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Study on Foamed Concrete Used as Gas Isolation Material in the Coal Mine Goaf

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Abstract: In view of the serious threat of gas accumulation in the coal mine goaf and the limitations of the existing gas sealing materials, the orthogonal experiment was developed to study a new type of foamed concrete for mine gas sealing. Dry density, gas permeability, and compressive strength were studied as the material indicators according to the demands of the gas isolation material in the coal mine goaf, and the experimental results showed that foam content was the most important factor. Meanwhile, the optimum mix was selected according to the influence of foam content as well as the engineering requirement. Then two application modes of this foamed concrete for goaf gas isolation were put forward, after which the convection-diffusion model of gas was built by COMSOL Multiphysics (COMSOL Inc., Stockholm, Sweden) to reveal the mechanism of different application modes using the parameters of the new foamed concrete. Simulation results showed that this foamed concrete used as isolating material for goaf gas could significantly decrease the gas concentration in workface, which can provide a reference for similar engineering.

Keywords: foamed concrete; orthogonal experiment; optimum mix; coal mine goaf; gas isolation

1. Introduction

In recent years, China has widely used the comprehensive mechanized coal mining method, which has the characteristics of fast advancement speed and long workface. However, this method has a high degree of disturbance to the coal and rock mass, which can make the gas rapidly accumulate in the goaf and pose a serious threat to the safe production in a gas-rich coal mine [1–3]. Filling and sealing, as one of the key technologies to control the goaf gas, is a necessity to isolate the gassy areas and achieve permanent barriers between the workface and gas sources [4]. However, the existing inorganic gas-sealing materials are not efficient enough to seal the leaking gas, and the existing organic foam materials have negative impacts on the underground environment. Therefore, it is necessary to develop a low-cost, effective, and environmentally friendly material for roadway filling and sealing, which has the properties of compression, expansion, filling, sealing, and gastight, so as to ensure the safety, reliability, simplicity, and rapidity of coal mine underground work. Due to its low density, low thermal conductivity, low permeability, high expansibility, and high strength, foamed concrete has interested many experts [5,6]. Wang et al. [7] studied the effects of foam content, crumb rubber content, fly ash content, and water/binder ratio on the physical, mechanical, and waterproof properties of a lightweight foamed concrete by the single-factor and orthogonal tests. Ben et al. [8] investigated the mechanical characterization of non-autoclaved foam concrete according to its macro porosity. Khan et al. [9] investigated the effects of cement and recycled glass powder contents, water to cement ratio, and volume of foam on the plastic density, dry density, and compressive strength of foam concrete. Bing et al. [10] developed structural foamed concretes by using silica fume, fly ash, and polypropylene fiber and presented the use of fly ash for fully replacing sand to produce foamed concrete. Huang et al. [11] investigated the proportioning and properties of Portland cement-based ultra-lightweight foam concrete which was recommended to achieve energy efficiency in buildings. Zhao et al. [12] developed a new type of foamed concrete used as a seismic isolation material by orthogonal experiment. Hu et al. [13] developed a new type of foamed concrete and low-alkalinity sulphoaluminate cement, to control air leakage. However, the foamed concrete from the above studies is rarely applied in the coal mine goaf to control the gas. Some studies have studied the gas permeability of goaf or concrete: Dziurzynski et al. [14] developed a mathematical model for sealing mine goal based on the balance of the volume of a mixture supplied and contained in the body formed in the goaf. Based on the standard specimen test, Zhang et al. [15] studied the relationship between the gas permeability of slag high performance concrete and the carbonation depth, and the law of influence on carbonation depth of slag high performance concrete by the gas permeability is concluded. Md et al. [16] adopted two different procedures to carry out permeability tests on concrete specimens either unloaded or preloaded during the heating process, which showed that concrete permeability strongly depends on crack width and orientation.

Hence, this paper aims to determine the effect of mix proportions on the properties of foamed concrete and then produce a new type of foamed concrete that could be used as gas isolation material in the coal mine goaf. Firstly, the orthogonal experiment was developed to study the optimum mix, in which the dry density, gas permeability, and compressive strength were studied as material indicators. Then two application modes of the foamed concrete for gas isolation in a mining area were investigated. At last, taking a large-space goaf with high-strength and rapid advance as the engineering background, the convection-diffusion model of gas was built to reveal the mechanism of different application modes using the parameters of the new foamed concrete.

2. Material and Methods

The foamed concrete in this paper mainly consists of the foam, cement, water, and other admixtures. Foamed concrete has unique properties such as low density, low strength, high impact resistance, and thermal insulation. However, its expansibility and gas permeability are dominant when used as a gas isolation material in the coal mine goaf. The objective of the orthogonal experiment was thus to produce a new type of foamed concrete that had low density, certain strength, and low gas permeability.

2.1. Material

The materials used in this investigation mainly include the Portland cement (grade 42.5, China United Cement Group Co., Ltd., Xuzhou, China), naphthalene series superplasticizer, sodium silicate solution and concentrated high-efficiency cement foaming agent (Zhengzhou Pengyi Chemical Building Materials Co., Ltd., Zhengzhou, China). The properties of the Portland cement and the sodium silicate solution are shown in Tables 1 and 2.

Table 1. Indexes of ordinary Portland cement.

Fineness/%	Initial Setting Time/min	Final Setting Time/min	Compressive Strength/MPa		
			3 days	14 days	28 days
2.4	162	247	4.6	36.4	45.6

Table 2. Parameters of sodium silicate solution.

Baume Degree/°Be	Modulus	Density/(g/mL)	SiO_2/%	Na_2O/%	Fe/%
40	3.2	1.37	26.3	8.6	0.5

2.2. Design of the Orthogonal Experiment

The four main factors of foamed concrete that can affect its properties were chosen according to the experimental goal: water cement ratio, foam (by volume), water reducing agent (by weight), and sodium silicate solution (by weight) based on 1 kg mass of solid powder. For each component, there were four levels, and thus, in total, 16 concrete series were investigated. According to the early analysis of the single factor influence of foamed concrete, the most suitable proportioning interval is determined, as shown in Table 3.

