Rock and Soil Mechanics

Volume 41 | Issue 8 Article 6

1-22-2021

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Custom Citation

SONG Yu, LIU Bao-guo, LIU Hao, SUN Jing-lai, YU Ming-yuan, REN Da-rui, . Orthogonal test method for determination of the proportion of rock-like material based on properties of deformation and brittleness[J]. Rock and Soil Mechanics, 2020, 41(8): 2675-2684.

Rock and Soil Mechanics 2020 41(8): 2675−2684 ISSN 1000−7598
https: //doi.org/10.16285/j.rsm.2019.6711 rocksoilmech.researchcommons.org/journal

Orthogonal test method for determination of the proportion of rock-like material based on properties of deformation and brittleness

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Abstract: A systematic process for obtaining the proportion of the rock-like material with properties of deformation and brittleness similar to the prototype sandstone using orthogonal test has been proposed. The indexes of E/σ_c and σ_c/σ_t have been introduced to quantitatively represent the properties of deformation and brittleness, respectively. The rock-like material is composed with cement and microsilica as the binder material and quartz sand as the aggregate. First, orthogonal tests have been performed, and the various indexes of E/σ_c and σ_c/σ_t with different levels of water-binder, sand-binder and microsilica-cement ratio have been divided by statistical data of natural sandstone. Second, range analysis has been applied to describe the trend of the two indexes with different levels of these three factors. Third, multivariate polynomial equations have been used to obtain the proper proportion of the rock-like material with properties of deformation and brittleness similar to the prototype sandstone. The specimens with the determined proportion are found to be within the allowable error margin compared with the prototype sandstone, and properties of deformation and brittleness of the proposed rock-like material are consistent with the sandstone. Therefore, the newly proposed rock-like material can substitute rock blocks in the following laboratory test.

Keywords: rock-like material; orthogonal design; deformation properties; brittleness

1 Introduction

The physical and mechanical properties of natural rock specimens are different. Even though the specimens are taken from the same rock in the same area, the shape and distribution characteristics of the internal cracks cannot be uniform. Therefore, the laboratory tests related to the hydraulic and mechanical properties of natural rock bodies are not repeatable, and the test results are very discrete. To investigate the inclination angle of the structural surface *i* on the mechanical properties of rock mass, specimens made of plaster of paris cast with irregular surfaces were used in laboratory shear tests by Patton[1], which ensured the uniformity of the specimen structure. Since then, different rock-like materials have been made by scholars to simulate natural rocks for laboratory tests. Rock-like material is an artificial material with physical and mechanical properties similar to those of natural rock and it has stable material properties and high degree of homogeneity, which can be widely used in laboratory tests for investigations of hydraulic and mechanical properties of rocks and fractured rock masses.

Stimpson[2] summarized rock-like materials used in previous studies, and divided common rock-like materials into two categories: non-granular materials[3–5] and granular materials. Granular rock materials mainly include mortar materials using cement or gypsum as binder materials. As a friction material, the mortar material is proved to have mechanical properties similar to some rocks, such as sandstone. Therefore, to investigate the development of internal cracks and failure strength and deformation of rocks under load, granular rock materials instead of natural rock blocks have been widely used in these tests. Li et al.[6], Zhang et al.[7], Pu et al.[8], Wong et al.[9–10] and Li et al.[11] prepared different kinds of mortar-like rock materials to simulate rock materials, respectively. The crack surfaces with different distribution characteristics were preset in these materials to study the crack development process under load and the damage pattern of the specimen. In addition, granular rock-like materials are also widely used to make rock-like specimens with complex joints or joint networks. Tian et al.[12] poured the mortar material into the joint network model generated by 3D printing, and produced rock-like specimens with a complex joint network. Liu et al.[13–14] prepared mortar-like rock materials and made specimens with certain structural surfaces using silicone molds for shear tests.

Although rock-like materials are widely used in the study of the hydraulic characteristics and mechanical properties of jointed and fractured rock masses, simple methods are used for preparation of rock-like materials and there are limited studies focusing on whether its strength, deformation properties and parameter characteristics are similar to those of natural rocks. Some rock materials have insufficient brittleness, which leads to plastic failure of materials under load, and it is far from the brittle failure mode of natural rock. In addition,

Received: 9 October 2019 Revised: 13 January 2020
This work was supported by the Fundamental Research Funds for the Central Universities (2019YJS145).
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there are large differences in the strength and deformation parameters between rock-like materials and natural rock materials in some previous studies. The tensile strength, compressive strength and elastic modulus of some materials are one to two orders of magnitude lower than that of rock materials, which results in low accuracy in the quantitative description of parameters for rock-like materials in rock mechanics tests. This can hinder the application and promotion of rock-like materials in laboratory tests.

