

Research Article

Study on the Proportion of Conglomerate Similar Materials Based on the Orthogonal Test

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Similarity model test is one of the important methods to study the properties of rock engineering. In this paper, quartz sand, 42.5 ordinary Portland cement, and tap water are used as the similar test materials to simulate the properties of conglomerate. The three control factors are cement-to-water ratio, cement-to-sand ratio, and quartz sand particle size, and orthogonal tests are set at four levels. The permeability coefficient, compressive strength, elastic modulus, density, and Poisson's ratio are tested on specimens of similar materials of conglomerate, and the corresponding physical and mechanical indexes are obtained. The range analysis method is used to analyse the influence of various factors on the mechanical properties. The results show that (1) the physical and mechanical parameters of similar materials have a certain degree of dispersion under different proportions; (2) the proportion of similar conglomerate materials is cement : sand : water : water reducer = 1 : 2 : 0.4 : 0.6%; and (3) multiple linear regression analysis is carried out on the control factors and mechanical parameters to obtain the regression equation of the proportion of similar materials, which proves that the equation could be used to make the study of conglomerate similar materials under the stress coupling of seepage.

1. Introduction

In practical underground engineering, rock mass often exists in the complex geological environment with the coupling action of seepage field and stress field. In the process of roadway tunneling, coupled by ground stress and seepage pressure, the self-supporting capacity of surrounding rock is weakened, and the softening of surrounding rock is induced, resulting in rheological deformation, which brings serious safety hazards to the roadway tunneling. Therefore, it is extremely urgent to study the rock mass under the coupling action of seepage stress. At present, scholars' research focus on mudstone, red rock, clay rock, and coal rock [1–4]; the research on conglomerate is rare. But due to the destruction of conglomerate rock mass, this results in the mine roadway deformation of countless cases. Therefore, it is urgent to study the mechanical properties of conglomerate rock mass under seepage-stress coupling. Most of the natural conglomerate rocks used in the study are located in complex geological conditions, which are difficult to obtain large

quantities of specimen. Therefore, the development of similar materials that can be used to simulate the conglomerate under the coupling effect of seepage stress has become a necessary means to solve the dilemma. Geomechanical model test has become an effective method to solve the problem of underground geotechnical engineering [5–11].

The research on the ratio of similar materials is mainly based on the similarity criterion and factor analysis. By changing the influencing factors in the laboratory test, the influence law of one or more factors on the mechanical properties of similar materials is obtained. Through reading a large number of literatures [12–14], it is found that most researchers choose rock-like materials, such as cement mortar mixture and gypsum mixture, etc., and configure them in a certain proportion to simulate different rock properties. Wang et al. [15] obtained the regression equations of the ratio, density, residual water content and uniaxial compressive strength, elastic modulus and Poisson's ratio by studying the orthogonal tests of the mechanical

properties of similar materials with different sanding ratios, densities and water bearing properties. Chen et al. [16], Liu et al. [17], Liu et al. [18] and others all carried out a lot of experimental studies on the ratio of similar materials in rock mass, proving that the optimal ratio of similar materials in rock mass can be studied through orthogonal test and range analysis. Li et al. [19] studied new fluid-solid coupling similar materials and applied them to practical projects, which enriched the USES of fluid-solid coupling materials. Wang et al. [20] explored the influence of polyphosphoric acid (PPA) combined with SBS modified asphalt composition material on its viscoelasticity through orthogonal experiments. Wang et al. [21] developed a new fault surrounding rock similar materials to evaluate the changes of stress and deformation in the process of tunnel water inrush and applied them to the solid-liquid coupling model test. Chen and Bai [22] used quartz sand, gypsum, cement, water, glycerin, gelatin and other components to make model specimens, and obtained a formula suitable for rockburst model materials, which can be applied in large-scale physical simulation tests. Wu et al. [23] prepared similar soft rock materials with barite powder, gypsum, fine sand, washing clothes and water level raw materials. Wang et al. [24] took coal powder as aggregate to conduct similar material tests to simulate the process of coal and gas outburst. He et al. [25] developed fluid-solid two-phase model materials, which better solved the problem that the solid model materials tend to disintegrate when exposed to water.

