Development and Properties of a Similar Material to Coal

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Abstract: In the mining process, protective-seam mining is one of the most effective measures to prevent and control coal and gas outburst accidents across the world. To accurately obtain the fracture development characteristics for protected coal in a similar physical simulation (to two-dimensional (2D) protective-seam mining), a novel and similar material to coal was developed. The similar material was prepared by mixing pulverized coal with a certain particle-size distribution and a water solution of sodium humate, which were separately taken as the aggregate and binder, followed by pressing and drying. Numerous orthogonal proportioning tests revealed that, under the molding pressure of 15 MPa, the unit weight and porosity of the similar material tended to be stable and approach that of raw coal. The similar material has a high compressive strength that is regulatable over a range as wide as 0.5~2.8 MPa and has an approximately linear direct proportional relation with the binder concentration. The adsorption and desorption tests revealed that the similar material features favorable adsorption properties, and its adsorption isotherm agrees with that of raw coal. The similar material is also characterized by a low price for its raw materials, no toxic or side effects, simple proportioning, stable properties, and the convenient regulation of various physical and mechanical parameters. Therefore, it can be used to simulate raw coal with different strengths.

Keywords: similar material; pulverized coal; raw coal; coal briquette

1. Introduction

Coal is a major energy resource in China. Coal forms under extremely complex conditions and is subjected to long-term plate tectonics and tectonic stress from the plates. Therefore, coal is pulverized, and the fracture system therein is highly compressed, leading to the extremely low permeability of coal and the great difficulty of gas extraction. As a result, coal and gas outburst accidents occur frequently [1–3].

Protective-seam mining is a core technology that is effective in preventing and controlling coal and gas outbursts. In the protective-seam mining process, a caved zone, a fractured zone, and a bent subsidence zone are formed in the overlying strata. Transverse and vertical fractures widely develop in the coal and rock mass in the caved zone and the fractured zone, with coal-bed gas in the protected seam migrating to the working face in the protective seam. Under these conditions, leveraging the matching gas extraction technologies (surface boreholes, high-level intercepting boreholes, and extraction in goaf) can see the efficient extraction of the gas from the protected seam. At present, the development and evolution of fractures in mining-disturbed coal have been mainly explored through laboratories using similar simulations [4–6].

In view of this, scholars around the world have conducted much research and made great progress [7–15]. According to the similarity principles, if similarity models and materials can meet the similarity conditions and principles of the prototypes, the results of model tests can accurately reflect the properties of the simulated prototypes [7]. Hence, appropriate similar materials are the premise and guarantee for successful model tests.

For the development of similar materials to coal, Japanese researchers conducted laboratory simulation experiments on coal samples with gas ejection during outbursts in the
1960s. For example, Ujihira Masuyuki et al. [8] prepared porous media by mixing crystalline CO$_2$, rosin, or cement with coal samples. The material has the following shortcomings: when using materials without gas adsorption capacity, including ice, cement, or rosin, to prepare the models, either the physical and chemical properties or the mechanical properties of the model become greatly different to that of coal. Zhang et al. [9] prepared coal briquette using outburst-prone coal samples with a particle size of 1~5 mm and measured several physical and mechanical parameters. Deng et al. [10] simulated IV and V coal by pressing and molding outburst-prone coal samples without adding any additives and determined the relationship between the compressive strength of coal briquette and the molding pressure. Because coal briquette is molded only under pressure, coal briquette has a low strength. Xu et al. [14] pressed and molded pulverized coal through a 5~100 mesh on a test platform using certain proportions under the condition of not adding any additives. Ou [15] used pulverized coal and coal tar to prepare coal briquettes and prefabricated the coal samples into coal briquettes with different physical and mechanical properties by controlling the proportions of the pulverized coal and coal tar. However, the above similar materials exhibit disadvantages, including low strength and large differences to raw coal in terms of their physical and mechanical properties; therefore, they fail to meet the test requirements [16,17]. In view of this, a novel similar material for simulating coal and gas outbursts was developed by carrying out lots of proportioning tests according to the characteristics of coal and gas outbursts and referring to previous experience. The similar material has a unit weight and porosity that are approximated that of raw coal. The mechanical properties of the similar material can be conveniently regulated, and the adsorptivity is consistent with the raw coal.

