Experimental Study on the Ratio Model of Similar Materials in the Simulation Test of Coal and Gas Outburst

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Experimental Study on the Ratio Model of Similar Materials in the Simulation Test of Coal and Gas Outburst

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Abstract: In order to obtain similar materials with specific physical and mechanical parameters and adsorption and desorption indexes used in coal and gas outburst simulation tests, pulverized coal was selected as aggregate, sodium humate as cementing agent and river sand as auxiliary materials. Based on this, an orthogonal test with 6 factors and 5 levels was designed, and the tests of weighing, uniaxial compression, firmness and adsorption and desorption were carried out. The parameters such as density, uniaxial compressive strength, elastic modulus, firmness coefficient and adsorption-desorption index of similar materials with different ratios were obtained, and the sensitivity of each factor was analyzed by range analysis. The influence law of various factors on the parameters of similar materials was studied, the ratio model of similar materials was obtained and the reliability of the model was verified, and a complete method for determining the ratio model of similar materials of outburst coal was put forward. The results show that the density of similar materials increases with the increase of river sand content, the uniaxial compressive strength and elastic modulus increase significantly with the increase of pulverized coal ratio and sodium humate content, and the firmness coefficient increases linearly with the increase of pulverized coal ratio. The adsorption constant a increases linearly with the increase of sodium humate content, while the adsorption constant b decreases linearly with the increase of sodium humate content. The initial elution rate Δp of similar materials increases at first and then decreases with the increase of sodium humate content.

Keywords: Coal and Gas Outburst Simulation Test; Similar Materials; Orthogonal Test; Physical and Mechanical Parameters; Adsorption and Desorption Index; Ratio Model

1. Introduction

90% of the coal in China comes from underground mining. The average mining depth of the mines has reached 500m, the deepest point of some large and medium-sized coal mines has reached 1500m, and extends downward at an average rate of 20m every year [1-2]. With the increase of mining depth, the number of coal and gas outburst accidents increases. Many shallow non-outburst mines are transformed into outburst mines after entering deep mining, and the frequency and intensity of outburst also increase significantly. This is because the coal seam absorbs a large amount of gas under the action of high stress, and when disturbed by mining, the existing gas is released rapidly, resulting in instantaneous destruction of coal and rock structure, and coal and gas outburst is more likely to occur [3-6]. Among coal mine accidents in China from 2008 to 2013, gas accidents accounted for 27% of the total deaths, second only to roof accidents, and the number of deaths caused by coal and gas outburst accidents in gas accidents is nearly half [7]. Therefore, if coal and gas outburst accidents can be effectively curbed, the number of deaths of mine workers can be greatly reduced and the safety of coal mine production can be effectively guaranteed.

Coal and gas outburst is an extremely complex coal and gas dynamic phenomenon in coal mine production, and its prediction and prevention has always been one of the ticklish problems faced by the mining industry in the world [8-9]. In addition, most coal mines in China are characterized with low coal seam permeability, soft coal quality and complex geological conditions, so coal and gas outburst accidents are more likely to occur [10-11]. The simulation test of coal and gas outburst is an important means to study the mechanism of coal and gas outburst, and similarity simulation is also an important method to physically restore the phenomenon of coal and gas outburst. According to the principle of similarity, as long as the similarity
model and similar materials meet the similarity criterion of the prototype, the evolution process, mechanical
mechanism, dynamic effect and disaster-causing mechanism of coal and gas outburst can be simulated and
reproduced [12-15].

At present, scholars in China and abroad have obtained burgeoning volumes of research outputs through
simulating experiments of coal and gas outburst by using different test materials. Some scholars have done
simulation experiments on coal and gas outburst by using sand briquette produced by coal briquette. Kuroiwa T
carried out outburst test using cylindrical protruding device with volume cylinder. Under condition of gas
pressure 0.5 ~ 0.5°C, it was found that the larger gas pressure changed when outburst occurred, the smaller coal
particle was when outburst occurred; the greater the degree of coal pulverization is, the larger gas emission
quantity is [16]. Deng et al. selected coal powder with prominent coal seam to press briquette with strength IV
and V without adding additives. After filling high pure gas and fully adsorbing for 36 ~ 38 hours, they carried
out one dimensional simulation test [17]. Tang et al. placed coal powder into a 16 cm × 16 cm × 16 cm pressure
chamber of coal and gas outburst simulation instrument. After press-forming under 200t pressure tester,
pulverized coal was simulated under three-dimensional stress condition [18].

In addition, some scholars use cement such as pulverized coal or cement to produce outstanding
simulation test materials. Meng et al. selected coal samples prepared by adding 8.1% water particles with
diameter 0.1 ~ 0.2 mm coal particles. After filling gas and reaching adsorption equilibrium under
two-dimensional loading, they carried out a series of stress simulation tests under different pressures. There are
two typical types of failure between coal sample destruction and “cracking” and “outburst” [19]. Zhang et al.
conducted coal and gas outburst test in Schoczynski Mining Institute. The test simulated outburst failure
process of 3 kinds of outburst coal seam, briquette and bituminous briquette under different gas pressure,
established dimensionless parameter criterion for judging outburst failure of coal seam, and gave prediction
formula of outburst intensity of model coal sample [20]. Ou et al. selected soft stratified coal sample below
1mm diameter prepared by adding coal tar of different proportions under pressure 20 MPa. By using gas as
adsorption gas to simulate coal and gas outburst, they obtained outburst evolution rule of different intensity coal
samples [21].

Although scholars have obtained a large number of research achievements through outburst simulation
tests, it’s still not possible to physically restore the outburst phenomenon completely. The main reason is that
similarity between test materials and original outburst coal is low. As an important carrier of physical
simulation test of coal and gas outburst, outburst simulation similarity material directly determines physical
reduction capability and representative behavior of real environment [22-23]. For example, although coal
briquette directly press-formed by pulverized coal is not added with ash, its mechanical strength and firmness
coefficient are generally low; although the mechanical strength and firmness coefficient of coal briquette added
with cement, asphalt and other things are improved, the adding of ash content affects the adsorption and
permeability of coal briquette.

