Orthogonal Testing on Ratio of Physical Simulation Material Similar to Sandstone

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Abstract. In this paper, the ratio of physical simulation material similar to sandstone was studied through orthogonal testing, which was made up of five levels and four factors (sand-cement ratio, cement ratio, molding loading rate and molding pressure). Physical and mechanical parameters including density, uniaxial compressive strength, elastic modulus and tensile strength of the physical simulation material were obtained by the testing. The key influencing factors and variation rules of physical and mechanical properties of the material were analyzed by range analysis method. The results show that the factors affecting density from large to small are: molding pressure, sand-cement ratio, cement ratio and molding loading rate. The density increases with the increment of both molding pressure and sand-cement ratio. However, the density value decreases slowly with the increment of loading rate, and it does not change significantly with the increment of cement ratio. Uniaxial compressive strength (UCS) is influenced by factors including sand-cement ratio, molding pressure, cement ratio and loading rate. The UCS decreases with the increment of both sand-cement ratio and loading rate, and increase with the increment of cement ratio and molding pressure. Both elastic modulus and tensile strength are influenced by sand-cement ratio, cement ratio, molding pressure and loading rate, too. The elastic modulus and tensile strength decrease with the increment of sand-cement ratio and loading rate, and increase with the increment of cement ratio. Meanwhile, they increase slowly with the increment of molding pressure. The linear regression equations between all considering factors are obtained through the testing, which provide scientific basis for the reasonable selection of the material ratio in the physical simulation experiment.

1. Introduction

Physical simulation experiment is based on an experimental model made of physical simulation material with similar physical and mechanical properties as the prototype, which is scaled down to a certain scale. Various of excavation are carried out on the model, so the possible mechanical phenomena and pressure distribution rules of the prototype can be deduced. The selection of simulation material and the determination of ratio, as the basic work for the physical simulation experiment, are also the keys to the correct simulation[1-2].

In recent years, abundant scholars have done lots of research on the physical simulation material ratio, some significant achievements have been achieved. Ma Fangping developed a specific material composed of magnetite concentrate powder, river sand, gypsum or cement, water and additives[3].
Zuo Baocheng made the simulation of limestone with simulation material composed of quartzs, gypsum and cement, studied the aggregate-cement ratio, the proportion of cement material in cement, and the influence of different curing methods on the strength of the specimen[4]. Through a large number of ratio experiments, Wang Hanpeng developed a specific material made of iron powder, barite powder and quartz sand as aggregate, rosin and alcohol solution as cement, and gypsum as regulator[5]. Zhang Qiangyong developed a new kind of cementitious geotechnical simulation material, which was made by mixing and compacting iron ore powder, barite powder, quartz sand, gypsum powder, rosin alcohol solution[6]. By using iron powder, barite powder, quartz sand, binder and gypsum as raw material, Dong Jinyu obtained the qualitative influence rules of various factors on the parameters through range analysis method[7]. Shi Xiaomeng studied several factors including cement, gypsum, quartz sand and barite powder, analyzed the sensitivity of these factors to the material performance by range analysis method. In the end, he obtained the quantitative relationship between the UCS and these factors by regression analysis[8]. In addition, Li Baofu, Xu Zhao and Liu Liangliang studied the ratio of the simulation material by orthogonal design[9-15]. However, in most of these simulation testings, the material and proportions were only selected for specific experiments based on experience, and there were no quantitative rules available for reference.

In this paper, the orthogonal testing was used to study the ratio of simulation material composed of river sand as aggregate, gypsum and calcium carbonate as cementing agent and water as additive. Physical and mechanical parameters, such as density, the UCS, elastic modulus and tensile strength of simulation material with different processing technology and proportions, were obtained by the related testing. The key influencing factors of physical and mechanical properties of the material similar to the sandstone, and the variation regularity of physical and mechanical properties under the above-mentioned influencing factors were analyzed by the range analysis method. The results provided the scientific basis for the reasonable selection of physical simulation material, and further demonstrated the authenticity and reliability of experimental results.

2. Orthogonal testing Design

2.1. Selection of raw material
River sand with particle size of 30 mesh sieve was selected as aggregate in this testings. The river sand is natural and its color is grayish yellow. Gypsum and calcium carbonate were selected as cement. Gypsum is a kind of industrial and building material, which is mainly composed of calcium sulfate hydrate, and calcium carbonate is a kind of material that can effectively alleviate the rate of condensation when gypsum is palced in water. Therefore, gypsum and calcium carbonate were combined as cement, and water was used as additive for preparation of simulation material.