Table 3. Parameters for orthogonal experiment.

Level	Water Cement Ratio	Foam/L	Water Reducing Agent/%	Sodium Silicate Solution/%
1	0.40	0.5	0.2	0.5
2	0.45	1.0	0.4	1.0
3	0.50	1.5	0.6	2.0
4	0.55	2.0	0.8	3.0

2.3. Specimen Preparation

As shown in Figure 1, the specimen preparation can be summarized as follows: firstly, the foaming agent was diluted with water at a ratio of 1:20 (by volume) and then added to the foaming machine. Secondly, the Portland cement, water-reducing agent, and sodium silicate solution are mixed evenly according to a certain mix proportion to make a cement slurry of certain water cement ratio, and then the foam produced in the first step was added and mixed until a uniform slurry was produced. Thirdly, the specimens were poured into molds and compacted with an external vibrator, demolded after 24 h, and kept in a box at constant temperature (22 ± 2 °C) and humidity (95%) up to the day of testing.

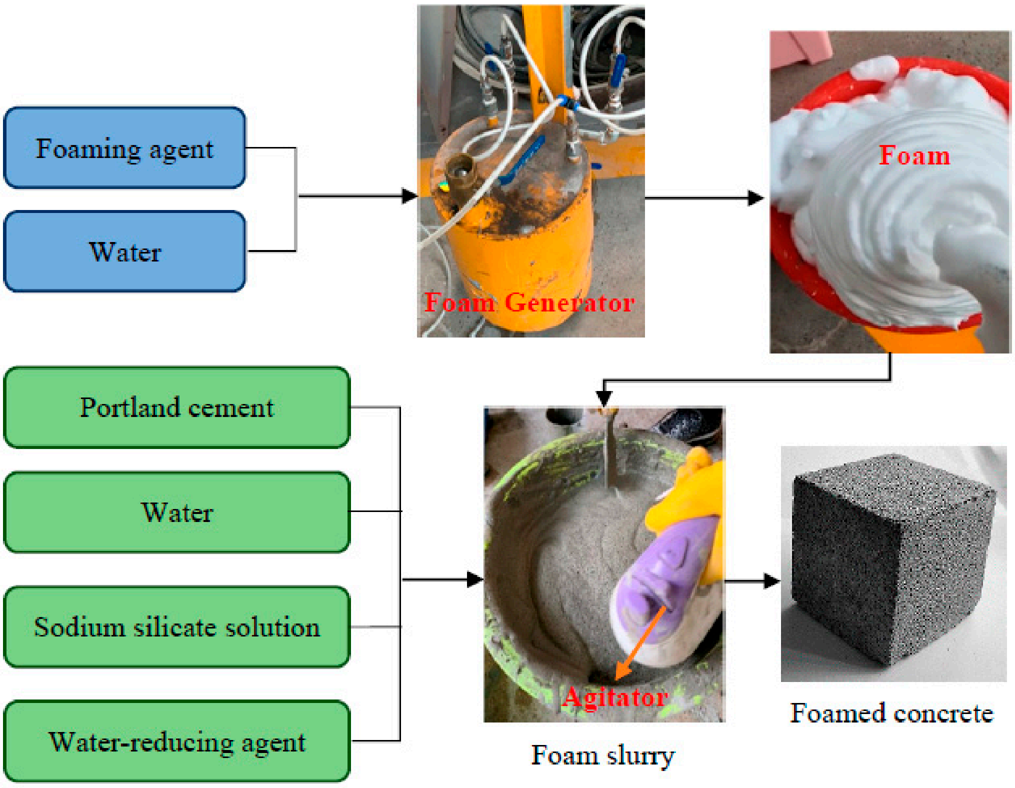


Figure 1. Procedure of specimen perpetration.

2.4. Test Contents and Methods

2.4.1. Dry Density

In order to save the engineering cost, foamed concrete needs to be of good expansibility, and dry density was chosen as the evaluation index of the expansibility, which is convenient for measurement. The standard cylindrical samples of 50 mm × 100 mm were selected, put into a constant temperature vacuum drying oven (see Figure 2), adjusted to 80 ± 5 °C for 24 h, and then the temperature adjusted to 120 °C until gaining the constant weight M. The diameter and height of the sample were measured, and its volume was calculated V. Then the dry density ρ of the concrete material can be obtained by the formula:

$$\rho = \frac{M}{V} \times 1000 \tag{1}$$

where, ρ is the dry density of the sample, kg/m^3; M is the mass of the sample after drying, g; V is the volume of the sample, cm^3.

Figure 2. Constant temperature vacuum drying oven.

2.4.2. Gas Permeability

The foamed concrete is mainly used to isolate gas in the coal mine goaf, so the gas permeability is used as anther evaluation index, which can be tested by gas permeability measurement system (see Figure 3). First, 50 mm of the samples was cut off in dry density test, a layer of epoxy resin was applied on the outside of samples, and the sample was put into the concrete gas penetration tester, ensuring the airtightness of the device. Then the air pressure was controlled to be about 0.1–0.2 MPa at the inlet in the tester, so that the gas entered into the sample from the lower surface and exited from the upper surface. The air inlet pressure P_1 and air outlet pressure P_2 were recorded under different air supply pressures. Then, the gas permeability of the sample can be easily obtained from the apparent gas permeability k_a, which can be calculated as follows:

$$k_a = \frac{Q}{A}\frac{2\eta h P_1}{P_1^2 - P_2^2} \tag{2}$$

where, k_a is the apparent gas permeability, m^2; Q is the gas flow, mL/min; A is the cross section area of the sample, mm^2; η is the viscosity of the compressed gas, Pa·s; h is the height of the test piece, mm; P_1 is the inlet pressure, bar; P_2 is the outlet pressure, bar.

