Experimental study on similar materials in model test based on orthogonal design

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Abstract. The selection of simulation materials of aquiclude has an important influence on the results of the model test, and has a high requirement in terms of mechanics and hydrologic properties. According to the high quality of river sand as aggregate, cement and gypsum mixed aqueous solution as cementing material, organic silicon mixture similar material as additive, in accordance with the principle of orthogonal test design, sand-binder ratio, cement plaster - and concentration of organic silicon as factors, each factor is equipped with four levels, specimen preparation into under the different ratio of similar model, carries on the uni axial compressive strength test, splitting test, penetration test and the moisture content test under the different ratio of compressive strength, tensile strength, permeability coefficient and softening coefficient, By means of the range analysis method of orthogonal experiment, the influence degree of each factor level on the similar material is summarized, and it is concluded that the ratio of sand gum to mechanical properties has great influence, and the concentration of organosilicone water has obvious influence on the water rational energy. The new solid-flow coupling simulation material developed in this paper can provide a new scheme for the model test of water-involved problems such as mining under confined water, water-retaining mining and construction in water-rich area, and has high application value.

Key words: Model test; simulation materials of aquiclude; orthogonal design; range analysis.

1. Introduction

Model test is an important research method for the study of geotechnical engineering problems. It has the advantages of simple operation, no need to create a constitutive model, and intuitive test results, etc. Based on the similarity principle, it uses similar materials to make models instead of prototypes, requiring similar materials to maintain similar mechanical properties with prototypes [1]. Researchers have long reached a consensus on the selection principles of similar materials, such as material availability, cost, environmental sensitivity, and mechanical stability. For the aggregate, binder and additive of similar materials, the basic material bank is established. Such as aggregate including river sand, sea sand, quartz sand and iron powder; Cementing materials include cement, gypsum, paraffin and resin, etc. The additive auxiliary materials include borate, glycerin and gasoline [2-8], etc. The general
regularity of the influence degree of each component on mechanical properties is also clarified, and then similar materials for different uses are prepared. In addition to those widely used in the industry over the years, some more characteristic ones have emerged in recent years, such as Shuangjian Niu[9], etc., which can simulate deep soft rock by using river sand and rosin alcohol solutions of different proportions. Zhuoli Chen etc. [10] simulated soft overburden by mixing lime, gypsum, quartz sand, mica powder and borax solution. With the deepening of the research, especially for the practical needs of water-related problems such as mining under confined water, water-retaining mining and construction in water-rich areas, the traditional solid-phase simulation materials have developed to solid-liquid coupling similar materials, and the model test has also developed from indirect water-related to direct water-related. The development of similar materials requires not only similar solid deformation but also similar hydrologic properties. The key to model test rock simulation lies in water-proof layer, and low permeability and non-disintegration when exposed to water are its main characteristics. Qingxiang Huang etc. [11] used quartz sand, bentonite, silicone oil and vaseline to realize similar simulation of plastic waterproof layer. Shucai Li etc. [12] developed a complex new fluid-solid coupled similar material (SCVO). The basic raw materials include sand, barite powder, talc powder, cement, vaseline, silicone oil, etc. Jiafu Zhou [13] prepared a non-hydrophilic fluid-solid coupling similar material by mixing sand, precipitated barium sulfate powder, ultrafine talcum powder, paraffin, white vanillin and silicone oil. Shuhong Dai[14] developed fluid-solid coupling model test similar materials by using fine sand, talcum powder, gypsum and liquid paraffin, etc. By adjusting its ratio, it could simulate soil with different physical and mechanical properties and water rational energy.

In this paper, based on the accumulation of previous experience in the research of similar materials with convection-solid coupling, a kind of similar material suitable for the simulation of non-hydrophilic water-barrier layer in the water-crossing model test was developed by using the organosilicone solution as the main regulating agent for the hydrologic properties and by using the orthogonal experimental design method and a large number of hydrologic and mechanical experiments.

