Research Article

Development and Application of Fluid-Solid Coupling Similar Materials in Discharge Test of Old Goaf Water

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To study the evolution law of the discharge pathway for the old goaf water in the Datong mining area, a new fluid-solid coupling similar material was developed based on the fluid-solid coupling similarity theory. In the developed similar material, sand and barite powder were used as aggregate, polyurethane and white portland cement as binder, and water and silicone oil as regulator. The effects of different proportions on mechanical properties and water physical properties of materials were obtained through the experiments. The results show that the strength of the developed material is mainly controlled by cement and polyurethane, the hydrophilicity is affected by silicone oil, and the permeability coefficient is mainly affected by cement and polyurethane. For grouting agent, cement can realize the overall control function, and polyurethane can realize the local control in a certain range. As an ideal fluid-solid coupling similar simulation material, the developed material can simulate rock mass with different permeability and different strength. Besides, this material has been successfully applied to an experimental study on the mechanism of old goaf water discharge in an extra-thick coal seam in the Datong mining area, and the development and evolution characteristics of the old goaf water discharge pathway is obtained. This new kind of fluid-solid coupling similar material is developed based on the fluid-solid coupling similarity theory, which is suitable for revealing the evolution law of discharge pathway for the old goaf water in the Datong mining area.

1. Introduction

As a large coal mining country, China has rich coal resources with a vast geographical distribution. However, the hydrogeological conditions of coal deposits are complex, and China is also one of the countries with the most serious mine water disasters [1, 2]. With the continuous increase of mining depth, major and critical water inrush hazards occur frequently. The old goaf water inrush hazards account for more than 70% of all kinds of coal mine water disasters [3, 4]. Water inrush in the old goaf has the characteristics of large water volume, short time, and strong destructiveness. As a result, serious accidents of casualties and water inrush hazards are easily caused, which seriously threaten the safe production of the coal mine [5, 6].

Due to complex causes of water inrush from the old goaf, the water inrush problem cannot be comprehensively analyzed by theoretical analysis and numerical simulation. Nev-

ertheless, the fluid-solid coupling model test can intuitively and comprehensively reflect the disaster-causing mechanism under the coupling action of a mining-induced stress field and seepage field [7, 8]. Besides, this test can be mutually verified with the mathematical model. Different from the traditional model test of similar materials, the influence of a water body on a rock mass should be considered in the fluid-solid coupling model test [9, 10].

The scientific and reasonable nature of hydrophilic similar simulation material is the premise and foundation of the fluid-solid coupling model test. Zhang and Hou [11] developed a solid-liquid two-phase mold material, in which sand was used as aggregate and paraffin as binder. Then, a model test on coal mining under water-rich aeolian sand layer was carried out. Huang et al. [12] studied similar solid-liquid coupling materials in which bentonite and quartz sand were taken as the aggregate and silicone oil and Vaseline as the binder for clay aquiclude. Li Shuca et al. [13] and Li Shuzhen

et al. [14] used Vaseline and paraffin as the grouting agent and sand and talc as the aggregate and developed the fluid-solid coupling similar simulation material. This material can be applied in a tunnel water inrush model test to simulate low and medium strength rock materials with different permeability. Sun et al. [15] and Chen et al. [16] used paraffin and Vaseline as the grouting agent, river sand and calcium carbonate as the aggregate, and hydraulic oil as the regulator, then developed a new type of fluid-solid coupling similar material for the deep water-resisting layer. When paraffin and Vaseline are taken as the grouting agent in similar materials, the problems of water disintegration and strength change of rock material are solved [17]. However, these materials need heating treatment in the development process, the preparation process is complex with high difficulty, and the application process is easily affected. Wang et al. [18] employed latex and white cement as a grouting agent and developed a new type of surrounding rock material suitable for the fluid-solid coupling model test. Huang and Hu [19] used soil as the grouting agent and rapeseed oil and water as regulators and obtained the best similar proportion of clay aquiclude. Combined with a large number of data at home and abroad, organic materials are selected as grouting agents for fluid-solid coupling similar materials, which can maintain strength without disintegration. In addition, similar materials must meet two similar conditions of solid deformation and permeability simultaneously [20].

Previous studies mainly focused on the complex cementing agents produced by paraffin. On this basis, a more concise material which satisfies the hydrodynamic and mechanical properties is developed. More precisely, polyurethane is selected as a new type of grouting agent and incorporated with cement and silicone oil in this paper. According to the fluid-solid coupling similarity theory, through the proportioning test, a new type of similar material for the fluid-solid coupling test is successfully developed and applied in the old goaf water discharge experiment in the Datong mining area.