At present, some progress has been made in the research field of similar materials, but some problems still exist: (1) at present, it is rare to study conglomerate under seepage stress coupling. (2) Due to the lack of research on the ratio of conglomerate similar materials under the action of seepage stress coupling, the empirical expression of obtaining function has not been proposed systematically. Aiming at the existing problems, based on the previous research results, the optimization of conglomerate similar materials is carried out in this paper. According to the similarity criterion and orthogonal test, the influences of cement-to-water ratio, cement-to-sand and quartz sand particle size on the permeability coefficient, compressive strength, elastic modulus, density, and Poisson's ratio of similar materials are discussed. Through the data regression analysis, the empirical formula of the ratio of conglomerate similar materials under the action of seepage stress coupling is obtained, which provides support for the research of conglomerate materials in laboratory.

2. Selection of Similar Materials

2.1. Similarity Criterion under Seepage Stress Coupling. According to the similarity experiment principle, the model needs to have geometric similarity, gravity similarity, stress similarity, inertia force similarity, external load similarity, and other criteria under the seepage-stress coupling action.

After similar theoretical analysis on the mathematical model of continuous homogeneous medium seepage-stress coupling, combined with the research characteristics of this paper and the dimensional analysis method, balance equation, geometric physical equation, and fluid-solid coupling familiar model, etc., the parameters and ratios of similar materials should satisfy the following formula:

$$\begin{aligned}
 C_\varphi &= C_\mu = C_\gamma = 1, \\
 C_\sigma &= C_{\sigma c} = C_{\sigma t} = C_E = C_c, \\
 C_\sigma &= C_L C_\gamma, \\
 C_\delta &= C_\varepsilon C_L, \\
 C_\sigma &= C_\varepsilon C_E, \\
 C_K &= \sqrt{\frac{C_L}{C_\gamma}},
 \end{aligned} \tag{1}$$

where C_μ is Poisson's ratio similarity ratio; C_ε is the strain similarity ratio; C_φ refers to the friction angle similarity ratio; C_σ is the stress similarity ratio; $C_{\sigma c}$ similarity ratio of compressive strength; $C_{\sigma t}$ is the similarity ratio of tensile strength; C_E is the similarity ratio of elastic model; C_c is the similarity ratio of cohesion; C_L is geometric similarity ratio; C_γ was the severe similarity ratio. C_δ is displacement similarity ratio; and C_K is the similarity ratio of permeability coefficient.

2.2. Selection of Conglomerate Similar Materials. The selection of test materials should meet the requirements of four aspects: (1) the main physical and mechanical properties are close to real rocks or have certain similarity; (2) physical mechanics and chemical properties are stable and not easily affected by changes in the external environment; (3) good brittleness can be obtained; (4) the forming process of the specimen is convenient. On the basis of the existing similar materials research, combined with the basic physical parameter analysis of conglomerate, the main materials of conglomerate similar materials this time are quartz sand, 42.5 ordinary Portland cement, tap water and water-reducing agent, etc. The particle size range of quartz sand is, respectively, 0.25 mm–0.50 mm, 0.50 mm–1.0 mm, 1.0 mm–2.0 mm, and 2.0 mm–4.0 mm.

3. Analysis of the Orthogonal Experimental Scheme and Results of Similar Materials

3.1. Design Scheme of the Orthogonal Experiment. In order to more accurately and scientifically determine the similar ratio that satisfies this research, the orthogonal design

method is used to design the ratio of quasi-conglomerate similar material, the main consideration is the cement-to-water ratio (water-cement mass ratio), cement-to-sand ratio (quality ratio of quartz sand to cement), and quartz sand particle size, the test taking three factors and four levels orthogonal design L16 (3^4). The orthogonal design level of conglomerate-like materials is shown in Table 1.