2. Tests

2.1. Selection of the Similar Material

The similarity simulation tests for underground engineering require the conventional physical and mechanical properties of similar materials to that of coal and its rock mass to meet the similarity criterion. In addition, similar materials also need to meet the adsorption and desorption properties. According to the preparation concepts of overall control and regulation, researchers have made efforts to regulate a single index by a single composition of the materials [18]. Previous research has shown that if the unit weight of similar materials is the same as that of raw coal, the conversion between model and actual engineering and physical parameters can be substantially simplified. This can also better reflect the influences of the self-weight stress field. Therefore, scholars tend to select materials with a unit weight comparable to that of raw coal [19]. Because coal has special gas adsorption and desorption properties, pulverized coal with a certain particle size was selected as the basic aggregate. Based on previous experience, the coal briquettes prepared by compressing pulverized coal alone have low strength. Therefore, to prepare the coal briquettes with a high strength that can be regulated over a wide range, a certain binder has to be added. An appropriate binder also needs to guarantee that the adsorption and desorption properties of the similar materials are not affected when ensuring the strength of the coal briquette. By selecting and comparing materials via many orthogonal tests, the water solution of sodium humate was selected as the binder because sodium humate itself is an extractant of coal and also has good adsorption properties [20].

Particle size distribution mainly refers to the distribution of the particle sizes of raw materials in the coal briquette. According to the Gaudin–Schuhman equation, the coal briquette has the highest strength when the particle size distribution index, m, is about 0.25 (the weight ratio of coal, with the particle size of 1~3 mm, to that with a particle size of 0~1 mm, being 24:76). If m deviates from the optimal value, the strength of the coal briquette reduces.

The molding water content exerts a large influence on the molding and strength of the coal briquette. The tests revealed that when the molding water content is lower than 8%, the coal particles are non-uniformly wetted, and the coal briquette has low strength. If
the molding water content exceeds 13%, the coal is too wet, such that the coal particles in the hopper of a molding machine agglomerate and bridge, and the water overflows under high-pressure pressing. This affects the molding quality and reduces the strength of the coal briquette.

2.2. Specimen Preparation and Test Steps

Coal briquette has various properties and complex influencing factors. Considering this and solving the problem pertaining to the low strength and realizing the convenient preparation of the coal briquette, pulverized coal with a distribution of particle sizes in a fixed ratio of 0~1 mm: 1~3 mm = 0.76:0.24 was used. Tests reveal that the water is slowly evaporated when using water as the solvent for the binder. Regarding drying, the molding water content was fixed at 8%.

To measure the physical and mechanical properties of the coal briquette, multiple groups of specimens were prepared with dimensions of 50 mm × 50 mm × 35 mm, as shown in Figure 1. The preparation process is shown as follows:

1. Raw coal collected from an outburst-prone coal seam was crushed using a jaw crusher and screened using standard sieves. Then, the coal with the preset particle size distribution was mixed uniformly;
2. The aggregate and binder were weighed in strict accordance with the proportion, and the water was also measured according to the proportion;
3. The binder was dissolved in water and, after sufficient dissolution, it was poured into the aggregate and stirred;
4. The similar material, after sufficient stirring, was poured into a mold and compressed under the preset pressure for 10 min;
5. The specimens were demolded, labeled, and cured.

Figure 1. Specimens proportioned using pulverized coal and sodium humate. (a) Pulverized coal; (b) sodium humate; (c) drying oven; (d) and coal briquette specimens.
2.3. Tests of Basic Physical and Mechanical Parameters

(1) Unit weight

Because the mass of the solvent (water) is large compared to that of the pulverized coal, the pressed and molded material was relatively compact under a large molding pressure, which is not conducive to the drying of the specimens. Therefore, the specimens were dried using two modes: natural drying and drying in an oven. The drying of the specimens under the natural condition and in an oven is displayed in Figure 2.

The drying results show that the specimens were dried rapidly in the first 3 d under the natural condition, with the drying slowing down thereafter. The specimens were completely dried within 7 d. In the oven (40 °C), the specimens could be dried within 2 d, that is, the drying duration was obviously shortened.

The mass of the specimens was weighed after drying the material. Then, the volume and unit weight of the specimens were calculated according to the dimensions of the coal briquette (Figure 3).
(2) Porosity

The porosity of coal refers to the ratio of the total volume of the pores in coal to the total volume of the coal. It can be determined by measuring the true density and apparent density of coal. The porosity of coal in different units has the following relationship with the true density and apparent density.

\[
K = \frac{1}{\rho_p} - \frac{1}{\rho_t}
\]

(1)

where \( \rho_p \) denotes the apparent density of coal, that is, the density of coal including pores (t/m\(^3\)); \( \rho_t \) refers to the true density of coal, that is, the density of coal excluding pores (t/m\(^3\)).

