a filling pump, conveyed via a double-trip high-pressure pipeline, and directed into a mixing device through a slurry pipe for uniform blending. Subsequently, it is filled into the abandoned roadway from bottom to top.

The abandoned roadway slurry filling technology process mainly consists of three parts: filling preparation, slurry filling, and post-filling cleaning and finishing. The basic process flow is illustrated in Figure 14.

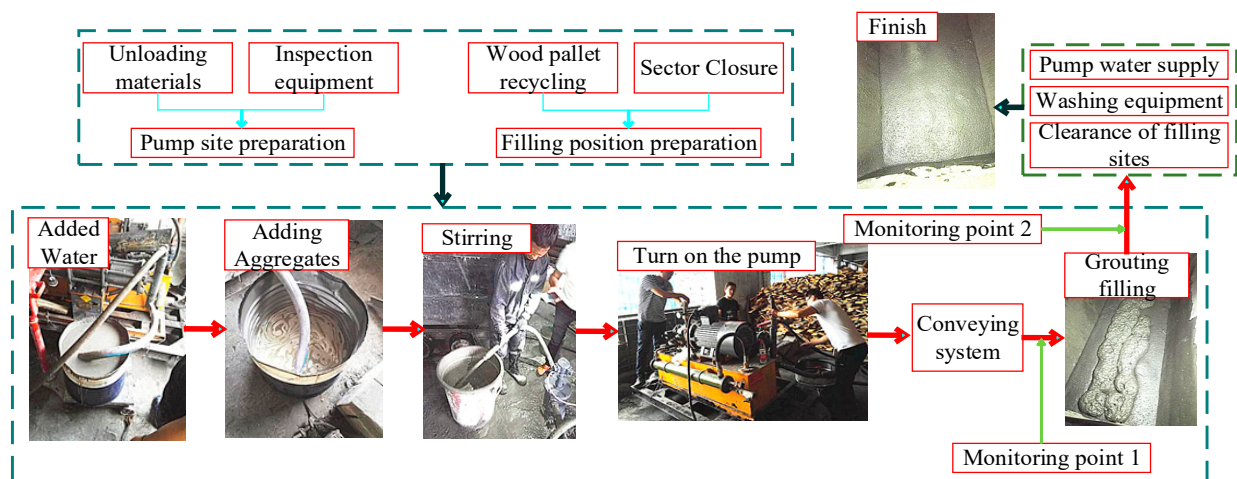


Figure 14. Flow chart of the filling process of the abandoned roadway.

- (1) Filling preparation. The unloading worker loads and unloads the grouting material at the material stacking area, while personnel from each work type coordinate operations and prepare the pumping station. Prior to filling, the abandoned roadway should be cleared by removing wooden pallets and erecting temporary containment walls to seal off the section.
- (2) Grouting and filling. Following the specified ratio of material components, the mixer will dispense the materials into the mixing bucket for thorough blending. Once the slurry is prepared, start the pump and use the conveyor system to transport the materials to the filling location for grouting. During the filling process of the abandoned roadway, at least two monitoring points should be established to observe the slurry condition and filling progress, respectively.
- (3) Cleaning and finishing. After completing the filling of the section, seal the grouting holes, activate the pump to flush water through the system, clean the grouting pipeline, organize the equipment, and prepare for the next section of grouting and filling.

5.2. Field Test of Inorganic Cementitious Material for Abandoned Roadway

As shown in Figure 15, the transport roadway of the 3122 working face of Jingxin Coal Industry is a trapezoidal section, with an upper width of 3700 mm, a lower width of 4300 mm, and a height of 2750 mm, and the abandoned roadway of the 3122 working faces is rectangular, with a width of 4500 mm, and the height of 5000 mm, considering that there is a height difference of 2250 mm between the transport roadway of 3122 and the abandoned roadway, the grouting pipe leads out from the transport roadway of 3122 and injects grout into the abandoned roadway diagonally upwards, leaving a 0.5 m distance between the end position of the pipe and the top plate of the abandoned roadway. To facilitate the operation, the slurry pipe can be designed to be installed on the wall of the roadway and fixed with wire. In the underground filling test, due to the limitations of the site construction conditions, the pipeline system has not been perfected, and it is necessary to lift the pipe manually, spray slurry in the bucket in advance, and observe the foaming and solidification phenomenon, to ensure that the slurry can be foamed normally before carrying out the filling test on the abandoned roadway.

