processes

MDPI

Article

Orthogonal Experimental Study on the Construction of a Similar Material Proportional Model for Simulated Coal Seam Sampling

Jie Pang *, Xinghua Zhang and Bailin Zhang

School of Safety and Emergency Management Engineering, Mingxiang Campus, Taiyuan University of Technology, Taiyuan 030024, China; zxh1969@163.edu.com (X.Z.); bai_bailin@126.com (B.Z.)
* Correspondence: 17835686128@163.com; Tel.: +86-178-3568-6128

Abstract: The development of similar materials is crucial for conducting simulated coal seam sampling experiments. These materials must comprehensively consider the similarity of mechanical properties with raw coal. To ensure a high degree of similarity between the simulated coal seam similar material and raw coal, cement and coal powder were selected as the main influencing factors. This study employed sensitivity analysis and analysis of variance methods to investigate the impact of various factors on the compressive strength, elastic modulus, Poisson's ratio, and density of comparable materials. The influence of moisture content on the compressive strength and elastic modulus of these materials was also analyzed, as well as the effect of cement and coal powder on moisture content. The results showed that cement was the main controlling factor for the mechanical properties of similar materials. Moreover, the variation of tensile strength and elastic modulus of similar materials in response to the moisture content can be divided into three distinct stages. Based on the influence law, the ratio formula of coal powder and cement for the strength and moisture content of similar materials was obtained, and a proportional model for simulated coal seam sampling similar materials was constructed. The approximate ranges of various parameters that can be achieved by this model are as follows: compressive strength of 1~11.4 MPa, elastic modulus of 0.27~3.62 GPa, Poisson's ratio of 0.229~0.357, and density of 1.044~1.341 g·cm^{-3}. The error in mechanical parameters for this model has been verified to be within 20%. Finally, similar materials were created for simulated coal seam sampling by employing an appropriate ratio. A self-developed drilling test platform was utilized to successfully conduct an experiment, further demonstrating the reliability of the proportional model.

Keywords: coal seam sampling experiment; similar materials; moisture content; compressive strength; proportional model

Citation: Pang, J.; Zhang, X.; Zhang, B. Orthogonal Experimental Study on the Construction of a Similar Material Proportional Model for Simulated Coal Seam Sampling. *Processes* **2023**, *11*, 2125. https://doi.org/10.3390/pr11072125

Academic Editor: Hsin Chu

Received: 23 June 2023
Revised: 12 July 2023
Accepted: 13 July 2023
Published: 17 July 2023

1. Introduction

Gas content serves as the crucial fundamental parameter for gas management and coalbed methane development. Accurate determination of gas content forms the basis for gas disaster prevention in coal mines, while the development of precise sampling technology is the key to accurate determination of coal seam gas content. However, traditional sampling methods used in most coal mines often result in significant errors between the measurement results and the actual situation, leading to the "low content prominence" in some mines. In response to this situation, a loss-free borehole in-situ sampling device has been developed to achieve high sampling efficiency and avoid the loss of coal gas samples. Laboratory simulation experiments are the most effective for the verification of the sampling effect. The study of similar material sampling is a critical basis for simulations, as the similarity between the materials and the raw coal determines the accuracy of the simulated coal seam sampling.

Similar material simulation has been widely employed to study the mechanical properties of rock masses since it started early and has been extensively researched by experts both domestically and internationally. Wang Bo applied the homogeneous design method to the proportioning and production of coal-based similar materials [1]. Zhang Shutong and Dai Linchao selected cement, sand, water, activated carbon, and coal powder as raw materials for similar materials and studied their mechanical properties using different ratios. Building upon the previous literature [2], Wang Gang et al. further optimized the ratios of coal–rock similar materials to further improve their similarity to raw coal in terms of deformation and permeability properties [3]. Qin Lei performed the mechanical property measurements on various proportioned coal–rock similar material specimens. They drew the conclusion that when the coal powder: gypsum: cement: yellow sand ratio was set to 4:1:3:2, the specimens exhibited mechanical properties similar to those of raw coal. Based on previous research [4], Li Shugang used river sand as the aggregate, employed varying ratios of ordinary cement and corn starch, and conducted parameter testing and research [5]. Wu Botao derived the regression equations for proportioning, density, uniaxial compressive strength, elastic modulus, and Poisson's ratio using an orthogonal test on mechanical parameters of similar materials with different sand rates and densities [6]. Cui Ximin analyzed the sources of errors in rock and surface movement simulation experiments in terms of similar principles and similar materials [7].

Some progress has been made in the field of similar materials research, with a wide variety of material selection and proportioning methods. However, certain issues still persist. (1) Researchers have primarily investigated the factors which affect the performance of similar materials from the perspective of raw materials. For example, Zhang Shutong and Dai Linchao identified cement, sand, and coal powder as the influencing factors; Qin Lei considered coal powder, gypsum, cement, and yellow sand; while Li Shugang examined ordinary cement and corn starch. However, the influence of moisture content on similar materials has not received sufficient attention. The impact of moisture content on the stability of similar materials has been overlooked. (2) When analyzing the factors influencing the mechanical parameters of similar materials, researchers often derive a single proportioning scheme based on a specific coal characteristic. For example, Qin Lei determined a ratio of coal powder: gypsum: cement: yellow sand ratio = 4:1:3:2, which yielded similar mechanical properties to the studied raw coal. However, little consideration has been given to constructing a similar material proportional model by deriving equations.

In response to the existing issues, studies, based on previous research, were conducted to investigate similar materials used for simulated coal seam sampling experiments. This study analyzed the impact of moisture content on the strength of these materials and developed a mathematical formula that correlated moisture content with material strength. Cement and coal powder were chosen as influencing factors, and through orthogonal experiments and correlation analysis, this study analyzed the effects of these raw materials on various properties. A proportional model for simulated coal seam sampling was constructed and validated to determine the approximate range of parameters achievable by the model. These findings provide valuable references for the development of hydraulic fracturing and coal seam sampling simulations.

2. Similar Materials Experiments

2.1. Design of Orthogonal Experiments and Selection of Material Proportion

In order to accurately reflect the mechanical law of the coal seam system, it is necessary to choose similar materials that closely resemble the physical and mechanical properties of both the physical model and the engineering prototype [8–10]. According to the requirements for similar materials [11], the basis for selecting similar materials is as follows:

(1) The mechanical parameters of the model closely resemble those of the simulated coal body;
(2) The materials exhibit stable mechanical performance during testing, being less susceptible to environmental factors;
(3) The material proportions and specific mechanical parameters can be modified and adjusted to meet the requirements of similar conditions;

(4) The manufacturing process is convenient, with a short setting time;
(5) The materials offer advantages such as low cost and abundant availability of resources.

Based on the previous experience [12], this similar material experiment selected coal powder, No. 32.5 silicate [13] cement from Taiyuan Lionhead Cement Co., Ltd. (Taiyuan, China), sand with a grain size of 4 mm, Jiati brand cooked gypsum powder, and water as raw materials. These materials were chosen based on their advantages, such as well observability, stable mechanical properties, excellent adaptability, ease of processing, wide availability, and cost-effectiveness.

As large-sized specimens were to be prepared later, the setting time should be appropriate. Previous experiments [14] and relevant literature demonstrated that a ratio of 0.3:1:0.5 for gypsum, water, and sand yields an initial setting time of approximately 20 min, which is considered suitable. Therefore, proportional experiments were carried out at this ratio. It was found that when the mass ratio of cement to water exceeded 1, the pasting phenomenon was severe and no slurry could be formed, so this experimental study was conducted at a mass ratio of cement to water of below 1. The influencing factors of this orthogonal test were set as cement content and coal powder content. To ensure stability and a wide range of experimental selection points, the same values were chosen for both factors. Since the ratio of gypsum to water is constant, all three levels are based on the moisture content to fix the variables. Orthogonal experimental design is a method for investigating multi-attribute and multi-level experiments. This method selects a subset of representative points from a comprehensive full factorial design based on orthogonality. The selected representative points possess distinctive qualities of being "uniformly dispersed" and "comparable". Serving as a primary form of partial factorial design, orthogonal experimental design is a highly efficient, expedient, and cost-effective approach to experimental design. In order to ensure that the physical and mechanical properties of similar materials closely resemble those of the prototype, orthogonal tests were conducted to evaluate the uniaxial compressive strength, elastic modulus, Poisson's ratio, and density of the similar materials with various raw material proportions. As is exhibited in Table 1, the similar material ratios design used a "2-factor, 3-level" ratio design table.

Table 1. Proportion design of similar coal materials.

Sample Grouping	Coal Powder:Water	Cement:Water	Sand	Gypsum:Water
Sample 1	1 (level 1)	1 (level 1)	0.5	0.3
Sample 2	1	0.5 (level 2)	0.5	0.3
Sample 3	1	0.1 (level 3)	0.5	0.3
Sample 4	0.5 (level 2)	1	0.5	0.3
Sample 5	0.5	0.5	0.5	0.3
Sample 6	0.5	0.1	0.5	0.3
Sample 7	0.1 (level 3)	1	0.5	0.3
Sample 8	0.1	0.5	0.5	0.3
Sample 9	0.1	0.1	0.5	0.3

2.2. Procedures for Making Similar Materials Specimens

The preparation process is as follows:

(1) Selecting raw materials: choose coal powder, cement, gypsum, and sand according to Table 1. Considering the various properties and complex influencing elements of pulverized coal, the coal powder was selected with a fixed proportion of particle size. The coal sample was smashed using the drop hammer method and classified using a standard sieve to select a 0.2 mm particle size of coal powder [15];
(2) Weighing: use an electronic balance to weigh the material according to the proportions in Table 1;
(3) Stirring: after thoroughly blending all the raw materials, gradually add the pre-weighed water to the mixture. Simultaneously, stir the mixture slowly and steadily to

prevent discrepancies in the initial moisture content of similar materials caused by water splashing. It was crucial to control the process within 5 min to prevent material agglomeration, which could affect the strength of the specimens;
(4) Filling the mold: pour the homogeneous slurry into a 50 mm × 100 mm mold;
(5) Conservation: place the specimens in a constant temperature and humidity maintenance chamber to keep them at a relatively uniform temperature and undergo natural drying for a duration of over 14 days in accordance with the related standards;
(6) Molding: pry the side of the mold with an awl to loosen the specimen from the inner surface of the mold and release it.

Figure 1 demonstrates the specific experimental steps.