In the equation, \( \rho_p \) and \( \rho_t \) can be measured in the laboratory. The larger the difference between the true density and the apparent density, the greater the porosity of the coal. After being dried, the specimens were weighed using an electronic balance to acquire the mass. Then, the apparent density of the specimens was calculated according to the dimensions of the coal briquette. The true density of the specimens was tested using a 5E fully automatic industrial analyzer, and by referring to previous research [21,22]. The porosity of the similar material can be calculated using Equation (1). Test results indicate that the water content in the coal specimen of the similar material was 4.52%, which is slightly higher than in raw coal (4.09%); the ash content in the coal specimen for the similar material was 15.52%, which approaches that of raw coal (15.36%); the volatile content in the coal specimen for the similar material is 31.24%, also very approximate to that of raw coal (31.17%).

(3) Adsorption and desorption properties

Adsorption and desorption properties are important properties in coal. Only when these properties for the similar material are consistent with those of raw coal can the rapid gas desorption and diffusion and the gas expansion energy be better simulated. In the laboratory, the high-pressure volumetric method is generally used to determine the adsorption and desorption properties of coal specimens. To obtain more accurate data, specimens damaged in the tests (for determining mechanical parameters) were classified and collected according to the proportion of the material and were then crushed using the jaw crusher, and screened using standard sieves. Particles smaller than 0.2 mm were taken as the sample. The similar material was measured by referring to previous research [23], as shown in Figure 4.

![Figure 4. Adsorption tests of the similar material. (a) Specimens in the adsorption tests; (b) the tester of the adsorption constant.](a) (b)

(4) Tests of mechanical parameters

A WDW-500 microcomputer-controlled electronic universal testing machine was adopted to test the mechanical parameters. Three specimens were prepared based on
each proportion, and the average of their strengths was taken. The typical stress–strain curve of the specimens is illustrated in Figure 5. The elasticity modulus $E$ was acquired by calculating the slope of the curve in the elastic deformation stage, and the Poisson’s ratio $\mu$ was measured using the electrometric method.

![Figure 5](image.png)

**Figure 5.** Uniaxial compressive strength test. (a) Uniaxial compression test; (b) typical stress–strain curve.

The uniaxial compression test results suggest that the specimens prepared with the same proportions show approximate uniaxial compressive strengths, indicating the high stability of the proportions in the similar material. The compressive strength of the similar material can be adjusted over a large range, as wide as 0.5~2.8 MPa, in the specimens prepared with different proportions. Therefore, the similar material can be used to simulate raw coal of differing strengths, as illustrated in Figure 6.

![Figure 6](image.png)

**Figure 6.** Uniaxial compressive strength of materials prepared with different proportions.

Due to the low strength of the similar material, Brazilian splitting tests were carried out to indirectly test their tensile strength by using square specimens measuring 50 mm $\times$ 50 mm $\times$ 30 mm and using the specific testing mold. According to the test results from the pressure sensors, the tensile strength of the specimens was calculated. The shear strength indices (cohesion, $c$, and internal friction angle, $\phi$) for the similar material were tested using a ZJ-4A strain-controlled direct shear apparatus. On this basis, the shear strength was computed.

The mechanical parameters, including the compressive strength, elasticity modulus, tensile strength, cohesion, and internal friction angle of raw coal and some of the specimens of the similar material, with different proportions, are displayed in Table 1.
weight and porosity of the specimens (prepared under different molding pressures) are illustrated in Figures 7 and 8.

When other parameters remain constant, the relationship between molding pressure and the unit weight of the similar material are mainly influenced by the molding pressure. The test results reveal that the molding pressure significantly affects the unit weight and porosity of the specimens. When other parameters remain constant, the relationship between molding pressure and the unit weight and porosity of the specimens (prepared under different molding pressures) are illustrated in Figures 7 and 8.