3.2. Sample Preparation and Sample Equipment. According to the standard requirements, the sample size should be satisfied 48 mm~54 mm in diameter, the height-to-diameter ratio of the rock sample should be between 2.0 and 2.5, and the size of the rock sample should be 50 mm × 100 mm cylinder sample with the diameter greater than 10 times of the largest particle diameter in the rock sample. According to Table 1, the relationship between various factors should be strictly controlled. In order to simplify the workload and speed up model making, the PP-R hot water pipe with a diameter of $\Phi 60$ mm × 8.7 mm produced by Shanghai Lingyu Pipe Industry Co., Ltd. is used as the mold. During sample preparation, similar materials are prepared according to the ratio of similar conglomerate materials. The specific preparation process is applying mold release agent (Vaseline), vibrating into the mold, initial curing and demolding, and steam curing. The processed conglomerate specimens are subjected to a water saturation test to ensure that the pores of the conglomerate specimens are filled with water; soaking time is not less than 48 h. The conglomerate samples are shown in Figure 1.

3.3. Analysis of Conglomerate Similar Material Test Results. By using orthogonal design assistant software, the design level of each factor in Table 1 is arranged in accordance with orthogonal design table L-16 (3^4), and a total of 16 matching schemes have been made. Each matching scheme gets four horizontal comparison specimens, for a total of 256 specimens. The density, Poisson's ratio, permeability coefficient, compressive strength, and elastic modulus of conglomerate similar materials are obtained by conducting conventional physical and mechanical tests on quasi-conglomerate similar material, which are shown in Table 2.

By comparing the physical and mechanical parameters of natural conglomerate specimens and combining with the percolation-stress coupling problem studied in this study, the permeability coefficient, compressive strength, elastic modulus, density, and Poisson's ratio of conglomerate are taken as the main similar parameters of similar materials. The results show that the density of similar materials ranged from 1.76 to 2.17 g/cm³, the compressive strength ranged from 18.78 to 30.08 MPa, the permeability coefficient ranged from 1.52×10^{-6} to 2.84×10^{-4} cm/s, the elastic modulus ranged from 1.53 to 2.86 GPa, and the Poisson's ratio ranged from 0.102 to 0.194. Under the condition of corresponding similarity ratio, the prepared materials can meet the similarity requirements of some common rocks.

3.4. Influence Factors and Level of Conglomerate Similar Material Parameters. The range analysis method was used to determine the influence of the same factor on the experimental indexes at different levels. The large range indicated that the indicators were different at different levels of the factor, and the influence of the factor on the experimental results was obvious.

3.4.1. Influence Factors and Level of Permeability Coefficient. According to the results of 16 orthogonal experiments (Table 2), the permeability coefficient was studied by single-index range analysis method. Through calculation, the mean values and range of three different factors of water-to-cement ratio, sand-to-cement ratio, and quartz sand particle size at four levels are shown in Table 3, and the sensitivity factor analysis of permeability coefficient is shown in Figure 2. It can be seen that the range of quartz sand particle size is the largest, so the data has a great discrete nature, and this factor has the greatest influence on the permeability coefficient of conglomerate material; the range of cement-to-water ratio is the smallest, indicating that the data has good concentration, and this factor has little influence on the permeability coefficient of conglomerate materials.

The influence of various factors on permeability coefficient ranged from large to small for quartz sand particle size, cement-to-sand ratio, and cement-to-water ratio.

3.4.2. Influence Factors and Level of Compressive Strength. When subjected to the range analysis of compressive strength, through calculation, the mean values and range of three different factors of water-to-cement ratio, sand-to-cement ratio, and quartz sand particle size at four levels are shown in Table 4. A curve is drawn with the calculated range value for sensitivity analysis, which is shown in Figure 3. It can be seen that the range of water-cement ratio is the largest, so the data has a great discrete nature, and this factor has the greatest influence on the compressive strength of conglomerate materials. If the range of quartz sand size is the smallest, the data has a good concentration, and this factor has the least influence on the compressive strength of conglomerate materials. The influence of various factors on compressive strength ranged from large to small for cement-to-water ratio, cement-to-sand ratio, and quartz sand particle size.

3.4.3. Influence Factors and Level of Elastic Modulus. When subjected to the range analysis of elastic modulus, through calculation, the mean values and range of three different factors of water-to-cement ratio, sand-to-cement ratio, and quartz sand particle size at four levels are shown in Table 5. A curve is drawn with the calculated range value for sensitivity analysis, which is shown in Figure 4. It can be seen that if the range of water-to-cement ratio is the largest, the data has a great discrete property, and this factor has the greatest influence on the elastic modulus of conglomerate materials. The range between the ratio of sand to gum and

TABLE 1: Orthogonal design levels of quasi-conglomerate similar material.

