Modeling the relationship between the influencing factors and the multiple responses of coal-like materials using Taguchi-Gray correlation analysis for their utilization in gas seepage studies

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Abstract
Coal-like sampling obtained through compression molding is an important application of powder compression molding technology in mining engineering. To obtain ideal coal-like samples for the revelation of the seepage property of low-permeability soft coals, gas seepage studies, which utilized the Taguchi method, were performed on coal-like materials with different particle sizes, activated carbon weight, Portland cement weight, and forming pressure. The effect of a single factor on the fluid-solid coupling property of coal-like materials was analyzed. The results indicate that the permeability and axial stress curves that correlated with strain in the conventional triaxial tests can be divided into three clear phases, and that layered damage appears in all tested specimens. The stress-permeability relationship model of coal-like materials is proposed. The influence of process parameters on the strength and permeability of coal briquettes during gas seepage tests was experimentally investigated. The Taguchi method and gray correlation analysis were integrated to determine the best combination of input factors through the key indicator of the gray relational grade, which is required to satisfy multiple quality goals in gas seepage coal-like materials. The contribution percentage of the input factors to the outputs was determined using analysis of variance; it indicated that coal particle size was the prominent influencing parameter followed by activated carbon, forming pressure, and Portland cement.

Keywords
coal-like materials, gas seepage, gray correlation analysis, permeability, Taguchi design

1 | INTRODUCTION

Powder compression molding has shown significant and rapid development in recent times and is widely used in various applications (eg, formulation of tablets,1,2 producing coal briquettes,3,4 and analog simulation tests5,6). It is well known that the behavior of the granular material is significantly affected by many factors, such as particle size, wetting liquid, interparticle forces,7 and cementitious material. Therefore, studying the influence mechanism of these factors facilitates in producing the ideal powder material.

Coalbed methane is a type of clean energy source; however, its emission (due to poor application of extraction techniques [manually] or increasing pressure [naturally]) from coal seams causes serious accidents (eg, outburst) that threaten the safety of both coal mine production and workers.
When extracting coalbed methane, permeability is a key parameter used to evaluate gas migration capability. However, controlling methane release from unstable/loose and high-gas coal seams is difficult. Therefore, understanding the seepage and migration rules of gas in soft coal seams is pivotal to avert disasters. In a laboratory setting, the typical problems encountered while studying the seepage of gas from soft coal seams include (a) difficulty in drilling raw coal samples, and (b) large discreteness of the result. Furthermore, scientific studies require using samples with repeatable properties, which is difficult to fulfill especially in experiments involving coals. Therefore, it is necessary to use a material whose properties are similar to those of coal. In this regard, the coal and gas seepage analog simulation test is effective to further study the mechanical mechanism underlying coal and gas seepage.

In an analog simulation test, an analog material and a model are required. It is important that the analog material satisfies the demands of simulation to improve the reliability of the test results. The simulation test has been widely used to simulate the mechanical mechanism and percolation theory of raw coal. For example, Jiang et al performed a gas seepage analog simulation test on a compression molding mixture of approximately 40-80-mesh crushed coal and a small amount of pure water; they found that the coal briquette specimen and raw coal specimen exhibit some similarity in deformation characteristics and compressive strength. Standard coal briquette specimens were used by Yu et al in a ZYS-1 equipment for the measurement of permeability to study the effects of confining stress, axial stress, and temperature on the permeability of coal briquette specimens. Skoczylas et al prepared coal briquettes of various porosities (13.5%-33%); they were found to exhibit mechanical and gaseous properties similar to those of normal and altered coal. Coal briquette specimens could also be used to study the relational expression between moisture content and permeability of coal containing gas by measuring the gas seepage flux under the combination of moisture, confining pressure, and gas pressure.