2. The selection of similar materials and experimental design

2.1. The selection of similar materials for water barrier
The selection of similar materials has an important influence on the mechanical properties of specimens. For the model test involving water, similar materials should be guaranteed to have the characteristics of hydrophobicity, low permeability and non-disintegration when exposed to water. Specifically, fine sieve river sand (river sand is widely available, cheap, stable and not easy to react with other materials, which has a great impact on mechanical properties) is used as aggregate. Take cement and gypsum as cementing agent (cement and gypsum are cheap and easy to obtain, cement has water resistance, stable performance and low permeability after molding, gypsum has the characteristics of fast molding and high strength); Silicone solution (available everywhere in the building materials market, has a good waterproof effect, can adjust the non-hydrophilic test pieces) as a regulator.

2.2. The test program
Orthogonal test method is suitable for multi-factor tests. It selects some representative points from the comprehensive test to carry out the test. These points are uniform and neat, and can quickly determine the degree of influence of different factors on the test results. The method has high efficiency and saves the test material and time cost, and is adopted in the design of the simulated material.

In the orthogonal experiment, the sand-cement ratio (the ratio of river sand content to cementing material content), cement gypsum ratio (the ratio of cement content to gypsum content in cementing material) and organosilicone concentration (the ratio of organosilicone solution to aqueous solution) were taken as factors, and each factor had 4 levels, as shown in Table 1. Orthogonal design scheme with 3 factors and 4 levels was selected, as shown in Table 2.
Table 1. The orthogonal experimental design arrangement

| Sand binder ratio | Cement gypsum ratio | Organosilicon concentration(%) |
|-------------------|--------------------|--------------------------------|
| 1 6:1             | 4:6                | 11%                            |
| 2 7:1             | 5:5                | 16%                            |
| 3 8:1             | 6:4                | 21%                            |
| 4 9:1             | 7:3                | 26%                            |

Table 2. The design of orthogonal experimental scheme

| Sand binder ratio | Cement to gypsum ratio | Organosilicon concentration(%) |
|-------------------|------------------------|--------------------------------|
| 1 6:1             | 4:6                    | 11                             |
| 2 6:1             | 5:5                    | 16                             |
| 3 6:1             | 6:4                    | 21                             |
| 4 7:1             | 4:6                    | 11                             |
| 5 7:1             | 5:5                    | 21                             |
| 6 7:1             | 6:4                    | 26                             |
| 7 7:1             | 7:3                    | 21                             |
| 8 7:1             |                        | 26                             |
| 9 7:1             |                        | 11                             |
| 10 8:1            |                        | 21                             |
| 11 8:1            |                        | 26                             |
| 12 8:1            |                        | 11                             |
| 13 9:1            |                        | 16                             |
| 14 9:1            |                        | 26                             |
| 15 9:1            |                        | 11                             |
| 16 9:1            |                        | 21                             |

3. The preparation and parameter determination of similar materials

According to the following test items and standard procedures, standard cylindrical specimens are prepared by mold method. First, a certain amount of material was weighed and fully stirred evenly according to the ratio, and then a certain proportion of organic silicon aqueous solution was added for further stirring. Then, the mixed material was put into the mold, tamped, and let stand for initial setting and stripping. Then, it was placed in a ventilated and dry place and dried naturally for 7 days. The specimens in curing are shown in Figure 1.

During the preparation of the specimen, the following considerations should be made:

(1) In order to reduce accidental errors, the average value of multiple measurements should be taken, and the number of specimens in the same experimental item should not be less than three.

(2) To ensure the homogeneity of the specimen, the specimen with the same ratio should be made at one time. To ensure the consistency of density, similar materials should be quantitatively loaded and tamped in the same way.

(3) To ensure the appearance quality of the specimen, daub vaseline on the inner wall of the mold before stripping to avoid damaging the surface and edge of the specimen.