Test level	Cement-to-water ratio	Cement-to-sand ratio	Quartz grain size (mm)
1	0.30	2	0.25 ~ 0.50
2	0.35	3	0.50 ~ 1.00
3	0.40	4	1.00 ~ 2.00
4	0.45	5	2.00 ~ 4.00



FIGURE 1: Molds of experimental specimens.

TABLE 2: Physical and mechanical parameters of quasi-conglomerate similar material.

Number	Cement-to-water ratio	Cement-to-sand ratio	Quartz grain size (mm)	Osmotic coefficient k (cm/s)	Compressive strength σ_c (MPa)	Elasticity modulus (GPas)	Density ρ (g/cm ³)	Poisson's ratio (μ)
L-1	0.3	2	0.5	8.52×10^{-6}	21.15	1.82	1.76	0.142
L-2	0.3	3	1	9.67×10^{-6}	20.82	1.57	2.01	0.115
L-3	0.3	4	2	1.09×10^{-4}	19.06	1.74	1.91	0.121
L-4	0.3	5	4	2.13×10^{-4}	18.78	1.53	2.14	0.102
L-5	0.35	2	1	8.23×10^{-6}	24.47	1.72	1.87	0.136
L-6	0.35	3	0.5	3.87×10^{-6}	23.26	1.84	2.07	0.161
L-7	0.35	4	4	1.58×10^{-4}	21.14	1.65	2.11	0.153
L-8	0.35	5	2	2.06×10^{-4}	19.78	1.96	1.86	0.154
L-9	0.4	2	2	2.54×10^{-5}	28.91	2.86	1.95	0.148
L-10	0.4	3	4	2.38×10^{-4}	28.27	2.03	2.08	0.139
L-11	0.4	4	0.5	2.57×10^{-5}	27.41	2.23	1.93	0.187
L-12	0.4	5	1	1.01×10^{-4}	26.53	2.16	2.17	0.181
L-13	0.45	2	4	2.84×10^{-4}	30.08	2.07	1.88	0.176
L-14	0.45	3	2	9.42×10^{-5}	28.72	1.76	2.12	0.169
L-15	0.45	4	1	9.16×10^{-5}	27.65	1.81	2.03	0.162
L-16	0.45	5	0.5	7.47×10^{-5}	25.86	1.96	1.96	0.194

TABLE 3: Range analysis of permeability coefficient.

	Cement-to-water ratio	Cement-to-sand ratio	Quartz sand particle size
\bar{k}_1	8.51×10^{-5}	9.72×10^{-5}	2.82×10^{-5}
\bar{k}_2	9.40×10^{-5}	8.64×10^{-5}	5.26×10^{-5}
\bar{k}_3	1.13×10^{-4}	9.61×10^{-5}	1.24×10^{-4}
\bar{k}_4	1.36×10^{-4}	1.49×10^{-4}	2.23×10^{-4}
R	5.11×10^{-5}	6.22×10^{-5}	1.95×10^{-4}

the particle size of quartz sand is small and similar, indicating that the data has good concentration, and this factor has little influence on the elastic modulus of conglomerate

materials. The influence of various factors on the modulus of elasticity ranged from large to small for cement-to-water ratio, cement-to-sand ratio, and quartz sand particle size.

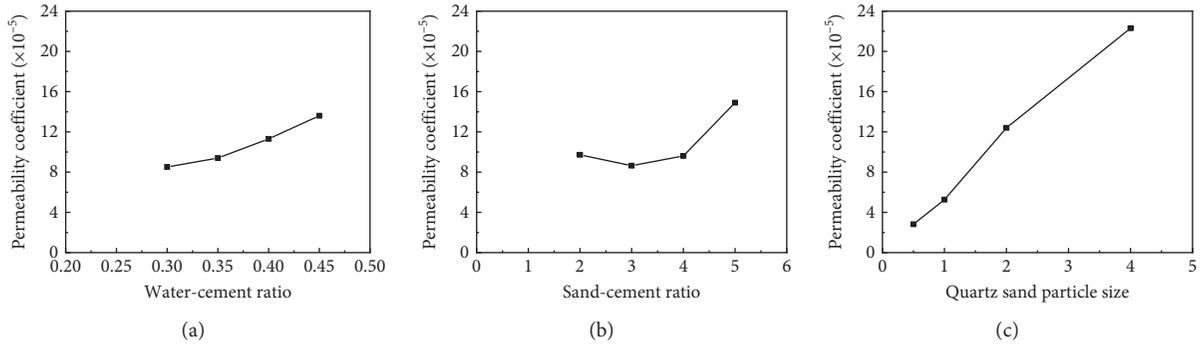


FIGURE 2: Permeability coefficient sensitivity analysis.