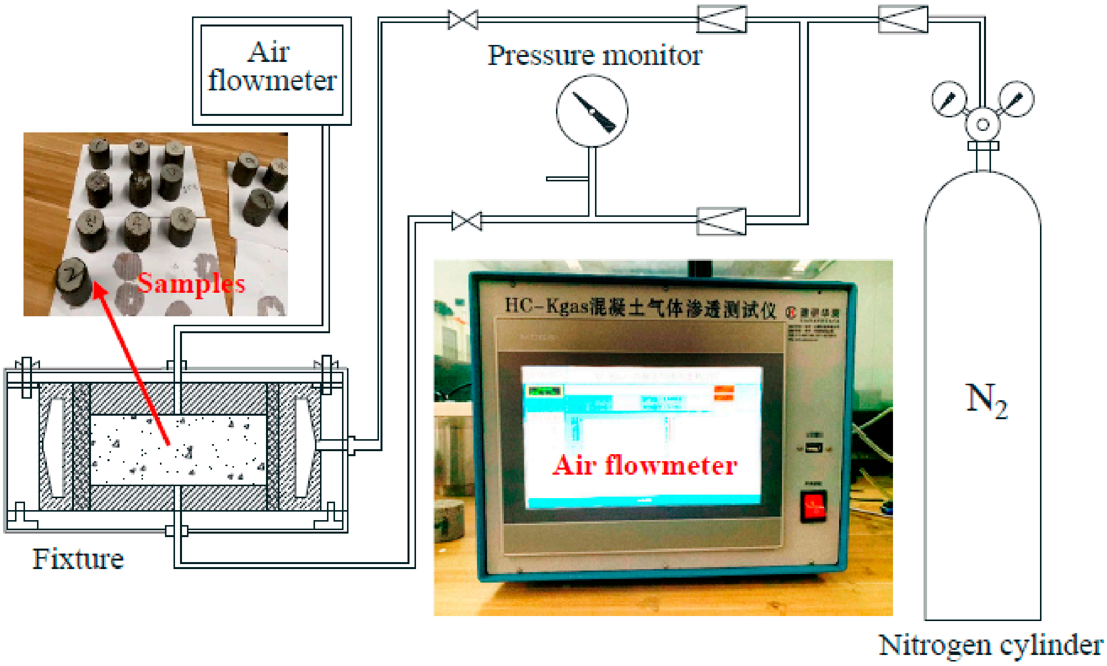


Figure 3. Gas permeability measurement system.

2.4.3. Compressive Strength

Although there is less requirement for the compressive strength of the foamed concrete, the higher the compressive strength, the more stable the whole goaf can be maintained, and the more conducive to the mining of the adjacent workface. Considering the short time filling effect and long time supporting effect, the compressive strength of 3 days and 28 days of the foamed concrete were selected as the other evaluation indexes, which can be tested by universal testing machine CSS-14100 (see Figure 4). Cube samples of 70.7 × 70.7 × 70.7 mm were taken, their dimensions measured, and the contact area A_1 was calculated. Then the sample was placed on the press plate center of the universal testing machine. The testing machine was started and controlled with a displacement loading speed of 0.02 mm/s. When the specimen cracks and reaches the complete failure state, the test is finished and the data as well as the maximum axial pressure F is recorded in the computer. Then the compressive strength σ of the foamed concrete can be obtained by the formula:

$$\sigma = \frac{F}{A_1} \tag{3}$$

where, σ is the compressive strength of the sample, MPa; F is the maximum failure load of the sample, N; A_1 is the contact area of the sample, mm^2.

As a result, the dry density, gas permeability, compressive strength of 3 days and 28 days, which were used as four test indexes according to the demands of the foamed concrete for gas isolation, were obtained by the methods above [17,18].

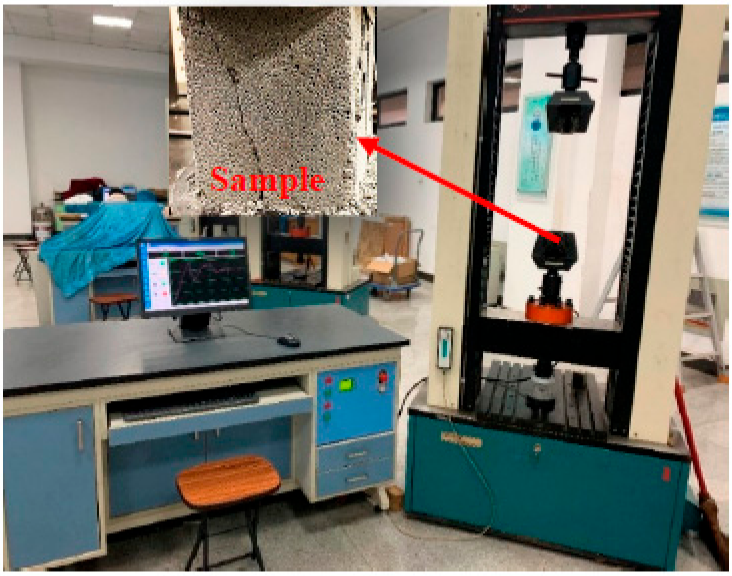


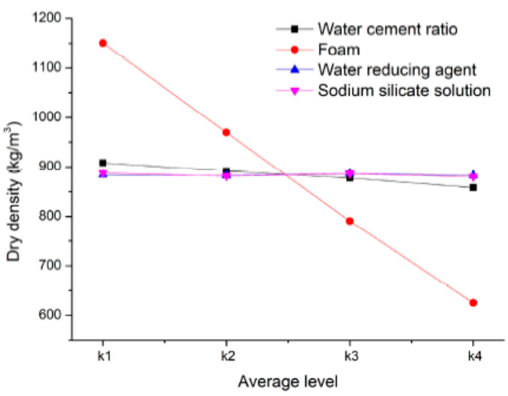
Figure 4. Universal testing machine.