Scholars in China have also conducted a significant amount of research on the influence laws of coal and
gas outburst simulation materials on the properties of similar materials, especially binder ratio and
aggregate ratio. Kong and Li et al. carried out experimental research on similar materials using cement and
gypsum as cementing agent. Experiment results show that compressive strength and density increase with sand
binder ratio and water ratio, the cementing material ratio is a major factor to improve compressive strength of
similar materials [24-25]. Liu et al. carried out an experimental study on low strength similar materials using
gypsum, fly ash as cementing agent and sand as aggregate. It was found that the elastic modulus and
compressive strength of similar materials have a linear relation with sand binder ratio and a power correlation
with cementing agent ratio [26]. Kang et al. carried out experimental studies on similar materials of simulated
raw coal using sand and pulverized coal as aggregates respectively, and compared and analyzed the differences
between the two kinds of aggregates: when pulverized coal is aggregate, the material strength has a linear
negative correlation with it, while when sand is aggregate, the material strength has a nonlinear negative
correlation with it [27]. Zhang et al. carried out an experimental study on similar materials of outburst coal using
cement as binder and pulverized coal as aggregate. It was found that there was a linear relation between the
specific gravity of cement and cement sand and the uniaxial compressive strength and density of the specimens
[28].

To sum up, most researches on outburst test materials and outburst simulation similar materials done by
scholars in China and abroad focus on the similarity of physical and mechanical properties with raw coal, and
the similarity of adsorption and desorption property is rarely studied. Therefore, in order to ensure that similar
materials have high similarity with the original outburst coal in terms of physical and mechanical properties and adsorption and desorption properties, a model test study on the proportion of similar materials of outburst coal is carried out in this paper, with the aim to make a certain range of physical and mechanical parameters and adsorption indicators of similar materials needed for outburst simulation test, and prepare for large-scale coal and gas outburst simulation test.

2. Similarity indexes of outburst simulation test materials

Based on the analysis of the mechanical mechanism of coal and gas outburst, the similarity theory of coal and gas outburst simulation test is divided into three parts: 1) The static deformation and failure of coal in the preparation stage of outburst are similar, so it needs to meet the similarity of geometric shape, material properties, load and displacement constraints[29-31]. 2) The fragmentation of gas-bearing coal in the stage of outburst initiation and development is similar, so it needs to meet the similarity of parameters such as porosity, gas pressure and crack length[32-35], and 3) The movement of broken coal gas flow in mining space is similar. Since the gas flow of outburst crushed coal is solid-gas two-phase flow, it needs to meet the similarity of parameters such as gas occurrence and gas emission [36-38].

Among the similarities of these parameters, the similarity of mechanical parameters, porosity, gas occurrence, and emission etc. in outburst simulation test is determined by properties of similar materials. Therefore, on the premise that the outburst coal body shows the same homogeneity, using homogeneous continuous medium model theory of scholars such as Zhao [39], Li [40], Li [41], Guo [42], Yin [43], this paper derives model material similarity ratio, the model is as follows:

\[
\frac{\partial^2}{\partial x^2} + (\lambda + G) \frac{\partial^2 u}{\partial y^2} + (\lambda + 2G) \frac{\partial^2 u}{\partial z^2} = 0
\]

In the formula: \(P = P^p\), \(S(p) = \frac{n + ab}{p(1+bp)^2}\), \(K_x, K_y, K_z\) are permeability coefficients on the direction of three coordinate axes, \(W\) is source sink term, \(G = \frac{E}{2(1+\mu)}\) is shear elastic modulus, \(\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}\) is Laplace operator, \(\lambda = \frac{\mu E}{(1+\mu)(1-2\mu)}\) is Lame constant, \(e = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z}\) is volume strain.

These equations are applicable for prototype \((^*)\) and model \((^\circ)\), given: \(C_{\sigma} = \frac{G^\circ}{G^*}\) is similarity ratio of shear modulus, \(C_u = \frac{u^\circ}{u^*}\) is displacement similarity ratio, \(C_{\lambda} = \frac{\lambda^\circ}{\lambda^*}\) is Lame similarity ratio, \(C_x = \frac{E^\circ}{E^*}\) is elastic modulus similarity ratio, \(C_i = \frac{X^\circ}{X^*}\) is geometric similarity ratio, \(C_e = \frac{e^\circ}{e^*}\) is volume strain similarity ratio, \(C_r = \frac{X^\circ}{X^*}\) is bulk density similarity ratio, \(C_p = \frac{\rho^\circ}{\rho^*}\) is density similarity ratio, \(C_t = \frac{t^\circ}{t^*}\) is motion time similarity ratio, \(C_f = \frac{f^\circ}{f^*}\) is external load similarity ratio, \(C_p = \frac{p^\circ}{p^*}\) is gas pressure similarity ratio, \(C_g = \frac{g^\circ}{g^*}\) is gravity acceleration similarity ratio and \(C_{\sigma}\) is stress similarity ratio.

