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Research Article

Experimental Study on the Ratio of Similar Materials in Weak Surrounding Rock Based on Orthogonal Design

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In the aspect of stability analysis of tunneling engineering, geomechanical model test is an important research method. A similar material is the prerequisite for the success of geomechanical model test. In the field of major engineering applications, a variety of similar materials are prepared for different geological conditions of surrounding rock and applied in some major engineering. With the use of standard sand, fine sand, and silt clay as materials, similar materials for weak surrounding rock were developed. Based on the orthogonal design method, through the direct shear test, the range analysis and variance analysis of various factors affecting the physical and mechanical parameters of weak surrounding rock are carried out. The results show similar material can meet the requirements in weak surrounding rock. Standard sand is the key factor that influences the internal friction angle of similar materials, and silt clay is the key factor affecting the cohesion of similar materials. Similar materials can meet the elastic modulus and severe requirements of the weak surrounding rock and can be used for the weak surrounding rock engineering. The new type of similar material configuration is widely used in shallow buried tunnel entrance section and urban shallow buried excavation engineering, in addition to tunnel engineering in loess stratum, and the problems of engineering design and construction are solved through geomechanical model test.

1. Preface

In recent years, with the ongoing national infrastructure, as an important part of the traffic on the scale of import and export increase, tunnel engineering is growing. The special stratum in tunnel surrounding rock belongs to soft rock, because of soft rock mechanics parameters, and because tunnel stability is poor, so the study of soft stratum properties is the key to the design and construction of the tunnel.

At present, there are many research methods for the engineering properties of surrounding rock for weak surrounding rock. The field test has the characteristics of difficult sampling, long cycle, and high cost. The numerical calculation module has the characteristics of large deviation between calculation result and field practice and inability to directly use the field practice. Indoor model test is a test method which is made of materials similar to the physical and mechanical properties of the prototype and is made into scale models based on certain similarity relations. Research and practice in geotechnical engineering often need the help of a similar model test method, to explore the complex problems of analytic method and numerical simulation method is not easy to solve, with which can simulate the engineering geological environment, the failure characteristics and cost control, strong circulation, and other advantages, where the means study on engineering properties of soft rock is more effective, and to get the test results with the actual development of similar material is the key; it is related to the model which can correctly reflect the characteristics of the prototype, but also related to the model where processing is not easy, and testing can be carried out smoothly.

Many scholars at home and abroad have carried out a lot of research work on the preparation of similar materials of rock mass. Han Boli introduced use of barite powder, iron powder, and film rosin alcohol solution mixing and similar materials; the elastic modulus of materials can be effectively adjusted according to film thickness. Its disadvantage was chloroprene rubber adhesive powder containing toluene, but the side effects on the human body were larger [1].

Peng Haiming introduced cement gypsum as rock simulation material. Through a large number of cement gypsum laboratory tests, the physical and mechanical properties of cement gypsum similar materials were studied. This kind of material was characterized by low price and easy processing, but the model had slower drying and longer curing time [2].

Ma Fangping developed the NIOS geological mechanical model material, mainly composed of magnetite ore concentrate, river sand, adhesive plaster or cement, and mixing water and additives, to overcome some past model materials which are unable to simulate high density material, easily rust, and have high cost of defects [3].

Wang Yiping combined with orthogonal experimental design method, through computer and mathematical analysis, to evaluate the influence degree of various parameters on slope stability. Combined with engineering practice, sensitivity analysis was carried out on important factors affecting slope stability [4].

According to the similarity principle of geomechanics model test, Zhang Qiangyong had developed a new type of iron crystal sand cemented rock and soil similar material through a lot of mechanical tests. The material had many notable advantages, such as high gravity, wide range of mechanical parameters, stable performance, low cost, fast drying, simple manufacturing process, innocuity, and harmlessness. It could be used to simulate most of rock materials from soft rock to hard rock. The 3D geomechanical model test study of iron sand cemented rock and soil similar material was applied to the large bifurcation tunnel of Hu-Rong west highway, which effectively reveals the mechanical deformation characteristics of the surrounding rock of the bifurcated tunnel [5].

Zou Chenglu based on orthogonal design method, relying on the Shanghai expressway, making a cohesive force and the friction angle of surrounding rock as the research target, used fly ash, dry river sand, and mixing oil as raw materials and better simulated the V level of surrounding rock. Through a large number of experiments, the influence factors of similar material physical parameters, and sensitivity analysis, the reasonable proportion of material was determined finally [6].