3. Results and Optimum Mix

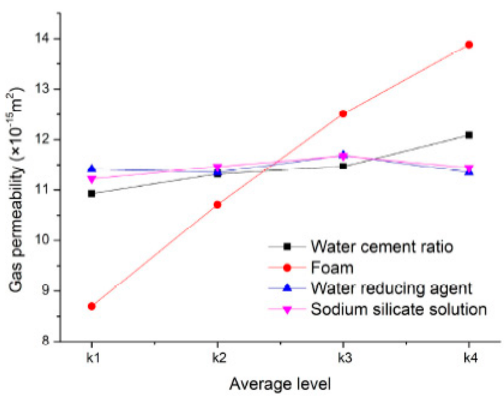
3.1. Test Results and Analysis

Average level is the average value of each factor at the same level. The average level of four indicators (dry density, gas permeability, compressive strength of 3 days and 28 days) under different factors can be seen in Figure 5a–d, and it can be noted that the foam is the main factor influencing the four indexes as mentioned above. The dry density and compressive strength drop and the gas permeability increases as the volume of foam increases. In order to further investigate the mechanism of this phenomenon, a microscope was used to magnify the samples with different foam content for 500 times, as shown in Figure 6.

When the foamed concrete sample is magnified by microscope, it can be seen that when the amount of foam is less, there are fewer pores in the sample, and these pores are small, airtight, and smooth. With the increase of foam content, both the number and the diameter of pores increase significantly. When the amount of foam reaches 2 L, the pores in the samples are denser and larger, and the connected pores are formed, which leads to larger gas permeability of the foamed concrete. At the same time, since the fact that foam helps to produce more pores, the increase of foam content can lead to a decrease in other solid materials in the unit volume, resulting in a decrease in density and strength.

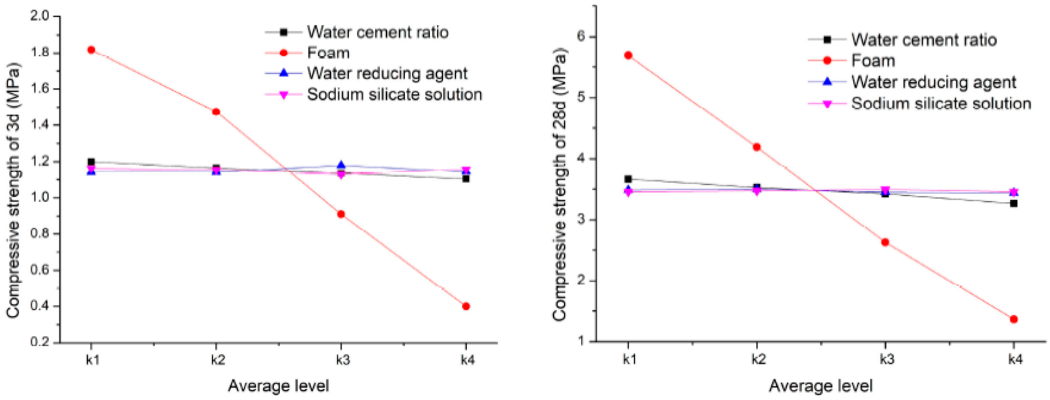


(**a**)



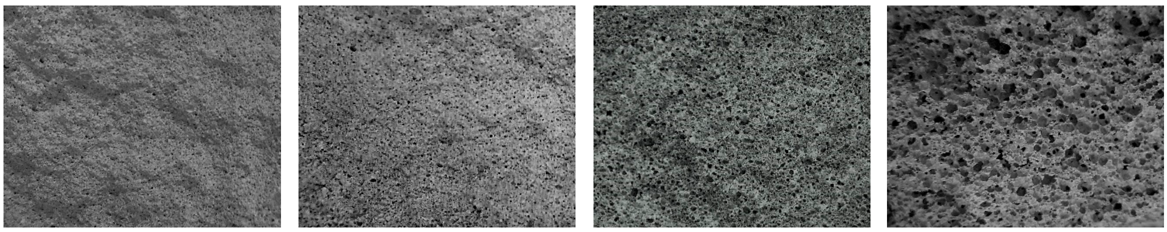
(**b**)

Figure 5. *Cont.*

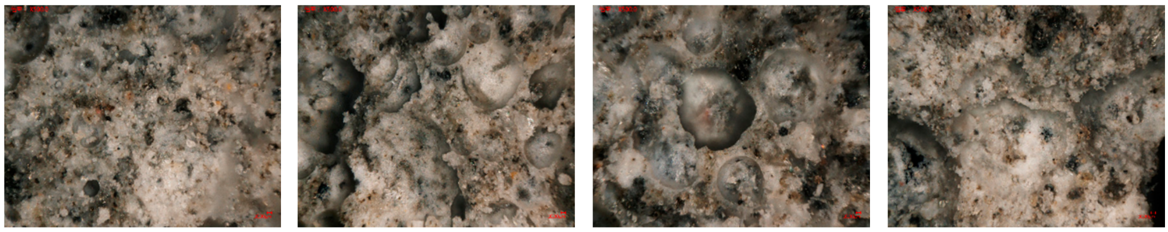


(**c**) (**d**)

Figure 5. Average level of indicators under different factors: (**a**) average level of dry density; (**b**) average level of gas permeability; (**c**) average level of compressive strength of the 3rd day foamed concrete; (**d**) average level of compressive strength of the 28th day foamed concrete.



(**a**) (**b**) (**c**) (**d**)

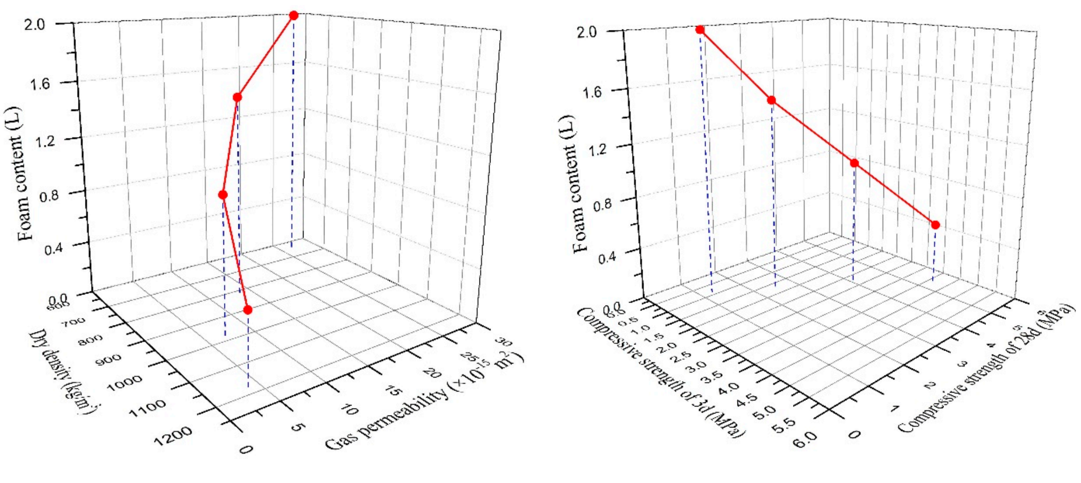


(**e**) (**f**) (**g**) (**h**)