The craftsmanship of making coal briquette specimens and the factors influencing their properties have been studied. Hu et al suggested using a mixture of cement, crushed coal, water, sand, and activated carbon as raw materials for producing coal-like materials with coal and gas outburst tendency. Wang et al developed a novel material exhibiting characteristics similar to those of methane-bearing coal by using a mixture of a pulverized material with a specific particle-size distribution (aggregate) and a humid acid sodium aqueous solution (cementing agent). Cheng et al analyzed the optimization design of low-strength mechanical tests and orthogonal tests to simulate the mechanical properties of thick and extra-thick coal seams accurately in a material simulation test. Tu et al used activated carbon as the analog material for the gas-enriched area and coal as the material for the normal area to induce artificial gas outbursts. Niu et al investigated the adsorption capacity, swelling effect, and permeability characteristics of coal seams with and without tectonic damage by using reconstituted coal produced by simulating in situ geological conditions.

These studies on seepage simulation materials improved our understanding of coal and gas seepage mechanisms and suggested new possible views. Unfortunately, they all considered only a single factor, such as coal particle size, without considering the interaction between them. Thus, although many qualitative studies have been reported, only few quantitative studies on coal and gas seepage mechanisms have been performed.

The permeability of coal is sensitive to stress, as it is a weak rock with cleat aperture. Many researchers have reported that the permeability decreases exponentially when stress increases. The seepage channels within microfractures may become narrower or even close completely under stress; consequently, permeability decreases significantly at high stress levels.

An optimization test is generally conducted by altering one parameter with the values of other factors remaining constant to understand the effect of that individual parameter. However, this test requires multiple number of experiments and is time-consuming. Furthermore, it is costly and cannot determine the mutual interactions between the parameters.

By contrast, a design of experiment (DoE) can provide accurate and reliable information. Using the Taguchi method, several variables can be examined at one point with few experimental runs; nevertheless, quantitative information can be obtained. However, the traditional Taguchi method is not without limitations: it can only be applied to solve single objective problems and cannot be used for multiobjective optimization problems. To overcome this problem, the Taguchi method must be combined with GCA to optimize both multiple characteristics and multiple objectives. GCA is suitable for solving problems that have little information and with uncertainty, as well as for resolving multiple goals. This process can convert multiple responses into the gray relational grade, from which optimal process parameters are used by acquiring the response table. Coupling Taguchi’s method with GCA is effective and practical for solving multiresponse problems.

Coal briquetting is a useful method to ensure the continuous supply of research material for gas seepage studies. In this work, we focus on the mechanical and gaseous properties of coal briquettes and the optimization of process parameters for coal-like materials, which was accomplished using
Taguchi–GCA. Tests were conducted for an orthogonal layout of $L_9$ having different factors (coal particle size, activated carbon, Portland cement, and forming pressure), each of which exhibits three different levels. Minitab 17 was used to analyze the test results. The interaction effect between the factors and primary effects of each factors was studied.

2 | MATERIALS AND METHODS

2.1 | Coal-like materials

The coal samples were obtained from the N1641 working face of the M6-3 coal seam (i.e., the protective layer of the Shihao coal mine of the Chongqing Energy Investment Group Co., Ltd). The location and geology columnar of the targeted coal seam are shown in Figure 1. The destructive type of the seam is V, and the average thickness is 0.87 m. It is a soft coal seam and contains a gas of 14.67 m$^3$/t. The gas pressure of the seam is 1.4 MPa. The permeability coefficient is 0.0015 m$^2$/((MPa$^2$·d)). The parameters of the coal seam are listed in Table 1. The microcrystalline structure parameters of the coal were tested by X-ray diffraction (XRD), and the results are shown in Figure 2.

Based on the previous achievements of using similar materials in gas seepage simulation, we chose crushed coal, cement, activated carbon, and water as the raw materials, which are listed in Table 2.

2.2 | Test equipment

The triaxial servo-controlled seepage device for fluid-solid coupling of coal containing gas was used to perform the gas seepage tests. As shown in Figure 3, there are four subsystems in the test equipment, namely, servo-controlled loading system, triaxial compression cell, pore pressure control system, and data recording system.