(4) To distinguish and compare different proportioning schemes, timely label the prepared specimens.

3.1. The mechanical properties and water rationality can be determined

Through uniaxial compressive strength test, splitting test, water absorption test and permeability test to determine the mechanical properties and water rational energy of the specimen, including compressive strength, tensile strength, water absorption, softening coefficient and permeability coefficient. Before the test of water rationality, the specimen was immersed in water for 72h to ensure that the specimen was in a state of natural saturation. The specific testing process is shown in Figure 2.
Figure 1. The specimens in curing

Figure 2. The test process

The test data are given by the following formula:

1. The compressive strength

\[ \sigma_c = \frac{P}{A} \]  

Where, \( \sigma_c \) is the compressive strength (MPa) of the specimen, \( P \) is the maximum load (N) at failure, and \( A \) is the cross-sectional area (mm\(^2\)) of the specimen.

2. The tensile strength

\[ \sigma_t = \frac{2P}{\pi dh} \]  

Where, \( \sigma_t \) is the tensile strength (MPa) of the specimen. \( P_1 \) is the load (N) received by the specimen during failure; \( d \) is the diameter of the specimen (mm); \( h \) is the height of the specimen (mm).

3. The coefficient of water absorption

\[ \omega = \frac{m_1 - m_2}{m_2} \]  

Where, \( \omega \) is the coefficient of water absorption, \( m_1 \) is the mass of the specimen after full soaking, and \( m_2 \) is the drying mass of the specimen without soaking.

4. The softening coefficient

\[ \eta = \frac{\sigma_{\omega}}{\sigma} \]  

Where, \( \eta \) is the softening coefficient of the specimen, \( \sigma_{\omega} \) is the uniaxial compressive strength (MPa) of the specimen after full water absorption, and \( \sigma \) is the uniaxial compressive strength (MPa) of the specimen under dry condition.

5. The permeability conductivity

\[ k = 2.3 \frac{aL}{At(t_2 - t_1)} \log \frac{H_1}{H_2} \]  

Where, \( k \) is the permeability coefficient of the specimen (mm/s), \( a \) is the sectional area of the variable-head tube (mm\(^2\)), \( L \) is the height of the specimen (mm), \( A \) is the cross-sectional area (mm\(^2\)) of the specimen, \( t_1 \) is the time at the beginning of the test (s), \( t_2 \) is the time at the end of the test (s), \( H_1 \) is the head height at the beginning of the test (mm), and \( H_2 \) is the head height at the end of the test (mm).

4. The analysis of test results

Poor by orthogonal test method, according to the principle, will be the same level of various factors on average, the same factors as the difference between the maximum and minimum values is poor, very poor level changes reflect the factors influence on indexes, the greater the poor show that the large difference of factors at different levels, as the important factor, have obvious effects on the test results. In this experiment, the sensitivity of various factors to the mechanical properties and water rational energy of similar materials was evaluated by range analysis. The effects of various factors on the mechanical properties and water rational energy of similar materials at different levels were studied by averaging the data of mechanical properties and water rational energy of similar materials at the same level.
4.1. The analysis of the influence of compressive strength

The influence of various factors on the compressive strength of similar materials is shown in Figure 3. It can be seen that the sanding ratio has the largest range, and the cement gypsum ratio has the smallest range. The sanding ratio is the main factor affecting the compressive strength, and its sensitivity is as follows: sanding ratio > organosilicon concentration > cement gypsum ratio.

(1) With the increase of the sand-binder ratio, the compressive strength of similar materials decreases. When the sand-binder ratio increases to 8:1, the compressive strength decreases faster. The strength of similar materials is related to the cementing property of the specimen. When the ratio of sand to cement increases, the cementing property of the specimen will become worse and the compressive strength of similar materials will be reduced.