Figure 6. Pore structures of different foam content in 1 kg mass of solid powder: (**a**) 0.5 L foam; (**b**) 1.0 L foam; (**c**) 1.5 L foam; (**d**) 2.0 L foam; (**e**) 0.5 L foam (×500 times); (**f**) 1.0 L foam (×500 times); (**g**) 1.5 L foam (×500 times); (**h**) 2.0 L foam (×500 times).

3.2. Effect of Foam Content on Properties of Foamed Concrete

In order to further verify the effect of foam content on the properties of foamed concrete, the samples of 0.5, 1.0, 1.5, and 2.0 L foam based on 1 kg mass of solid powder with a water cement ratio of 0.40 was prepared, and the change rules of gas permeability, dry density, and compressive strength were studied. As shown in Figure 7, when other conditions remain unchanged, the dry density and compressive strength decrease with the increase of foam content, and the gas permeability increases with the increase of foam content, which is consistent with the above results.



(**a**) (**b**)

Figure 7. (**a**) The effect of foam content on dry density and gas permeability; (**b**) the effect of foam content on compressive strength of 3d and 28d.

3.3. Optimum Mix

The comprehensive balance method was used to compare the results of each factor. As the effect of foam content on foamed concrete is far greater than the other three factors, we first determined the foam content. Due to the large consumption of foamed concrete in the coal mine goaf, considering the economy, Level 1 and Level 2 were excluded according to the dry density in Figure 5a. Meanwhile, considering the stability of the foamed concrete after consolidation, it can be seen that the compressive strength of Level 4 is far below the average level according to Figure 5c,d, so the foam content was selected at Level 3.

As can be seen from Figure 5, the water cement ratio is the secondary factor. In order to isolate gas better, Level 4 with highest gas permeability was first eliminated according to Figure 5b. Considering the economy, the water cement ratio should be as large as possible, so Level 3 was selected according to Figure 5a.

The above analysis can preliminarily determine the selection of the 11th mix proportion of 16 concrete series. In the 11th mix proportion, water reducing agent is at Level 1 and sodium silicate solution is at Level 2, which is very economical. According to the research results and the actual engineering requirements, the 11th mix proportion was chosen to be the optimum mix which can be seen in Table 4, as well as its engineering properties.

Table 4. Proportions and properties of the new foamed concrete.

Optimum Mix Proportions		Engineering Properties	
Water cement ratio	0.5	Dry density/kg·m^{-3}	781
Foam/L	1.5	Gas permeability/$\times 10^{-15}$ m^2	12.13
Water reducing agent/%	0.2	Compressive strength of 3 days/MPa	0.90
Sodium silicate solution/%	1.0	Compressive strength of 28 days/MPa	2.56

4. Application Modes of the Foamed Concrete

4.1. Application Modes

For the gas-rich coal mine, the gas flows into the goaf from the coal wall, the falling coal and the roof, which makes a large number of high concentration gas accumulated in the goaf, causing the gas leakage into the workface. Under normal conditions, the air pressure between the goaf and workface is basically balanced, and the gas in the goaf is mainly brought out from the upper corner by the roadway air from the lower corner, as shown in Figure 8. In order to reduce the gas concentration and ensure the safety and stability during the operation of the workface, two ways of isolating gas by using the foamed concrete are put forward:

- Sealing the gas, that is separating the goaf gas from the workface air by building the gas separation walls on both lower and upper corners.
- Replacing the gas, that is using the foamed concrete to replace the gas in the goaf void, after which the void can be filled and there is little space for gas accumulation.

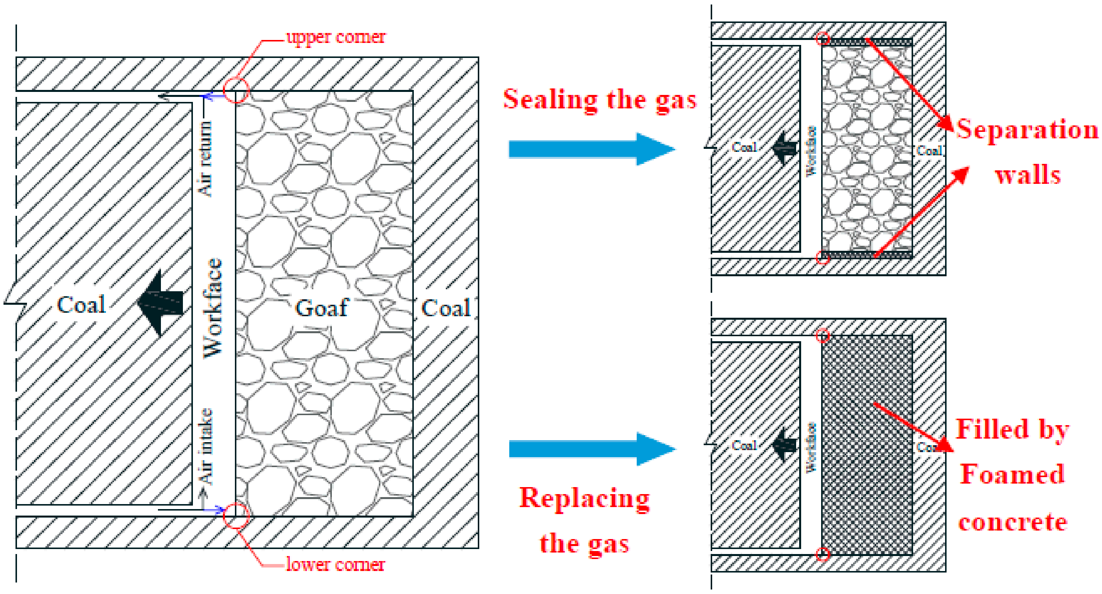


Figure 8. Schematic diagram of application modes.