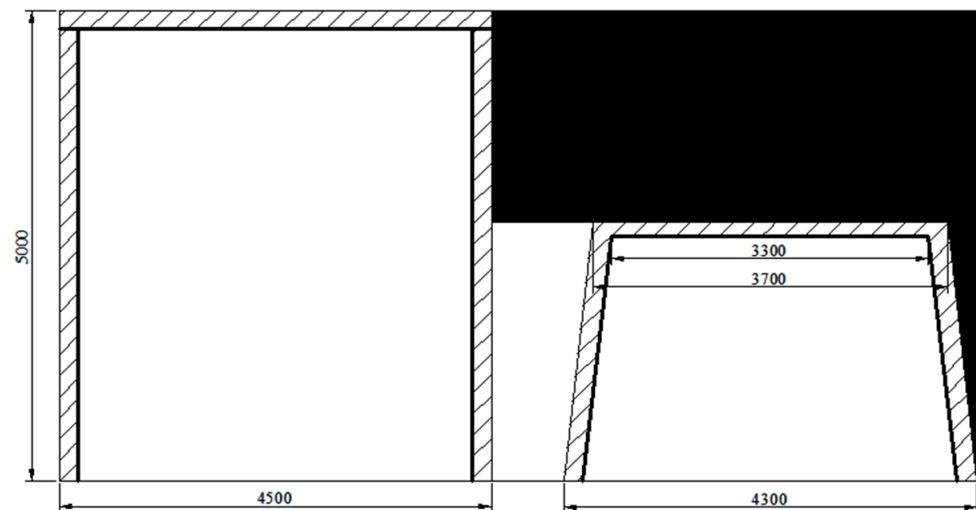


Figure 15. Position of abandoned roadway section.

Through the initial test downhole, the filling equipment operated effectively. The slurry is prepared according to the material proportion in Program 5. In the underground environment, the slurry displays excellent foaming properties with a stable internal structure. Initially, a few bubbles may escape from the surface as the slurry begins to foam. Once sufficiently foamed, the slurry fills the container with a concave-convex shape on the contact surface, indicating a good foaming effect. As shown in Figure 16, after the slurry is prepared and shaped, it enters the test site to be filled through the conveying system, and the filling material can rely on its fluid pressure to be completely paved and covered inside the abandoned roadway, the surface is even and flat after filling, and no accumulation of slurry is found.

The slurry began to foam and expand once it was filled into the abandoned roadway. Initially, air bubbles escaped from the middle of the filled section, causing the slurry to bulge and form stripes and unevenness. Gradually, it spread to fill the entire space. Through the underground filling practice, it was observed that using the new type of inorganic cementitious filling material for grouting and filling the abandoned roadway resulted in good slurry foaming, meeting the filling requirements. Further observation of mine pressure during later mining stages will help understand the distribution of the surrounding rock stress and deformation, ensuring smooth passage through the abandoned roadway and enabling safe and efficient mine production.