The strength, deformation parameters and brittleness characteristics of rock-like materials should meet the requirements of general sandstone, problems such as insufficient strength, large difference in the elastic modulus value, or insufficient brittleness which affect the applicability of rock-like materials should also be avoided. Thus, the strength and deformation parameters of rock-like materials should first meet the statistical range of corresponding parameters of natural sandstone.

Deere et al.[15] calculated the range of the ratio of tangent elastic modulus E to uniaxial compressive strength σ_c at 50% compressive peak strength of different types of sedimentary rocks and proposed a classification standard for sedimentary rocks based on E/σ_c. Stimpson[2] used this statistical range as a reference, and determined the values of E/σ_c for many kinds of granular or non-granular materials used as rock-like materials. Then the range that conforms to statistical range of this deformation index can be used to simulate rock-like materials. Based on the statistical index proposed by Deere et al.[15], Tatone[16] introduced the tensile-compression strength ratio σ_c/σ_t as a brittleness index to determine the suitability of rock-like materials. He proposed that these two indexes used to characterize deformation and brittleness of rock-like materials must meet the statistical range of the corresponding indexes of natural rocks. Then it was indicated that the parameters of this rock-like material were similar to that of the corresponding rock, which can be used to replace the rock in tests for measurement of mechanical properties. This method clarified the criteria for the feasibility of replacing natural rocks with rock-like materials. Liu et al.[13] used the method proposed by Tatone[16] to produce mortar-like rock materials using E/σ_c and σ_c/σ_t as criteria and the mortar that meets the corresponding parameter range of natural rocks can be treated as a rock-like material.

In order to prepare rock-like materials to replace selected natural rocks in tests, it is necessary to quantitatively determine the optimal proportions of materials to meet the basic strength and deformation characteristics of the selected rocks. Li et al.[17] and Zhang et al.[18] obtained the response law of the proportion of each raw material in the mortar mixture to the basic physical and mechanical properties through orthogonal tests. The optimal proportion was found, and materials similar to specific rock properties were prepared for further investigations. Moreover, Shi et al.[19–20] and Chu et al.[21] used multivariate linear fittings based on orthogonal tests to obtain the optimal proportions of materials. These studies have improved the accuracy of testing with rock-like materials instead of natural rocks to a certain extent.

Based on previous research on rock-like materials by many scholars, sandstone is selected as the prototype in this study to investigate method of preparing the rock-like material with similar strength and deformation characteristics by analyzing degeneration and brittleness characteristics of rock-like materials. The cement with microsilica is used as the rock-like material to simulate specific sandstone, and the proportions of different components of the rock-like material are designed by the orthogonal method. Using the deformation index E/σ_c and the brittleness index σ_c/σ_t as the parameters, the proportions of the rock-like material with the property that is within ranges of statistical parameters E/σ_c and σ_c/σ_t of the sandstone are obtained. The relationships between E/σ_c, σ_c/σ_t, and the proportioning factors of the rock-like material are calculated by multivariate polynomial equations based on the range analysis. Then the desired proportions of the rock-like material can be generated using E/σ_c and σ_c/σ_t of the selected natural sandstone. The brittleness and deformation characteristics, and mechanical parameters of the rock-like material prepared by this method are consistent with the selected rock, which ensures the feasibility and accuracy of the rock-like material in the laboratory test. Meanwhile, the orthogonal test proportions which initially meet the requirement of the deformation and brittleness indexes of sandstone are used to solve the multivariate polynomials, which reduces the times of material preparations, and improves the preparation efficiency.

2 Test design

2.1 Raw material selection

The rock selected in this study is medium-grained sandstone (grain size 0.25–0.5 mm) produced in Hebei Province. The composition of the rock debris is mainly quartz, and the composition of the cement is mainly carbonate, which is the younger sandstone after the Mesozoic. This sandstone is a medium-strength rock and basic physical and mechanical parameters obtained from the natural density test, uniaxial compression test and Brazilian splitting test are shown in Table 1.