2. Similarity Theory of Fluid-Solid Coupling

On the basis of three similar theorems, the similarity relation between the model and the prototype parameters is derived by using the fluid-solid coupling mathematical model of the continuous medium, and the following similarity relation is derived [21]:

The seepage equation is expressed as

$$K_x \frac{\partial^2 p}{\partial x^2} + K_y \frac{\partial^2 p}{\partial y^2} + K_z \frac{\partial^2 p}{\partial z^2} = S \frac{\partial p}{\partial t} + \frac{\partial e}{\partial t} + W, \quad (1)$$

where K_x , K_y , and K_z are the permeability coefficients (cm/s) in the x , y , and z coordinate directions; p is the water pressure (MPa); S is the water storage coefficient; e is the volume strain; W is the source sink term; and t is the time.

The equilibrium equation is described as

$$\sigma_{ij,i} + X_j = \frac{\rho \cdot \partial^2 u_i}{\partial t^2}, \quad (2)$$

where $\sigma_{ij,i}$ is the total stress tensor, ρ is the density (g/cm³), and X_j is the volume force.

The effective stress equation is expressed as

$$\sigma_{ij} = \bar{\sigma}_{ij} + \alpha \delta p, \quad (3)$$

where $\bar{\sigma}_{ij}$ is the effective stress tensor, α is the Biot effective stress coefficient, and δ is the Kronecker sign.

According to Equations (1), (2), and (3), the main similarity between the fluid-solid coupling variable model and the prototype is deduced as follows:

The model similarity relation is

$$C_G = C_\lambda. \quad (4)$$

The geometric similarity relation is

$$C_u = C_e C_l. \quad (5)$$

The gravity similarity formula is

$$C_G C_e = C_\gamma C_l. \quad (6)$$

The stress similarity formula is

$$C_\sigma = C_\gamma C_l. \quad (7)$$

The external load similarity formula is

$$C_h = C_\gamma C_l^3. \quad (8)$$

The similarity formula of the water storage coefficient is

$$C_S = \frac{1}{C_\gamma \sqrt{C_l}}. \quad (9)$$

The permeability coefficient similarity formula is

$$C_K = \frac{\sqrt{C_l}}{C_\gamma}, \quad (10)$$

where C_λ refers to the lame constant similarity scale, C_u is the displacement similarity scale, C_e is the volume strain similarity scale, C_γ is the volume weight similarity scale, C_G is the mass similarity scale, and C_l is the geometry similarity scale.

3. Development of Fluid-Solid Coupling Similar Materials

3.1. Selection of Raw Materials. For fluid-solid coupling materials, stability, nonhydrophilicity, and good deformation characteristics are basic requirements. Therefore,

nonhydrophilic organic cementitious material should be selected as the grouting agent. Referring to the domestic and foreign research, proportion tests, and observation studies, transparent polyurethane, cement, and silicone oil are selected as the grouting agent, river sand and barite powder are used as the aggregate, and then appropriate mixing water is added to make the nonhydrophilic similar material, as shown in Figure 1.

- (1) *Grouting Agent*. White portland cement and transparent polyurethane are used as the grouting agent. White portland cement is a hydraulic cementitious material. Its mechanical strength, deformation characteristics, and water can be adjusted. However, the single use of white portland cement cannot fully adjust the material properties and cannot make the material have good water physical property. Therefore, white portland cement is used with another grouting agent. Transparent polyurethane is a polymer liquid material made of VAE and high polymer emulsion as a raw material after process modification. Its characteristics include homogeneous water-based material, high polymer, strong adhesion, non-toxic and pollution-free, short bonding time, stable performance, and nonhydrophilic. With cement, the material properties can be improved stably.
- (2) *Aggregate*. Sand and barite powder are selected as the aggregate. River sand with particle size ≤ 2 mm is selected to ensure uniform distribution of internal components of the material when it is cemented together under the action of the grouting agent. Barite powder with fineness of 625 meshes is selected as the fine aggregate. The grain size of the river sand is relatively coarse, and its nonhydrophilicity cannot be guaranteed. Thus, barite powder is used to fill the gap between the river sand to ensure the nonhydrophilicity.
- (3) *Regulator*. Dimethyl silicone oil and water are selected as the regulators. As the mixing water, water mainly reacts with cement. The silicone oil can make the surface of the material more compact, ensure the adequate reaction of cement and water, and improve the strength of the material, so that the material will not collapse when encountering water.