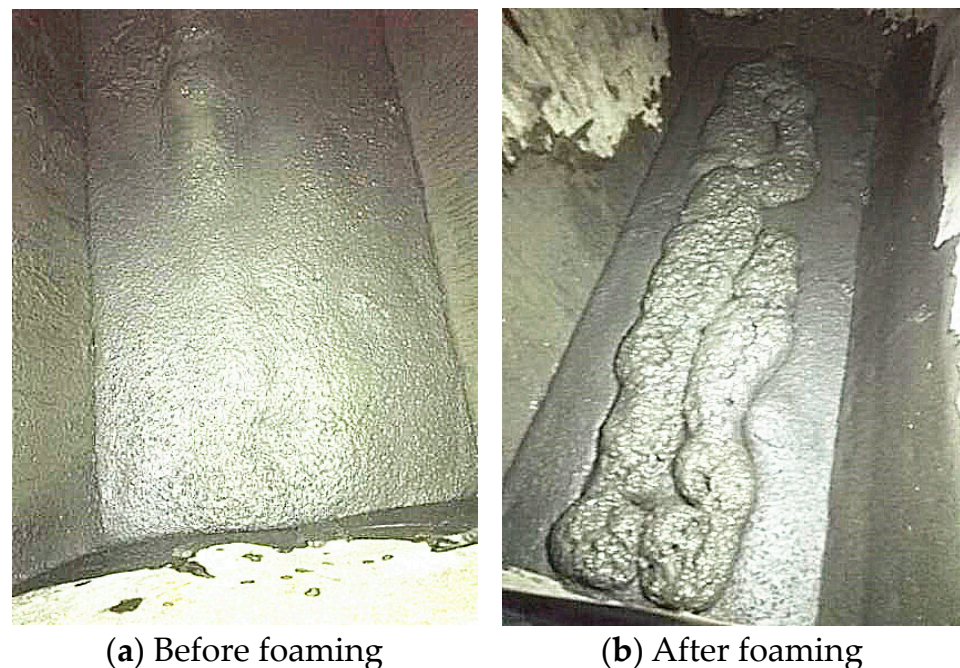


Figure 16. Abandoned roadway filling effect.

5.3. Observation of Mine Pressure

Mine pressure observation was carried out in the process of mining the back of the 3122 comprehensive faces, to analyze the mine pressure manifestation law of the 3122 comprehensive faces after filling the abandoned roadway and the peripheral rock deformation of the transport roadway. Two end hydraulic supports were selected in the part of the working face close to the end of the transport roadway to carry out the observation of the support resistance, record the change rule of the hydraulic support resistance with the advancing distance of the working face, and set the displacement measurement station in the transport roadway at a distance of 30 m from the cutting-off. At the same time, a displacement station was set 30 m from the cutting-off in the transport roadway to observe the roof subsidence and the displacement of the roadway gang in the transport roadway, as shown in Figure 17.

The Jingxin Coal Industry 3122 comprehensive face end hydraulic support model ZT11600/18/26 pump station has a working pressure of 31.5 MPa and an initial support force of up to 8728 KN. As shown in Figure 18, the working face hydraulic support resistance distribution curve can be seen, and the 3122 comprehensive face in the process of mining has not been found in the mining anomalies. The 2# hydraulic support working resistance is slightly greater than the 1# hydraulic support resistance, presumably due to the 2# hydraulic support being closer to the transport roadway in the part of the vertical contact between the abandoned roadway and the working face.

Table 4 is based on the hydraulic support resistance distribution curve statistics of the pressure step distance. The mine pressure is not obvious during the mining. From the 1# hydraulic support, the cycle pressure step of the 3122 working face is 10 m, and the initial pressure step is 18 m. From the 2# hydraulic support, the cycle pressure step of the 3122 working face is 11 m, and the initial pressure step is 12 m.

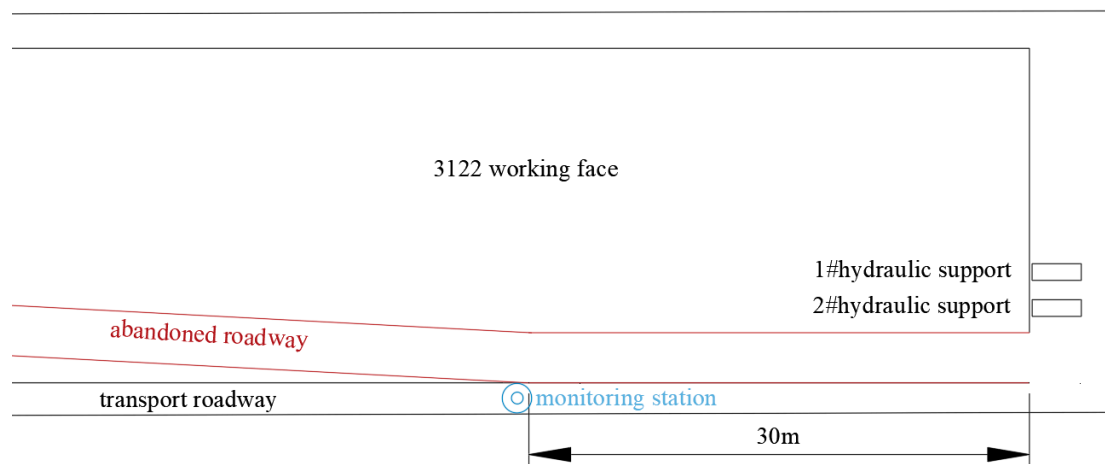


Figure 17. Survey station layout schematic.