Table 1 Basic parameters of the prototype sandstone

ρ_0 / (g • cm^{-3})	σ_c / MPa	σ_t / MPa	E / GPa	μ
2.16	51.56	3.28	16.34	0.31

Based on the material composition and mechanical parameters of the selected natural rock, cement mortar is used as the basic material to make rock-like materials in this study, following the preparation steps of reactive powder concrete (RPC)[22]. Microsilica is added in the cement mortar material as an active powder material to further reduce the porosity and increase the strength of the material. Moreover, the mechanical properties of the rock-like material can be adjusted and improved.

As the main raw materials, the relative amount of cement and quartz sand directly affects the internal cohesion and granular friction of the material, which can be adjusted to obtain the friction properties similar to natural rocks. In addition, the dilatancy effect usually appears in granular materials, and the addition of aggregate can make the material exhibit a dilatancy effect similar to natural rocks. Microsilica can be well filled in the pores between cement particles after being mixed with cement mortar, which makes the structure denser. Moreover, it can be also combined with free $Ca(OH)_2$ to form a stable C-S-H gel, which further improves the compactness and strength of the structure[22–23]. The fineness of microsilica is about 100 times that of cement, and it has strong water absorption. Therefore, when microsilica is added to the cement mortar material, it is necessary to increase the water amount in order to ensure the fluidity of the mixture.

According to the above requirements, the P.O 42.5 cement and microsilica are selected as the binder materials, and quartz sand with the granular size close to sandstone is selected as aggregate to make the rock-like material. The parameters of selected raw materials are shown in Table 2.

Table 2 Parameters of raw materials

Material	Picture	Brand	Type	Granular size / μm	Ingredient / %		Density / (g • cm^{-3})
					CaO	SiO_2	
Cement		Hebei Jun	P.O. 42.5	30.0–60.0	64–67	20–23	3.10
Microsilica		Shandong Sepsen	No. 95	0.1–5.0	—	>95	2.05
Quartz sand		Sinoma	ISO standard	250.0–650.0	—	>99	1.42
Water-reducing agent		Hebei Sika	Sika 3301		—	—	—
Defoaming agent		Guangdong Zilibon	B-49		—	—	—

2.2 Orthogonal design

The mass ratio of water to binder materials (water-binder ratio), the mass ratio of quartz sand aggregate to binder materials (sand-binder ratio), and the mass ratio of microsilica in the binder materials to cement (microsilica-cement ratio) are used as the three factors in the orthogonal test. Five levels are set for each factor, and the interaction between factors is not considered to simplify the result analysis. After trial tests, level settings for specific factors are shown in Table 3.

Table 3 Orthogonal design levels of the rock-like material

Level	Water-binder ratio	Sand-binder ratio	Microsilica-cement ratio
1	0.25	0.5	0.0
2	0.30	1.0	0.1
3	0.35	1.5	0.2
4	0.40	2.0	0.3
5	0.45	2.5	0.4

Note: The content of water-reducing agent is 1% of the mass of the binder material; and the content of defoaming agent is 0.1% of the mass of the binder material. There is no corresponding research on these two factors in this test.

When using the orthogonal table to arrange the test, it is necessary to select the orthogonal table according to the level and number of factors. The orthogonal table with the same number of levels and the column number no less than factors number should be selected as a reference. Therefore, the orthogonal table corresponding to the 6-factor 5-level orthogonal design scheme L25 (5^6) is used in this test. The factor levels in the first 3 columns of the table are selected and combined to design the 3-factor and 5-level orthogonal test. The orthogonal test schemes are shown in Table 4.

2.3 Basic physical and mechanical properties test

The materials of the orthogonal test group are mixed in the mortar mixer (see Fig.1(a)) to make cube specimens with dimensions of 15 cm. The specimens are vibrated on the vibrating table for 1 to 3 minutes, until no bubbles are discharged from the surfaces of the specimens and the surfaces of the specimens are slightly slurried. Vibration can reduce the bubbles inside the mold and form a specimen with good internal granular distribution and high isotropy. The