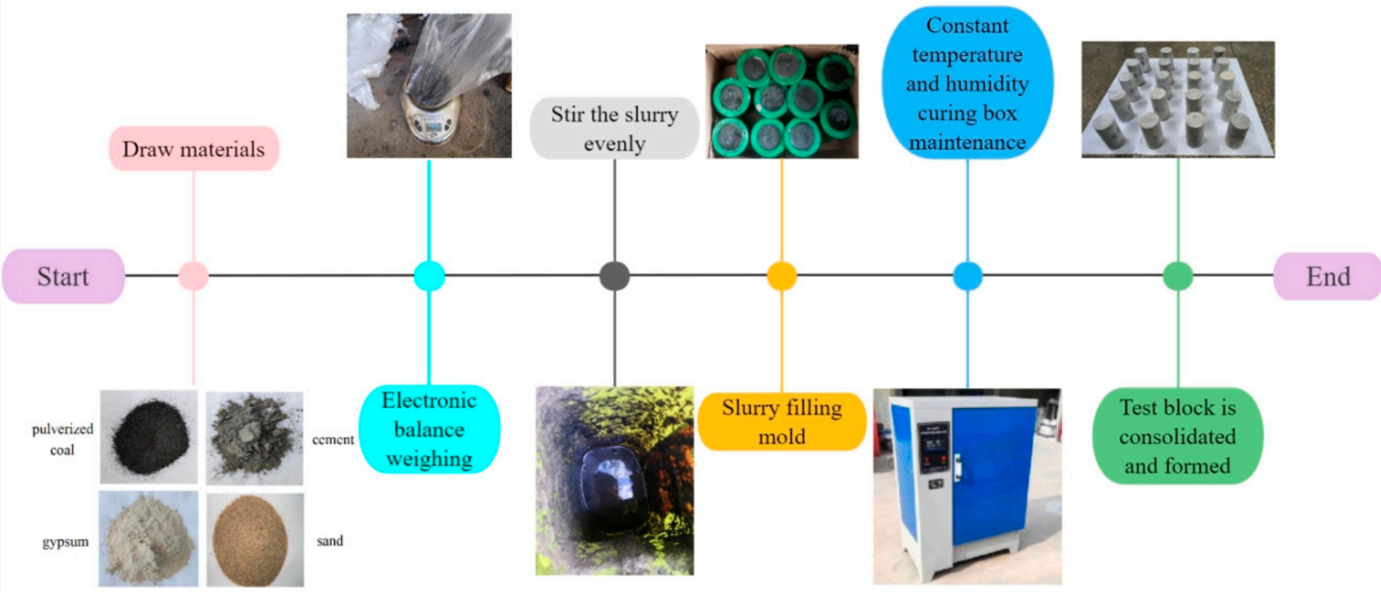


Figure 1. Flowchart of experimental procedure.

3. Parametric Results and Discussion

3.1. Determine the Mechanical Parameters

The objective of this study is to develop suitable similar materials that fulfill the requirements of drilling and sampling experiments for specific coal mines, where mechanical parameters are critical to simulated sampling experiments [16]. Drilling in similar materials can be seen as a process of axial compression. Therefore, this simulation experiment focused on the compressive strength, elastic modulus, and Poisson's ratio of the coal samples [17]. Since similar materials with different proportions have different mechanical properties [18], the mechanical parameters of the specimens should be determined to derive data for proportions similar to that of the coal samples [19].

Basic mechanical parameters tests were carried out on nine specimens to determine the basic mechanical parameters of the specimens. Three specimens were made for each set of experiments and twenty-seven experiments were carried out in total, with the determination process depicted in Figure 2. The force test system was loaded at a speed of 0.1 mm/min until the specimen was damaged, as shown in Figure 3.

Uniaxial compression tests were primarily conducted to obtain the uniaxial compressive strength and elastic modulus of similar materials. Figure 4 presents the stress–strain curves for nine sets of similar materials with varying ratios, with one specimen selected for each ratio to plot the stress–strain curve. Notably, the physical and mechanical parameters of similar materials, such as the uniaxial compressive strength, exhibit significant variations across different proportions. The uniaxial compressive strength of similar materials ranges from 0.85 to 11.4 MPa for different proportions. The overall stress–strain curve is N-shaped, which is similar to the curve of coal samples in the literature [20]. Figure 4 shows that the stress–strain curves are resemblant to similar materials with the same cement content. Different physical and mechanical parameters of the specimen can be changed by varying the proportions to meet different stress similarity ratios in various engineering contexts.

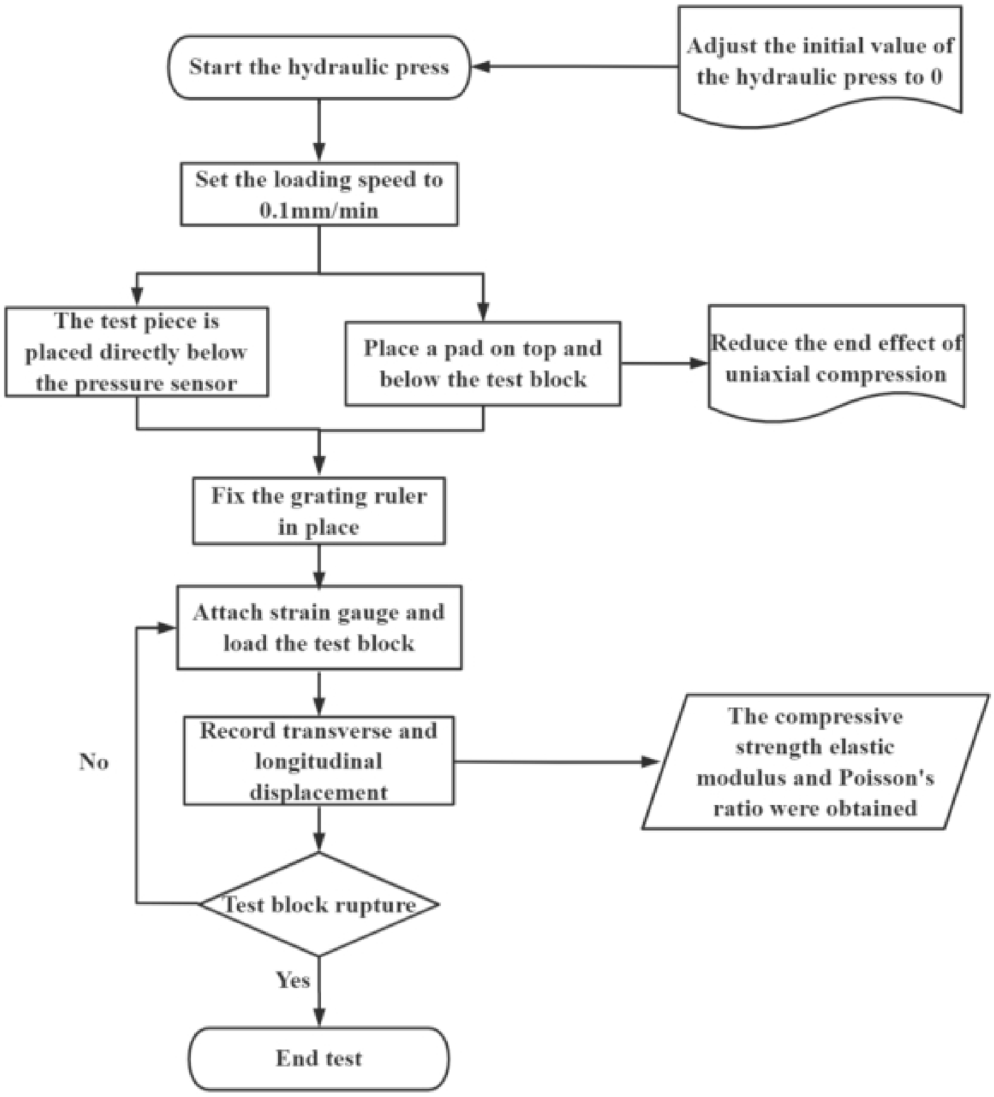


Figure 2. Experimental process of mechanical parameters under uniaxial compression.

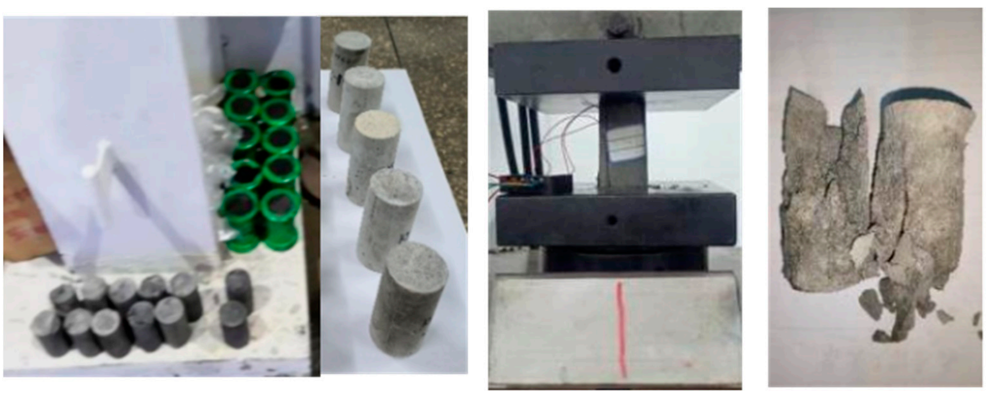


Figure 3. Sample rendering before and after the experiment.

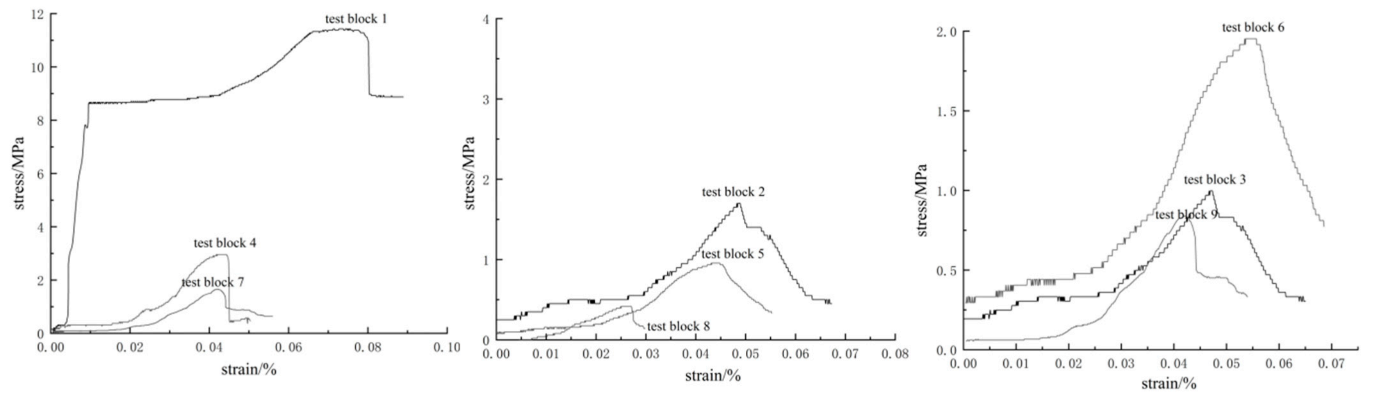


Figure 4. Specimen stress and strain curves.

The experimental results are provided in Table 2, from which the Poisson's ratio distribution of similar materials with different proportions ranges from 0.120 to 0.252 and the density distribution ranges from 1.04 to 1.37 g·cm^{-3}. The average value of uniaxial compressive strength for specimen 1 was the highest, measuring 11.4 MPa, while the average value for specimen 9 was the lowest at 0.85 MPa. Similarly, the average value of elastic modulus for specimen 1 was the highest, measuring 3.49 GPa, while the average value for specimen 9 was the lowest at 0.27 GPa.

Table 2. Measurement results.