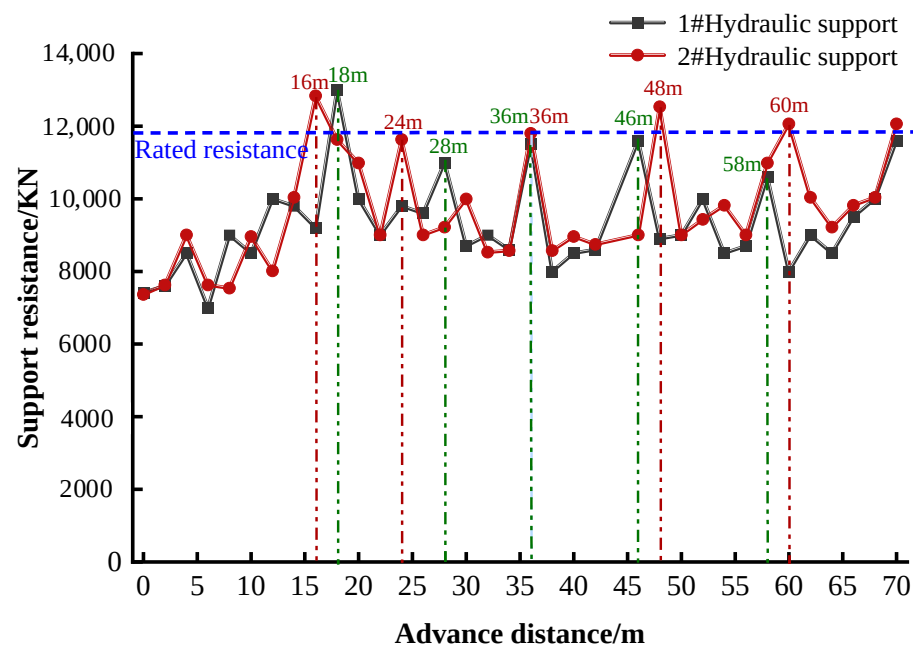


Figure 18. The distribution diagram of the working resistance.

Table 4. Working face pressure step distance.

Hydraulic Support Number	Initial Pressure Appearance Distance/m	Cycle to Pressure Distance/m				Average Cycle to Pressure Distance/m
		1	2	3	4	
1#	18	10	8	10	12	10
2#	16	8	12	12	12	11

To monitor peripheral rock deformation in the transport roadway, displacement monitoring points are strategically placed to track top and bottom plate sinking and peripheral rock movement towards the two gangs. Figure 19 illustrates the arrangement of these monitoring points. Displacement observation on the roadway surface follows a ‘cross’ distribution method. At the 3122 transport roadway measuring station, four measuring base points—W, S, G, and H—are selected. Holes are drilled, and pins are installed at these points to record top and bottom slab deformation as well as gang movement. Base

points W and S align with the centerline of the roadway, while G and H are positioned at the waistline.

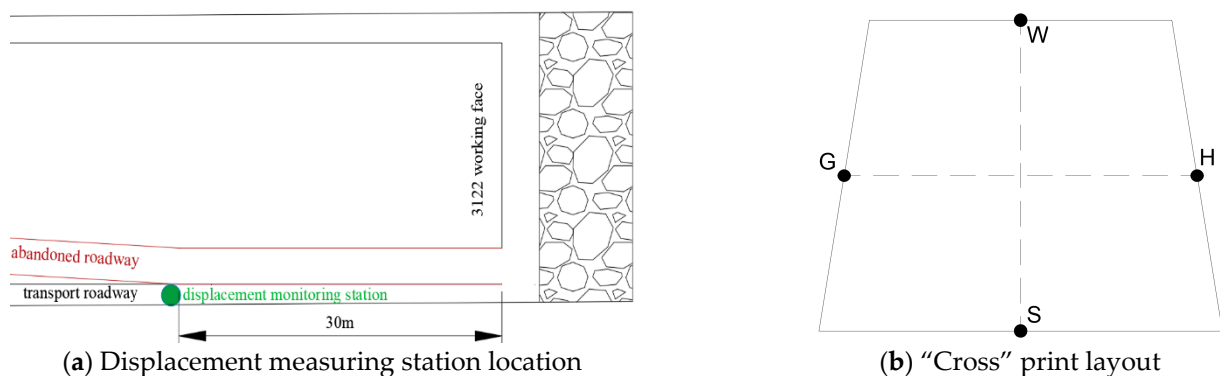


Figure 19. Layout diagram of displacement observation.