Dong Jinyu, in the previous research on the basis of similar material, applied orthogonal design method to the iron powder, barite powder, binder concentration, and gypsum content into 4 factors, each factor set 5 with levels, designing 25 sets of material proportioning, with the physical and mechanical properties of similar materials of different proportions. The sensitivity of various factors was analyzed by range analysis method, and the direct analysis diagram of the influence of various factors on physical and mechanical parameters of similar materials was made, and the influence rules of various factors on similar material parameters were analyzed [7].

Miao Yuanbing used clay, barite powder, silt sand, and bentonite as raw material, prepared in shaking table model test of soil and similar materials; based on the orthogonal design method and the ratio of influence factors on soil physical mechanical parameters of similar material for sensitivity analysis, the configuration can meet most of the requirements of similar material of the model test of soil [8].

Guan Zhenchang used iron ore powder, barite powder, silt material, rosin, alcohol as binder, gypsum powder as modifier, and rock system in shaking table model test of similar materials, with the orthogonal design method to use the 12# ratio as a similar material for simulating the medium weathered coarse-grained granite layer in the shaking table model test [9].

In the rock mass ratio of similar materials, using the method of orthogonal design of proportioning test design can greatly reduce the number of tests, combined with the existing research level of similar materials for soft rock and formation characteristics, applying the similarity principle and selection principle, model selection of various materials, and susceptibility testing of different materials by orthogonal design principle, taking a lot of proportioning test study on the system, different ratio of similar materials, and developing a new type of similar material.

The new type of similar material force has the characteristics of high similarity in mechanical properties, easiness in extracting raw materials, and lower cost. It can be used for reference in similar projects and has good application prospects and positive social effects.

2. Principle of Similar Material

It is impossible to develop a similar material that completely reflects the physical and mechanical properties of the prototype. It is only a prototype that completely reflects the physical and mechanical properties of the prototype. Therefore, the main similarity criteria should satisfy the specific conditions of the experiment. In the test, it needs to satisfy similar deformation condition of the strength to satisfy the similar deformation property of the model as possible.

The selection of similar materials generally follows the following principles.

(1) Follow the Principle of Similarity. The performance of the model material should meet similar requirements of the model design. Based on the elastic modulus, Poisson's ratio, gravity, and various strength parameters, different proportioning tests are carried out to compare the material proportions that meet the requirements of similar proportions.

(2) Follow the Test Criterion. Due to the difference of engineering background, the purpose of different model tests is different. The test is most common to satisfy the deformation characteristics or strength failure characteristics. Therefore, similar materials should be selected and configured for the purpose of testing.

(3) Good Physical Stability. Similar material after construction has good physical stability, is not affected by the change of temperature and humidity, and not easily shows physical or chemical reaction. The material has high mechanical properties and high stability.

Table 1: Main mechanical parameters of similar material prototypes and models.

Material	Cohesion (KPa)	Internal Friction Angle (°)
Prototype	30.0	23.0
Model	1.0	23.0

(4) Security. Similar material should not be disadvantageous to the health of the staff and does not cause pollution to the surrounding environment.

(5) Easy to Configure. Similar materials should have the convenience of drawing material, simple forming, easy mixing and processing, quick forming after forming, short sting time, and satisfying the test requirements.

(6) Economy. Because there are many factors affecting indoor geomechanical model test, usually multiple model tests are required. Each test should be carried out with similar material configuration, and similar material cannot be reused, so it requires similar material price to be lower and ensure economy test.

3. Selection of Similar Materials

According to the model test platform size and similar material selection principle, we determined the similarity of the cohesion ratio to be 30, and the internal friction angle is 1. As is shown in Table 1, rock physical and mechanical parameters were based on the investigation data of the project and combined with the design specification of highway tunnel values, similar material model, and prototype mechanical parameters.

The same physical quantity with the same dimension had the same similarity ratio, so the similarity ratio of the internal friction angle of the same unit and the two physical quantities of the cohesive force was equal. Figures 1–3 showed the test material selection of standard sand, fine sand, and silt clay with adjustment of the internal friction angle; the cohesion of the silt clay had the characteristics of adjustment.

Figure 1: Standard sand.

Figure 2: Fine sand.

Figure 3: Silt clay.

4. Experimental Study on the Ratio of Similar Materials

4.1. Orthogonal Experimental Design Theory. The test for 3 or more than 3 factors at the same time is called multifactor test. Multifactor experimental design methods are commonly used comprehensive test method, test method, and orthogonal test method. If a comprehensive test is carried out, the scale of the test will be very large, and it is often difficult to implement because of the limitation of the test conditions. Although the simple test method has few test times, the test points are not representative, the result of the test is not reliable, and the order of the main and secondary factors are unable to be found. Orthogonal test method needs lower number of experiments; data point distribution can distinguish between primary and secondary factors. The results of the test can be treated by mathematical statistics, and the results obtained are better and superior. The test belongs to the category of multifactor experimental research, and the orthogonal test method should be adopted.