Sample Number	Compressive Strength/(MPa)	Elastic Modulus/(GPa)	Poisson's Ratio	Density/(g·cm^{-3})
Sample 1-1	11.2	3.52	0.235	1.232
Sample 1-2	11.5	3.45	0.229	1.231
Sample 1-3	11.5	3.5	0.292	1.224
Average value	**11.4**	**3.49**	**0.252**	**1.229**
Sample 2-1	1.72	0.54	0.315	1.129
Sample 2-2	1.65	0.52	0.301	1.134
Sample 2-3	1.73	0.56	0.320	1.133
Average value	**1.70**	**0.54**	**0.312**	**1.132**
Sample 3-1	1.09	0.32	0.351	1.051
Sample 3-2	0.93	0.3	0.361	1.059
Sample 3-3	0.98	0.31	0.359	1.052
Average value	**1.00**	**0.31**	**0.357**	**1.054**
Sample 4-1	2.67	0.86	0.234	1.254
Sample 4-2	2.92	0.92	0.235	1.324
Sample 4-3	2.81	0.86	0.239	1.211
Average value	**2.8**	**0.88**	**0.236**	**1.263**
Sample 5-1	2.64	0.68	0.270	1.111
Sample 5-2	2.29	0.81	0.266	1.391
Sample 5-3	2.42	0.79	0.286	1.053
Average value	**2.45**	**0.76**	**0.274**	**1.185**
Sample 6-1	1.98	0.64	0.348	1.094
Sample 6-2	1.91	0.58	0.351	0.874
Sample 6-3	1.96	0.67	0.342	1.164
Average value	**1.95**	**0.63**	**0.347**	**1.044**
Sample 7-1	1.62	0.5	0.215	1.244
Sample 7-2	1.73	0.52	0.242	1.414
Sample 7-3	1.6	0.54	0.230	1.365
Average value	**1.65**	**0.52**	**0.229**	**1.341**

Table 2. *Cont.*

Sample Number	Compressive Strength/(MPa)	Elastic Modulus/(GPa)	Poisson's Ratio	Density/(g·cm^{-3})
Sample 8-1	1.02	0.35	0.253	1.234
Sample 8-2	1.14	0.28	0.254	1.252
Sample 8-3	0.99	0.36	0.255	1.225
Average value	**1.05**	**0.33**	**0.254**	**1.237**
Sample 9-1	0.84	0.29	0.351	1.227
Sample 9-2	0.93	0.21	0.347	1.147
Sample 9-3	0.78	0.31	0.350	1.001
Average value	**0.85**	**0.27**	**0.349**	**1.125**

3.2. Sensitivity Analysis

3.2.1. Analysis of Extreme Deviations

Considering that the raw materials content indirectly affects the drilling and sampling process, the effect of each factor on the performance of similar materials was analyzed based on the results of orthogonal experiments. The influence of factors on specimen parameters could be judged by the value of the extreme deviations. The larger extreme deviations mean that the corresponding factor has a greater influence on the parameters of the specimen [21]. The analysis of the extreme deviations table is shown in Table 3.

Table 3. Range analysis.

Compressive Strength/(MPa)			Elastic Modulus/(GPa)		Poisson's Ratio		Density/(g·cm^{-3})	
Factor	Cement	Pulverized coal	Cement	Pulverized coal	Cement	Pulverized coal	Cement	Pulverized coal
Average of level 1	5.28	4.70	1.67	1.49	0.239	0.307	1.278	1.138
Average of level 2	1.73	2.40	0.54	0.76	0.280	0.286	1.845	1.164
Average of level 3	1.27	1.18	0.40	0.38	0.351	0.277	1.074	1.234
Range	4.01	3.52	1.27	1.11	0.112	0.030	0.204	0.096

The test blocks 3, 6, and 9 possessed a constant cement proportion of 0.1, while the proportion of coal powder varied among them. The relatively small cement proportions in all test blocks made the proportion of coal powder a dominant factor influencing the mechanical parameters of the blocks. As observed in the literature [15,19], the stress–strain curves exhibited similar patterns in response to varying proportions of cement and coal powder.

It is evident in Table 4 that the compressive strength, elastic modulus, Poisson's ratio, and density are affected to a greater degree of sensitivity for cement than for coal powder. A range trend diagram was made to obtain a more visual picture of the effect and trend of the factors on the test indicators in Figure 5.

Based on Figure 5a,b, it can be observed that the cement content has a significant impact on the compressive strength and elastic modulus of similar materials. An increase in cement content implies a larger proportion of filling material, leading to a denser network structure formed by coal powder and sand. As a result, the compressive strength and elastic modulus also see an increase. Similarly, the compressive strength and elastic modulus increase with a rise in coal powder content, showing an approximately linear relationship. With higher coal powder content, a more stable framework is formed by coal powder and cement, resulting in a more stable distribution of aggregates in the similar materials and a corresponding rise in compressive strength. Figure 5c,d indicate that coal powder has a relatively stable influence on the Poisson's ratio and density of similar materials. As the coal powder content increases, the Poisson's ratio of the similar materials gradually goes up, while the density decreases. On the other hand, an increase in cement content leads to a decrease in the Poisson's ratio of the similar materials.

Table 4. Elastic modulus range analysis table.

Variance Analysis of Compressive Strength				Variance Analysis of Elastic Modulus			
Factor	Deviations sum of squares	Mean square	F	Factor	Deviations sum of squares	Mean square	F
Cement	28.95	14.47	1.47	Cement	2.90	1.45	1.46
Pulverized coal	19.14	9.57	0.97	Pulverized coal	1.93	0.97	0.97
Error	39.34	9.84		Error	3.98	0.99	
Variance Analysis of Poisson's Ratio				**Variance Analysis of Density**			
Factor	Deviations sum of squares	Mean square	F	Factor	Deviations sum of squares	Mean square	F
Cement	0.0193	0.0096	57.83	Cement	0.0621	0.031	104.38
Pulverized coal	0.0014	7.02×10^{-4}	4.22	Pulverized coal	0.0148	0.007	23.57
Error	6.65×10^{-4}	1.66×10^{-4}		Error	0.0012	2.97×10^{-4}	

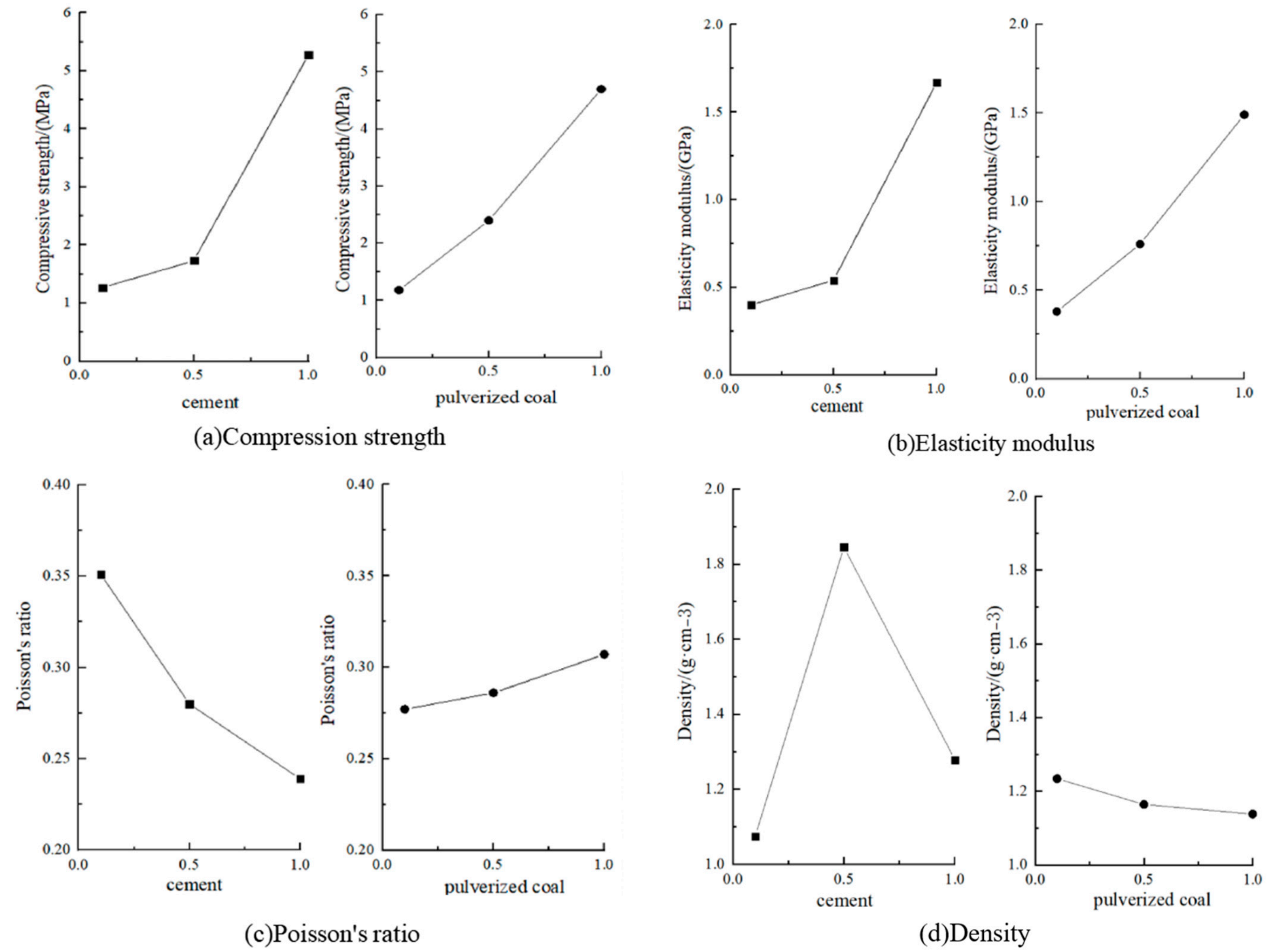


Figure 5. The impact trend of various factors on the experimental results.

3.2.2. Analysis of Variance

Variance analysis was employed to compensate for shortcomings of range analysis, thereby facilitating a deeper analysis of the sources and magnitude of experimental errors. The analysis tables of variance for each factor are presented in Table 4. In summary, the cement content plays a major role in controlling the parameters of similar materials. Therefore, it is crucial to pay attention to the cement-to-water content ratio in the proportioning process.

3.3. Effect of Moisture Content on Similar Materials

Given the significant influence of moisture content on the mechanical properties and damage mechanisms of similar materials, the impact of moisture content on the strength of similar materials should be further investigated [14]. The moisture content of the samples would affect the slagging rate. Excessive moisture content would lead to severe sample adhesion within the sampler, resulting in difficulties in smooth sample extraction and consequently reducing sampling efficiency. Therefore, sampling simulation experiments should fully account for the moisture content as a factor so that a range of moisture contents appropriate for simulated sampling can be investigated.

The following steps were applied to measure the moisture content of the test blocks:

(1) Place the test block on an electronic scale (0.1 g) to obtain its wet weight ($M_{w)}$;
(2) Use a drying oven to dry the fractured test block, after which its dry weight ($M_{d)}$ was measured;
(3) Calculate the moisture content of the test block using the following equation [14]:

$$\rho = (M_w - M_d)/(M_d) \quad (1)$$

In the equation, ρ represents the water content (in percentage), M_w represents the wet weight of the test block (in grams), and M_d represents the weight after drying (in grams).

The test procedures are exhibited in Figure 6 with test data shown in Table 5.