When the above relation is brought into the second equation of equation (1), the following formula can be obtained:

\[
C_{\sigma} C_{i}^2 = C_{\sigma} C_{i}^2 = C_{\sigma} C_{i}^2 = C_{\sigma} C_{i}^2 = C_{\sigma} C_{i}^2 = C_{\sigma}
\]
As it is a mathematical model of homogeneous continuous medium, \( K_x = K_y = K_z = K \), the following functions are introduced: \( C_k = \frac{K^l}{K^0} \) is similarity ratio of permeability coefficient, \( C_q = \frac{Q^l}{Q^0} \) is gas flow similarity ratio, \( C_s = \frac{S^l}{S^0} \) is similarity ratio of gas storage coefficient and \( C_i = \frac{l^x}{x^0}, C_j = \frac{y^j}{y^0}, C_k = \frac{z^k}{z^0} \) is geometric similarity ratio of 3D direction. When it is brought into the seepage equation (1), the following formula can be obtained:

\[
\frac{C_k C_p}{C_s^2} = \frac{C_k C_p}{C_s^2} = \frac{C_k C_p}{C_s^2} = \frac{C_i C_p}{C_i^2} = \frac{C_i C_p}{C_i^2} = \frac{C_x}{C_y} = \frac{C_x}{C_y} = \frac{C_x}{C_y}
\]

(3)

Through analysis of formula (2) formula (3), and in combination with geometric similarity ratio of \( C_l = 10 \) and the bulk density similarity ratio of \( C_r = 1 \) between the test model and the prototype, the following relation can be derived: geometric similarity: \( C_n = C_l = 10 \), elastic modulus and gravity similarity: \( C_e = C_o = C_r C_g = 10 \), stress similarity: \( C_p = C_r C_g = 10 \), gas storage coefficient similarity: \( C_s = \frac{1}{C_s C_r} = 0.1 \), seepage coefficient: \( C_k = \frac{\sqrt{C_i}}{C_r} \approx 3.2 \).

Through consulting statistics of characteristic parameters of each outburst coal in Yuyang Coal Mine and combining with similar model material similarity ratio, this paper determines the characteristic parameters range of coal and outburst simulation test materials, as shown in Table 1.

| TABLE 1 Characteristic parameters of outburst coal and model material. |
|--------------------------|-------------------|---------------|---------------|-----------------|-----------------|
| Material | Density (g/cm³) | Uniaxial compressive strength (MPa) | Elastic modulus (MPa) | F value | Adsorption constant | Initial speed of emission (Δp) |
|-----------|-----------------|---------------------------------|----------------------|--------|------------------|-----------------------------|
| Outburst coal | 1.21~1.72 | 4.3~37.8 | 1135~4602 | 0.11~0.50 | 15~60 | 0.2~2 | 11~39 |
| Model material | 1.21~1.72 | 0.43~3.78 | 113.5~460.2 | 0.11~0.50 | 15~60 | 0.2~2 | 11~39 |

3. Model experiment of ratio model for outburst coal similar materials

3.1. Experiment scheme

3.1.1 Selection of raw materials

Selection of raw materials for similar materials should conform to the following principles: 1) easy to largely control material performance index; 2) meet prototype material characteristic requirements; 3) raw material has stable performance; 4) production process is simple; 5) materials are safe and pollution-free [44-45].

Raw materials of similar materials are generally composed of aggregates, binder and auxiliary materials. Combined with characteristics of model materials, M8 coal seam above 80 meshes and pulverized coal (anthracite) of 40 ~ 80 meshes from Yuyang Coal Mine are selected and used as aggregate; sodium humate of 80 ~ 100 meshes is selected and used as cementing agent. With strong adsorption capacity, sodium humate can easily adjust adsorption and desorption index of similar materials; river sand of 0.425 ~ 0.850mm is selected and used as auxiliary materials, which makes it easy to adjust the density of similar materials.

3.1.2 Selection of raw materials

(1) Physical and mechanical property
Orthogonal experimental method was adopted to design the experiment. Coal ratio (above 80 meshes and 40 ~ 80 meshes of pulverized coal mass ratio), sodium humate content and sand quality were selected as three factors of the orthogonal experiment. Each factor was set 5 levels respectively. See Table 2 for details.

**TABLE 2** Regressional orthogonal experiment design.

| Level | Pulverized coal ratio | Sodium humate content (%) | River sand content (%) |
|-------|-----------------------|---------------------------|------------------------|
| 1     | 1:5                   | 0.5                       | 1                      |
| 2     | 2:5                   | 2.5                       | 3                      |
| 3     | 3:5                   | 4.5                       | 5                      |
| 4     | 4:5                   | 6.5                       | 7                      |
| 5     | 5:5                   | 8.5                       | 9                      |

An orthogonal table of 6 factors and 5 levels was selected in the experiment. See Table 2 for the specific material ratio schemes.

**TABLE 3** Ratio table of physical and mechanics parameters for similar materials of L25 (5%).

| Experiment no. | Pulverized coal ratio | Sodium humate content (%) | River sand content (%) |
|----------------|-----------------------|---------------------------|------------------------|
| 1              | 1:5                   | 0.5                       | 1                      |
| 2              | 1:5                   | 2.5                       | 3                      |
| 3              | 1:5                   | 4.5                       | 5                      |
| 4              | 1:5                   | 6.5                       | 7                      |
| 5              | 1:5                   | 8.5                       | 9                      |
| 6              | 2:5                   | 0.5                       | 3                      |
| 7              | 2:5                   | 2.5                       | 5                      |
| 8              | 2:5                   | 4.5                       | 7                      |
| 9              | 2:5                   | 6.5                       | 9                      |
| 10             | 2:5                   | 8.5                       | 1                      |
| 11             | 3:5                   | 0.5                       | 5                      |
| 12             | 3:5                   | 2.5                       | 7                      |
| 13             | 3:5                   | 4.5                       | 9                      |
| 14             | 3:5                   | 6.5                       | 1                      |
| 15             | 3:5                   | 8.5                       | 3                      |
| 16             | 4:5                   | 0.5                       | 7                      |
| 17             | 4:5                   | 2.5                       | 9                      |
| 18             | 4:5                   | 4.5                       | 1                      |
| 19             | 4:5                   | 6.5                       | 3                      |
| 20             | 4:5                   | 8.5                       | 5                      |
(2) Properties of firmness and adsorption desorption

Under the premise that the pulverized coal ratio is the main factor controlling the physical and mechanical properties of similar materials, and under the condition of fixed sodium humate and river sand content, this paper mainly investigates the influences of the pulverized coal ratio (pulverized coal mass ratio above 80 meshes and 40 ~ 80 meshes) and the firmness coefficient of similar materials. Due to the strong adsorbability of sodium humate, under the condition of fixed pulverized coal ratio and river sand content, this paper examines the influence of different sodium humate content and adsorption and desorption indexes of similar materials.