2.2. Design scheme
There are many factors that affect the physical and mechanical properties of simulation material. In the testing design, the influence of four main factors (represented by A, B, C and D respectively) on the physical and mechanical properties of simulation material similar to sandstone was studied: sand-cement ratio, cement ratio, molding loading rate and molding pressure. These four factors could be taken to the corresponding level, and form many combinations. Taking time consumption and data processing into account, five levels were chosen. In the orthogonal testing, the collocation of each factor and each level was balanced. Without affecting the testing results, the number of experiments should be reduced as much as possible. This experiment was of four factors and five levels, and a L25 (56) orthogonal table was selected to arrange the experiment. In the orthogonal table, the occurrence frequency of different numbers in each column was equal. According to the collocation of factors and level numbers, a total of 25 groups of experiments were arranged, as shown in table 1.
Table 1. Schemes of orthogonal testing design.

| Test | A  | B  | C (N/s) | D (kN) |
|------|----|----|---------|--------|
| 1    | 5:1| 1:9| 50      | 5      |
| 2    | 5:1| 2:8| 100     | 10     |
| 3    | 5:1| 3:7| 150     | 15     |
| 4    | 5:1| 4:6| 200     | 20     |
| 5    | 5:1| 5:5| 250     | 25     |
| 6    | 6:1| 1:9| 150     | 10     |
| 7    | 6:1| 2:8| 200     | 15     |
| 8    | 6:1| 3:7| 250     | 20     |
| 9    | 6:1| 4:6| 50      | 25     |
| 10   | 6:1| 5:5| 100     | 5      |
| 11   | 7:1| 1:9| 250     | 15     |
| 12   | 7:1| 2:8| 50      | 20     |
| 13   | 7:1| 3:7| 100     | 25     |
| 14   | 7:1| 4:6| 150     | 5      |
| 15   | 7:1| 5:5| 200     | 10     |
| 16   | 8:1| 1:9| 100     | 20     |
| 17   | 8:1| 2:8| 150     | 25     |
| 18   | 8:1| 3:7| 200     | 5      |
| 19   | 8:1| 4:6| 250     | 10     |
| 20   | 8:1| 5:5| 50      | 15     |
| 21   | 9:1| 1:9| 200     | 25     |
| 22   | 9:1| 2:8| 250     | 5      |
| 23   | 9:1| 3:7| 50      | 10     |
| 24   | 9:1| 4:6| 100     | 15     |
| 25   | 9:1| 5:5| 150     | 20     |

2.3. Preparation of specimens

25 groups of uniaxial compression test and Brazilian splitting test were arranged in this experiment. Among them, the specimens in the uniaxial compression test were cylindrical, with a diameter of 50mm and a height of 100 mm, while the specimens in the Brazilian splitting test were disc-shaped, with a diameter of 50 mm and a thickness of 25 mm. In order to ensure the reliability of the results, six specimens were arranged for each test group. In this paper, a cylinder stainless steel mold with a diameter of 50mm and a height of 170 mm was used to make specimens. When making specimens, firstly, the corresponding amount of material was added in the mold according to the designed scheme, then it was mixed and stirred evenly. The stirred material was loaded into the cylinder stainless steel mold and placed on the platen of electro-hydraulic servo universal testing machine, then the parameters were set on the software. Demould while the molding pressure reached the set value. The finished specimens were shown in figure 1.
3. **Testing of physical and mechanical parameters.**

After 3 days of indoor curing at 20 °C, the size and weight of the specimens were measured by vernier caliper and electronic scale, then the density was calculated. The MTS C43.504 electronic universal testing machine was used to test the UCS and tensile strength of simulation material, then the parameters including stress-strain curve, the UCS, elastic modulus, tensile strength and tension-compression ratio etc. could be obtained.

In the process of testing, considering the low strength of simulation material, the speed control strategy was adopted. The test speed was set as 1mm/min, the preload was 10 N, and the fracture sensitivity of specimens was 30%. When testing the UCS, the failure forms of specimens were mainly X conjugated incline plane shear failure, single incline plane shear failure and tensile failure (see figure 2), which was similar to the failure mode of rock under uniaxial compression. During the splitting test, the initial failure location of all specimens was in the center of specimens, that is, the diameter of the disc-shaped specimens. The results of the orthogonal test were shown in table 2.

As shown in table 3, the results of the orthogonal test showed that the density of simulation material similar to sandstone was 1.58~1.92 g/cm³, the UCS was 0.18~1.32 MPa, the elastic modulus was 67.29~255.26 MPa, and the tensile strength was 0.017~0.125 MPa. The tension-compression ratio was 0.09~0.12, and the tension-compression ratio of rock was about 0.1. Therefore, it could be concluded that the properties of simulation material and rock were essentially similar in compressive and tensile strength.