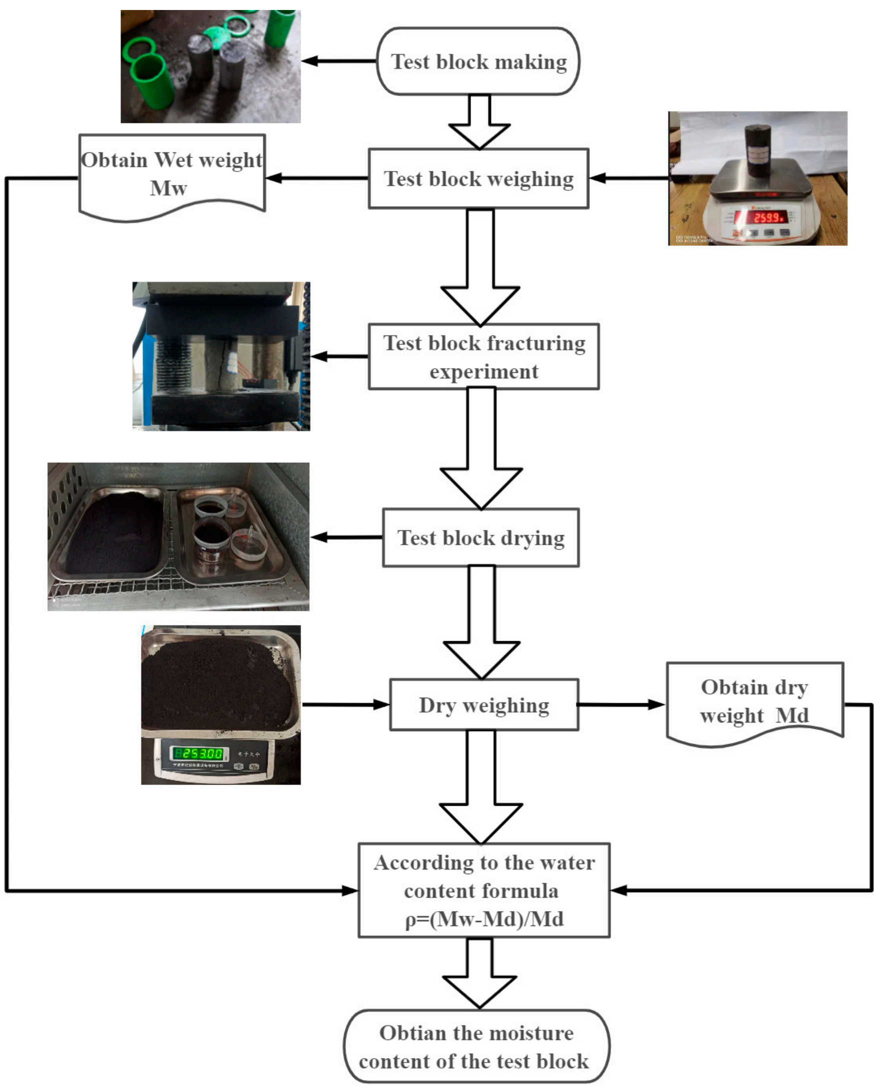


Figure 6. Flowchart for measuring water content of test blocks.

Table 5. Table of water content testing for similar materials.

Test Block Number	Cement:Water	Pulverized Coal:Water	Moisture Content
1	1	1	0.026
2	0.5	1	0.030
3	0.1	1	0.034
4	1	0.5	0.031
5	0.5	0.5	0.032
6	0.1	0.5	0.036
7	1	0.1	0.034
8	0.5	0.1	0.036
9	0.1	0.1	0.040

The test results revealed that the strength of similar material blocks tends to increase as the moisture content decreases, with the amplitude exhibiting the same trend. Based on the existing research [14,22], it is hypothesized that the change in the strength of similar material blocks with water content and the difference between the strength of blocks at a specific water content and the final strength of the blocks are proportionate to the water content of the test blocks. Therefore,

$$d_y/d_z = (y - z) \times z \tag{2}$$

The following equation can be obtained through the differential equation.

$$y = e^{az+b} + c \tag{3}$$

In the equations, y represents the strength of a similar material block, z represents the moisture content, while a, b, and c represent constants to be determined.

The data were fitted by using Origin to obtain the results in Figure 7.

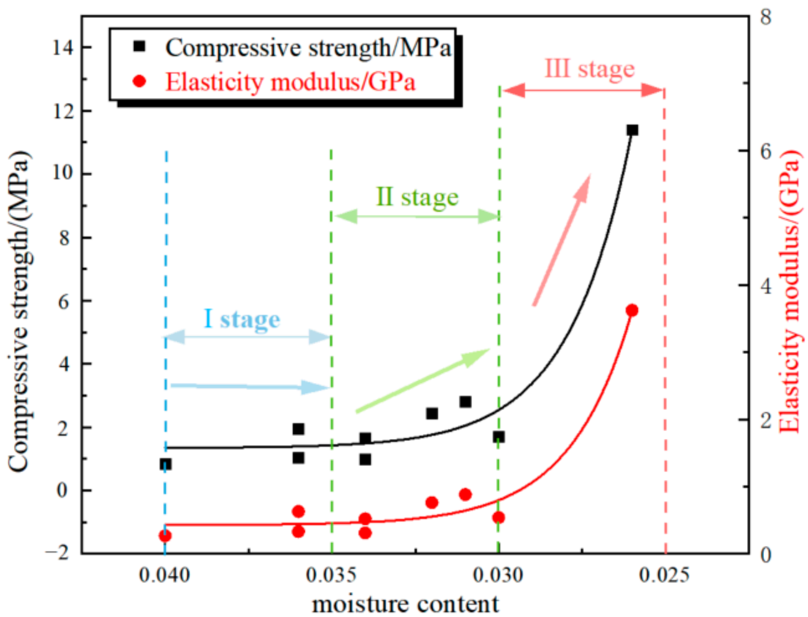


Figure 7. Relationship between moisture content and strength of similar materials.

The specific expression is shown below:

$$\begin{cases} Y_1 = e^{-534.36\times Z+16.37} + 1.35 \\ R^2 = 0.958 \end{cases} \tag{4}$$

$$\begin{cases} Y_1 = e^{-539.68\times Z+15.36} + 0.43 \\ R^2 = 0.969 \end{cases} \tag{5}$$

In the equations, Y_1 represents the strength of similar materials (in MPa), Y_2 represents the elastic modulus of similar materials (in MPa), and Z represents the moisture content of similar materials.

From the graph, it can be observed that the relationship between different moisture content and the compressive strength and elastic modulus of the similar materials varies, roughly following an exponential pattern. The variation in tensile strength with moisture content can be divided into three stages: stage I represents a stable growth phase, stage II indicates a gradual increase, and stage III signifies a significant increase. When the moisture content is less than 0.03, the tensile strength and elastic modulus of similar material specimens increase sharply as the moisture content decreases, which is mainly caused by many pores inside similar materials. When moisture enters the pores, the associative properties within similar materials become weaker, leading to a reduction in compressive strength.

In summary, the influence of moisture content on the strength of similar materials within the range of 0.025–0.040 was investigated. It was found that the changes in compressive strength and elastic modulus with moisture content can be divided into three stages: stable growth, gradual increase, and significant increase. This study analyzed the effect of moisture content on the strength of similar materials by fitting equations with stage growth trend analysis. This analysis offers a valuable reference for further research on the correlation between moisture content and the strength of similar materials. The data suggest that the proportion of moisture content should be minimized to formulate similar materials for drilling and sampling experiments. It is crucial to control the moisture content in the range of 0.025 to 0.03, corresponding to a mass ratio of both cement and coal powder to water exceeding 0.5. The moisture content reaches a minimum value of 0.026 when the mass ratio of cement and coal powder to water is 1.

3.4. Analysis of Similar Material Patterns

To further consider the impact of the two factors, namely cement and coal powder, on the strength and moisture content of similar materials, one factor was kept constant while the other factor varied. The trend of strength with the changing factor was plotted to observe the influence of the two factors on similar materials. From Figure 8, it can be observed that within a reasonable range of coal powder content, an increase in cement content consistently results in an improvement in the strength of the samples. When the coal powder content is held constant at 0.1 and 0.5, the increase in strength remains steady. However, when the coal powder content reaches 1, the range of strength increase expands with a rise in cement content.

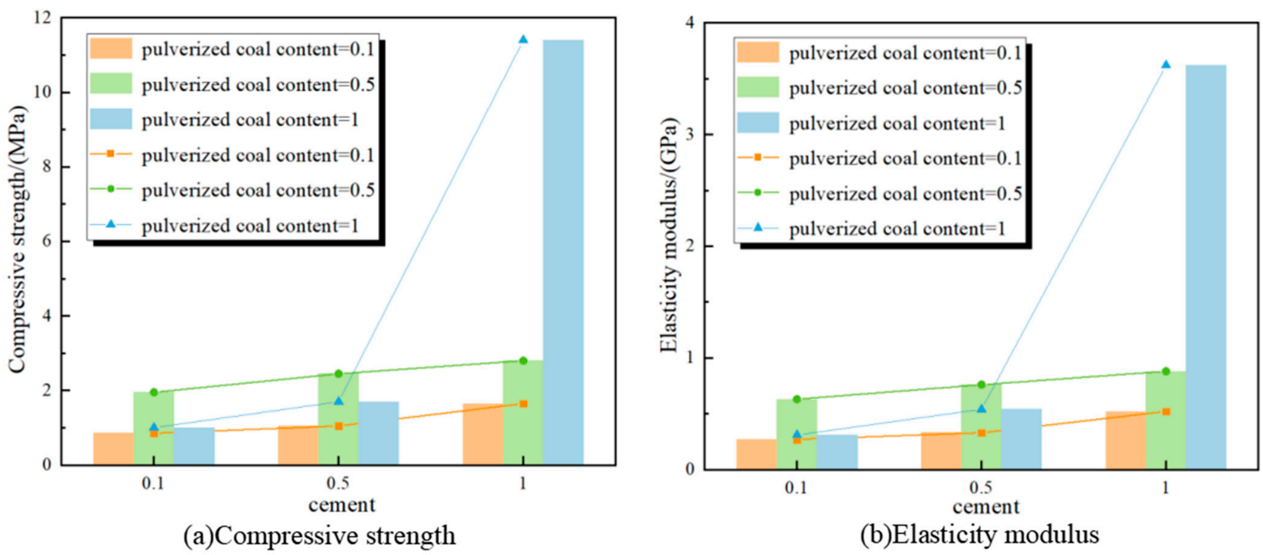


Figure 8. Trend chart of strength variation with cement under fixed coal powder content.

As can be seen from Figure 9, when the cement content is 0.1 and 0.5, the strength of similar materials first rises as the coal dust content rises and then falls after breaking the turning point. However, the overall strength of the material will not exceed the strength maximum corresponding to a coal powder content of 0.5. When the cement content is held at 1, the strength of similar materials exhibits an upward trend as the coal powder content increases. Therefore, the relationship between the strength of similar materials and coal powder and cement is presumed to be exponential.