The experimental design is shown in Table 4.

### TABLE 4 Ratio table of firmness coefficient, adsorption and desorption index of similar materials.

| Experiment no. | Pulverized coal ratio | Sodium humate content (%) | River sand (%) | Firmness coefficient | Experiment no. | Pulverized coal ratio | Sodium humate content (%) | River sand (%) | Adsorption desorption index |
|----------------|-----------------------|---------------------------|---------------|----------------------|----------------|-----------------------|---------------------------|---------------|---------------------------|
| 1              | 0.2                   | 0.5                       | 4             | 6                    | 6              | 0.4                   | 4                         | 0.5           |                           |
| 2              | 0.4                   | 0.5                       | 4             | 7                    | 7              | 0.4                   | 4                         | 2.5           |                           |
| 3              | 0.6                   | 0.5                       | 4             | 8                    | 8              | 0.4                   | 4                         | 4.5           |                           |
| 4              | 0.8                   | 0.5                       | 4             | 9                    | 9              | 0.4                   | 4                         | 6.5           |                           |
| 5              | -                     | -                         | -             | 10                   | 10             | 0.4                   | 4                         | 8.5           |                           |

3.2. Experiment process

Under the condition that the loading speed is 50N/S, the forming pressure is 20MPa and the pressure-holding time is 15min, the TAW-2000 microcomputer is used to control the electro-hydraulic servo rock triaxial testing machine and the mold with inner diameter of 50mm and height of 100mm is used to press the standard specimen according to the material ratio in Table 3 and Table 4. Two new processes of stack moulding and stack retting curing are adopted in the production process. The production process of similar material specimens is as follows: raw material preparation→ material mixing (sodium humate dry powder mixed with pulverized coal and river sand first and then add 10% water) → stack retting curing (48h) → test mold preparation → loading & tamping → pressing molding (materials are loaded to each specimen in three divided times on average) → demoulding marking →natural curing (15d). The rock triaxial testing machine is shown in Figure 1, the pressing mold is shown in Figure 2, and the curing specimen is shown in Figure 3.
3.3. Analysis of experiment results

Size measurement, weighing, uniaxial compression test, firmness, adsorption and desorption tests were carried out on 25 groups of standard specimens in Table 3 and 9 groups of standard specimens in Table 4 (two standard specimens were pressed in each group). The uniaxial compressive strength, elastic modulus, density, firmness coefficient, adsorption constant and initial velocity of diffusion were measured, and the average values of the measured data are shown in Table 5 and Table 6.
| Experiment no. | Uniaxial compressive strength (MPa) | Elastic modulus (MPa) | Density (g/cm³) |
|---------------|------------------------------------|----------------------|----------------|
| 1             | 1.335                              | 117.45               | 1.308          |
| 2             | 1.485                              | 133.65               | 1.342          |
| 3             | 1.598                              | 144.05               | 1.364          |
| 4             | 1.633                              | 162.20               | 1.378          |
| 5             | 1.599                              | 152.55               | 1.392          |
| 6             | 1.518                              | 146.15               | 1.344          |
| 7             | 1.587                              | 148.50               | 1.350          |
| 8             | 1.655                              | 153.60               | 1.356          |
| 9             | 1.753                              | 185.05               | 1.386          |
| 10            | 1.910                              | 192.65               | 1.328          |
| 11            | 1.698                              | 158.00               | 1.382          |
| 12            | 1.746                              | 180.10               | 1.39           |
| 13            | 1.733                              | 173.35               | 1.407          |
| 14            | 2.085                              | 206.55               | 1.342          |
| 15            | 1.867                              | 184.60               | 1.365          |
| 16            | 1.838                              | 174.45               | 1.412          |
| 17            | 1.789                              | 172.00               | 1.425          |
| 18            | 2.201                              | 218.85               | 1.349          |
| 19            | 1.925                              | 194.15               | 1.366          |
| 20            | 2.383                              | 272.65               | 1.384          |
| 21            | 1.867                              | 188.90               | 1.438          |
| 22            | 1.963                              | 204.35               | 1.372          |
| 23            | 2.197                              | 233.10               | 1.396          |
| 24            | 2.527                              | 302.00               | 1.404          |
| 25            | 2.459                              | 279.90               | 1.413          |

**TABLE 6** Firmness coefficient and adsorption-desorption index of similar materials.

| Experiment no. | Material ratio | Parameter          | Material ratio | Adsorption constant | Parameter |
|----------------|----------------|--------------------|----------------|---------------------|-----------|
|                | Pulverized coal ratio | Firmness coefficient (f) | Pulverized coal ratio | a | b | Initial velocity of diffusion (ΔP) |
| 1              | 0.2            | 0.13               | 0.4            | 25.6248             | 1.7734    |
| 2              | 0.4            | 0.17               | 0.4            | 27.4399             | 1.7205    |
| 3              | 0.6            | 0.19               | 0.4            | 28.6718             | 1.6884    |
Comparing the test results of Table 5, Table 6 and Table 1, it is found that the configured density range of similar materials is $[1.308, 1.438] \subseteq [1.21, 1.72]$ (model material density), uniaxial compressive strength range $[1.335, 2.527] \subseteq [0.43, 3.78]$ (model material uniaxial compressive strength), elastic modulus range $[117.45, 302.00] \subseteq [113.5, 460.2]$ (model material elastic modulus). The range of firmness coefficient is $[0.13, 0.23] \subseteq [0.11, 0.50]$ (model material firmness coefficient), and the range of adsorption constant $a$ $[26, 32] \subseteq [15, 60]$ (model material adsorption constant $a$), adsorption constant range $b [1.3, 1.8] \subseteq [0.2, 2]$ (model material adsorption constant $b$), diffusion initial velocity range $[16, 22] \subseteq [11, 39]$ (model material diffusion initial velocity). Therefore, it can ensure that the prepared similar materials have good similarity with outburst coal in physical and mechanical properties, firmness, adsorption and desorption properties.