TABLE 4: Range analysis of compressive strength.

	Cement-to-water ratio	Cement-to-sand ratio	Quartz sand particle size
\bar{k}_1	19.95	26.15	24.42
\bar{k}_2	22.16	25.27	24.87
\bar{k}_3	27.78	23.82	24.12
\bar{k}_4	28.08	22.74	24.57
R	8.13	3.42	0.75

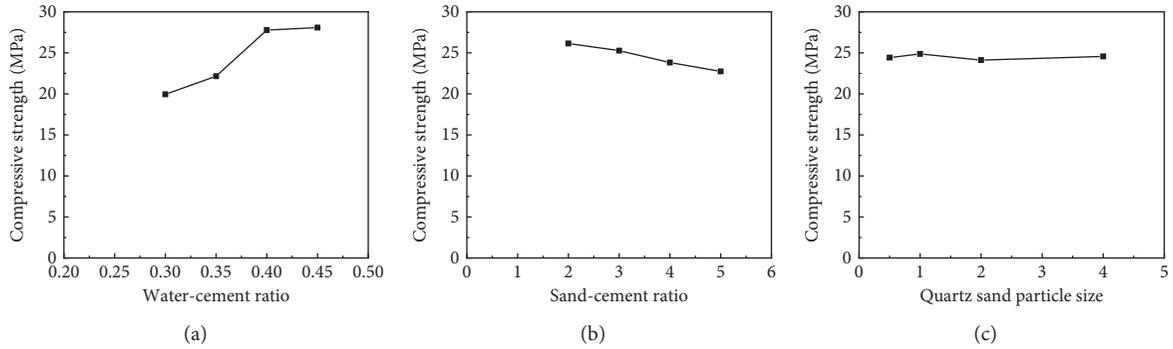


FIGURE 3: Sensitivity analysis of compressive strength.

TABLE 5: Range analysis of elastic modulus.

	Cement-to-water ratio	Cement-to-sand ratio	Quartz sand particle size
\bar{k}_1	1.67	2.12	1.97
\bar{k}_2	1.79	1.80	1.82
\bar{k}_3	2.32	1.86	2.08
\bar{k}_4	1.9	1.90	1.82
R	0.66	0.32	0.27

3.4.4. *Influence Factors and Level of Density.* When subjected to the range analysis of density, through calculation, the mean values and range of three different factors of water-cement ratio, sand-cement ratio, and quartz sand particle size at four levels are shown in Table 6. A curve is drawn with the calculated range value for sensitivity analysis, which is shown in Figure 5. It can be seen that the maximum range of

the sand-cement ratio means that the data has a great discrete property, and this factor has the greatest influence on the density of glue-like materials. The range of water-cement ratio and quartz sand particle size is small, indicating that the data has a good concentration, and the influence of this factor on the density of conglomerate-like materials is small. The influence of each factor on the density ranged