The triaxial compression cell is shown in Figure 4, and it is the primary structure of the seepage equipment. The system has a maximum axial stress and confining pressure of

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**FIGURE 1** Location and geology columnar of coal seam
2.3 | Manufacture of coal sample specimens

The coal samples were first crushed, and subsequently sieved, and graded as 40-60 mesh, 60-80 mesh, and 80-100 mesh sized. A prespecified weight of sieved coal, cement, and activated carbon were mixed evenly with 10% percent of water. A rectangular pressing mold was subsequently used to compress the mixture at different pressures for 30 minutes using a TAW-2000 electrohydraulic servo triaxial testing machine. The processed coal-like material was ground into standard specimens of diameter of 50 mm and length 100 mm, as shown in Figure 5.

2.4 | Experimental design

To maintain the consistency of the experimental procedure for every coal-like specimen and reduce the effect of the test operation on the result, the experiment procedures for every specimen were maintained. The conventional triaxial experiment was conducted on the specimens simultaneously with the gas seepage experiment at room temperature as follows:

1. Axial stress was gradually applied to the value of 2 MPa under the hydrostatic pressure conditions;
2. Gas of pressure 1.0 MPa was continuously input until the end of the experiment;
3. To ensure that the following testing procedure is not influenced by the time-dependent deformation induced by confining pressure and gas adsorption, the adsorbed process is maintained for 24 hours for every specimen and the gas is completely adsorbed by the coal. With the confining pressure and gas pressure constant, the axial stress was loaded continuously until the specimen was broken. The axial displacement loading rate is 0.1 mm/min.

2.5 | Choosing of variables

After the coal particles, cement, and activated carbon were mixed with water, minerals in the cement began to react with the water (physical and chemical reactions). During the hydration reaction, a cement paste was formed with the gelation of particles, thus bonding the dispersed coal particles completely. Thus, cement hydration directly affects the strength, elastic modulus, and permeability of the coal-like materials.39 To decrease the effects of cement on the adsorption and permeability of coal-like materials, activated carbon was introduced to compensate for the loss of surface area on the coal particles resulting from cement addition. The forming pressure and coal particle size also affect the forming cohesion and permeability of the pulverized coal (see Figure 6); therefore, the coal particle size (Part Size), activated carbon (Act Carb), Portland cement (Cement), and forming pressure (Form Press) were determined as variables.

| TABLE 1 | Parameters of the coal seam |
|---------|----------------------------|
| Item                | Moisture content | Ash content | Volatile content | Consistent coefficient | Porosity | Gas adsorption volume constant | Gas adsorption pressure constant |
| Values             | 1.11%         | 29.95%      | 8.48%           | 0.21-0.38             | 5.23%    | 33.51 m³/t                  | 1.16 MPa⁻¹                   |

| TABLE 2 | Coal-like materials and their compositions |
|---------|---------------------------------------------|
| Type                | Raw material              | Model/particle size | Note                                    |
| Aggregate           | Crushed coal              | 40-100 mesh         | Coal sample from M6-3 coal seam of Shihao coal mine |
| Cementitious material | Cement                  | 425# ordinary Portland cement |
| Auxiliary material  | Activated carbon            | >60 mesh            | Powder sample                            |
|                     | Water                      |                     | Pure water                              |
**FIGURE 3** Triaxial servo-controlled seepage device for fluid-solid coupling of coal and gas

**FIGURE 4** Triaxial chamber

**FIGURE 5** Composition of the coal-like specimens
Taguchi designed an orthogonal matrix with different combinations of input parameters to perform experimental work uniquely. Four factors (coal particle size, active carbon, Portland cement, and forming pressure) were considered in the experimental array design using Taguchi's DoE. Each factor was varied through three levels as shown in Table 3.

To calculate the minimum number of experiments to be performed, the following formula was used:

\[
\text{Minimum experiments} = [(L-1) \times P] + 1 = [(3-1) \times 4] + 1 = 9 = L_9, \tag{1}
\]

where “L” is the number of levels and “P” is the number of factors.

The level values for the inner \(L_9\) orthogonal matrix are presented in Table 4.

3 | RESULTS

Twenty-seven specimens (thrice at every trials) were conducted in a predetermined order at room temperature, and the gas that flowed through the specimens under axial loading was measured using a gas mass flow controller and recorded in real time, such that the permeability transformation of the coal briquette during the test could be calculated. The typical correlation curves of permeability and principal stress with strain in the triaxial test of the specimens, and the thrice destructive mode at every trial are shown in Figure 7.