3.3.1 Analysis of the influence of physical and mechanical properties

(1) Sensitivity analysis of various factors

The factors that affect the density, uniaxial compressive strength and elastic modulus of the specimen in the orthogonal test results are calculated at each level, as shown in Table 5. It can be seen that for the density of similar materials, the range of river sand content is the largest, which shows that river sand content has the strongest controlling effect on the density of similar materials, followed by the ratio of pulverized coal to coal, and finally the content of sodium humate; for the uniaxial compressive strength and elastic modulus of similar materials, the sensitivities of various factors are highly consistent, and the range of sodium humate content and pulverized coal ratio is much larger than that of river sand content, but the strongest controlling effect is the pulverized coal ratio, followed by sodium humate content, and finally the river sand content.

**TABLE 7** The range of each level of each factor.

| Factor                  | Density (g/m$^3$) | Uniaxial compressive strength (MPa) | Elastic modulus (MPa) |
|------------------------|-------------------|-------------------------------------|-----------------------|
| Pulverized coal ratio  | 0.048             | 0.489                               | 66.59                 |
| Sodium humate content  | 0.009             | 0.422                               | 52.244                |
| River sand content     | 0.073             | 0.107                               | 18.264                |

In order to analyze the influence law of various factors on similar material parameters in an intuitive way, it is necessary to calculate the mean value of each factor at each level, and then use Origin software to make a visual analysis diagram of the influence of various parameters on similar material parameters, see Figure 4 ~ Figure 6. It can be seen that the density of similar materials increases with the increase of river sand content, first increases and then does not change with the increase of pulverized coal ratio, and the uniaxial compressive strength and elastic modulus of similar materials increase significantly with the increase of pulverized coal ratio and sodium humate content, but there is no obvious change with the increase of river sand content.

**FIGURE 4** Effect curve of similar material density
(2) Multiple linear regression analysis

Through the above sensitivity analysis of various factors, it can be seen that there is an obvious linear relation between each factor and some parameters of similar materials. Multiple linear regression analysis was carried out by using SPSS software. Let pulverized coal ratio be the equal of $K_1$, sodium humate content $K_2$, river sand content $K_3$, density $M_1$, uniaxial compressive strength $M_2$, elastic modulus $M_3$. The regression equations were obtained as follows:

\[
\begin{align*}
M_1 &= 0.065K_1 + 0.008K_2 + 1.295 \\
M_2 &= 0.844K_1 + 0.053K_2 + 1.11 \\
M_3 &= 120.285K_1 + 8.062K_2 + 78.704
\end{align*}
\]

Under the condition that the pulverized coal ratio, the sodium humate content and the river sand content are known, the density, uniaxial compressive strength and elastic modulus of similar materials can be calculated through formula (4). However, in order to obtain the raw material ratio of similar materials with a specific parameter, the formula (4) is solved and the following empirical formula is obtained:

\[
\begin{align*}
K_1 &= 16.41M_2 - 0.12M_3 - 11.13 \\
K_2 &= -280.24M_2 + 1.97M_3 + 156.3 \\
K_3 &= 125M_2 - 133.33M_3 + 0.98M_3 - 71.44
\end{align*}
\]

Under the condition that the density, uniaxial compressive strength and elastic modulus of similar materials are known, the pulverized coal ratio, sodium humate content and river sand content of similar materials can be calculated through formula (5). The ratio of pulverized coal $K_1 \in [0, \infty]$, the sodium humate content $K_2 \in [0, 1]$ and the river sand content $K_3 \in [0, 1]$ in formula (5). When calculating the material ratio by using the above equation, if the calculation result exceeds the range of appeal value, it shows that the selection...
of similar materials for this kind of raw material configuration under this process condition does not meet the experiment requirements, and it is necessary to select other raw materials or change the process conditions.

3.3.2 Analysis of the influence of firmness and adsorption and desorption performance

(1) The firmness of similar materials

The firmness of coal differs from the strength of coal. As a comprehensive index of the ability to resist external damage determined by various properties of coal, it is also one of the main identification indexes of outburst coal seam in the detailed rules for Prevention and Control of Coal and Gas Outburst. Therefore, it is listed as one of the important indexes in the test of similar materials of outburst coal [35-36].

\[ f = 0.16K_1 + 0.1 \]

\[ R^2 = 0.9846 \]

A visual analysis diagram of the effect of different pulverized coal ratio on the firmness coefficient of similar materials under the condition of fixed sodium humate and river sand content is made according to Table 6, as shown in Figure 7. Figure 7 shows that the firmness coefficient of similar materials increases linearly with the increase of pulverized coal ratio, and the fitting degree \(R^2\) of the relational formula is as high as 0.9846, showing good fitting effect. The relational formula (6) is obtained.

(2) Adsorption and desorption properties of similar materials

\[ a = 0.7478K_2 + 25.401 \]

\[ R^2 = 0.9919 \]

A visual analysis diagram of the effect of different sodium humate content on the adsorption constant of similar materials under the condition of fixed pulverized coal ratio and river sand content is shown in Figure 8. Figure 8 shows that the adsorption constant of similar materials increases linearly with the increase of sodium humate content, and the fitting degree \(R^2\) of the relational formula is as high as 0.9919, showing good fitting effect. The relational formula (8) is obtained.
\[ b = -0.0644K_2 + 1.855 \]
\[ R^2 = 0.8237 \]

FIGURE 9 The curve of sodium humate content and adsorption constant b under the condition of fixed pulverized coal ratio and river sand content

\[ a = 0.7478K_2 + 25.401 \]
\[ b = -0.0644K_2 + 1.855 \]

(7)

A visual analysis diagram of the effect of different sodium humate content on the adsorption constant and initial diffusion velocity of similar materials is made according to Table 7, as shown in Figure 8 ~ Figure 10. It can be seen from the above figure that the adsorption constant a of similar materials increases gradually with the increase of sodium humate content, but the adsorption constant b decreases gradually, showing a good linear relationship. The linear fitting degree \( R^2 \) between adsorption constant a and sodium humate content is as high as 0.9919, the fitting degree \( R^2 \) of adsorption constant b is 0.8237. The relationship obtained by fitting is shown in formula (7). The initial diffusion velocity of similar materials increases at first and then decreases with the increase of sodium humate content.