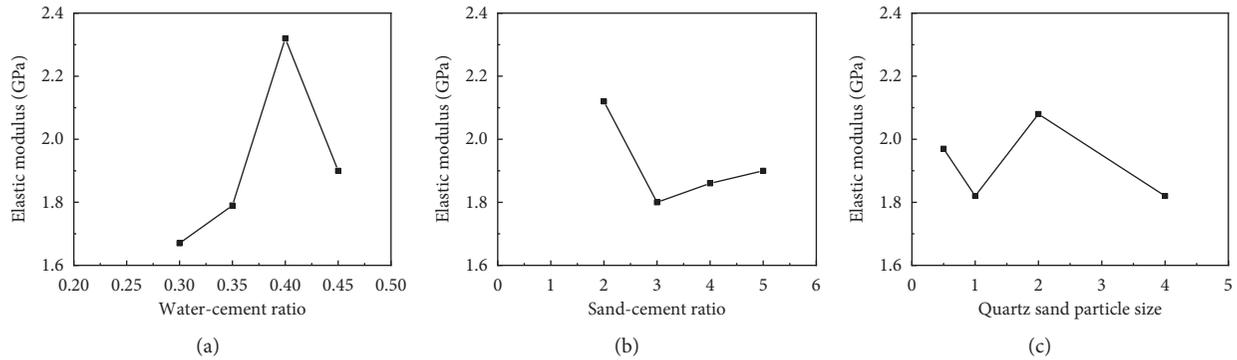


FIGURE 4: Sensitivity factor analysis of elastic modulus.

TABLE 6: Range analysis of density.

	Cement-to-water ratio	Cement-to-sand ratio	Quartz sand particle size
\bar{k}_1	1.96	1.87	1.93
\bar{k}_2	1.98	2.07	2.02
\bar{k}_3	2.03	2.00	1.96
\bar{k}_4	2.00	2.03	2.05
R	0.07	0.20	0.12

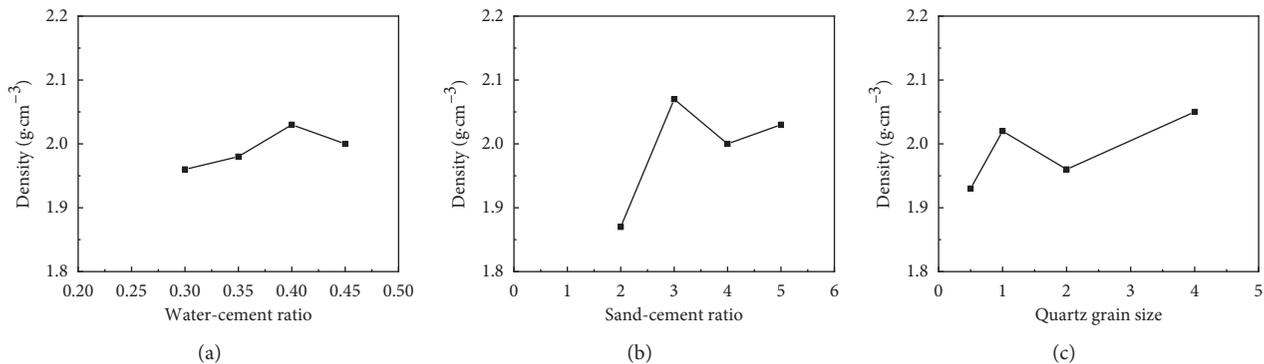


FIGURE 5: Sensitivity factor analysis of density.

from large to small for cement-to-sand ratio, quartz sand particle size, and cement-to-water ratio.

3.4.5. Influencing Factors and Levels of Poisson's Ratio.

When subjected to the range analysis of Poisson's ratio, through calculation, the mean values and range of three different factors of water-cement ratio, sand-cement ratio, and quartz sand particle size at four levels are shown in Table 7. A curve is drawn with the calculated range value for sensitivity analysis, which is shown in Figure 6. It can be seen that if the range of water-cement ratio is the largest, the data has a great discrete property, and this factor has the greatest influence on the Poisson's ratio of conglomerate materials. The quartz sand particle size and the range of the cement-to-sand ratio are small, indicating that the data has a good concentration, and this factor has little influence on Poisson's ratio of conglomerate materials. The influences of

various factors on Poisson's ratio ranged from large to small, including cement-to-water ratio, quartz sand particle size, and cement-to-sand ratio.

4. Multiple Linear Regression Analysis and Verification

4.1. Multiple Linear Regression Analysis and Verification.

According to the data in Table 2, through the analysis and calculation of three groups of single-factor range and the study of the rule of factors at different factor levels, it is not difficult to find that the permeability coefficient, compressive strength, elastic modulus, density and Poisson's ratio of water-cement ratio, sand-cement ratio, and quartz sand particle size are linearly related to similar materials. Suppose the water-cement ratio is X_1 , the sand-cement ratio is X_2 , and the particle size of quartz sand is X_3 . Permeability coefficient

TABLE 7: Range analysis of Poisson's ratio.