### Table 1. Mechanical parameters of raw coal and some of the specimens of the similar material, with different matching ratios.

| Specimens  | Uniaxial Compressive Strength/MPa | Elasticity Modulus/GPa | Tensile Strength/MPa | Internal Friction Angle/(°) | Cohesion/MPa | Poisson's Ratio/µ |
|------------|----------------------------------|-----------------------|----------------------|----------------------------|--------------|------------------|
| Raw coal   | 24.5                             | 4.450                 | 2.35                 | 30                         | 0.850        | 0.24             |
| Specimen 1 | 0.8                              | 0.125                 | 0.09                 | 29                         | 0.080        | 0.25             |
| Specimen 2 | 1.7                              | 0.265                 | 0.16                 | 28                         | 0.170        | 0.24             |
| Specimen 3 | 2.6                              | 0.495                 | 0.25                 | 30                         | 0.275        | 0.25             |

### 3. Influencing Factors

By carrying out lots of tests on the proportions and the physical and mechanical parameters, the main factors influencing the physical and mechanical properties of the similar material were analyzed. The influences of each component and preparation factor on the relevant physical and mechanical indices were analyzed.

1. Influencing factors of the unit weight and porosity of the similar material.

Because the aggregate of the similar material was pulverized coal with a fixed particle size distribution and very low binder content, these two factors exert a low influence on the unit weight of the similar material. The unit weight and porosity of the similar material are mainly influenced by the molding pressure. The test results reveal that the molding pressure significantly affects the unit weight and porosity of the specimens. When other parameters remain constant, the relationship between molding pressure and the unit weight and porosity of the specimens (prepared under different molding pressures) are illustrated in Figures 7 and 8.

![Figure 7. Effects of molding pressure on porosity.](image)

![Figure 8. Effects of molding pressure on density.](image)

As shown in the figures, the porosity of the specimens gradually reduces when the unit weight gradually increases with the rising molding pressure. Under a low molding pressure, the unit weight and porosity change, with large gradients. Under a high molding
pressure, the change gradients of the unit weight and porosity are small. Under a molding pressure above 15 MPa, the compression ratio of the specimens is very small, and the unit weight and porosity of the specimens change slowly.

(2) Influencing factors of adsorption and desorption properties of the similar material.

The adsorption and desorption properties of the similar material were slightly affected by the proportion of the material. Figure 9 displays the adsorption and desorption isotherms of the raw coal and those of the similar material prepared with 20% sodium humate solution as the binder. According to the adsorption and desorption isotherms, the similar material has adsorption and desorption properties consistent with that of raw coal. This indicates that the sodium humate solution is an appropriate binder that exerts ignorable influences on the adsorption and desorption properties of the similar material.

![Figure 9. Comparison between gas adsorption of coal and the similar material.](image)

(3) Influencing factors on compressive strength.

When preparing the similar material, the molding pressure exerts obvious influences on the strength of the specimens (Figure 10). The compressive strength and elasticity modulus of the specimens can be altered by changing the molding pressure. When other conditions remain constant, the higher the molding pressure is, the greater the compressive strength of the specimens. When other conditions are fixed, the compressive strength of the specimens increases if there is an increase in the molding pressure. Under a low molding pressure, the increasing gradient is large, while the increasing gradient is small if the molding pressure is large. When the molding pressure reaches 15 MPa, the compressive strength of the specimens grows very slowly, which agrees with the influence of the molding pressure on the unit weight and porosity of the specimens. The results suggest that 15 MPa is the molding pressure which enables stable physical and mechanical properties within the similar material prepared.

Among the components of the similar material, the binder concentration plays a decisive role in the strength of the specimens, as displayed in Figure 11. The compressive strength and elasticity modulus of the specimens can be regulated by changing the concentration of the sodium humate binder. Changes in the strength of the specimens with binder concentrations in the range of 1%~20% were measured. The results indicate that, under a fixed molding pressure, the higher the sodium humate concentration is, the greater the compressive strength of the specimens is, and the two are in an approximately linear direct proportional relation.
4. Conclusions

By referring to previous experience and conducting lots of orthogonal proportioning tests, a novel similar material to gas-bearing coal was developed. Under the molding pressure of 15 MPa, the material has a unit weight and porosity very approximate to that of raw coal. The similar material shows a high compressive strength that is regulatable over a range as wide as 0.5–2.8 MPa. The similar material exhibits favorable adsorptivity, which is consistent with raw coal. The similar material is also characterized by a low price for its raw materials, no toxic or side effects, simple proportioning, stable properties, and the convenient regulation of various physical and mechanical parameters. Therefore, the material can be used to simulate raw coal of differing strengths.

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