The observation results of surface displacement of the 3122 transport roadways are shown in Figure 20. From the figure, it can be seen that, during the mining process of the 3122 working face, the maximum relative displacement of the top and bottom plates of the transport roadway is 142 mm, and the maximum relative displacement of the two gangs is 95 mm. When the working face advances to 30–40 m, nearing the displacement station, the deformation rate of the top and bottom plates of the transport roadway and the two gangs peaks. However, the deformation rate of the peripheral rock in the transport roadway slows down after the working face advances to 50 m. Generally speaking, the deformation rate of the peripheral rock of the transport trench increases with the mining of the working face and finally tends to be stable. In the actual mining process, when the working face passes through the abandoned roadway, no large deformation occurs in the transport chute, and there are no accidents of sheet gangs and roofing, which indicates that the filling of the abandoned roadway effectively controls the deformation of the peripheral rock of the roadway, maintains the safety and stability of the transport chute, and realizes the safe production of the working face.

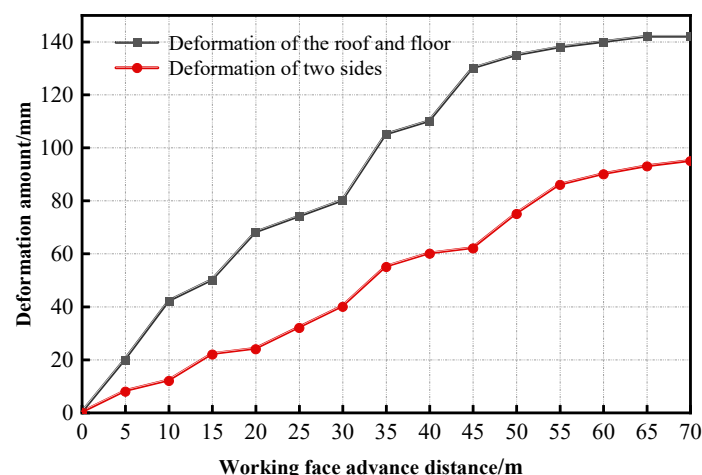


Figure 20. Deformation observation curve of surrounding rock.

6. Discussion

In this paper, detailed geological conditions of the 3122 working face in the Jingxin Coal Industry are presented. Phenomena such as roof fractures and instability of the two gangs are attributed to the surrounding rock's inability to withstand the overhead support pressure during back mining, emphasizing the importance of filling the abandoned

roadway for safety. A new type of inorganic cementitious filling material, developed based on existing foamed cement methods, is introduced. This material boasts low cost, ease of cutting, convenience in washing and selection, and excellent filling performance. Previous literature extensively discusses abandoned roadway filling materials [8–15]. This paper introduces an innovative method for preparing a new type of inorganic collodion filling material. The main ingredients include cement, lime powder, foam stabilizer, and foaming agent, mixed and stirred at a 1:1.5 water/cement ratio. After solidification, the mixture is foamed 2–3 times to achieve the desired filling properties. Compared to other filling materials, this new material exhibits sufficient strength, quick solidification, and the ability to fully expand and connect with the roof. These features enhance efficiency in filling working faces, reduce filling costs, and advance the development of inorganic cementitious filling materials.

In this paper, the specific implementation plan of using new inorganic gel filling material to fill the abandoned roadway is proposed and successfully applied in the abandoned roadway of the 3122 working faces in the Jingxin Coal Industry. Compared with other filling materials, the new inorganic cementitious filling material can not only ensure the safety of the working face through the abandoned roadway but also has the advantages of safety, ease of cutting and washing, low cost, and so on. The inorganic cementitious filling technology provides new materials, new techniques, and new perspectives for filling air shafts, and provides valuable insights for other mines encountering similar challenges.