Table 4 Orthogonal test schemes of the rock-like material

Group number	Water-binder ratio	Sand-binder ratio	Microsilica-cement ratio
1	0.25	0.5	0.0
2	0.25	1.0	0.1
3	0.25	1.5	0.2
4	0.25	2.0	0.3
5	0.25	2.5	0.4
6	0.30	0.5	0.1
7	0.30	1.0	0.2
8	0.30	1.5	0.3
9	0.30	2.0	0.4
10	0.30	2.5	0.0
11	0.35	0.5	0.2
12	0.35	1.0	0.3
13	0.35	1.5	0.4
14	0.35	2.0	0.0
15	0.35	2.5	0.1
16	0.40	0.5	0.3
17	0.40	1.0	0.4
18	0.40	1.5	0.0
19	0.40	2.0	0.1
20	0.40	2.5	0.2
21	0.45	0.5	0.4
22	0.45	1.0	0.0
23	0.45	1.5	0.1
24	0.45	2.0	0.2
25	0.45	2.5	0.3

standard curing method is adopted for 28 days, during which the temperature in the curing room is maintained at 20 ± 1℃ and the relative humidity is greater than 99%. When the curing is completed, the cores are taken and the standard specimens corresponding to the uniaxial compression test and the Brazilian splitting test are respectively made (see Fig.1(b)). This method effectively avoids the problem of unevenness caused by bubbles generated at the surfaces where the specimens are contacted with the mold during the pouring process and improves the uniformity of the specimens.

(a) Electric mortar mixer (b) Specimens prepared according to the orthogonal design

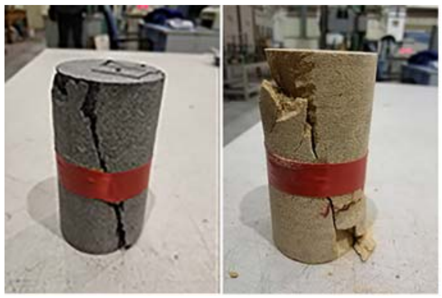
Fig. 1 Electric mortar mixer and specimens prepared according to the orthogonal design

The basic physical property test, uniaxial compression test, and Brazil splitting test are performed on the cured specimens to obtain the natural density ρ_0, uniaxial compressive strength σ_c, tensile strength σ_t, tangent elastic modulus E of 50% compressive peak strength and the Poisson's ratio υ as listed in Table 5. The instrument used in the uniaxial compression test, and Brazil splitting test is a hydraulic universal tester produced by Changchun Chaoyang Testing Instrument Co., Ltd and the applied force is measured by a pressure sensor with a range of 500 kN. Moreover, the loading rate is maintained at 1 kN/s, and the sampling frequency is 1 (s^{-1}) during the test。

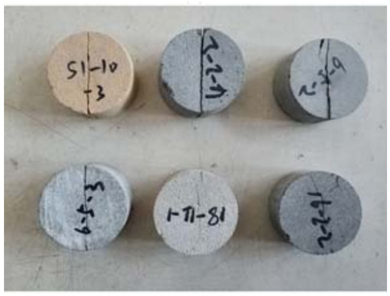
Table 5 Basic parameters of materials designed by orthogonal method

Group number	ρ_0 / (g • cm^{-3})	σ_c / MPa	σ_t / MPa	E / GPa	μ
1	2.28	107.03	3.75	32.38	0.25
2	2.14	85.97	5.18	35.48	0.22
3	2.12	86.48	4.79	31.83	0.20
4	2.27	89.69	6.72	54.58	0.35
5	2.24	91.37	6.45	35.70	0.25
6	2.16	103.72	3.63	23.90	0.20
7	2.01	62.90	4.93	25.00	0.20
8	2.08	60.42	4.65	31.15	0.22
9	2.16	54.16	5.75	34.21	0.18
10	2.12	60.68	4.17	52.44	0.45
11	1.94	73.82	4.18	33.16	0.34
12	2.10	79.63	4.32	26.55	0.15
13	2.06	64.04	4.55	35.95	0.29
14	2.24	61.70	5.30	39.77	0.29
15	1.84	34.15	3.13	24.91	0.32
16	1.84	59.69	3.64	28.94	0.38
17	1.98	62.21	4.39	20.74	0.34
18	2.24	53.17	5.06	26.69	0.18
19	2.07	49.68	4.25	34.74	0.23
20	1.75	27.21	2.47	22.21	0.21
21	1.80	61.88	3.43	14.30	0.32
22	1.98	42.65	3.32	30.60	0.19
23	2.15	51.47	4.62	40.93	0.15
24	2.03	57.02	3.57	28.33	0.22
25	1.81	27.93	2.55	14.07	0.16

The failure modes of the original sandstone and the specimens in the uniaxial compression test and the Brazilian splitting test are compared in Fig.2, and it is proved that the two specimens have similar failure modes. Therefore, it is feasible and meaningful to obtain the parameters of the rock-like material similar to the original rock by adjusting the proportions.