3.2. Experimental Scheme and Sample Making. A large number of experiments have shown that the properties of materials are mainly determined by cement and polyurethane. Therefore, cement content and polyurethane content are taken as two factors in the experimental design. Each factor is set at five levels. When the content of other components is fixed, the cement mass ratio is kept unchanged and the polyurethane content is changed, or the polyurethane content is kept unchanged and the cement content is changed. The experimental scheme is shown in Table 1. 25 groups of samples were made with a double opening mold with a diameter of 50 mm and a height of 100 mm. 10 samples were made for each group, and 250 samples were made for the

experimental study. The sample making process is shown in Figure 2.

4. Property Tests of Similar Materials

4.1. Hydrophilicity Test. As an important index of water rationality of similar materials, hydrophilicity can be measured by water absorption. The smaller the water absorption, the stronger the nonhydrophilicity. The water absorption rate was obtained by comparing the cured dry sample with the sample soaked for 24 hours, as shown in Figure 3. The test results show that the average water absorption rate of the sample is between 1.012 and 1.060%, which indicates that the material meets the requirements of nonhydrophilicity and is a nonhydrophilic material.

4.2. Test of Uniaxial Compressive Strength and Softening Effect. In this test, a WSM-10KN universal testing machine was used to carry out the uniaxial compression test on samples after maintenance, so as to determine the total stress-strain curve of the sample in the process of uniaxial compression. The slope of the elastic section is the elastic modulus E . The failure mode of the sample on the test machine is similar to that of the rock, as shown in Figure 4. Figure 5 shows the stress-strain curve of 14 groups of samples.

In order to simulate the coupling effect between the water flow and deformation failure of the surrounding rock, it is necessary to consider the softening effect of similar materials under long-term immersion. The water absorption sample was immersed into water for 7 days, and then the compressive strength of the immersed sample was compared with that of samples in the natural state. As shown in Table 2, the effect of immersion on the compressive strength is within 6%~20.3%, and it can be concluded that the softening effect of the material basically meets the experimental requirements.

4.3. Uniaxial Tensile Strength Test. The tensile strength of the sample was indirectly tested by the Brazilian splitting method, and the tensile strength of the sample is calculated from the following formula:

$$\sigma_t = \frac{2P}{\pi Dt}, \quad (11)$$

where D is the diameter of the sample, P is the pressure value when the sample is damaged, and t is the thickness of the sample. The tensile and compressive strength values of some samples are shown in Table 3.

As shown in Table 3, the tension-compression ratio σ_t/σ_c range of similar materials is 0.091-0.11, which is very close to 0.1 (the average tension-compression ratio of rock). It indicates that similar materials can well simulate the tensile properties of rock.

4.4. Brittleness Analysis. To simulate the permeability evolution caused by rock fracture and its influence on the mechanical properties of rock mass, it is necessary to analyze and verify the brittleness characteristics of the developed material, so as to ensure that the material is still

FIGURE 1: Raw similar materials.

TABLE 1: Experimental proportioning scheme.

Level	Factor					
	Cement content (%)	Polyurethane content (%)				
1	2	2	4	6	8	10
2	4	2	4	6	8	10
3	6	2	4	6	8	10
4	8	2	4	6	8	10
5	10	2	4	6	8	10

brittle after coupling with water. In this paper, the method proposed by Pan et al. [22] was used to define brittle rocks. In other words, E/λ of the prepeak and postpeak weakening modulus of the stress-strain curve was analyzed to determine the brittleness of the material. Materials with different E/λ have different brittleness characteristics. It is stipulated that materials with $E/\lambda < 3$ are brittle materials; otherwise, they are not brittle materials. As shown in Table 4, the developed materials are all brittle materials with $E/\lambda < 3$, which meet the fracture and mechanical similarity requirements of rock.

FIGURE 2: Sample preparation process.

FIGURE 3: Hydrophilicity test.

(a) Failure modes of sample 1

(b) Failure modes of sample 2

FIGURE 4: Typical failure modes of samples.

FIGURE 5: Stress-strain curve of 14 groups of similar materials.

TABLE 2: Strength comparison of some samples in natural state and after immersion.

Group number	Compressive strength (MPa)	Compressive strength of material after 7 days of immersion (MPa)	Strength reduction rate (%)
1	0.2	0.167	20%
7	0.73	0.56	13%
14	0.86	0.77	12%
20	1.46	1.36	9%
25	1.99	1.85	6%

TABLE 3: Tensile strength values of some test blocks.

Group number	Compressive strength σ_c (MPa)	Tensile strength σ_t (MPa)	σ_t/σ_c
01	0.20	0.020	0.11
02	0.44	0.045	0.10
03	0.68	0.067	0.098
04	0.92	0.084	0.091
05	1.16	0.126	0.108

TABLE 4: Test results of brittleness characteristics of some similar materials.