4. Verification analysis of the matched model of similar materials
The specific method of verification analysis: select three groups of similar material parameters from Table 293, calculate the material ratio of each group of parameters through formula (5), and make the standard specimen with these three groups of raw materials under the same standard pressing process, then determine the parameters of the specimen, and then compare and analyze the parameters with the three groups of similar material parameters selected, and verify the ratio model through the difference of the two parameters. It can be seen from Figure 5 and Figure 6 that the effects of pulverized coal ratio, sodium humate content and river sand content on uniaxial compressive strength and elastic modulus are highly consistent, so only density and uniaxial compressive strength are considered in this verification test. The selected three groups of parameters and the calculated material ratio are shown in Table 8.

**TABLE 8** Raw material ratio of similar materials.

| Experiment no. | Parameter | Material ratio |
|----------------|-----------|----------------|
|                | Density (g/m³) | Uniaxial compressive strength (MPa) | Pulverized coal ratio | Sodium humate (%) | River sand (%) |
| 1              | 1.308     | 0.753          | 0.2                 | 1.3               | 0.1           |
| 2              | 1.390     | 1.055          | 0.5                 | 3.8               | 7.7           |
| 3              | 1.396     | 1.454          | 0.8                 | 7.2               | 5.8           |

The same raw materials and abrasive tools were selected to press the standard specimens according to the three groups of materials in Table 8 in the same environment and the same standard production process, and the density and uniaxial compressive strength of the specimens were measured in the same curing time. The measured and analyzed data are shown in Table 9.

**TABLE 9** Comparison of experiment values and original values of density and uniaxial compressive strength of similar materials.

| Experiment no. | Density (g/m³) | Uniaxial compressive strength (MPa) |
|----------------|----------------|-------------------------------------|
|                | Original values | Experiment values | Relative deviation | Original values | Experiment values | Relative deviation |
| 1              | 1.308          | 1.352                  | 3.36%              | 1.335          | 1.104              | 17.30%             |
| 2              | 1.390          | 1.386                  | 0.29%              | 1.746          | 1.437              | 17.70%             |
| 3              | 1.396          | 1.377                  | 1.36%              | 2.197          | 1.908              | 13.15%             |

In addition, under the matching conditions of pulverized coal ratio 0.4, sodium humate content 0.5% and river sand content 4%, the set of parameters of similar materials with firmness coefficient 0.17, adsorption constant a 25.6248, adsorption constant b 1.7734 and initial diffusion velocity 19 were also selected from Table 6 and Table 7. The ratio of materials back calculated by formula (6) and formula (7) is 0.4 and the content of sodium humate is 0.3%. In the case of fixed river sand content of 4%, the specimen was pressed with the same standard production process, and the firmness coefficient and adsorption and desorption index were determined after curing for 15 days (see Table 10), and then compared with the original index to verify the formula.

**TABLE 10** Comparison of adsorption constant, firmness coefficient and initial diffusion velocity of similar materials between experiment values and original values.

| Experimental data | Raw material ratio | Parameter |
|-------------------|--------------------|-----------|
|                   | Pulverized coal ratio | Sodium humate content (%) | River sand content (%) | Adsorption constant a | Initial velocity of diffusion (ΔP) | Firmness coefficient (f 值) |
| Original values   | 0.4                | 0.5       | 4        | 25.6248 | 1.7734 | 19                          | 0.17 |
| Experiment values | 0.4                | 0.3       | 4        | 24.5461 | 1.8325 | 16                          | 0.15 |
| Relative deviation| -                  | -         | -        | 4.21%   | 3.33%  | 15.8%                       | 11.8% |
In the model experiment of similar materials, there is no clear specification for the allowable error of the characteristic parameters of similar materials. According to the Basic Performance Test Method of Building Mortar [37], the difference between the maximum or minimum value and the average value of the material performance index shall not exceed 20%, so the maximum difference between the experiment value and the original value of the similar material shall not exceed 20%, which is also used as a standard to measure the regression equation and the experiment value. As can be seen from Table 9 and Table 10, the relative deviations of similar material density, uniaxial compressive strength, firmness coefficient, adsorption constant, initial velocity of diffusion and original parameters calculated by regression equation (5), formula (6) and formula (7) are all less than 20%. Therefore, the empirical formula obtained from this experimental study can be effectively used to configure the model materials in the simulation test of coal and gas outburst.

5. Conclusions

(1) By using the method of orthogonal design, 25 groups of material ratio schemes are designed based on three factors: sodium humate content, pulverized coal ratio and river sand content. Each factor is set at 5 levels. Similar materials with density range of 1.308~1.438g/cm³, uniaxial compressive strength range of 1.335~2.527MPa and elastic modulus range of 117.45~302.00MPa were obtained under different material ratio conditions.

(2) The sensitivity of various factors to the physical and mechanical properties of similar materials is analyzed by range analysis. The effect on the density of similar materials is in the following order: river sand content > pulverized coal ratio > sodium humate content, and the effects on uniaxial compressive strength and elastic modulus of similar materials are as follows: pulverized coal ratio > sodium humate content > river sand content.