(a) Uniaxial compression test（left: rock-like material, right: sandstone）



(b) Brazilian splitting test（S1-10-3: sandstone，other specimens: rock-like material）

Fig. 2 Comparison of failure modes between sandstone and rock replicas

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DOI: 10.16285/j.rsm.2019.6711

3 Determination of the proportions of the rock-like material

3.1 Statistical method to determine the applicability of the proportions of the rock-like material

The tangent elastic modulus E of 50% compressive peak strength, uniaxial compressive strength σ_c, and tensile strength σ_t of 25 groups of specimens obtained by the orthogonal test are substituted into statistical data of deformation index of modulus-strength ratio for sandstone determined by Deere et al.[15] and statistical data of the brittleness index of tensile and compression strength for sandstone determined by Tatone[16]. The groups in the orthogonal test which meet the requirement of the statistical range of deformation indexes and brittleness indexes, are shown in Figs.3 and 4.

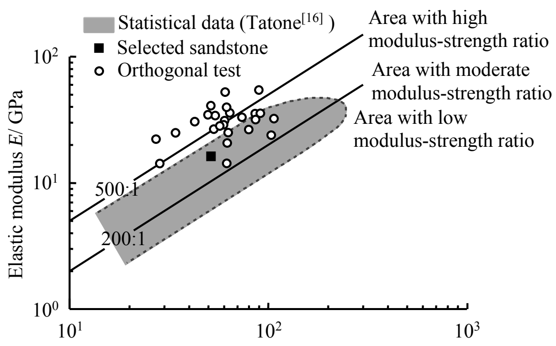


Fig. 3 Comparison of the rock replica and natural sandstone based on the ratio of E to σ_c (data from Tatone[16])

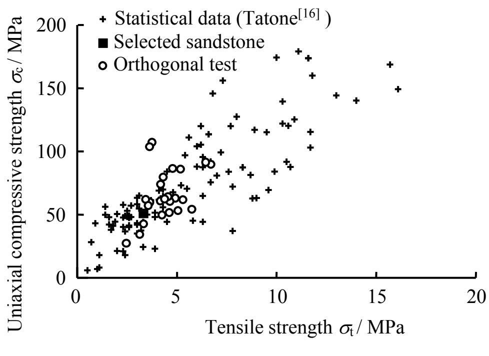


Fig. 4 Comparison of the rock replica and natural sandstone based on the ratio of σ_c to σ_t (data from Tatone[16])

Comparing the statistical data of the natural sandstone in the figure and the results of the orthogonal test, it is found that the groups that meet the basic deformation indexes and brittleness indexes of the natural sandstone in the orthogonal design tests are 2, 3, 5, 7, 12, 17 and 21, respectively. This statistical method is used to screen the deformation indexes and brittleness indexes of the rock-like material, which can avoid quantitative problems such as large difference in elastic modulus between the rock-like material and natural sandstone, insufficient strength and brittleness of the rock-like material. It is ensured that the strength and deformation characteristics and related parameter values of the rock-like material are comparable with that of the selected sandstone, and the applicability of the rock-like material is also guaranteed.

3.2 Sensitivity analysis of the proportioning factors of the rock-like material

The modulus-strength ratio and the tensile-compression strength ratio for different design levels obtained by the orthogonal test are used as the response indexes to perform range analysis and determine the sensitivity of each factor to the response indexes. The results are shown in Table 6. Only the effect of a single factor is considered in the range analysis, and the combined effect of other two factors is excluded. Therefore, range analysis indicates the difference between the maximum and minimum values of the response index affected by a certain factor at different levels, and its magnitude is used to initially determine the sensitivity of the response indexes to changes in the level of this factor. In this study, the sand-binder ratio has a significantly higher impact on the deformation index and the brittleness index than the water-binder ratio and the microsilica-cement ratio, which is the main influencing factor. Figure 5 visually shows the corresponding relationship between the average value of the response indexes of the material and three proportioning factors of different levels. E/σ_c is found to increase with an increase in the sand-binder ratio and decrease with an increase in the microsilica-cement ratio. A decrease in σ_c/σ_t can be observed with an increase in the sand-binder ratio and microsilica-cement ratio. In addition, as the water-binder ratio becomes larger, E/σ_c gradually increases until the water-binder ratio is 0.4 and then begins to decrease. On the contrary, σ_c/σ_t gradually decreases until the water-binder ratio is 0.4 and then begins to increase.