4.2. Mechanism of Application Modes

4.2.1. Establish Mathematical Model

According to the characteristics of gas migration in the large-space goaf under the condition of high-intensity and rapid mining advance, the Brinkman seepage equation and Fick diffusion equation can be coupled to solve the transient process of gas diffusion under the action of air flow, so as to study the mechanism of the two application modes.

The convection and migration process of gas diffusion in goaf includes two physical processes: gas ventilation convection and concentration diffusion [19,20]. The gas diffusion equation conforms to Fick diffusion law, that is

$$\delta t\frac{\partial C}{\partial t}+\nabla\cdot(-D\nabla C)+v\cdot\nabla C=R \tag{4}$$

where, δt is the instantaneous time proportion coefficient, which is equivalent to porosity; C is the gas concentration, mol/m^3; ∇ is the lalpace operator; D is the diffusion coefficient, m^2/s; v is the average velocity, m/s; R is the source term, mol/(m^3·s).

Under the condition of fully mechanized coal mining, the goaf caving area is composed of broken caving rock mass, which can be regard as the large porous medium. Its compaction degree is related to the support pressure above the goaf, in which the air flow channel system is relatively complex, and the Brinkman seepage equation is more suitable, that is

$$\frac{\eta}{k}\cdot\mathrm{v}=\nabla\cdot(-pI+\eta(\nabla v+(\nabla v)^T))+F \tag{5}$$

where, v is the flow velocity of fluid, m/s; k is the permeability, m^2; η is the dynamic viscosity coefficient, Pa·s; p is the fluid pressure, Pa; I is the unit vector; F is the fluid resistance.

In the calculation model of this paper, the simultaneous equations (Equations (4) and (5)) can solve the transient process of gas diffusion under the action of air flow, which can be calculated by numerical simulation software COMSOL Multiphysics.

COMSOL Multiphysics is a large-scale advanced numerical simulation software developed by the Swedish company COMSOL. Based on the finite element theory, COMSOL Multiphysics is developed to simulate various physical phenomena, which can better simulate the coupling of multiple physical fields and describe physical phenomena by solving various mathematical models [19].

4.2.2. Model Calculation

Referring to the actual size of the comprehensive mechanized coal mining workface, the calculation model of 80 × 195 m was established by COMSOL Multiphysics (in order to simplify the calculation, this paper only studied the goaf area formed by about one week of coal mining without considering the dynamic process). As shown in Figure 9, the width of the roadway is 5.6 m, so the lower 5.6 m part of the left side is treated as the boundary of air inlet, and the upper 5.6 m part of the left side is treated as the boundary of air outlet, and the other boundaries are airtight. Since the air flow in the roadway of workface accounts for the majority, and the air flow penetrating into the goaf only accounts for the minority, the pressure difference between air inlet and outlet is set as 100 Pa. At the same time, the air inlet and outlet are set as the convection boundary, between which is the airtight boundary, and the gas concentration flux was supplied by the other boundaries. There are 1 atm and 3 mol/m^3 initial concentration gas in the goaf, and the other numerical simulation parameters are shown in Table 5.

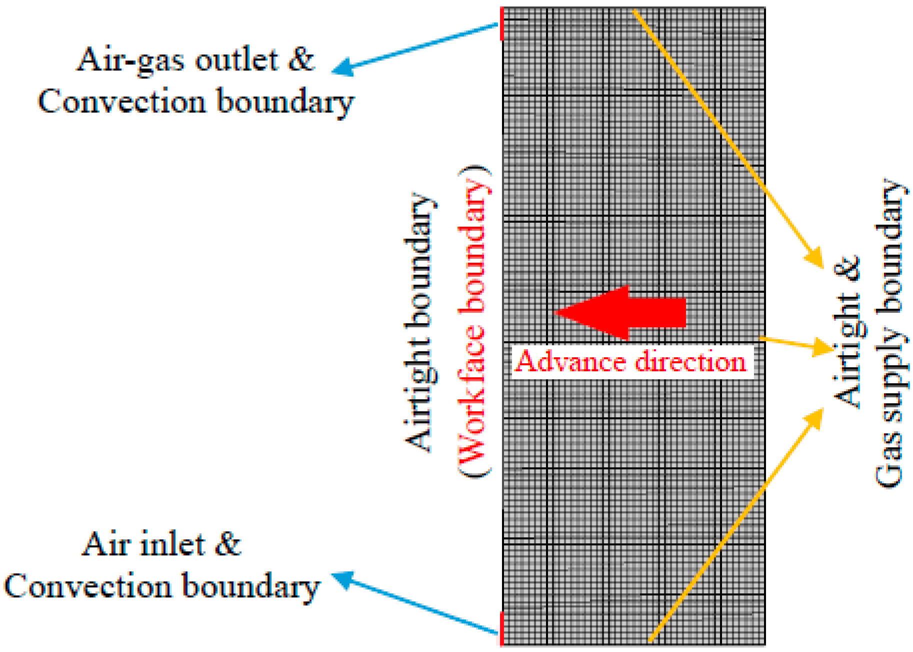


Figure 9. Computational mode and its boundary conditions.

Table 5. Numerical simulation parameters.