Group no.	Elastic modulus Prepeak E (MPa)	Weakening modulus After peak λ (MPa)	E/λ
1	42	20	2.1
2	68	31	2.2
3	94	36	2.6
4	96	34	2.8
5	123	49.2	2.5

4.5. Determination of Permeability Coefficient. The permeability coefficient is another important property index to characterize the water rationality of similar materials. The permeability of the developed material is low. Since the water flow is small and the water level is difficult to control, the variable head method is used. However, the conventional permeameter is only suitable for testing the permeability coefficient of granular materials, and there is a problem of lax sealing between the sample and the sleeve side wall of the sample. To this end, a set of a sealed permeability coefficient testing device was designed and developed by glue injection based on the principle of variable water head test

FIGURE 6: Test and test principle of permeability coefficient of similar materials.

FIGURE 7: Effect of cement and polyurethane content on tensile strength of materials.

and Specification of Soil Test SL237-1999 [23, 24]. Then, the self-developed device was used to test the permeability coefficient of the sample, as shown in Figure 6. The range of the permeability coefficient measured by the device is 7.12×10^{-7} – 5.18×10^{-5} , namely, the simulation has a wide range. After the cement and polyurethane are added, the permeability coefficient of the material decreases integrally. When the proportionality of cement increases, the gap between the materials decreases, which has an important influence on the permeability coefficient of the materials.

5. Analysis of Factors Affecting the Properties of Similar Materials

As shown in Figures 7 and 8, the compressive and tensile strengths increase with the increase of cement or polyurethane content when the content of other components is fixed. When the cement content is less than 6%, the tensile and compressive strengths of the material increase rapidly with the increase of polyurethane. At this time, the strength of the material is mainly determined by the cohesiveness of

FIGURE 8: Effect of cement and polyurethane content on compressive strength of materials.

FIGURE 9: Effect of cement and polyurethane content on permeability coefficient of materials.

polyurethane. When the cement content is more than 6%, the tensile and compressive strengths of the material increase rapidly with the increase of cement content. As the cement content increases, the cementitious material produced by the hydration reaction increases, which affects the cementation ability of polyurethane. At this time, the strength of the material is mainly determined by the cement. Comparing the influence of the two substances, it is found that the

cement content determines the strength of the material comprehensively, and the polyurethane content can adjust the strength within a certain range. When the content of cement and polyurethane is at 4%, the permeability coefficient decreases with the increase of silicone oil.

Through a large number of experiments, it is proven that the amount of cement and polyurethane can adjust the permeability coefficient. As shown in Figure 9, with the increase

FIGURE 10: Effect of silicone oil on permeability coefficient of materials.

TABLE 5: Proportion of model test.

No.	Lithology	Thickness (m)	Model thickness (cm)	Compressive strength (MPa)		Material ratio (sand : barite powder : cement : cement : polyurethane : silicone oil)
				Actual strength	Simulation strength	
1	Silty mudstone	12	6	42.5	0.14	1 : 0.125 : 0.011 : 0.017 : 0.024
2	Fine sandstone	17.5	8.75	55.2	0.18	1 : 0.125 : 0.014 : 0.017 : 0.011
3	#14 coal	3.4	1.7	16.5	0.06	1 : 0.111 : 0.009 : 0.001 : 0.046
4	Coarse-grained sandstone	11.1	5.55	39.5	0.13	1 : 0.125 : 0.012 : 0.017 : 0.048
5	Medium-grained sandstone	12.2	6.1	40.6	0.13	1 : 0.125 : 0.013 : 0.017 : 0.023
6	Silty mudstone	21.1	10.55	42.5	0.14	1 : 0.125 : 0.011 : 0.017 : 0.024
7	Fine sandstone	14.1	7.05	55.2	0.18	1 : 0.125 : 0.014 : 0.017 : 0.011
8	Sandy conglomerate	15.1	7.55	54.6	0.18	1 : 0.125 : 0.012 : 0.0177 : 0.24
9	Siltstone	10.3	5.15	40.1	0.13	1 : 0.142 : 0.012 : 0.017 : 0.024
10	Silty mudstone	12.1	6.05	42.5	0.14	1 : 0.125 : 0.011 : 0.017 : 0.024
11	Sandy conglomerate	16.2	8.1	54.6	0.18	1 : 0.125 : 0.012 : 0.0177 : 0.24
12	Carbonaceous mudstone	7	3.5	26.4	0.09	1 : 0.142 : 0.01 : 0.014 : 0.024
13	#3-5 coal	21	10.5	16.5	0.06	1 : 0.111 : 0.009 : 0.011 : 0.023
14	Medium sandstone	20.1	10.05	42.5	0.14	1 : 0.125 : 0.013 : 0.017 : 0.024