Regarding the changes of the two indexes with the water-binder ratio, it is believed that the selected water-binder ratio range is relatively large due to the difference in the amount of quartz sand and micro- silica added in the orthogonal design. Without considering effects of sand-binder ratio and microsilica-cement ratio, uniaxial compressive strength σ_c, elastic modulus E and tensile strength σ_t all decrease with the increase of water-binder ratio. The decreasing rate of uniaxial compressive strength σ_c is smaller than that of elastic modulus E and greater than that of tensile strength σ_t. But when the water-binder ratio exceeds a certain value, the decreasing rate of uniaxial compressive strength σ_c becomes greater than that of elastic modulus E and smaller than that of tensile strength σ_t, resulting in changes in the effect of the water-binder ratio on E/σ_c and σ_c/σ_t in the range analysis diagram.

Table 6 Range analysis of orthogonal test results

Parameters	E/σ_c	σ_c/σ_t
Water-binder ratio	150.580	5.381
Sand-binder ratio	321.205	9.512
Microsilica-cement ratio	176.528	1.812

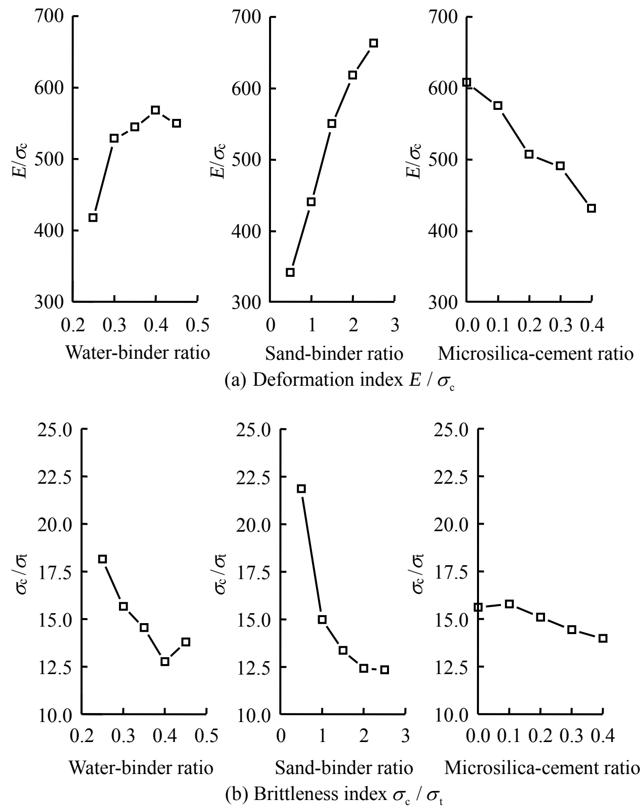


Fig. 5 Range analysis diagram of material parameters

According to the change trend shown in the figure, the deformation and brittleness index of the rock-like material can be corrected and approach the corresponding index value of the selected sandstone to a certain extent by adjusting its proportions.

3.3 Determination of the proportions of the rock-like material

In the laboratory tests of rocks and rock masses, the mechanical characteristic parameters of the rock blocks are important factors affecting the deformation and failure process of the rock mass. In tests of studying the mechanical properties of the rock specimens under load, the deformation and brittleness index of the rock-like material must be as same as the original rock in order to ensure that the specimens made of the rock-like material can bear the load as the natural rock and can be used to obtain the accurate strength–deformation relationship. Under this condition, the accurate proportions of the rock-like material should be determined in further investigations to make the specimens with mechanical properties similar to the original rock.