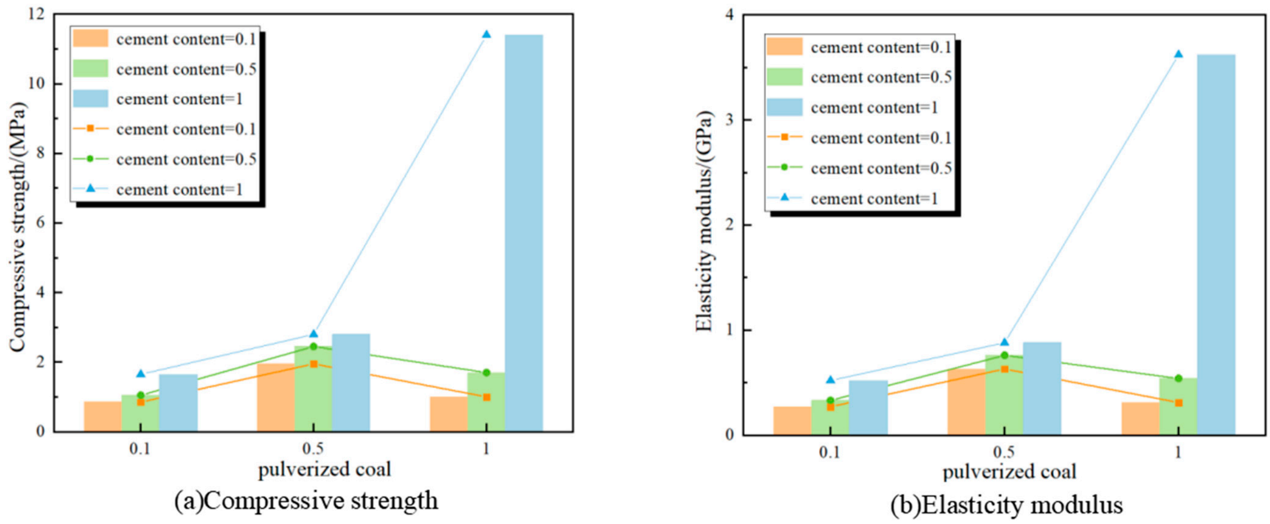


Figure 9. Trend chart of strength variation with coal powder under fixed cement content.

Considering that the content of coal powder and cement has an influence on the moisture content of similar materials, the corresponding laws of influence need to be studied.

As depicted in Figure 10, under a gypsum-to-water mass ratio of 0.3, the moisture content of similar materials linearly decreased when either the cement or aggregate content was kept constant while the other increased. This observation leads to the inference that there exists a linear relationship between moisture content and the coal powder and cement content.

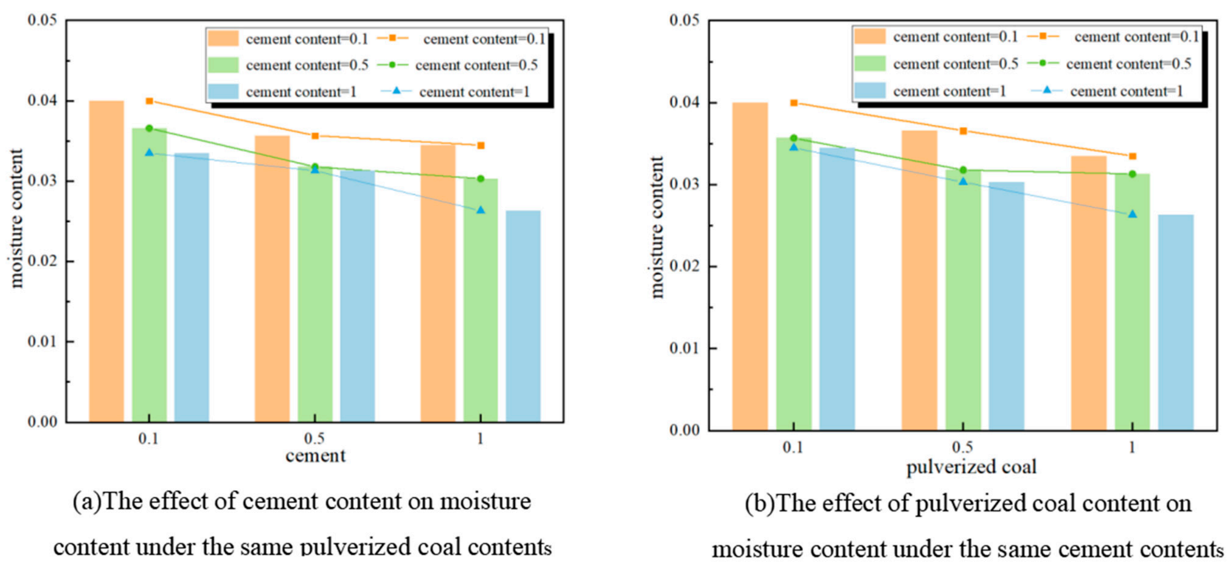
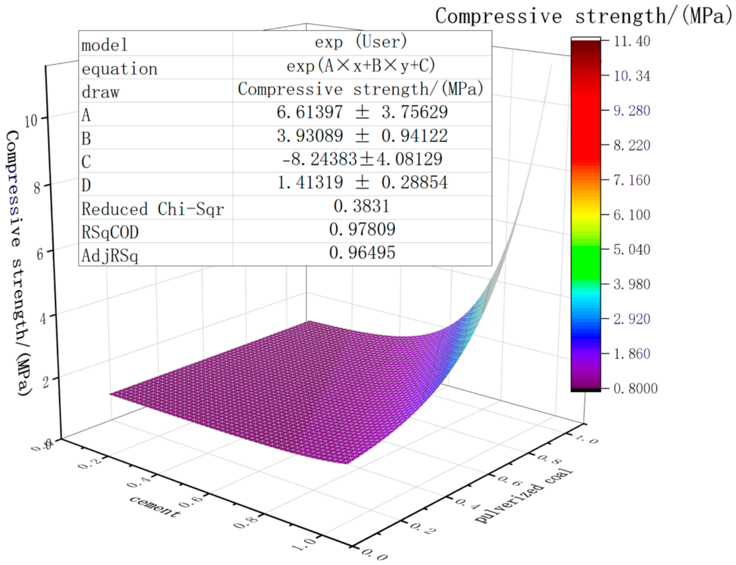


Figure 10. Effect of coal powder and cement on similar materials when the coal slurry ratio is 1.

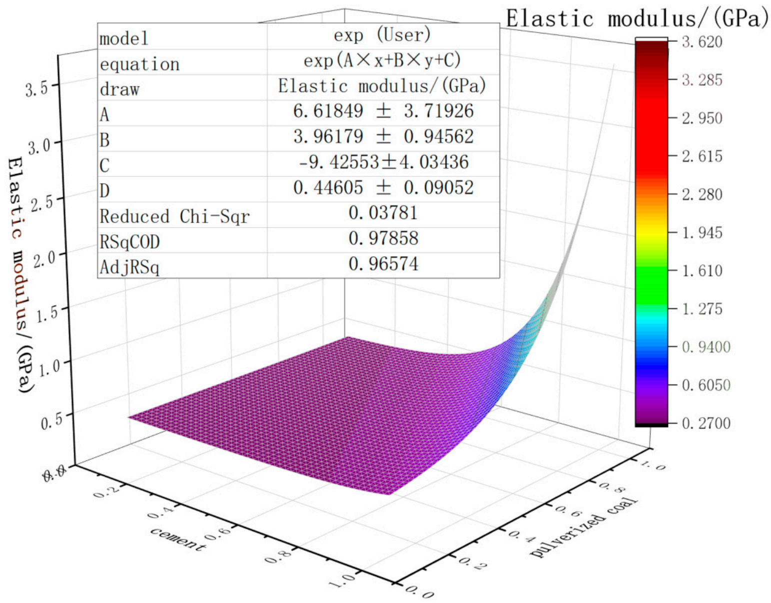
Based on the above patterns, the mass ratio of coal powder to cement should be kept at around 1 with a gypsum-to-water ratio of 0.3 in order to prepare similar materials with a wide range of strength. Moreover, the mass ratio of cement and coal powder to water should be held at around 1 to obtain similar materials with greater strength. The above conclusions can provide some guidance for the proportioning of similar materials.

3.5. Constructing the Model

A fitting analysis of the orthogonal experimental data determined the quantified relationship between two factors of similar materials and the experimental indicators. This provided a foundation for a mixed-proportion model for similar materials, as shown in Table 6. The data were analyzed using a method of the three-dimensional response surface, where the cement content (x) and the coal powder content (y) were represented as independent variables. The effects of the cement content and coal powder content on each factor of the specimen were separately examined, and corresponding equations were fitted accordingly. The results of this analysis are illustrated in Figure 11.

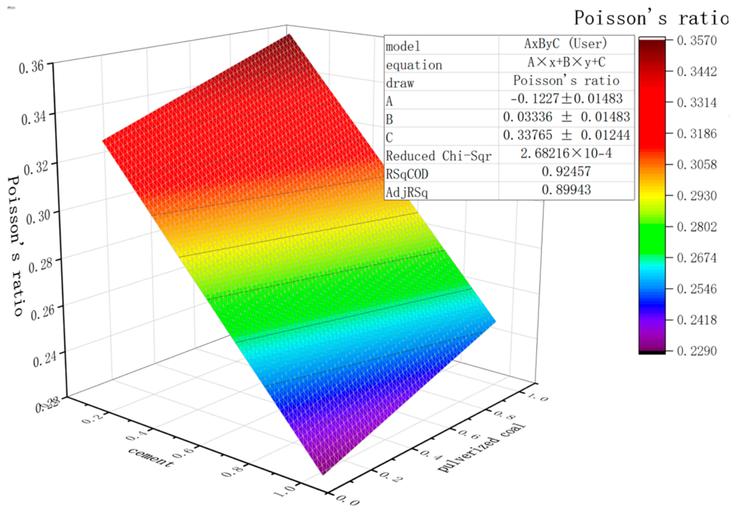


(**a**)

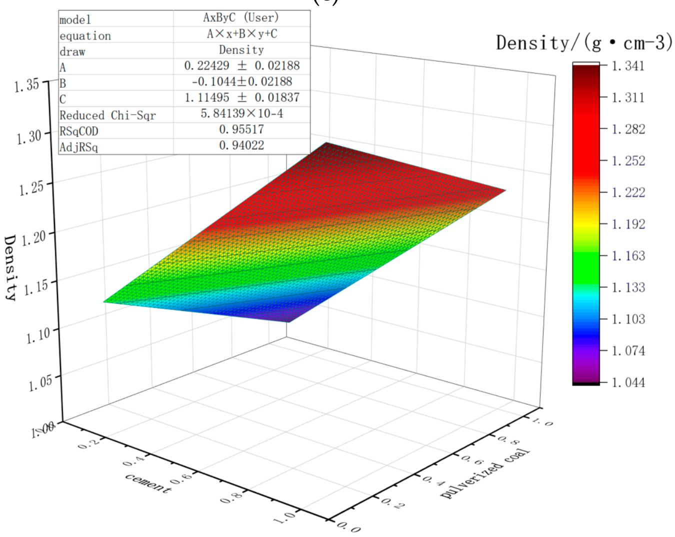


(**b**)

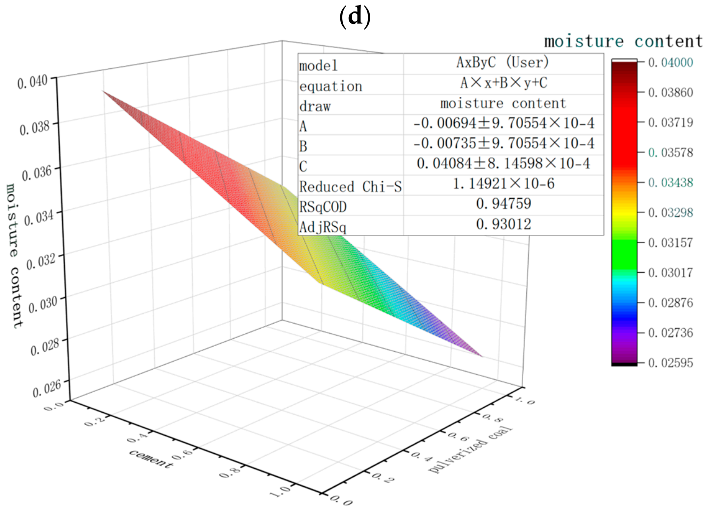
Figure 11. *Cont*.