Parameters	δt	D (m^2/s)	R mol/(m^2·s)	η (Pa·s)	k (m^2)
Value	0.55	2×10^{-5}	3×10^{-6}	1.8×10^{-5}	3.24×10^{-8}

When simulating 'gas sealing', the gas separation walls with equal width of roadways were arranged on both sides of the goaf, the parameters of which were set as the foamed concrete in Table 4, and the remaining parts of the model were unchanged. When simulating 'gas replacement', the foamed concrete was used to block the entire cavity of the goaf and replace the gas in the empty hole, which could completely block the gas source. Since the replacement process was dynamic, the parameters of the whole calculation range were constantly changing. In order to simplify the study, the pressure difference between the air inlet and outlet was increased by five times in consideration of the displacement effect of the gas when the filling material was pumped, after which the parameters of the whole goaf were set as the foamed concrete in Table 4 [21–23].

4.3. Analysis of Simulation Results

4.3.1. No Gas Isolation

We drew the gas concentration distribution map in the goaf when the time was 0, 0.5, 1, 3, and 5 days, as shown in Figure 10a–e. The results show that under the condition of 100 Pa air pressure difference, it will take a certain time to start dispersing the gas because of the existence of 1 atm and 3 mol/m^2 initial concentration in the goaf. With the development of time, from the air inlet to the outlet, a fan-shaped concentration reduction area was gradually formed until it became stable about 5 days later, forming an accumulation area in the upper corner and keeping stable at 5–6 mol/m^2. If measures are not taken to isolate gas, the gas accumulation area near the upper corner will make the gas continuously flow out with the air, causing the hidden danger to the workface.

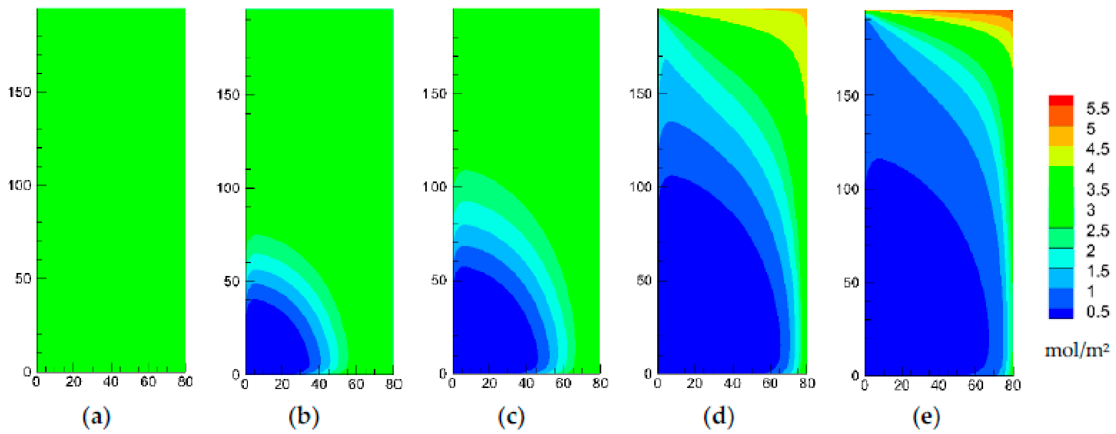


Figure 10. Concentration distribution in gas evacuation process: (**a**) t = 0 day; (**b**) t = 0.5 day; (**c**) t = 1 day; (**d**) t = 3 days; (**e**) t = 5 days.

4.3.2. Sealing the Gas

We drew the gas concentration distribution map in the goaf when the time was 0, 0.5, 2, 4, and 6 days, as shown in Figure 11a–e. Due to the existence of gas separation walls, the goaf is like a closed box, which is weakly affected by the air in roadways. Therefore, the gas accumulates continuously in the goaf instead of leaking into the workface. In addition to forming a low gas area near the air inlet, the gas concentration in most areas increases with time. It in dicates that the gas is sealed by the separation walls at two ends of the goaf instead of leaking into the workface, which ensures the safety and stability of the working face.

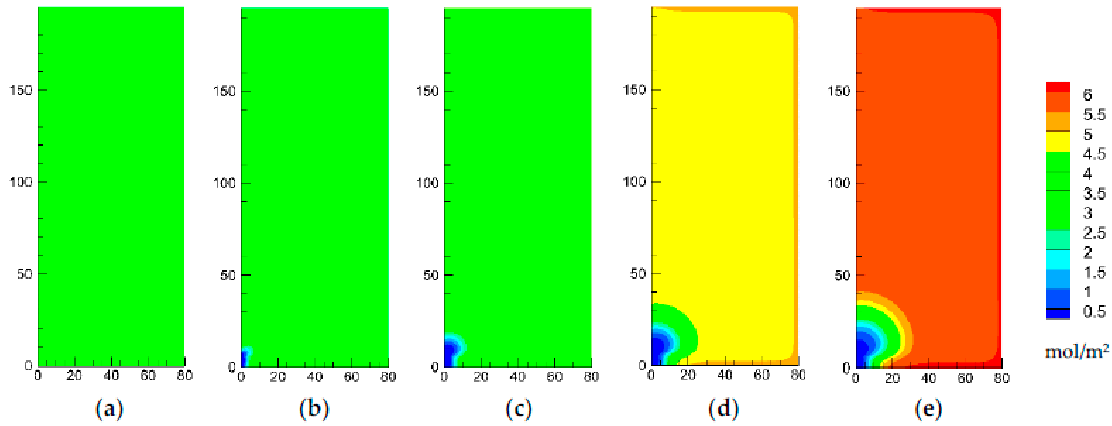


Figure 11. Concentration distribution in gas sealing process: (**a**) t = 0 day; (**b**) t = 0.5 day; (**c**) t = 2 days; (**d**) t = 4 days; (**e**) t = 6 days.

4.3.3. Replacing the Gas

We drew the gas concentration distribution map in the goaf when the time was 0, 0.125, 0.5, 1, and 3 days, as shown in Figure 12a–e. In the process of gas replacement by the foamed concrete, the gas is expelled into the air-return roadway from the outlet in a short time. Then the goaf become dense by filling with foamed concrete, so there is no new gas accumulation and the gas began to stabilize at a low level from the third day.