(2) With the increase of cement gypsum ratio, the compressive strength of similar materials increases in a linear proportional relationship, and the overall variation range is small. The cementation strength of cement is better than that of gypsum. With the increase of cement content, the compressive strength of similar materials also increases.

(3) With the increase of organosilicon concentration, the compressive strength of similar materials decreases. When the concentration of organosilicon is less than 21%, the compressive strength decreases rapidly with the increase of organosilicon concentration. When the concentration of organosilicon increases to 21%, the compressive strength decreases gently. From the mechanism analysis, the content of silicone with good waterproof effect increases, which affects the hydration degree of cementing material, weakens the cementing property of similar materials, and thus reduces the compressive strength of similar materials.

4.2. The analysis of influence of tensile strength

The influence of various factors on the tensile strength of similar materials is shown in Figure 4. It can be seen that the range of sand-binder ratio is the largest, the range of cement gypsum ratio is the smallest, sand-binder ratio is the main factor affecting the tensile strength, its sensitivity is: sand-binder ratio > organosilicon concentration > cement gypsum ratio.

(1) With the increase of the sand-binder ratio, the tensile strength of similar materials decreases. In the small stage of sand-binder ratio, when the sand-binder ratio increases, the tensile strength declines rapidly, and the reduction principle of the tensile strength is the same as the reduction of the compressive strength.

(2) With the increase of cement gypsum ratio, the overall tensile strength of similar materials increases, and there is a period of decline from 5:5 to 6:4, which does not affect the overall trend.

(3) With the increase of organosilicon concentration, the tensile strength of similar materials decreases, and its effect is essentially the same as the compressive strength.

4.3. The analysis of the influence of coefficient of water absorption

The influence of various factors on the coefficient of water absorption of similar materials is shown in Figure 5. It can be seen that the range of organosilicon concentration is the largest, and the range of sand-binder ratio is the smallest. The concentration of organosilicon is the main factor affecting water absorption, and its sensitivity is: organosilicon concentration > cement gypsum ratio > sand-binder ratio.
(1) The coefficient of water absorption of similar materials decreases with the increase of the sand-binder ratio. When the sand-binder ratio exceeds 8:1, the water absorption rate decreases rapidly. River sand is a non-hydrophilic material, and cementation material is a hydrophilic material. The increase of sand-binder ratio and the decrease of hydrophilic material result in the decrease of water absorption rate and hydration reaction of similar materials, but the overall effect is not significant.

(2) The water absorption rate of similar materials is negatively correlated with the cement-gypsum ratio, and the water absorption rate decreases first and then increases. The hydrophilicity of gypsum is greater than that of cement. When the cement content of the specimen increases and the gypsum decreases, the water absorption of similar materials will decrease.

(3) The water absorption rate of similar materials is inversely proportional to the concentration of organosilicone. In the stage from 11% to 21%, the water absorption rate drops rapidly. When the concentration of organosilicone increases to 21%, the water absorption rate drops gently and the effect is weakened. Organosilicon waterproof performance is significant, can effectively fill the pores of specimen, prevent water from entering, reduce the water absorption rate of similar materials.

4.4. The influence analysis of softening coefficient

The influence of various factors on the softening coefficient of similar materials is shown in Figure 6. It can be seen that the range of organosilicon concentration is the largest, and the range of sanding ratio is the smallest. The concentration of organosilicon is the main factor affecting the softening coefficient, and its sensitivity is: organosilicon concentration > cement gypsum ratio > sand-binder ratio.

(1) The softening coefficient of similar materials is positively correlated with the change of sand-binder ratio. With the increase of sand-binder ratio, the growth rate of softening coefficient becomes smaller and smaller. River sand is a hydrophilic material, cementing materials for hydrophilic materials, the full water compressive strength test, the more hydrophilic material, reduce the compressive strength of will, the more the softening coefficient of similar materials will decrease with the increase in the number of hydrophilic material, when sand-binder ratio increases, hydrophilic material decreases, and the softening coefficient of similar material increase.