(c)



(d)



(e)

Figure 11. The 3D curve of mechanical parameters. The (**a**) 3D curve of compressive strength for coal powder content and cement content; (**b**) 3D curve of elastic modulus for coal powder content and cement content; (**c**) 3D curve of Poisson's ratio for coal powder content and cement content; (**d**) 3D curve of density for coal powder content and cement content; and (**e**) 3D curve of moisture content for coal powder content and cement content.

Table 6. Summary table for regression analysis of similar materials.

Test Indicators	Influence Factor	Fitting Formula	R^2
Compressive strength	Cement, coal powder	$Y_1 = e\hat{}(6.61 \times X_1 + 3.93 \times X_2 - 8.24) + 1.41$	0.978
Elasticity modulus	Cement, coal powder	$Y_2 = e\hat{}(6.62 \times X_1 + 3.96 \times X_2 - 9.43) + 0.44$	0.966
Poisson ratio	Cement, coal powder	$Y_3 = -0.122 \times X_1 + 0.033 \times X_2 + 0.338$	0.899
Density	Cement, coal powder	$Y_4 = 0.224 \times X_1 - 0.104 \times X_2 + 1.115$	0.940
Moisture content	Cement, coal powder	$Z = -0.007 \times X_1 - 0.007 \times X_2 + 0.041$	0.930

Figure 11 visually demonstrates the significant increase in compressive strength and elastic modulus of the specimens as the coal powder and cement content ranges from 0.5 to 1. This result indicates that the impact of coal powder and cement on the compressive strength and elastic modulus is most significant within this content range. Additionally, the moisture content of the specimens uniformly decreases as both coal powder and cement content ranges from 0.1 to 1. Furthermore, the graph reveals that the cement content exerts a dominant influence on the Poisson's ratio and density of similar materials.

Figure 12 depicts the comparison curves between the experimental results and the calculated results by the fitting equation for each parameter. Analyzing the curves and linear correlation coefficient R^2, it is evident that calculated data fluctuate around the test values with errors within reasonable limits. The results imply that the fitting equation effectively captures the trend exhibited by each physical and mechanical parameter, thus demonstrating the feasibility and reliability of this empirical formula.

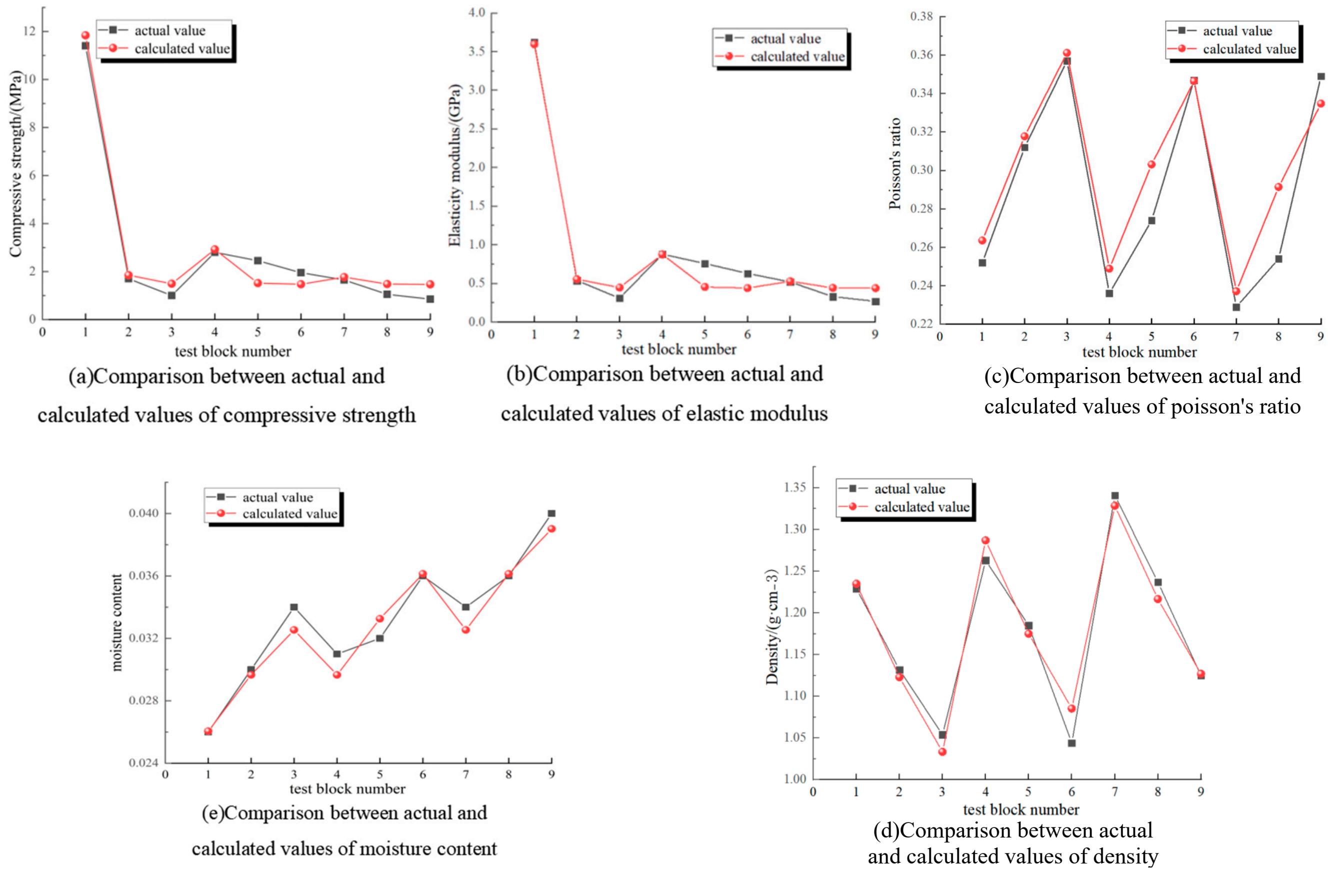


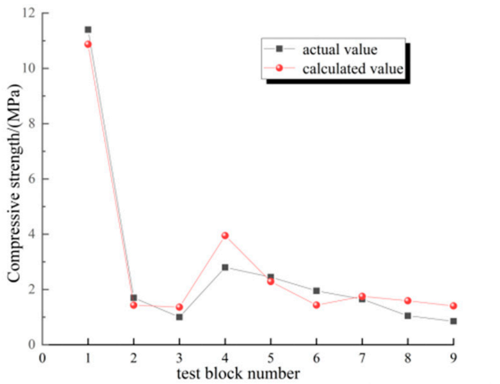
Figure 12. Comparison between test results and calculation results of various parameters.

Similar material proportional models can be derived from integrated analysis of Equations (4) and (5), and the fitting equations in Table 7. The ratios for specific coal samples can be obtained by substituting the physical and mechanical parameters of the corresponding coal samples into the equation. Table 7 demonstrates the proportional model and steps.

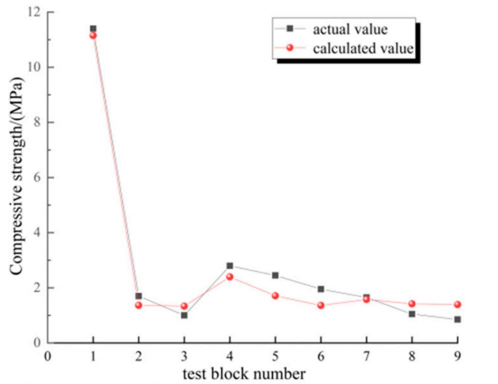
Table 7. Similar material ratio model and steps.

Step	Illustrate	Formula
Calculate moisture content	Determine moisture content based on compressive strength or elastic modulus	$Z = (16.37 - \ln(Y_1 - 1.35))/534.36$ $Z = (15.36 - \ln(Y_2 - 0.43))/539.68$
Calculation method 1	Calculate the cement content according to the water content and Poisson's ratio Calculate the content of pulverized coal according to the water content and Poisson's ratio	$X_1 = 3.428 - 30.45 \times Z - 6.452 \times Y_3$ $X_2 = 2.538 - 112.486 \times Z + 6.454 \times Y_3$
Calculation method 2	Determine the cement content based on moisture content and density Determine the content of coal powder based on moisture content and density	$X_1 = -1.542 - 45.294 \times Z + 3.049 \times Y_4$ $X_2 = 7.31 - 97.58 \times Z - 3.049 \times Y_4$
Test and verify	Use fitting formulas to reverse calculate compressive strength and elastic modulus for verification	$Y_1 = e\hat{}(6.61 \times X_1 + 3.93 \times X_2 - 8.24) + 1.41$ $Y_2 = e\hat{}(6.62 \times X_1 + 3.96 \times X_2 - 9.43) + 0.44$

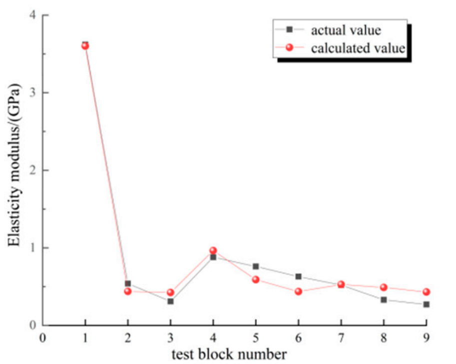
As shown in Figure 13, the comparison between actual results and the validation results of each specimen was carried out to verify the reliability of the similar material proportional model.



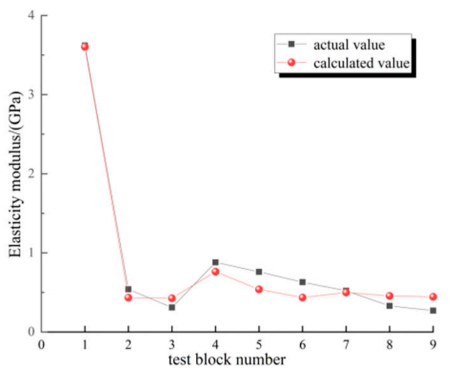
(a)Comparison between actual and verified values of compressive strengths (calculated using Method 1)



(b)Comparison between actual and verified values of compressive strength (calculated using Method 2)



(c)Comparison between actual and verified values of elastic modulus (calculated using Method 1)



(d)Comparison between actual and verified values of elastic modulus (calculated using Method 2)

Figure 13. Comparison between actual results and validation results of each sample.

Through an analysis of the curves, it is evident that the validation data fluctuate around the actual values, with errors falling within acceptable limits. This outcome signifies the feasibility and reliability of the formula used in the proportioning model. Furthermore, this indirectly validates the rationality of expressing the strength formula of similar materials in terms of moisture content.

Remark: X_1 represents the cement content (range from 0.1 to 1); X_2 represents the coal powder content (range from 0.1 to 1); Y_1 represents the compressive strength (in MPa); Y_2 represents the elastic modulus (in MPa); Z represents the moisture content (range from 0.025 to 0.04); Y_3 represents Poisson's ratio; Y_4 represents the density (in gram per cubic centimeter).