4.2. Orthogonal Experimental Design. According to the theory of orthogonal design, based on the literature, fine sand material internal friction angle and cohesion have little effect compared with standard sand material internal friction angle which has great influence, similar to the great influence of silt clay on the cohesion of the material, so the choice is of fine sand adjusting the density of the material and as a base material. We used standard sand and silt clay content as the variable and set two factors; orthogonal test was four levels; four levels of standard sand were 30%, 33%, 36%, and 39%. The four levels of silt clay are 40%,43%, 46%, and 49%.

4.3. Similar Material Configuration Test. The mold was made with the diameter of 5 cm and height of 10 cm, and the mold

Table 2: Orthogonal test ratio parameter results of similar materials.

Number	Fine sand /%	Standard sand/%	Silt clay /%	Cohesion /KPa	Internal friction angle /°
1	30	30	40	0.81	22.6
2	27	30	43	0.96	22.4
3	24	30	46	1.03	22.1
4	21	30	49	1.21	21.8
5	27	33	40	0.79	23.8
6	24	33	43	0.94	23.5
7	21	33	46	1.0	23.1
8	18	33	49	1.18	22.8
9	24	36	40	0.75	25.1
10	21	36	43	0.92	24.8
11	18	36	46	0.98	24.5
12	15	36	49	1.15	24.1
13	21	39	40	0.72	26.4
14	18	39	43	0.89	26.0
15	15	39	46	0.96	25.4
16	12	39	49	1.1	25.1

Figure 4: Mold forming.

Figure 5: Static maintenance.

was cleaned and applied to the mold before making the specimen. The material was mixed and stirred by the material test mixer to ensure the uniform bonding of the material. The sample was formed in Figures 4 and 5.

As is seen in Figure 6, the samples were made up of 16 specimens according to the ratio of different materials. The samples were labeled and maintained for 7-15 days in the basement.

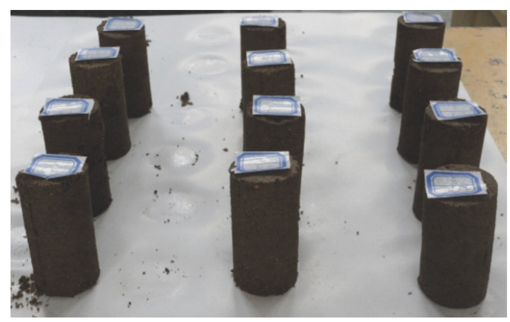

Figure 6: Different samples.

The main indexes of physical and mechanical properties of weak stratum were elastic modulus, cohesive force, and internal friction angle of soil. The mechanical parameters test of the material of the loess model was divided into two parts: the cohesive force and the internal friction angle were measured by direct shear test.

4.4. Orthogonal Test Analysis. Orthogonal test ratio parameter results of similar materials are shown in Table 2. Figures 7 and 8 showed that the content of standard sand increases, the material internal friction angle increases, and the material cohesion decreases. Figures 9 and 10 showed that the silt clay content increases, the friction angle of material decreases, and the cohesion of material increases. Table 3 showed that the difference between the influences of standard sand on the cohesion of materials is 0.06, the difference between the influences of the silt clay on the cohesion of materials is 0.39, the difference between the standard sand and the internal friction angle of materials is 3.47, and the influence of silt clay on the internal friction angle of materials is 1.1.

Table 3: Results of extreme difference calculation and analysis.

Level	Cohesion		Internal friction angle	
	Standard sand	Silt clay	Standard sand	Silt clay
1	0.82	0.77	22.23	24.5
2	0.8	0.93	23.3	24.1
3	0.79	1	24.6	23.8
4	0.76	1.16	25.7	23.4

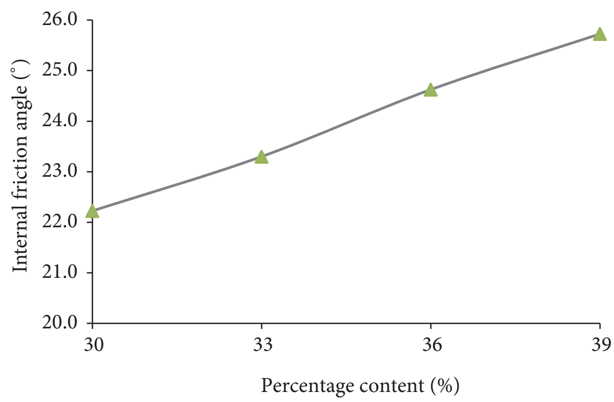

Figure 7: Influence of standard sand on the internal friction angle.