3.1 | Relation between permeability and axial stress

The typical permeability and axial stress correlated with strain in the test are shown in Figure 7. To study the

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**TABLE 3** Experimental parameters with levels

| S. no. | Factor       | Symbol | Level 1         | Level 2         | Level 3         |
|--------|--------------|--------|-----------------|-----------------|-----------------|
| 1      | Coal particle size | A      | 80-100 mesh     | 60-80 mesh      | 40-60 mesh      |
| 2      | Active carbon   | B      | 0               | 1%              | 5%              |
| 3      | Portland cement | C      | 0               | 5%              | 10%             |
| 4      | Forming pressure| D      | 20 MPa          | 60 MPa          | 100 MPa         |

**TABLE 4** \(L_9\) Orthogonal matrix

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influence law of different input parameters on the permeability and stress in every trial, the gradient of stress correlated with strain was used to judge every phase. The basis of the judgment is that briquettes with different input parameters would produce different amounts of damage in the loading process, thus directly deciding the permeability of the briquettes. Therefore, three clear phases exist in both the permeability and axial stress curves, according
to the different gradients of stress correlated with strain: The large amounts of gradient in the elastic phase, elastic-plastic phase, and plastic phase are almost unchanged with the increase in strain, and decrease with increasing strain; in small amounts, they were almost unchanged with an increase in strain, as shown in Figure 8.

Phase I: elastic phase. The permeability coefficient decreases as the strain and axial stress increase (almost linearly with increase in strain) in the elastic phase. Phase II: elastic-plastic phase. At the elastic-plastic phase, permeability continues to decline with axial strain at a slower rate. Permeability shows a corresponding obvious change, and is reduced at a slowly decreasing speed at the turning point of the axial stress. Phase III: plastic phase. The permeability coefficient remains stable or recovers partly with strain at the plastic phase. The principal stress reaches its ultimate strength and increases only slightly, with permeability showing a slight change at this phase. Similar conclusions were reported by Wang et al.38

3.2 | Failure pattern

The failure pattern of the specimens after the test was recorded in photographs, and was used in the test curves with the sketch of the fracture, as shown in Figure 7. The result shows that the specimens were divided into several parts by the fractures apart from Trial No. 1, in which all the three specimens were powdered. Several fracture surfaces are perpendicular to the axial direction in the specimens that produce a layered damage. Connected fissures skew with the axis are found in some specimens, indicating enhanced permeability. The deformation and failure characteristics affected the permeability of the specimens significantly.

3.3 | Stress-permeability relationship model of coal-like materials

According to the alternative relation of stress-strain and the corresponding permeability of the nine typical specimens in Figure 7, the stress-permeability law after the turning point of the axial stress can be summarized as a three-step model of stress-permeability relationship of coal-like materials, as shown in Figure 9: (a) relationship model of strain hardening and permeability reduction, and the corresponding specimen is Trial No. 1. In this model, the axial stress slowly increases and the permeability decreases gradually with the increase in axial strain, (b) The relationship model of perfectly plastic and permeability remained constant, and the corresponding specimens are Trial Nos. 5 and 9. In this model, the axial stress and permeability remain invariant while the axial strain increases, and (c) The relationship model of strain softening and permeability exhibits an increasing trend, and the corresponding specimens are Trial Nos. 2, 3, 4, 6, 7, and 8. In this model, the axial stress slowly decreases and the permeability increases gradually with the increase in axial strain. This indicates that the input control parameters have an obvious influence on the stress-strain relationship and on the permeability of coal-like materials specimens in the postpeak phase.

4 | DISCUSSIONS

4.1 | Univariante analysis

Using the orthogonal matrix of L9, the output parameter was measured and the average value was calculated among the three specimens for every trial, as presented in Table 5. The peak value (MPa), elastic modulus (MPa), initial permeability (mD), and mini-permeability (mD) for the nine trials are shown in Figures 10 and 11. The signal-to-noise ratio (S/N ratio)41 for peak value (MPa), elastic modulus (MPa), initial permeability (mD), and mini-permeability (mD) were calculated using the following equation.42

\[ S/N = -10 \log \left( \frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_i^2} \right), \]

where \( n \) is the number of levels of the indicative factor (noise factor); in the present work, it is equal to the number of imputes at each trial run condition and \( y_i \) is the response variable.