	Cement-to-water ratio	Cement-to-sand ratio	Quartz sand particle size
\bar{k}_1	0.12	0.151	0.171
\bar{k}_2	0.151	0.146	0.149
\bar{k}_3	0.164	0.156	0.148
\bar{k}_4	0.175	0.158	0.143
R	0.055	0.012	0.028

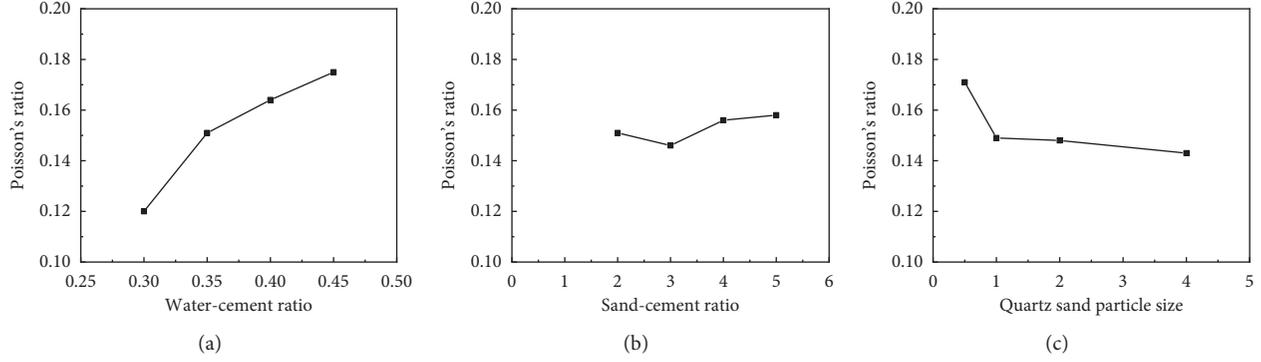


FIGURE 6: Sensitivity factor analysis of Poisson's ratio.

is Y_1 , compressive strength index is Y_2 , elastic modulus index is Y_3 , density index is Y_4 , and Poisson ratio index is Y_5 . Multiple linear regression analysis was performed on the data and the regression equation was obtained as follows:

$$\begin{aligned}
 Y_1 &= (34.48X_1 + 1.64X_2 + 5.64X_3 - 18.53) \times 10^{-5}, \\
 Y_2 &= 6.12 + 59.99X_1 - 1.17X_2 - 0.016X_3, \\
 Y_3 &= 2.47X_1 - 0.059X_2 - 0.022X_3 + 1.24, \\
 Y_4 &= 0.365X_1 + 0.043X_2 + 0.053X_3 + 1.66, \\
 Y_5 &= 0.357X_1 + 0.003X_2 - 0.006X_3 + 0.02.
 \end{aligned} \quad (2)$$

By comparing the index points calculated in formula (2) with the experimental data, it was found that the difference was very small and only a few points had a large error, which was related to the accuracy and inevitable error of the operation of the experimental personnel and could be treated as invalid error data, which is shown in Figure 7, where E represents the test data and Y denotes the fitting data.

4.2. Validation of Applicability of the Regression Formula.

The natural conglomerate specimens retrieved from the site were analysed by x-ray diffraction (XRD), and the chemical composition of the conglomerate layer was 50.5% quartz sand, 31.3% sodium feldspar and 18.2% microplagioclase. Three cylindrical samples are processed with sizes of 50 mm \times 100 mm for triaxial compression experiment by the use of conglomerate getting back from the site. The TAW-2000 rock testing machine is used to perform uniaxial compression test on the conglomerate sample to obtain the full stress-strain curve of the conglomerate. At the same time, the GDS soft rock rheometer is used for the permeability test. The sample process refers to GB/T50266-2013 (Standard for Test Method of Engineering Rock Mass), and