(a)X conjugated incline plane shear failure. (b)Single incline plane shear failure. (c)Tensile failure.

**Figure 2. Typical failure modes of specimens in uniaxial compression test.**
Table 2. Results of orthogonal test.

| Test | Density / g/cm³ | Uniaxial compressive strength / MPa | Elastic modulus / MPa | Tensile strength / MPa | Tension-compression ratio |
|------|-----------------|-------------------------------------|-----------------------|------------------------|---------------------------|
| 1    | 1.74            | 1.08                               | 75.79                 | 0.092                  | 0.09                      |
| 2    | 1.76            | 1.15                               | 109.51                | 0.123                  | 0.11                      |
| 3    | 1.79            | 1.22                               | 129.2                 | 0.119                  | 0.10                      |
| 4    | 1.82            | 1.28                               | 181.15                | 0.125                  | 0.10                      |
| 5    | 1.92            | 1.32                               | 255.25                | 0.120                  | 0.09                      |
| 6    | 1.73            | 0.92                               | 150.18                | 0.081                  | 0.09                      |
| 7    | 1.76            | 0.95                               | 105.2                 | 0.089                  | 0.09                      |
| 8    | 1.79            | 1.02                               | 91.52                 | 0.091                  | 0.09                      |
| 9    | 1.89            | 1.21                               | 94.78                 | 0.123                  | 0.10                      |
| 10   | 1.70            | 1.12                               | 129.96                | 0.108                  | 0.10                      |
| 11   | 1.75            | 0.62                               | 154.05                | 0.058                  | 0.09                      |
| 12   | 1.77            | 0.71                               | 115.102               | 0.079                  | 0.11                      |
| 13   | 1.88            | 1.08                               | 67.29                 | 0.102                  | 0.09                      |
| 14   | 1.67            | 0.85                               | 93.48                 | 0.091                  | 0.11                      |
| 15   | 1.70            | 0.88                               | 92.64                 | 0.082                  | 0.09                      |
| 16   | 1.76            | 0.43                               | 114.57                | 0.040                  | 0.09                      |
| 17   | 1.86            | 0.88                               | 139.63                | 0.081                  | 0.09                      |
| 18   | 1.63            | 0.51                               | 101.52                | 0.048                  | 0.09                      |
| 19   | 1.69            | 0.54                               | 87.66                 | 0.051                  | 0.09                      |
| 20   | 1.73            | 0.62                               | 68.36                 | 0.065                  | 0.10                      |
| 21   | 1.83            | 0.18                               | 93.63                 | 0.017                  | 0.09                      |
| 22   | 1.58            | 0.21                               | 86.73                 | 0.019                  | 0.09                      |
| 23   | 1.67            | 0.25                               | 110.65                | 0.022                  | 0.09                      |
| 24   | 1.72            | 0.31                               | 89.41                 | 0.038                  | 0.12                      |
| 25   | 1.74            | 0.38                               | 72.8                  | 0.041                  | 0.11                      |

4. Result Analysis and Discussion

4.1. Range analysis

Range analysis is to analyze problems according to the range of each factor. Range R is obtained by subtracting the minimum value from the maximum value of the average of each level. Its value can directly reflect the influence of different levels of each factor on the experimental results. The larger range indicates the greater difference between different levels, and hence it is the key influencing factor and has obvious impact on the final results. The range analysis method was adopted to analyze the influence of various factors on the physical and mechanical properties of simulation material. As shown in table, $K_1$, $K_2$, $K_3$, $K_4$ and $K_5$ respectively represent the sum of test results corresponding to the same level (density, the UCS and elastic modulus) of four factors A, B, C and D, $k_1$, $k_2$, $k_3$, $k_4$ and $k_5$ respectively represented the mean values of each level, and R was the range of $K_1$, $K_2$, $K_3$, $K_4$ and $K_5$.

The range analysis concerning the influencing factors of density of the specimens was carried out, and the results were shown in table 3. It can be seen that the range of factor D was the largest, the range of factor A was the second largest, and the factor C and factor B was the smallest, indicating that the order of influence of each factor on density was D>A>C>B. In order to analyze the influence of various factors on the density more directly, a diagram of the influence of various factors on the density was drawn according to table 3. As can be seen from the figure 3, the density of the specimens increased with the growth of molding pressure and sand-cement ratio, it decreased slowly with the increase of molding loading rate, while it did not change significantly with the increase of cement ratio.
The range analysis of the influencing factors of the UCS was carried out, and the results were shown in table 4. It can be seen that the range of factor A was the largest, the range of factor D was the second largest, the range of factor B and factor C was the smallest. The order of influence of each factor on the UCS was A>D>B>C. A diagram of the influences from various factors on the UCS was drawn according to table 4. As can be seen from the figure 4, the UCS of the specimens decreased with the rise of sand-cement ratio, it increased with the growth of cement ratio, it decreased with the increase of molding loading rate, and it increased with the rise of molding pressure.