The test results indicate that when the quality of cement increases from 0% to 5%, the peak value and elastic modulus increased by 9.49% and 91.1%, respectively; by contrast, the initial permeability and mini-permeability decreased by 79% and 83.5%, respectively. With further increase in cement...
quality from 5% to 10%, the peak value and elastic modulus increased by 6.4% and 12.8%, respectively, whereas the initial permeability and mini-permeability decreased by 74% and 65.6%, respectively. This was due to the cement enhancing the strength of the specimens, while the fracture between the coal particles was sealed, thus reducing the permeability of the specimens.

When the coal particle size is changed from 80-100 mesh to 60-80 mesh, the peak value and elastic modulus decreased by 14.8% and 31.5%, respectively, and the initial permeability and mini-permeability increased by 65.9% and 60%, respectively. However, when the coal particle size is changed from 60-80 mesh to 40-60 mesh, the peak value, elastic modulus, initial permeability, and mini-permeability decreased by 11.0%, 14.2%, 30.6%, and 7.1%, respectively. The result shows that the coal particle size has a significant effect on the strength and permeability of the coal briquettes.

An increase in peak value by 33.3% was observed when increasing the forming pressure from 20 to 60 MPa accompanied with an increase in elastic modulus by 53.9%, and decreases in initial permeability and mini-permeability by 79.6% and 71.8%, respectively. By increasing the forming pressure from 60 to 100 MPa, peak value increases by 7.4%; however, the elastic modulus, initial permeability, and mini-permeability decrease by 38.1%, 9.2%, and 44%, respectively. This result suggested that an increase in the forming pressure increased the strength and decreased the permeability of the coal briquette samples.

### 4.2 Interaction analysis

Figures 12-14 show the relationship between the peak value, elastic modulus, initial permeability, and mini-permeability. When the elastic modulus increases, the peak value increases proportionally, as shown in Figure 12. The mini-permeability

![Figure 9](https://example.com/figure9.png)

**Figure 9** Stress-permeability relationship model
fluctuate with the elastic modulus, as shown in Figure 13. The mini-permeability varied proportionally to the initial permeability, as shown in Figure 14.

The larger-the-better condition was used to calculate the S/N ratio. Table 6 shows the normalizing and deviation sequence values of the individual S/N ratio calculated using the gray relational technique. After the data were normalized and the deviation sequence, the gray relational coefficient (GRC) was calculated for every output. In this study, all four responses should be higher and therefore, the larger-the-better method was used. The average GRC corresponding to the input factor level value was considered, and the gray relational grade (GRG) was calculated as presented in Table 7. To calculate the weighted GRG, weightages were assigned to every GRC. All the output responses were assigned as equal weightages.
The weighted GRG (100%) is given as follows:

\[
\text{Weighted GRG (100\%)} = \frac{\text{GRC of Peak value + GRC of Elastic Modulus + GRC of Initial Permeability + GRC of Mini-Permeability}}{4}.
\]  

(3)

For trial No. 2, the GRG can be calculated as

\[
\text{Weighted GRG (100\%)} = \frac{0.7559 + 0.5518 + 0.4824 + 0.4430}{4} = 0.5583.
\]  

(4)

For determining the optimal condition of the input factors chosen, the weighted gray grade averaged corresponding to the level values of every factor as listed in Tables 8 and 9 is considered. Results from the response table indicate that the most critical parameter is coal particle size, which has the highest deviation in average GRG. As shown in the response table, the best conditions are as follows: coal particle size, 80-100 mesh; activated carbon, 0%; Portland cement, 10%; forming pressure, 20 MPa.

From the response table, the primary effect plot is shown for the weighted GRG, as shown in Figure 15, which also shows the optimal conditions.

The interaction plot between the input factors and weighted GRG is shown in Figure 16. In the plot, nonparallel lines reveal the existence of a relationship, whereas parallel lines reveal otherwise. In this work, nonparallel lines exist between all the input factors, implying that these input factors cross influence each other and should be studied in depth.