3.6. Model Proportioning Validation and Application

To further validate the reliability of the proportional model for similar materials, four sets of coal sample parameters were selected based on the published literature [23,24]. The required raw material proportions and moisture content were calculated using the proportional model based on these coal sample parameters. Then, the parameters were back-calculated using the fitting formula. A comparison was made between the raw coal parameters and the model verification values to validate the reliability of the mix proportion model, as shown in Table 8. Table 8 reveals minor discrepancies between the verification values and the raw coal indicators, with the errors for each parameter below 20% [25]. The relationship between the factors and the mechanical parameters is shown in Figure 14.

Table 8. Validation of experimental data and error analysis.

Sampling Locations	Indicators of Raw Coal			Validation and Error					
	Average of Compressive Strength/MPa	Average of Elastic Modulus/GPa	Poisson's Ratio	Compressive Strength/MPa	Error/%	Elastic Modulus/GPa	Error/%	Poisson's Ratio	Error/%
No. 3 coal seam in Gucheng coal mine	8.69	2.52	0.32	8.09	6.90	2.32	7.93	0.30	6.25
No. 13 coal seam in Lotus Hill coal mine	5.24	0.97	0.24	4.84	17.85	1.09	18.56	0.24	0
No. 9 coal seam in Hamijo Lake coal mine	8.74	1.36	0.23	9.23	5.61	1.62	19.1	0.24	4.34
Wangjiazhai coal mine	1.78	1.33	0.28	1.72	3.37	1.58	11.2	0.29	3.57

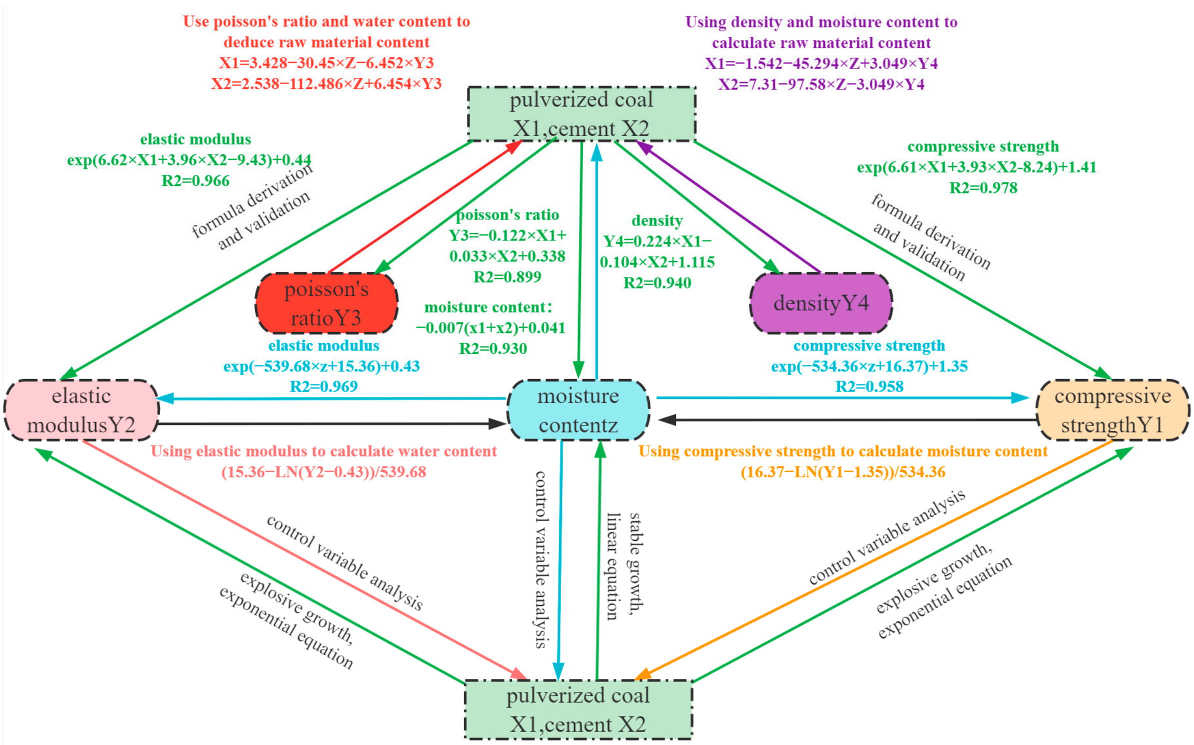


Figure 14. Relationship diagram between various factors and mechanical parameters.

In practice, the physical and mechanical properties of coal show regional variations attributed to various factors, including geological formations, burial depth, etc. In order to facilitate the study of the drillability of similar materials, a coal sample from the Jinjiazhuang Coal Mine in Shanxi Province was selected as the target. The parameters of the target sample were analyzed to determine the feasibility of research on similarity.

Based on published literature [26], it is known that coal samples from NO. 110403 working interface in the Jinjiazhuang No. 4 coal seam corresponds to a compressive strength of 13.0 MPa, elastic modulus of 3.0 GPa, and Poisson's ratio of 0.252. According to the accessed data, sample 1 corresponds to a compressive strength of 11.4 MPa, elastic modulus of 3.49 GPa, and Poisson's ratio of 0.252, which fits the actual data well.

Table 9 analyzes the error analysis between the coal samples and test specimens.

Table 9. Error table of coal sample and sample.

	Compressive Strength/MPa	Elasticity Modulus/GPa	Poisson's Ratio
Lüliang Jinjiazhuang coal mine coal sample from coal seam 4	13.0	3.00	0.3
Test block 1	11.4	3.49	0.252
Relative error/%	**12.31**	**16.3**	**16**

According to Table 9, the relative errors for the uniaxial compressive strength, elastic modulus, and Poisson's ratio are determined to be 12.31%, 16.3%, and 16%, respectively, all falling within the acceptable range of 20%. Hence, the overall errors remain manageable. A mix proportion scheme that closely matches the coal seam of the coal mine was obtained, with a mass ratio of coal powder, cement, sand, gypsum, and water set at 1:1:0.5:0.3:1.

4. Stimulated Sampling Experiments

4.1. Preparation of Large-Sized Specimens

The raw materials were blended in accordance with the specified proportion outlined in sample 1, followed by a thorough stirring process. The mixture was poured into a production mold with internal dimensions of 1.35 m × 1.25 m × 1.00 m. The initial and final setting of cement would be affected by temperature, with lower temperatures requiring longer solidification times. Therefore, it is essential to enhance moisture curing during specimen preparation. To achieve this, the surface of the molds was first wrapped with aluminum foil and then covered with wet towels to facilitate heat absorption and dissipation, thereby accelerating the hardening process of the cementitious material. As shown in Figure 15a, the dark black portion above the large-sized test block is covered by a wet towel. However, the size and weight of the specimens were too large to fit into the constant temperature and humidity chamber. In order to prevent the cement specimens from being affected by weather changes, which may lead to cracking of the specimens, a template was experimentally designed and machined, which was used for placing the large-sized specimen slurry and sealing the specimens, as shown in Figure 15b below. In Figure 15c, the two baffle plates placed next to the large-sized specimen block are part of the large-sized specimen template. After being cured in a standard curing room at a temperature of 20 ± 2°C and relative humidity of above 95% for 28 days, the specimens were removed. Subsequently, they were naturally dried for a minimum of 14 days under uniform room temperature conditions. This ensured that the specimens underwent the same drying level within the same drying duration and at a consistent temperature, thus mitigating the potential impact of drying time and weather conditions on the cement specimens. Finally, the specimens were placed into the sampling simulation experimental platform, as depicted in Figure 15d.

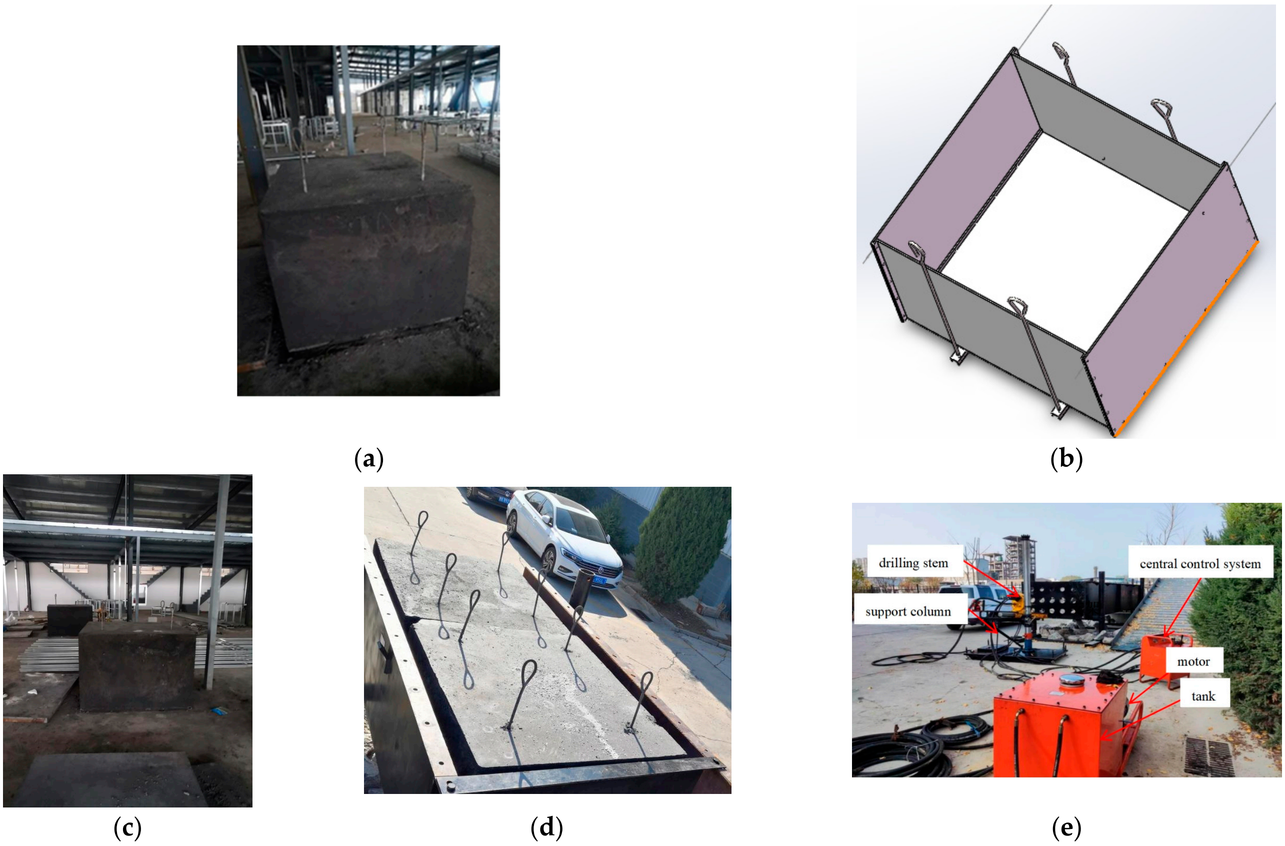


Figure 15. Establishment of experimental platform. (**a**) Moisture curing of the sample; (**b**) design drawing of large sample template; (**c**) physical image of large-sized sample template; (**d**) drawing of large sample preparation; (**e**) drilling system diagram.