Table 3. Range analysis of density g/cm³.

| Item | A   | B   | C   | D   |
|------|-----|-----|-----|-----|
| K₁   | 9.03| 8.81| 8.8 | 8.32|
| K₂   | 8.87| 8.73| 8.82| 8.55|
| K₃   | 8.77| 8.76| 8.79| 8.75|
| K₄   | 8.67| 8.79| 8.74| 8.88|
| K₅   | 8.54| 8.79| 8.73| 9.38|
| k₁   | 1.806| 1.762| 1.760| 1.664|
| k₂   | 1.774| 1.746| 1.764| 1.710|
| k₃   | 1.754| 1.752| 1.758| 1.750|
| k₄   | 1.734| 1.758| 1.748| 1.776|
| k₅   | 1.708| 1.758| 1.746| 1.876|
| R    | 0.098| 0.016| 0.018| 0.212|

Important order
D–A–C–B

Figure 3. Variation curve of the factors affecting density

Table 4. Range analysis of uniaxial compressive strength MPa.

| Item | A   | B   | C   | D   |
|------|-----|-----|-----|-----|
| K₁   | 6.05| 3.23| 4.25| 3.3 |
| K₂   | 5.22| 3.9 | 4.09| 3.56|
| K₃   | 4.14| 4.066| 3.845| 4.2 |
| K₄   | 2.95| 4.4 | 3.79| 4.81|
| K₅   | 1.326| 4.8  | 3.71| 5.465|
| k₁   | 1.21| 0.646| 0.85 | 0.66|
| k₂   | 1.044| 0.78 | 0.818| 0.712|
| k₃   | 0.828| 0.8132| 0.769| 0.84|
| k₄   | 0.59| 0.88 | 0.758| 0.962|
| k₅   | 0.2652| 0.96  | 0.742| 1.093|
| R    | 0.9448| 0.314| 0.076| 0.433|

Important order
A–D–B–C
The range analysis of the influencing factors of elastic modulus of similar specimens was carried out as well, and the results were shown in Table 5. It can be seen that the range of factor A was the largest, the range of factor B was the second largest, and the range of factor D and factor C was the smallest. The order of influence of each factor on elastic modulus was A>B>D>C. A diagram of the influence of various factors on the elastic modulus was drawn according to Table 5. As can be seen from the figure 5, the elastic modulus of the specimens decreased with the increase of sand-cement ratio, it increased with the rise of cement ratio, it decreased with the growth of molding loading rate, and it increased with the rise of molding pressure.

The range analysis of the influencing factors of tensile strength was also carried out, and the results were shown in Table 6. It can be seen that the range of factor A was the largest, the range of factor B was the second largest, while the range of factor D and factor C was the smallest. The order of influence on tensile strength was A>B>D>C. A diagram of the influence of various factors on the tensile strength was drawn according to Table 6. As can be seen from the figure 6, the tensile strength decreased with the increase of sand-cement ratio, it increased with the growth of cement ratio, it decreased with the rise of molding loading rate, and it increased slowly with the increase of molding pressure.

| Item | A  | B  | C  | D  |
|------|----|----|----|----|
| $K_1$ | 750.9 | 408.74 | 591.77 | 525.76 |
| $K_2$ | 575.51 | 450.59 | 578.73 | 537.74 |
| $K_3$ | 507.61 | 506.92 | 564.98 | 508.77 |
| $K_4$ | 447.03 | 622.52 | 553.97 | 519.72 |
| $K_5$ | 429.95 | 722.23 | 521.55 | 619.01 |
| $k_1$ | 150.18 | 81.748 | 118.354 | 105.152 |
| $k_2$ | 115.102 | 90.118 | 115.746 | 107.548 |
| $k_3$ | 101.522 | 101.384 | 112.996 | 101.754 |
| $k_4$ | 89.406 | 124.504 | 110.794 | 103.944 |
| $k_5$ | 85.99 | 144.446 | 104.31 | 123.802 |
| $R$ | 64.19 | 62.698 | 14.044 | 20.048 |