(3) The influence of various factors on the parameters of similar materials is studied. The density of similar materials increases with the increase of river sand content, increases first and then remains at a certain level with the increase of pulverized coal ratio, and the uniaxial compressive strength and elastic modulus of similar materials increase significantly with the increase of pulverized coal ratio and sodium humate content. However, there is no obvious change with the increase of river sand content, and the firmness coefficient of similar materials increases linearly with the increase of pulverized coal ratio (linear equation: \( f = 0.16K_1 + 0.1 \)); the adsorption constant a of similar materials increases linearly with the increase of sodium humate content (the linear equation: \( a = 0.7478K_2 + 25.401 \)), adsorption constant b decreases linearly with the increase of sodium humate content (the linear equation: \( b = -0.0644K_2 + 1.855 \ )); the initial diffusion velocity of similar materials increases at first and then decreases with the increase of sodium humate content.

(4) The multiple linear regression analysis of the experimental data is carried out by using SPSS software, and the empirical formula of the ratio of similar materials is obtained. The verification test shows that the similar material ratio calculated by the empirical formula and the similar material parameters prepared under the same standard production process meet the test requirements.

(5) By standardizing the similarity index of coal and gas outburst test materials, the raw materials of similar materials, the mold of similar materials and the pressing process of similar material specimens, and based on the empirical formula of the ratio of similar materials of outburst coal, this paper puts forward a complete method for determining the ratio model of similar materials of outburst coal.
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References

1. Xie HP, Zhou HW, Xue DJ, Wang HW, Zhang R, Gao F. Research and thinking on deep mining and limit mining depth of coal. *Journal of China Coal Society*. 2012;04:535-542.
2. Cheng YP, Wang L, Zhang XL. Environmental impact of coal mine methane emissions and responding strategies in China. *International Journal of Greenhouse Gas Control*. 2011;5(1):157-166.
3. Hu WY. Research status and development trend of deep coal resources and their development technical conditions. *Beijing: China Coal Industry Publishing House*. 2008:1-25.
4. Zhao H, Xiong ZQ, Wang W. Main problems and countermeasures of deep mining in mine. *Coal Engineering*. 2010;7:11-13.
5. Li HM, Fu K. Main technical problems and countermeasures in deep mining of coal mine. *Journal of Mining and Safety Engineering*. 2006;04(14):468-471.
6. Lu J, Zhang DM, Huang G. Effects of Loading Rate on the Compound Dynamic Disaster in Deep Underground Coal Mine. *International Journal of Rock Mechanics and Mining Science*. 2020.
7. Jing GX. Analysis on the law of coal mine gas accidents in China from 2008 to 2013 [J]. *Journal of Safety and Environment*. 2014;05:353-356.
8. Fu JH, Cheng YP. Present situation and prevention countermeasures of coal and gas outburst in coal mines in China. *Journal of Mining and Safety Engineering*. 2007;03:253-259.
9. Yang X, Wen G, Lu T. Optimization and Field Application of CO2 Gas Fracturing Technique for Enhancing CBM Extraction. *Natural Resources Research*. 2020;29(3):1875-1896.
10. Liu C, Yin GZ, Li MH. Deformation and permeability evolution of coals considering the effect of beddings. *International Journal of Rock Mechanics and Mining Science*. 2019;117:49-62.
11. Hu QT, Wen GC. Mechanical mechanism of coal and gas outburst. *Beijing: Science Press*. 2013.
12. Xu T. Similarity theory and model test. *Beijing: China Agricultural Machinery Press*. 1982.
13. Li SC, Li QC, Wang HP, Yuan L, Zhang YQ, Xue JH, Zhang B, Wang J. Development of large-scale real three-dimensional coal and gas outburst quantitative physical simulation test system. *Journal of China Coal Society*. 2018;43(S1):121-129.
14. Duan M., Jiang C., Xing H. Study on damage of coal based on permeability and load-unload response ratio under tiered cyclic loading. *Arabian Journal of Geosciences*. 2020;13(6):250.
15. Yuan L, Wang W, Wang HP, Zhang B, Liu ZZ, Yu GF, Zuo YJ. Simulation test system of coal and gas outburst induced by roadway driving [J]. *Journal of China University of Mining and Technology*. 2020;49(02):205-214.
16. KUROIWA T, TASHIRO T. Experimental study on coal pulverization and gas emission in a moment of out-bursts of gas and coal. *Journal of Japanese Mining*. 1960;76:227-233.
17. Deng QF, Luan YX, Wang YA. Simulation test of coal and gas outburst. *Coal Mine Safety*. 1989;11:5-10.
18. Tang JP, Pan YS, Yang L. Simulation experimental study on coal and gas outburst under three-dimensional stress. *Chinese Journal of Rock Mechanics and Engineering*. 2013;05:960-965.
19. Meng XY, Ding YS, Chen L, Bai RS, Tan QM. Two-dimensional simulation experimental study on coal and gas outburst. *Journal of China Coal Society*. 1996;01:57-62.
20. Zhang JG, Wei FQ. Outburst simulation test of gas-bearing coal. *Mining Safety and Environmental Protection*. 2002;01:7-12.
21. Ou JC. Simulation experimental study on the evolution process of coal and gas outburst. *Xuzhou: China University of Mining and Technology*. 2012.
22. Li SG, Zhao B, Zhao PX, Yang EH, Xu PY. Study on gas adsorption characteristics of coal-rock gas-solid-gas coupling similar materials. *Journal of Mining and Safety Engineering*. 2019;36(03):634-642.
23. Wang HP, Li QC, Yuan L, Li SC, Xue JH, Zhu HY, Duan CR, Wang SG. Coal and gas outburst simulation test research and development of similar materials and characteristic analysis of briquette. *Journal of Mining and Safety Engineering*. 2018;35(06):1277-1283.
24. Kong LQ, Sun JM. Experimental study on similar material ratio of simulated coal. *Opencast Mining Technology*. 2007;4:33-35.
25. Li BF, Ren YK, Qi LWi, Chang L. Experimental study on orthogonal proportion of low strength similar materials for coal and rock mass. *Coal Engineering*. 2011;04:93-95.
26. Liu LL, Wang HL, Liu JB, Chen SJ. Orthogonal proportion test of low strength similar materials. *Journal of Liaoning University of Engineering and Technology*. 2014;33(2):188-192.
27. Kang XT, Huang Y, Deng BZ, Han PB. Experimental study on similar materials simulating raw coal. *Journal of Northeastern University*. 2015;36(1):138-142.
28. Zhang ST, Dai LC, Wang B, Cao J. Experimental study on similar material ratio of simulated coal and gas outburst. *Coal Science and Technology*. 2015;43(6):76-80.
29. Yin GZ, Jiang CB, Wang JG, Xu J, Zhang DM, Huang G. A new experimental apparatus for coal and gas outburst simulation. *Rock Mech Rock Eng*. 2016;49:2005-2013.
30. Zhang CL, Xu J, Yin GZ, Shoujian Peng, Qixian Li, Chen YX. A novel large-scale multifunctional apparatus to study the disaster dynamics and gas flow mechanism in coal mines. *Rock Mechanics and Rock Engineering*. 2019;52:2889-2898.
31. Fan CJ, Li S, Luo MK, Du WZ, Yang ZH. Coal and gas outburst dynamic system. *International Journal of Mining Science and Technology*. 2017;27(2):49-55.
32. Lu YY, Wang HY, Xia BW, Li XH, Ge ZL, Tang JR. Development of a Multi-functional Physical Model Testing System for Deep Coal Petrography Engineering. *Rock Mech Rock Eng*. 2017;50:269-283.
33. Tu QY, Cheng YP, Guo PK, Jiang JY, Wang L, Zhang R. Experimental Study of Coal and Gas Outbursts Related to Gas-Enriched Areas. *Rock Mech Rock Eng*. 2016;49:3769-3781.
34. Guo BH, Li YZ, Jiao F, Luo T, Ma Q. Experimental study on coal and gas outburst and the variation characteristics of gas pressure. *Geomech. Geophys. Geo-energ. Geo-resour*. 2018;4:355-368.
35. Bin ZA, Jiang X, Peng SJ, Geng B, Yan FZ. Test system for the visualization of dynamic disasters and its application to coal and gas outburst. *International Journal of Rock Mechanics and Mining Sciences*. 2019;122:93-104.
36. Zhang QH, Yuan L, Wang HP, Kang JH, Li SC, Xue JH, Zhou W, Zhang DM. Establishment and analysis of similarity criterion for physical simulation of coal and gas outburst. *Journal of China Coal Society*. 2016;41(11):2773-2779.
37. Dai LC, Zhang ST, Cao J. Discussion on geometric parameters of similar model of coal and gas outburst. *Coal Mine Safety*. 2018;49(08):194-197.
38. Cao J, Sun HT, Dai LC, Sun DL, Wang B, Miao FT. Simulation study on dynamic effect of coal and gas outburst. *Journal of China University of Mining and Technology*. 2018;47(01):113-120.
39. Zhao YS. Multi-field coupling in porous media and its engineering response. *Beijing: Science Press*. 2010.
40. Li SG, Zhao PX, Lin HF, Xiao P, Wei ZY. Experimental study on similar material characteristics of “solid-gas” coupling physical simulation of coal and gas. *Journal of China Coal Society*. 2015;40(01):80-86.
41. Li SC, Feng XD, Li SC, Li LP, Li GY. Development and application of new solid-fluid coupling similar materials. *Journal of Rock Mechanics and Engineering*. 2010;29(02):281-288.
42. Guo Ping, Cao Shugang, Zhang Zanguo, Li Yi, Liu Yanbao, Li Yong. Solid-gas coupling mathematical model and numerical simulation of gas-bearing coal. *Journal of China Coal Society*. 2012;37(S2):330-335.
43. Yin GZ, Wang DK, Zhang DM, Huang G. Study on solid-Gas Coupling Dynamic Model and numerical Simulation of Gas-bearing Coal. *Journal of Geotechnical Engineering*. 2008;30(10):1430-1435.
44. Gu DZ. Similar materials and similar models. *Xuzhou: China University of Mining and Technology Press*. 1995.
45. Wu J. Study on microstructure and surface characteristics of outburst coal. *Journal of China Coal Society*. 1987;02:40-46.
466. Zhao XS, Hu QT, Zou YH, Kang JN. Principle and application of rapid determination of firmness coefficient of deep coal. *Journal of China Coal Society*. 2007;01:38-41.