(2) The softening coefficient of similar materials increases with the increase of cement gypsum ratio. Cement has a high water resistance, which will reduce the water absorption rate and reduce the influence of water on the strength of test pieces. Therefore, when the cement content increases, the softening coefficient of similar materials will increase.

(3) The concentration of organosilicon plays a leading role in the change of the softening coefficient of similar materials. The concentration of organosilicon has a significant effect on improving the softening coefficient in the range of 11% to 16%. However, with the constant increase of the
concentration of organosilicon, the effect on improving the softening coefficient gradually weakens. Due to the significant waterproof property of organosilicon, the contact between the material and water can be reduced, so when the concentration of organosilicon increases, the softening coefficient of similar materials will be increased.

4.5. The analysis of hydraulic conductivity
The influence of various factors on the permeability coefficient of similar materials is shown in Figure 7. It can be seen that the range of organosilicon concentration is the largest, and the range of cement-gypsum ratio is the smallest. The concentration of organosilicon is the main factor affecting the permeability coefficient, and its sensitivity is: organosilicon concentration > sand-binder ratio > cement gypsum ratio.

Figure 7. sensitivity analysis of permeability coefficient

(1) The permeability coefficient of similar materials increases with the increase of the sand-binder ratio. The permeability is mainly related to the porosity and compactness of the specimens. When the sand-binder ratio increases, the porosity will be increased and the compactness will be reduced, leading to an increase in the permeability coefficient of similar materials.

(2) The permeability coefficient of similar materials decreases with the increase of cement gypsum ratio, but the influence of cement gypsum ratio on the permeability coefficient is small.

(3) The increase of organosilicon concentration will rapidly reduce the permeability coefficient of similar materials, which is most significant when the concentration of organosilicon increases from 11% to 16%; when the concentration of organosilicon increases to 21%, the influence of the increase of organosilicon concentration on the permeability coefficient decreases significantly. Organosilicon has a significant waterproof effect. By closing the pores of specimens, water can be prevented from entering, thus reducing effective water passage and thereby reducing permeability.

According to the result of orthogonal experiment, the different proportion of similar material physical parameters with differences, has a wide distribution, the influence range of compressive strength is 0.73~2.38 (MPa) and the influence range of tensile strength is 0.074~0.163 (MPa), the influence of moisture content range of 4.34% ~ 12.36%, the softening coefficient affect the range of 64.16% ~ 86.38%, the permeability coefficient affect the range of 0.35 ~ 6.79 (10-6 cm/s), you can simulate much of the soil physical model test requirements. Sand-binder ratio has a great influence on the physical parameters of similar materials, which is the main factor affecting the compressive strength and tensile strength. The concentration of organosilicate has a great influence on the hydrological parameters of similar materials, and is the main factor for the variation of parameters such as water content, softening coefficient and permeability coefficient. It can be seen that organosilicates can effectively play a waterproof effect, providing raw materials for the production of fluid-solid coupling similar materials.

5. Conclusion
Based on wading model experiment of similar material simulation of water-resisting layer development as the goal, on the basis of thorough investigation, according to the principle of orthogonal test design to develop a test plan, consider sand-binder ratio, cement gypsum ratio, concentration of organosilicon,
three factors and four levels, each factor standard cylindrical specimen preparation into different ratio of similar materials, and for each test specimen under the mechanical properties and water rationality can be determined.

(1) By adjusting the distribution ratio of each group, a combination of different mechanical and water rational energies can be obtained in a relatively wide range, representing different rock strata, especially the low permeability and good non-hydrophilicity of organosilicon involved, which can effectively realize the simulation of water-proof layer in the wading-model test.

(2) The new solid-flow coupling simulation material developed in this paper can provide a new scheme choice for the model test of wading problems such as mining under confined water, water conservation mining and construction in water-rich areas, and has high application value.

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