7. Conclusions

In this paper, an inorganic gelling filling material for abandoned roadway filling has been successfully developed. On this basis, the abandoned roadway filling technology was proposed and effectively implemented in the actual underground operation. The following conclusions are drawn:

(1) Aiming at the actual needs of filling the abandoned roadway of the 3122 working faces in the Jingxin Coal Industry, a new type of inorganic cementitious filling material was prepared through laboratory experiments. According to the different ratios of material components A and B base materials and foaming agent, a total of 12 experimental programs are proposed, and the results show that:

1. When the amount of base material B is controlled in a certain proportion, it can not only improve the foaming effect of the slurry but also shorten the condensation time of the slurry and increase the compressive strength of the material. But when the proportion of the B material is more than a certain degree, the strength of the collodion material decreases instead of rising.
2. Foaming agent can control the slurry foaming times—the larger the amount of foaming agent, the higher the slurry foaming times. At the same time, it will reduce the compressive strength of the filling material; therefore, it is not a case of “the more, the better” with regard to the amount of foaming agent, and it is combined with the need for the strength of the material to be determined comprehensively.
3. The water/cement ratio is the main factor affecting the compressive strength of inorganic cementitious materials; the greater the water/cement ratio, the smaller the compressive strength of the material. But the material used to prepare the material is reduced, and thus the cost is lower. Taking into account the need for the material to have a certain strength, a water-cement ratio of 1:1.5 or so is appropriate.

(2) As a result of the comprehensive test, the inorganic cementitious filling materials of program 4, program 5, and program 8 with a water/cement ratio of 1:1.5, foaming multiples of 2~3 times, and strength of 0.7~0.9 MPa can meet the requirements for filling the abandoned roadway. Eventually, program 5 was chosen as the material ratio for filling the 3122 working faces of the Jingxin Coal Mine.

(3) Based on the actual situation of filling the abandoned roadway in the 3122 working face of the Jingxin Coal Industry, the filling scheme and technical process of the abandoned roadway were determined. Before filling, the wood stacks should be recovered, and then

filling should be carried out in sections. In addition to the temporary confinement of each section, both ends of the filling section and the gangway of the section in contact with the transport roadway should be closed. The filling system includes two parts—the slurry-making system and the conveying system. The filling technology includes three parts—filling preparation work, filling slurry injection work, and cleaning and finishing work after filling.

(4) The above research results for the Jingxin Coal Industry 3122 working face industrial testing show that the inorganic gel filling material field application effect is good, the mining process did not find mining pressure anomalies, the transport channel is safe and stable, and no large displacement occurred.

Author Contributions: L.S.: Formal analysis; Methodology; Writing—Original Draft. C.L.: Conceptualization; Writing—review and editing; Supervision, Funding acquisition. Z.X.: Methodology; Conceptualization. L.T.: Visualization; Writing—review and editing. Y.C.: Conceptualization. All authors have read and agreed to the published version of the manuscript.