4.2. Ground Sampling

Sampling simulation experiments on coal seams were conducted through a self-developed drilling experimental platform, along with a pneumatic impact sampling device, as shown in Figure 15e. The sampling time for the large-sized specimen was set at 3 min, which complied with the standards, and the debris drilled by the sampler could smoothly enter the sampling jar at the specified depth. Figure 16a illustrates that the front end of the sampler remained securely sealed after sampling. This result indicated that the large-sized specimen, produced in accordance with the specified proportions, satisfies the sampling conditions and verifies the feasibility of utilizing the sampler for coal seam sampling. Upon withdrawal of the sampler, a complete sampling path was left in the large-sized specimen without any hole collapse, as demonstrated in Figure 16b, proving that the large-sized specimen met the mechanical strength requirements. After the sampler was withdrawn, the sample was taken out and weighed. The volume of collected debris accounted for over 90% of the total volume of the sampling jar, meeting the sampling requirements, as depicted in Figure 16c. These results effectively demonstrated the reliability of similar materials for the simulation of coal seam sampling.

In summary, based on the proposed proportioning scheme, large-sized coal bodies were manufactured, and drilling simulation experiments were conducted through similar materials. The sampling phenomena were observed and analyzed, confirming the feasibility and reliability of similar materials as substitutes.

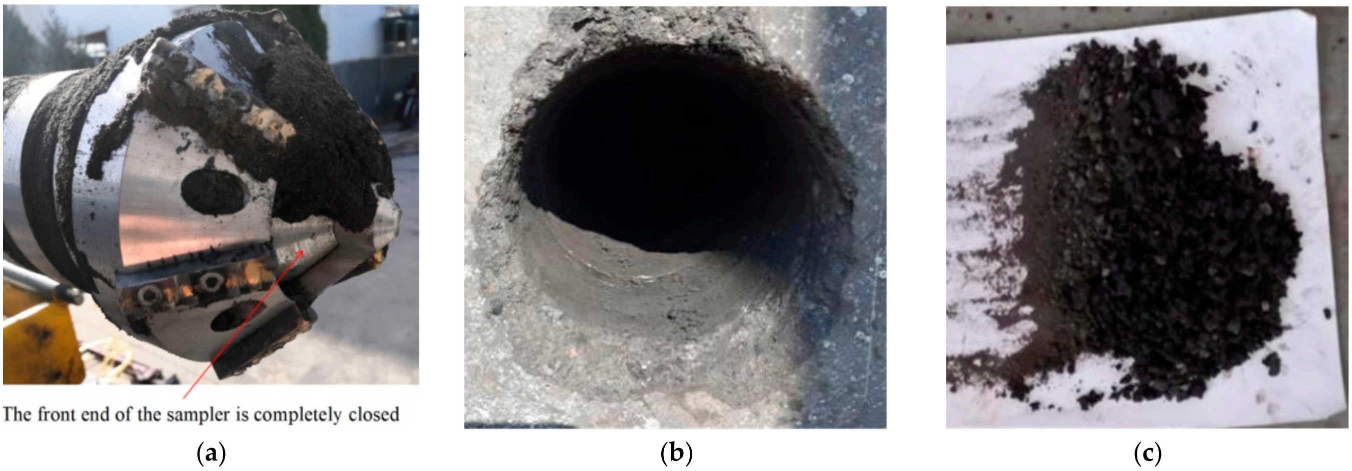


Figure 16. Experimental results. (**a**) Sampler front end diagram; (**b**) sample hole graph; (**c**) sample result graph.

5. Conclusions

(1) Orthogonal experimental methods were applied to study the effects of cement and coal powder on the compressive strength, elastic modulus, and Poisson's ratio density of similar materials. Cement was the primary controlling factor for each parameter. The influence of moisture content on the compressive strength and elastic modulus of similar materials was investigated. A mathematical equation was fitted to establish the relationship between moisture content and strength of similar materials, thereby providing ideas for future research on the association between moisture content and strength in such materials.

(2) A fitting analysis of the experimental data determined the fitting equation that correlates compressive strength, elastic modulus, moisture content, Poisson's ratio, and density with the proportions of cement and coal powder. The error of the fitting formula was judged to be kept within a reasonable range by analyzing R^2 and the plot of actual versus calculated values. From the experimental data obtained at different ratios, a proportional model was developed to establish the relationship between compressive strength, elastic modulus, Poisson's ratio, and density of similar materials. This model enables the determination of the cement–coal powder proportions and moisture content by submitting the given parameters of the raw coal. The approximate ranges of parameters that can be achieved by this model are as follows: compressive strength of 1 to 11.4 MPa, elastic modulus of 0.27 to 3.62 GPa, Poisson's ratio of 0.229 to 0.357, and density of 1.044 to 1.341 $g \cdot cm^{-3}$.

(3) This study produced a new kind of similar material depending on the proportioning model. Sampling simulation experiments on coal seams were conducted successfully through a self-developed experimental drilling platform. The large-sized sample was taken out and weighed. The volume of collected debris accounted for over 90% of the total volume of the sampling jar, meeting the sampling requirements. These results effectively demonstrated the feasibility of similar materials for the simulation of coal seam sampling and further validated the reliability of the proportioning model.

Author Contributions: Conceptualization, X.Z. and B.Z.; methodology, B.Z.; formal analysis, J.P.; investigation, J.P.; data curation, J.P.; writing—original draft preparation, J.P.; writing—review and editing, B.Z.; project administration, B.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: All data included in this study are available upon request by contacting the corresponding author.

Acknowledgments: We are grateful to the anonymous reviewers for their constructive reviews of the manuscript, and to the editors for carefully revising the manuscript.

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

References

1. Wang, B. The Experimental Design and Research of Coaly Similar Materials Based on Uniform Design Method. *Adv. Mater. Res.* **2013**, *850–851*, 233–236. [CrossRef]
2. Zhang, S.; Dai, L.; Wang, B.; Cao, J. Experimental Study on the Proportioning of Similar Materials for Simulating Coal and Gas Outburst. *Coal Sci. Technol.* **2015**, *43*, 76–80+145.
3. Wang, G.; Li, W.; Wang, P.; Yang, X.; Zhang, S. Deformation and gas flow characteristics of coal-like materials under triaxial stress conditions. *Int. J. Rock Mech. Min. Sci.* **2017**, *91*, 72–80. [CrossRef]
4. Qin, L. Research on Pore Structure Evolution Characteristics and Permeability Enhancement Mechanism of Liquid Nitrogen Cycle Fracturing Coal. Ph.D. Thesis, China University of Mining and Technology, Beijing, China, 2018.
5. Li, S.; Bie, C.; Zhao, P.; Li, L.; Lin, H. A Study on the Factors Influencing the Characteristics of Novel "Solid Gas" Coupled Similar Materials. *J. Min. Saf. Eng.* **2017**, *34*, 981–986.
6. Wu, B.; Zhu, H.; Xu, Q.; Ming, J. Experimental Study on Similar Materials of Class IV Weak Surrounding Rock. *Geotech. Mech.* **2013**, *34*, 109–116.
7. Cui, X.; Miao, X.; Su, D.; Ma, W. Error analysis of simulation test of similar materials for strata and surface movement. *J. Rock Mech. Eng.* **2002**, *12*, 1827–1830.
8. Liu, Q.; Chen, S.; Wang, S.; Chai, J.; Zhang, D. Experimental Development Process of a New Cement and Gypsum-Cemented Similar Material considering the Effect of Moisture. *Geofluids* **2020**, *2020*, 8831801. [CrossRef]
9. Chen, S.; Wang, H.; Zhang, J.; Xing, H.; Wang, H. Experimental Study on Low-Strength Similar-Material Proportioning and Properties for Coal Mining. *Adv. Mater. Sci. Eng.* **2015**, *2015*, 696501. [CrossRef]
10. Ning, Y.; Tang, H.; Zhang, B.; Shen, P.; Zhang, G.; Xia, D. Research on Rock Similar Material Proportioning Based on Orthogonal Design and Application of Bottom Friction Physical Model Test. *Geotech. Mech.* **2020**, *41*, 2009–2020.
11. Liu, Y.; Zhou, W.; Guo, B.; Ma, Q.; Xiao, H. Research on similar materials of marl in similar model experiment. *J. Rock Mech. Eng.* **2020**, *39*, 2795–2803.
12. Hu, Q.; Zhang, S.; Wen, G.; Dai, L.; Wang, B. Coal-like material for coal and gas outburst simulation tests. *Int. J. Rock Mech. Min. Sci.* **2015**, *74*, 151–156. [CrossRef]
13. Dai, Y.; Wang, M.; Wu, L.; Yan, Z. Research on the Effect of Admixtures on the Properties of Cement-based Similar Materials. *Coal Sci. Technol.* **2016**, *44*, 14–18.
14. Li, H.; Guo, G.; Zha, J. Study on time-varying characteristics of similar material model strength and the regulation measures. *Environ. Earth Sci.* **2017**, *76*, 518. [CrossRef]
15. Sun, H.; Zhu, M.; Cao, J.; Wen, G. Orthogonal experimental study on the construction of a similar material ratio model for outburst coal seams. *Coal Sci. Technol.* **2019**, *47*, 116–122.
16. Wang, X. Research on the Methods for Obtaining Mechanical Parameters in Rock Mass Engineering I: In Situ Testing and Quantitative Analogy. *J. Water Resour.* **2023**, *54*, 13–23.
17. Feng, G.; Fan, Y.; Wang, P.; Guo, J.; Wen, X.; Qian, R.; Zhu, L.; Zhang, P. Analysis of damage and failure process of rock like specimens under uniaxial compression under different material combinations and ratios. *J. Rock Mech. Eng.* **2023**, *42*, 3377–3390.
18. Zhan, K.; Xue, J. Development and Properties of a Similar Material to Coal. *Energies* **2022**, *15*, 6922. [CrossRef]
19. Yang, J. Development and application of a stress testing device for similar material model experiments. *Coal Sci. Technol.* **2019**, *47*, 114–119.
20. Li, S.; Qian, M.; Shi, P. Permeability coefficient strain equation during the full stress-strain process of coal samples. *Coal Geol. Explor.* **2001**, *29*, 22–24.
21. Chang, J. Research on Dynamic Identification of Mechanical Characteristics of Surrounding Rock during Impact Rotary Drilling with Holes. Master's Thesis, China University of Mining and Technology, Beijing, China, 2019.
22. Wang, P.; Shu, C.; Shi, F.; Hu, G.; Wang, H. Orthogonal experimental study on mechanical properties of materials with similar sand cement ratios, densities, and water content. *Geotech. Mech.* **2017**, *38*, 229–235.
23. Lei, S.; Gao, F.; Wang, X. Research on Statistics and Classification of Uniaxial Compressive Strength of Coal Body. *Coal Sci. Technol.* **2021**, *49*, 64–70.
24. Lei, S.; Gao, F. Laboratory coal deformation characteristics analysis and elastic modulus correlation model. *J. Min. Rock Control Eng.* **2021**, *3*, 51–59.

25. Zhu, M. Experimental Study on the Ratio Model of Similar Materials for Outburst Coal Based on Orthogonal Experiments. Master's Thesis, General Institute of Coal Science Research, Chongqing, China, 2019.
26. Chen, W. Analysis on relationship between stress and drill cutting weight using numerical modeling A case study in Jinjiazhuang coal mine. *Saf. Sci.* **2012**, *50*, 923–926.