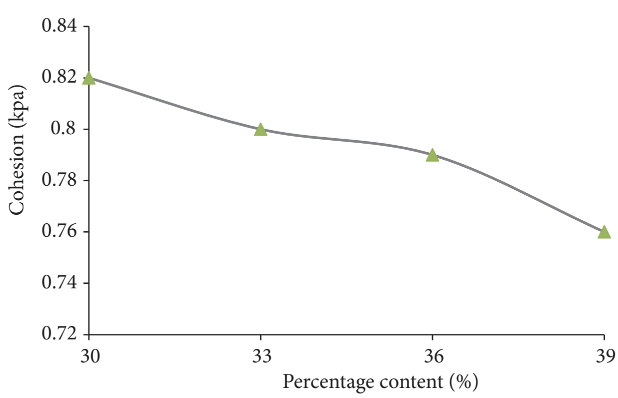

Figure 8: Influence of standard sand on cohesion.

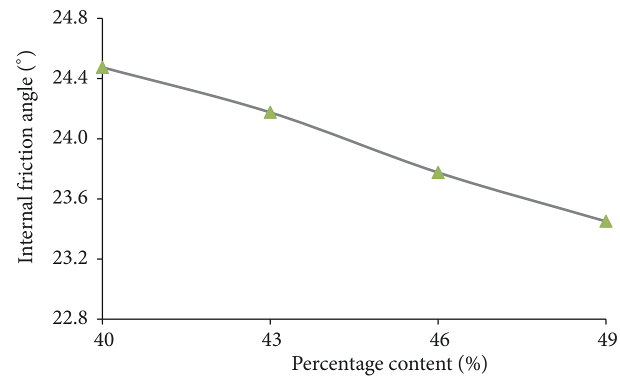

Figure 9: Influence of silt clay on the internal friction angle.

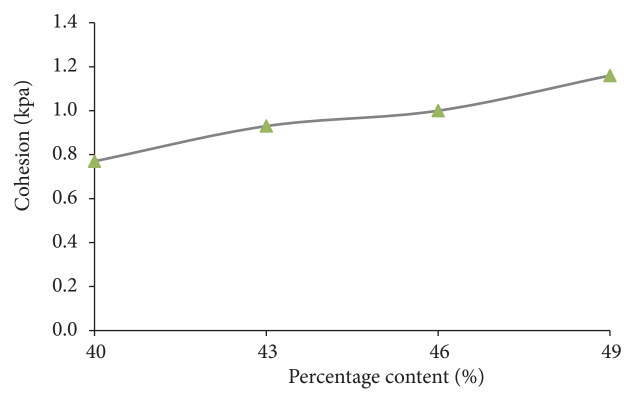

Figure 10: Influence of silt clay on cohesion.

Therefore, the influence of the standard sand on the internal friction angle of similar materials is obvious, and the silt clay has an obvious influence on the cohesion of the similar materials. According to the correlation between similar material and mechanical parameters of the material required for the final test of the model, the ratio of standard sand, fine sand, and silt clay is 33: 22: 45.

According to the ratio of three tests, the cohesive force of the mechanical parameters of the material is 1.0KPa, and the internal friction angle is 23.1°, which meets the requirements of the test.

5. Conclusion

According to the study on geomechanical model test of the ratio of similar material, selecting standard sand, fine sand, and silt clay as similar material can reduce the number of tests by using orthogonal test method. In the optimization test scheme, the ideal ratio of similar materials and set of the standard sand percentage, silt clay, and similar materials accounted for similar material percentage of 2 with a set of 3 factors, each factor level obtained by range analysis of laboratory tests on specimens of the results. The conclusions are as follows:

(1) The intersection test analysis shows that silt clay has an obvious influence on the cohesive force of similar materials, and the standard sand has an obvious influence on the internal friction angle of similar materials. The ratio of similar materials suitable for weak surrounding rock of standard sand, fine sand, and silt clay is 33: 22: 45.

(2) The newly developed weak surrounding rock similar materials meet the requirements of mechanical properties of materials. The basic materials are widely distributed, easy to

take, better in shape, lower in cost, and higher in economic benefits and can be wide-bound applied to geomechanical model tests of highway and railway tunnels.

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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