4.3 Analysis of variance (ANOVA)

As a statistical method for analyzing the effect of factors on the output response, ANOVA assigns response variable changes between the available factors.42 ANOVA pooling involves ignoring unimportant factors, as their contribution is small. The degrees of freedom of these factors are added to the errors. In this analysis, cement has the least significance, and therefore pooled (see Table 10).

As shown in Table 10, the ANOVA analysis indicates that the highest percentage of contribution (46.57%) belongs to the Part Size, and is hence the most influential factor. The others are Act Carb (25.63%) and Form Press (3.19%). The “S” value of ANOVA is 0.0423549 and the \(R^2\) value is 94.26%, which presents a better result.

4.4 Multiple linear regression modeling

The formula below expresses the multiple linear regression model42:

\[
y = \alpha_0 + \alpha_1x_1 + \alpha_2x_2 + \ldots + \alpha_kx_k + \epsilon,
\]  

(5)
where \( x \) is the input variable and \( y \) is the response. The parameter \( \alpha_j \), where \( j = 0, 1, \ldots, k \), is the regression coefficient. To predict the output responses for a given input value, these regression models were used.

Using the statistical software Minitab-17 (a comprehensive set of powerful methods and graphs to analyze data), \( 43 \) empirical models were obtained for the weighted GRG considering the input factors to predict the outputs. The empirical models obtained for the outputs are listed as the following equations.

In this study, the independent variables were coded as \( A_i, B_i, C_i, \) and \( D_i \) (\( i = 1, 2, 3 \), i.e., the level of the input parameters). These equations indicate that the relationship of the inputs can be predicted by the statistical method.

For coal particles of size 80-100 mesh:

\[
\text{Weighted GRG} = 0.6667 - 0.1031B_2 - 0.04639B_3 + 0.03053C_2 + 0.04835C_3 - 0.03576D_2 - 0.09487D_3. \tag{6}
\]

For coal particles of size 60-80 mesh:

\[
\text{Weighted GRG} = 0.5276 - 0.1031B_2 - 0.04639B_3 + 0.03053C_2 + 0.04835C_3 - 0.03576D_2 - 0.09487D_3. \tag{7}
\]

For coal particles of size 40-60 mesh:

\[
\text{Weighted GRG} = 0.60183 - 0.1031B_2 - 0.04639B_3 + 0.03053C_2 + 0.04835C_3 - 0.03576D_2 - 0.09487D_3. \tag{8}
\]

The residual curve is shown in Figure 17, which is obtained by optimizing empirical models for the weighted GRG. The normal probability curve of the weighted GRG residuals presents a linear relationship with the points. The histogram presents a bell-shaped curve, and the distribution of weighted GRG residuals follows a normal distribution. The residuals associated with the empirical model obtained to the observation order are plotted, and are extremely powerful in determining the input combination that affects the results.

### Table 7: GRC and weighted GRG

| Trail no. | gray relational coefficient | Peak value (MPa) | Elastic modulus (MPa) | Initial permeability (mD) | Mini-permeability (mD) | gray relational grade |
|-----------|-----------------------------|------------------|-----------------------|--------------------------|------------------------|----------------------|
| 1         |                             | 0.3333           | 0.3333                | 1.0000                   | 1.0000                 | 0.6667               |
| 2         |                             | 0.7559           | 0.5518                | 0.4824                   | 0.4430                 | 0.5583               |
| 3         |                             | 1.0000           | 0.6284                | 0.3333                   | 0.3333                 | 0.5738               |
| 4         |                             | 0.5489           | 0.4378                | 0.4425                   | 0.4235                 | 0.4632               |
| 5         |                             | 0.3514           | 0.4134                | 0.5431                   | 0.5830                 | 0.4727               |
| 6         |                             | 0.4266           | 0.4058                | 0.4681                   | 0.4810                 | 0.4454               |
| 7         |                             | 0.7314           | 1.0000                | 0.3409                   | 0.3852                 | 0.6144               |
| 8         |                             | 0.4128           | 0.3898                | 0.3982                   | 0.4144                 | 0.4038               |
| 9         |                             | 0.3977           | 0.4658                | 0.7586                   | 0.7217                 | 0.5859               |