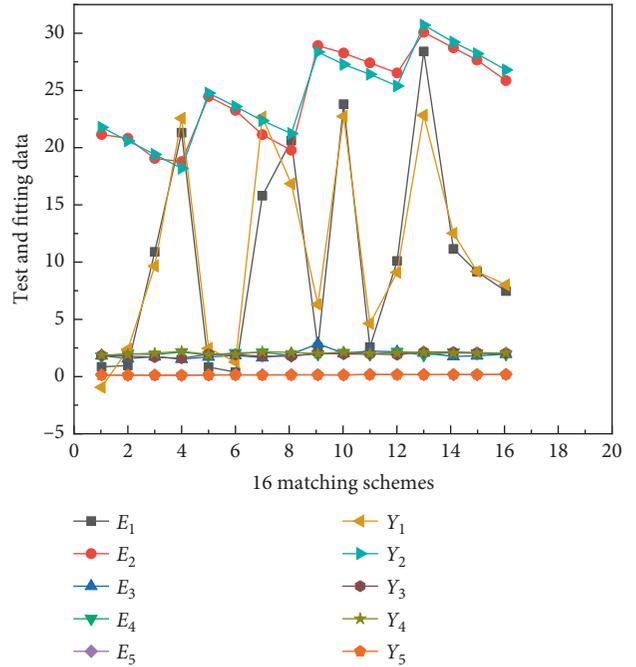


FIGURE 7: Comparison of test data and fitting data.

the measured physical indicators are averaged and recorded in Table 8.

According to the physical and mechanical parameters, chemical composition and regression formula of similar materials, the permeability coefficient $Y_1 = 1.44 \times 10^{-5}$ g/cm, uniaxial compressive strength $Y_2 = 29.76$ MPa, elastic modulus $Y_3 = 2.25$ GPa, density $Y_4 = 2.12$ g/cm³, and Poisson's ratio $Y_5 = 0.144$ are inserted into the equation, and $X_1 = 0.36$, $X_2 = 4.17$, and $X_3 = 2.84$. According to the empirical formula of the ratio and the accuracy conditions of

TABLE 8: Mechanical parameters of the nature and similar material specimen.

Test number	Permeability coefficient k (cm/s)	Compressive strength σ_c (MPa)	Elasticity modulus E (GPa)	Density ρ (g/cm ³)	Poisson's ratio (μ)
Conglomerate	1.44×10^{-5}	29.76	2.25	2.12	0.144
Similar material	1.76×10^{-5}	25.64	1.96	1.79	0.153

the actual operation, the water-cement ratio was selected to be 0.35, the sand ratio to be 4, and the quartz sand particle size to be 3 mm for the verification test. The same sample preparation standards and test methods as the natural conglomerate were adopted to obtain the average physical and mechanical parameters of similar materials, as shown in Table 8.

By comparing the mechanical parameters in Table 8, it is found that the permeability coefficient, compressive strength, elastic modulus, density, and Poisson's ratio errors of the specimens and the natural conglomerate obtained according to the regression formula are 18.18%, 13.84%, 12.89%, 15.57%, and 6.25%, respectively. Because the mechanical parameters of the test materials have certain discreteness, and the errors of the conglomerate similar materials under the coupling effect of seepage stress obtained by the mixture ratio are not large, it is believed that the regression equation obtained by linear regression can be used to study the conglomerate similar materials under the coupling effect of seepage stress of the mixture ratio. The ratio of similar conglomerate materials is cement:sand:water:water reducer = 1:2:0.4:0.6%.

5. Conclusion

- (1) Based on the orthogonal experiment to water-binder ratio, sand ratio, and quartz sand particle size of three factors for controlling factors, respectively, set up the four levels, permeability coefficient, compressive strength, elastic modulus, and Poisson's ratio, density measurement, to get the corresponding mechanical properties index, income distribution, similar material physical and mechanical parameters index distribution can satisfy the requirement of similar test.
- (2) Through the range analysis of each factor, the influence of each factor on the physical and mechanical parameters of similar materials is systematically analysed. Through multiple linear regression analysis, the regression formula of conglomerate similar materials under the action of seepage stress coupling was obtained, and the error was proved to meet the requirements by comparing with natural conglomerate samples. The ratio of conglomerate similar materials was cement:sand:water:water reducer = 1:2:0.4:0.6%.
- (3) The mechanical parameters of similar materials have a high degree of coincidence with the real conglomerate, which indicates that the proportion scheme of similar materials proposed in this paper can be configured according to the physical

parameters requirements of similar experiments and has certain applicability.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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