of cement and polyurethane content, the permeability coefficient of materials decreases. With the increase of cement and polyurethane content, the small gap between the materials becomes smaller and smaller, resulting in greater difficulty for water flow. When the polyurethane content is more than 6%, the permeability coefficient fluctuates from 1.01×10^{-5} to 7×10^{-6} . As shown in Figure 10, when the content of cement

and polyurethane is fixed, silicone oil, as a regulator, has a certain influence on the permeability coefficient. Since silicone oil has water retention and hydrophobicity, it can fully react with the cement, and a hydrophobic surface can be formed, resulting in more difficult water flow. Therefore, the permeability coefficient can be controlled in a certain range by changing the content of cement, polyurethane, and silicone oil.

FIGURE 11: Multifield coupling simulation test system of old goaf and water discharge.

6. Application of Similar Materials in Old Goaf Water Discharge Test

The Datong coalfield is a double system coalfield of Jurassic and Permo-Carboniferous. The upper 14# coal seam has been fully mined, and a large amount of old goaf water is stored in the goaf. When mining the 3-5# coal seams, due to the development of a fracture zone, the goaf of the upper coal seam is permeated. As a result, the old goaf water in the goaf of the upper coal seam flows downward, easily resulting in a water inrush accident of the 3-5# coal seams. In this test, water inrush in double series coal seam mining in the Datong mining area is taken as the research object, so as to explore the change of water pressure and the law of pathway formation and evolution when the old goaf is discharged. The geometric similarity ratio of the experiment is 1/200, and the model size is $1000 \times 1000 \times 200$ mm. The model applied a load of 0.03 MPa in the vertical direction and a load of 0.01 MPa in the horizontal direction. Then, water pressure of 0.001 MPa is applied according to the actual calculation. The ratio of rock mechanics parameters is shown in Table 5, and the physical figure of the model is shown in Figure 11.

As shown in Figure 12, as the working face moves forward from the open-off cut, the water pressure in the aquifer does not change significantly because the aquifer is far away from the mining coal seam, and the strength of the sandstone in the key layer has a good water isolation effect. In this process, the fracture formed by the tensile and shear failure of each layer in the open-off cut develops obliquely upward at a certain angle. At the same time, the development height of the crack also extends outwards. When the working face advances to about 140 m, the aquifer begins to fluctuate. At this time, the key layer is gradually damaged, and the water begins to seep out from the small fissures. When the working

FIGURE 12: Relation curve between displacement and water pressure.

face advances to 145 m, the key layer collapses, the water inrush pathway develops and penetrates, and the water pressure of the aquifer drops sharply and tends to 0 MPa. Therefore, the key layer has the function of water separation, which plays a decisive role in the generation of a water inrush pathway with the water pressure change [25].

A key layer refers to the strata which control the whole or partial overburden movement from the overburden to the surface. The clear location of the water inrush is in the middle of the key layer, and the period of water inrush occurs after the key layer is broken. As shown in Figure 13, under the influence of mining, the fracture of the key layer is a V-shaped structure. The vertical fracture and the fractures

FIGURE 13: Distribution of broken main key layer and water-conducting pathway.

formed at the open-off cut and coal wall of the working face are main water-conducting pathways, while the lead fracture on both sides of the goaf is not an effective water pathway. The application of the similar material reveals the damage characteristics of similar materials and the distribution characteristics of roof water inrush pathways. It is concluded that there is a high probability of water inrush at the open-off cut and the middle of the goaf. This finding has certain guiding significance for solving practical engineering problems.

7. Conclusions

- (1) A new type of fluid-solid coupling simulation material is developed and tested. The compressive strength of similar materials is 0.20-1.99 MPa, the tensile strength is 0.02-0.19 MPa, and the permeability coefficient is 7×10^{-7} - 5.18×10^{-5} . This material is suitable for the large-scale simulation test of most rock masses
- (2) The control effect of the new fluid-solid coupling similar material on the mechanical properties in different proportions is obtained. The tensile and compressive strengths are mainly controlled by cement, and polyurethane is adjusted within a certain range. The permeability coefficient is controlled by the cement and polyurethane. Silicone oil has the function of water retention. The deformation and water physical properties can be controlled by the proportionality of cement and polyurethane
- (3) The change of water pressure stress and the formation and evolution of the water-conducting pathway in the old goaf water discharge are preliminarily revealed. Mechanical properties and water physical

properties of the material are verified. This study provides a reference for solving the water inrush problems in the actual project.

Data Availability

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

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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