### Table 8: Response table of gray relational grade

| Factors       | Level 1 | Level 2 | Level 3 | Max-Min | Rank |
|---------------|---------|---------|---------|---------|------|
| Part size     | 0.5996  | 0.4604  | 0.5347  | 0.1391  | 1    |
| Act carb      | 0.5814  | 0.4783  | 0.5350  | 0.1031  | 2    |
| Cement        | 0.5053  | 0.5358  | 0.5536  | 0.0484  | 4    |
| Form press    | 0.5751  | 0.5393  | 0.4802  | 0.0949  | 3    |

### Table 9: Analysis of variance for gray relational grade (before pooling)

| Factors       | DoF | SS      | MS      | \( F \) value | \( P \) value |
|---------------|-----|---------|---------|---------------|--------------|
| Part size     | 2   | 0.029086| 0.014543| *             | *            |
| Act carb      | 2   | 0.016010| 0.008005| *             | *            |
| Cement        | 2   | 0.003588| 0.001794| *             | *            |
| Form press    | 2   | 0.013774| 0.006887| *             | *            |
| Error         | 0   | *       | *       |               |              |
| Total         | 8   | 0.062458|         |               |              |

*means there is no data
5 | VERIFICATION TEST

As mentioned above, the optimal combinations of the input factors are as follows: coal particle size, 80-100 mesh; activated carbon, 0%; Portland cement, 10%; forming pressure, 20 MPa. To verify this optimal situation, a gas seepage test under the same confining pressure and gas pressure on the briquette sample created under the optimal combination of input factors was conducted, and the result is shown in Figure 18. The result indicates that the strength, modulus of elasticity, and permeability coefficient satisfy the characteristics required by simulating the

![Primary effects curve for gray relational grade](image1)

![Interaction curve for gray relational grade](image2)

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| TABLE 10 | Analysis of variance for gray relational grade (after pooling) |
|---|---|---|---|---|---|---|
| Factors | DoF | SS | MS | F value | P value | % Contribution |
| Part size | 2 | 0.029086 | 0.014543 | 8.11 | 0.110 | 46.57% |
| Act carb | 2 | 0.016010 | 0.008005 | 4.46 | 0.183 | 25.63% |
| Form press | 2 | 0.013774 | 0.006887 | 3.84 | 0.207 | 22.05% |
| Error | 2 | 0.003588 | 0.001794 | | | 5.74% |
| Total | 8 | 0.062458 | | | | 100.00% |
low-permeability soft coal. The briquette sample created under the optimal combination of input factors can be used to study the seepage law of gas drainage technology in soft coal seam, such as vertical well drainage, drilling borehole down, across the seam underground, and hydraulic antireflection measures.

6 | CONCLUSIONS

Gas seepage studies on coal briquettes of different particle sizes, activated carbon weight, Portland cement weight, and forming pressure designed by the Taguchi method were performed using the triaxial gas seepage device for the solid-fluid coupling of coal with gas. The effect of single factor on the properties of coal briquettes was analyzed and characterized by mechanical and gaseous properties specific for gas seepage in coals. The results indicated that the permeability and axial stress curves correlated with strain in the triaxial test divided into three clear phases, and layered damages were found in all tested specimens. The stress-permeability relationship model of coal-like materials was proposed.

The Taguchi method and GCA were integrated to identify the optimal combination of input factors required to satisfy multiple quality objectives in gas seepage coal-like materials. The beneficial features of this study are the lesser number of experiments and reduced process time, which are attributed to Taguchi-based multiresponse optimization.

The ANOVA results indicated that coal particle size is the most important and influential input factor contributing to the GRG by 46.57%, followed by activated carbon, Portland cement, and forming pressure.

Between all the input factors, a considerable amount of interaction effect was observed. Using the empirical models acquired by the multiple linear regression method for different coal particle sizes, the prediction of GRG was achieved. The verification test result showed that the strength, modulus of elasticity, and permeability coefficient could satisfy the characteristics required by simulating the low-permeability soft coal.

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