Important order A–B–D–C
4.2. **Multiple linear regression analysis**

From figure 3 to figure 6, it can be seen that density, the UCS, elastic modulus and tensile strength have an obvious linear relationship with sand-cement ratio, cement ratio, loading rate as well as molding pressure. Density, the UCS, elastic modulus, tensile strength, sand-cement ratio,
cement ratio, loading rate and molding pressure of specimens were set as follows: \( y_\rho, y_\sigma, y_E, y_\tau, x_1, x_2, x_3, x_4 \). Then the model of simulation material similar to sandstone could be established as follows:

\[
\begin{align*}
y_\rho &= a_0 + a_1 x_1 + a_2 x_2 + a_3 x_3 + a_4 x_4 \\
y_\sigma &= b_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 + b_4 x_4 \\
y_E &= c_0 + c_1 x_1 + c_2 x_2 + c_3 x_3 + c_4 x_4 \\
y_\tau &= d_0 + d_1 x_1 + d_2 x_2 + d_3 x_3 + d_4 x_4
\end{align*}
\] (1)

A multiple linear regression analysis was performed on the experimental data by SPSS, and the following results were obtained:

\[
\begin{align*}
y_\rho &= 1.785 - 0.0236 x_1 + 0.0035 x_2 - 0.000088 x_3 + 0.0098 x_4 \\
y_\sigma &= 2.247 - 0.234 x_1 + 0.2048 x_2 - 0.00024 x_3 + 0.0075 x_4 \\
y_E &= 158.68 - 15.4 x_1 + 70.8 x_2 - 0.4808 x_3 + 0.6739 x_4 \\
y_\tau &= 0.214 - 0.022 x_1 + 0.0238 x_2 - 0.000054 x_3 + 0.00075 x_4
\end{align*}
\] (2)

The coefficient correlation of regression equation were 0.9689, 0.9631, 0.9560, that was, the regression equation (2) has relatively strong reliability.

In order to determine the parameters of sand-cement ratio, cement ratio, loading rate and molding pressure according to density, the UCS, elastic modulus, and tensile strength, equation (2) could be expressed as empirical equation as follows:

\[
\begin{align*}
x_1 &= 5.66 + 2.475 y_\rho - 7.718 y_\sigma + 0.00045 y_E + 34.304 y_\tau \\
x_2 &= -0.70121 - 1.02469 y_\rho + 1.549 y_\sigma + 0.0149 y_E - 15.49 y_\tau \\
x_3 &= 213.976 - 79.264 y_\rho + 3144.563 y_\sigma + 0.1215 y_E - 33446.7 y_\tau \\
x_4 &= -171.385 + 107.6545 y_\rho - 49.156 y_\sigma - 0.00532 y_E + 422.986 y_\tau
\end{align*}
\] (3)

When determining the material ratio in the physical simulation experiment, based on the density, the UCS, elastic modulus and tensile strength required by the experiment, by using the empirical formula (3), the sand-cement ratio, cement agent ratio, loading rate and molding pressure values of simulation material could be calculated.

5. Conclusion

The density of simulation material similar to sandstone was 1.58~1.92 g/cm³, the UCS was 0.18~1.32 MPa, the elastic modulus was 67.29~255.26 MPa, the tensile strength was 0.017~0.125 MPa, and the tensile-compression ratio of simulation material was 0.09~0.12, they were largely qualified concerning the requirements of simulation material.

The range analysis indicated that the critical factor affecting the density of physical simulation material to sandstone was molding pressure, followed by the sand-cement ratio, while the cement ratio and the molding loading rate had little influence. The density increased with the increment of both molding pressure and sand-cement ratio. However, the density value decreased slowly with the increment of molding loading rate, and it did not change significantly with the increment of cement ratio. The critical factor affecting the UCS was the sand-cement ratio, followed by molding pressure, while the cement ratio and molding loading rate had little influence. The UCS would decrease with the increment of both sand-cement ratio and molding loading rate, and increase with the increment of cement ratio and molding pressure. The critical factor affecting elastic modulus and tensile strength were sand-cement ratio, followed by cement ratio, while molding pressure and the molding loading rate had little influence. The elastic modulus and tensile strength would decrease with the increment of
sand-cement ratio and loading rate, and increase with the increment of cement ratio. Meanwhile, they increased slowly with the increment of molding pressure.

The regression equation between sand-cement ratio, cement ratio, molding loading rate and molding pressure and density, the UCS and tensile strength was obtained in the paper. There was an effective linear regression relationship between density, the UCS, elastic modulus, tensile strength and sand-cement ratio, cement ratio, molding loading rate, molding pressure.

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