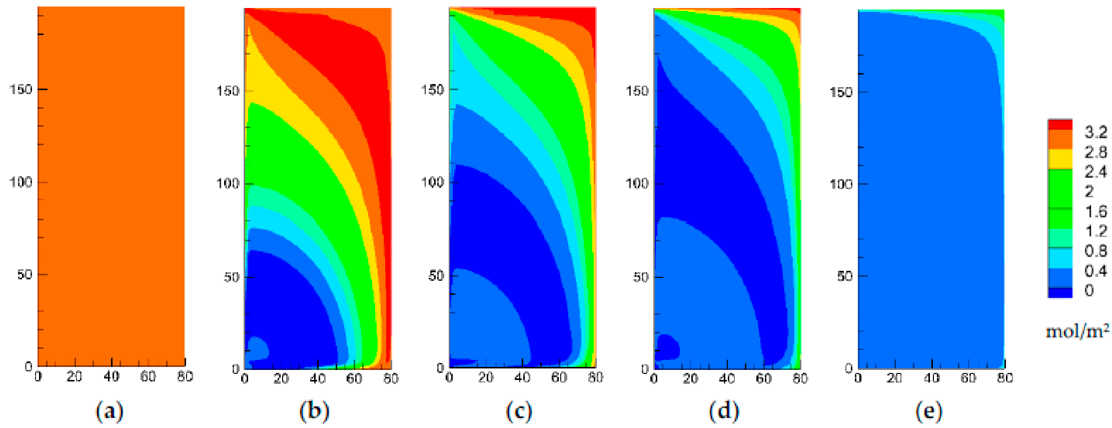


Figure 12. Concentration distribution in gas replacement process: (**a**) t = 0 day; (**b**) t = 0.125 day; (**c**) t = 0.5 day; (**d**) t = 1 day; (**e**) t = 3 days.

In this case, the gas in the workface will increase in a short time and the proper ventilation in roadways is necessary to carry out to remove the temporary high concentration gas near the outlet, after which the workface can be safely mined without any hidden danger of gas leakage.

4.3.4. Gas isolation Mechanism

Sealing and replacing are two very different methods of gas isolation. The former prevents the gas from leaking to workface by plugging the gas inlet and outlet using the foamed concrete. The latter firstly evacuates the existing gas, and then replaces the gas position with foamed concrete so as to fundamentally prevent gas leakage. The distribution curves of gas concentration along the workface boundary at different application modes is shown in Figure 13. The figure shows that when sealing the gas, since there is little influence of the air in roadway, only about 25 m range of the workface around the air inlet has the phenomenon of concentration reduction, and the gas concentration in the remaining part of workface exceeds the initial concentration and increases with time. However, when replacing the gas, the gas concentration of the workface boundary rapidly reduces to 0 near the inlet. The gas concentration along this boundary is lower than the initial concentration and decreases with the increase of time, until the entire boundary (except the outlet) remains at a very low level.

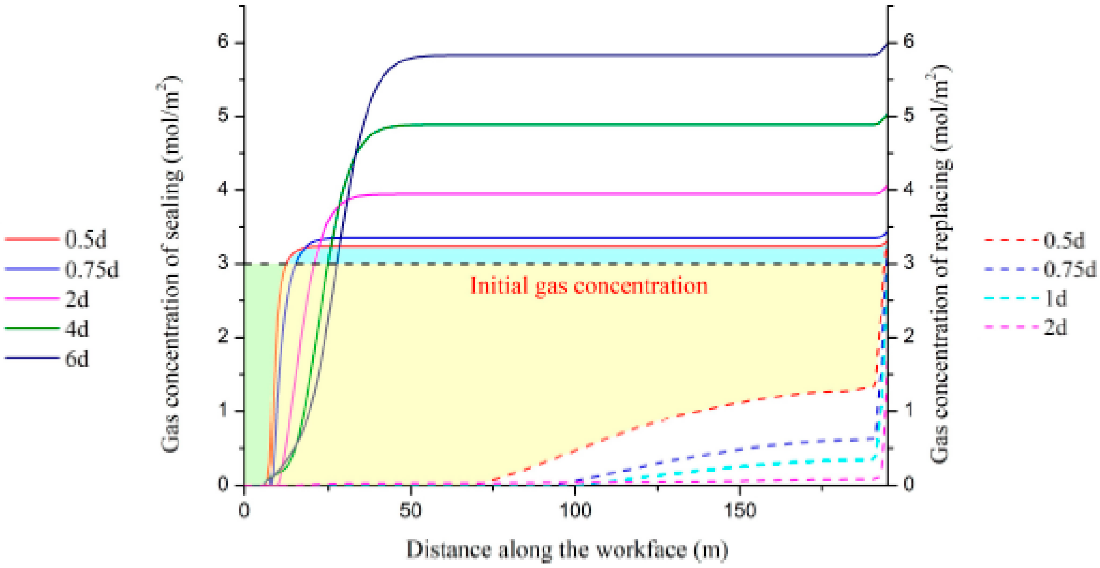


Figure 13. Concentration distribution along the workface.

5. Discussion and Conclusions

The mix proportions have a significant effect on the properties of foamed concrete, and the foam content is the most important factor. Based on the orthogonal experiment results, the optimum mix proportions were obtained, and a new type of foamed concrete was produced, which has low dry density, low gas permeability, and certain strength.

This new concrete material can be used to isolate the goaf gas in two forms: sealing the gas and replacing the gas. According to the convection-diffusion model of gas, the multi-field physic coupled simulation software COMSOL Multiphysics was utilized to conduct the numerical simulation. The simulation results indicated that when the foamed concrete is used to build air separation walls at both ends of goaf to seal the gas, the gas concentration in most of mined-out area increases with time except for a low gas area near the air inlet. When the foamed concrete is used to replace the gas in the goaf void, the gas can be expelled from the outlet in a short time, and then the gas concentration in the goaf is stable at a low level.

In view of its good gas isolation properties and the effective application modes, it is suitable and feasible to use this new type of foamed concrete as gas isolation material in the coal mine goaf, which can provide a reference for similar engineering.

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