467. State Administration of Coal Mine Safety Supervision. Prescribed reading for the prevention and control of coal and gas outburst. *Beijing: China Coal Industry Publishing House*. 2009.

468. Ministry of Construction of the People’s Republic of China. Test method for basic properties of JGJ70-90 building mortar. *Beijing: China Construction Industry Press*. 1990.
Figure 1

Rock triaxial testing machine controlled by TAW-2000 microcomputer
Figure 2

Φ50mm×100mm pressing mold

Figure 3

Specimen in curing
Figure 4

Effect curve of similar material density

Figure 5

Effect curve of uniaxial compressive strength of similar materials
Figure 6

Effect curve of elastic modulus of similar materials

Figure 7

Curve of pulverized coal ratio and firmness coefficient under the condition of fixed sodium humate and river sand content

\[ f = 0.16K_1 + 0.1 \]

\[ R^2 = 0.9846 \]
Figure 8

The curve of sodium humate and adsorption constant a under the condition of fixed pulverized coal ratio and river sand content

\[ a = 0.7478K_2 + 25.401 \]

\[ R^2 = 0.9919 \]

Figure 8

The curve of sodium humate and adsorption constant b under the condition of fixed pulverized coal ratio and river sand content

\[ b = -0.0644K_2 + 1.855 \]

\[ R^2 = 0.8237 \]
Figure 9
The curve of sodium humate content and adsorption constant $b$ under the condition of fixed pulverized coal ratio and river sand content

Figure 10
The curve of sodium humate and initial diffusion velocity ($\Delta P$) under the condition of fixed pulverized coal ratio and river sand content