Funding: This work was funded by the National Natural Science Foundation of China (Grant No. 52374140) and the GraduateInnovation Program of China University of Mining and Technology (2024WLKXJ022) and the Postgraduate Research & Practice Innovation Program of Jiangsu Province (KYCX24_2856).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data, models, or codes that support the findings of this study are available from the corresponding author upon reasonable request. The data are not publicly available due to privacy.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Wang, C.; Li, G.; Yu, Z.; Xu, B. Stability and Sealing of Abandoned Roadways under High Internal Pressure. *Min. Metall. Explor.* **2023**, *40*, 871–884. [\[CrossRef\]](#)
2. Shi, S.; Miao, Y.; Wu, H.; Xu, Z.; Liu, C. The Stress Evolution of Adjacent Working Faces Passing through an Abandoned Roadway and the Damage Depth of the Floor. *Energies* **2022**, *15*, 5824. [\[CrossRef\]](#)
3. Jiang, Z.; Wang, F.; Miao, K.; Cao, Q. Surrounding Rock Control Technology When the Longwall Face Crosses Abandoned Roadways: A Case Study. *Geofluids* **2021**, *2021*, 7867460. [\[CrossRef\]](#)
4. Yu, Y.; Lu, J.; Pan, Y.; Zhao, X.; Chen, D. Research and Practice on Filling Technology of Fully Mechanized Coal Mining Face through Trend Abandoned Roadway. *Sustainability* **2021**, *13*, 9920. [\[CrossRef\]](#)
5. Li, Y.; Ren, Y.; Wang, N.; Luo, J.; Li, N.; Liu, Y.; Li, G. A Novel Mining Method for Longwall Panel Face Passing through Parallel Abandoned Roadways. *Shock Vib.* **2021**, *2021*, 9998561. [\[CrossRef\]](#)
6. Luo, W.; Yu, Y.; Wang, W. Research on the Mechanism and Control of Strong Mine Pressure in Fully Mechanized Mining Face of Shandong Mining Area When Crossing Abandoned Roadways in the Same Coal Seam. *J. China Coal Soc.* **2024**. [\[CrossRef\]](#)
7. Meng, S. Mining technology for fully mechanized working face crossing large section abandoned roadway in close distance coal seam. *Coal Eng.* **2017**, *49*, 87–90.
8. Wang, H.; Luo, Y. Industrial Testing on Working Face Passing Abandoned Roadway under Pier Column Filling. *Saf. Coal Mines* **2014**, *45*, 46–49.
9. Deschamps, R.J. Using FBC and stoker ashes as roadway fill: A case study. *J. Geo-Tech. Geo-Environ. Eng.* **2008**, *124*, 1120–1127. [\[CrossRef\]](#)
10. Rashad, A.M. Metakaolin as cementitious material: History, scours, production, and composition—A comprehensive overview. *Constr. Build. Mater.* **2013**, *41*, 303–318. [\[CrossRef\]](#)
11. Scrivener, K.L.; Nonat, A. Hydration of cementitious materials, present and future. *Cem. Concr. Res.* **2011**, *41*, 651–665. [\[CrossRef\]](#)
12. Sun, Y. Preparation system design of filling material with coal gangue as coarse aggregate. *Nat. Resour. Sustain. Dev.* **2012**, *361*, 135–138. [\[CrossRef\]](#)
13. Zhao, G.Y.; Wu, H.; Chen, Y.; Xu, Z.W.; Li, Z.Y.; Wang, E.J. Experimental study on the load-bearing mechanism and compaction characteristics of mine filling materials. *J. China Univ. Min. Technol.* **2017**, *46*, 1251–1258.
14. Yao, Y.; Sun, H.; Jiang, S.; Zhang, R.; Su, D.; Feng, C.; Han, X. Performance and leaching analysis of a novel coal sludge-based backfill material. *Clean Technol. Environ. Policy* **2013**, *15*, 657–666. [\[CrossRef\]](#)

15. Sun, L.; Li, C.; Xu, Z.; Tai, L.; Cao, Y.; Zhang, X. Mitigating Risks in Coal Mining: Simulation-Based Strategy for Oxidation Zone Control Using Inorganic Paste Backfill at the Working Face Corners. *Appl. Sci.* **2023**, *13*, 13216. [[CrossRef](#)]
16. Xie, S.; Wang, E.; Chen, D.; Li, H.; Jiang, Z.; Yang, H. Stability analysis and control technology of gob-side entry retaining with double roadways by filling with high-water material in gently inclined coal seam. *Int. J. Coal Sci. Technol.* **2022**, *9*, 52. [[CrossRef](#)]
17. Li, T.; Chen, G.; Qin, Z.; Li, Q.; Cao, B.; Liu, Y. The gob-side entry retaining with the high-water filling material in Xin'an Coal Mine. *Geomech. Eng.* **2020**, *22*, 541–552.
18. Liu, Y.F.; Wu, X.H.; Zhu, T.; Wang, X.J.; Zhang, G.Y.; Wang, Z.G. Influence of Mechanical Properties of Filling Paste on Overlying Strata Movement and Surface Settlement. *Shock Vib.* **2022**, *2022*, 4687200. [[CrossRef](#)]
19. Yu, Y. Development for the New Backfilling Cementing Materials and Research on Its Properties in Coal Mine. Ph.D. Thesis, China University of Mining & Technology, Beijing, China, 2017.
20. Wu, W. Investigation on uniaxial compressive strength of flocculated slurry backfill materials for minefill applications. *Rock Soil Mech.* **2010**, *31*, 3367–3372.
21. Cui, Z.; Sun, H. The preparation and properties of coal gangue-based site paste-like backfill material. *J. China Coal Soc.* **2010**, *35*, 896–899.
22. Zheng, B.; Zhou, H.; He, R. Experimental Research on Coal Gangue Paste Filling Material. *J. China Univ. Min. Technol.* **2006**, *23*, 460–463.
23. Zhang, M.; Tian, Q.; Xu, L.; Kong, D.; Dai, J.; Guo, H. Status and Prospects of Research on Foamed Cement. *Bull. Chin. Ceram. Soc.* **2014**, *33*, 2547–2551. [[CrossRef](#)]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.