Based on the parameters of seven groups of orthogonal tests which meet the deformation and brittleness indexes of natural sandstone materials, the relationships between the response indexes and factors of each level are determined by the multivariate polynomial solution method. Furthermore, the relationship between the characterizing parameter and the proportioning factor can also be obtained. This relationship can be used in the design of specimen proportions characterized by water-binder ratio, sand-binder ratio, and microsilica-cement ratio to find the material with parameters closest to the selected rock.

The deformation index E / σ_c and the brittleness index σ_c / σ_t are respectively selected as the response indexes y to solve the equation. The two indexes of the seven groups and the three factors of orthogonal design are substituted into the solution to determine the exact relationship between the factors and the response indexes. Water-binder ratio, sand-binder ratio, and microsilica-cement ratio are represented by x_a, x_b and x_c, respectively in the process of the multivariate polynomial solution. Because the interaction between the two factors is ignored in the orthogonal design, there is no cross term in these three factors and each factor plays a role independently in the process of solving the polynomial. Based on the number of orthogonal test groups used for the solution and the relationship between the response indexes of the rock-like material and the factor level in the range analysis diagram, a quadratic function is used to describe the relationship between the water-binder ratio and the response index, and linear functions are used to describe relationships between the sand-binder ratio, the microsilica-cement ratio and the response indexes in the process of solving the relationship between the deformation index E / σ_c and the proportioning factor. For the brittleness index, the relationship between the sand-binder ratio and the response index is expressed as an inverse proportional relationship, which is also used in the relationships between the water-binder ratio, the microsilica-cement ratio and the response index. The general form of the multivariate polynomial equation is as follows:

$$\begin{aligned} y &= b_0 + b_1 x_a^2 + b_2 x_a + b_3 f(x_b) + b_4 x_c = \\ &\quad b_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 + b_4 x_4 \end{aligned} \tag{1}$$

where $f(x_b) = x_b$ for E / σ_c; $f(x_b) = x_b^{-1}$ for σ_c / σ_t.

In order to ensure the comparability of the data and avoid effects of the absolute values of the three factors of water-binder ratio, sand-binder ratio, and microsilica-cement ratio on the solution results, the normalized levels of proportioning factors are shown in Table 7. In Eq. (1), the original proportioning variable parameters are represented by $x_1 - x_4$, respectively. Substituting the response indexes of seven groups and the corresponding normalized factor levels into Eq. (1), the equation can be written as a non-homogeneous linear system of equations:

$$\boldsymbol{XB} = \boldsymbol{Y} \tag{2}$$

where

$$\boldsymbol{X} = \begin{bmatrix} 1 & x_{21} & x_{22} & x_{23} & x_{24} \\ 1 & x_{31} & x_{32} & x_{33} & x_{34} \\ 1 & x_{51} & x_{52} & x_{53} & x_{54} \\ 1 & x_{71} & x_{72} & x_{73} & x_{74} \\ 1 & x_{121} & x_{122} & x_{123} & x_{124} \\ 1 & x_{171} & x_{172} & x_{173} & x_{174} \\ 1 & x_{211} & x_{212} & x_{213} & x_{214} \end{bmatrix} \tag{3}$$

$$\boldsymbol{B} = \begin{bmatrix} b_0 & b_1 & b_2 & b_3 & b_4 \end{bmatrix}^{\mathrm{T}} \tag{4}$$

$$\boldsymbol{Y} = \begin{bmatrix} y_2 & y_3 & y_5 & y_7 & y_{12} & y_{17} & y_{21} \end{bmatrix}^{\mathrm{T}} \tag{5}$$

The first (two) digits of the subscript of matrix $\boldsymbol{X}$ indicate the number of the orthogonal test group, and the last digit indicates its position number in Eq. (1). Since the matrix is a 7×6 matrix, which cannot be inverted, the pseudoinverse $\mathrm{pinv}(\boldsymbol{X})$ is used in the solution process using Matlab. The solution obtained is a least square solution. The pseudoinverse $\mathrm{pinv}(\boldsymbol{X})$ has the following property:

$$\boldsymbol{A}\mathrm{pinv}(\boldsymbol{A})\boldsymbol{A} = \boldsymbol{A} \tag{6}$$

Therefore, $\boldsymbol{B}$ can be expressed as

$$\boldsymbol{B} = \boldsymbol{X} \,/\, \boldsymbol{Y} = \mathrm{pinv}(\boldsymbol{X}) \times \boldsymbol{Y} \tag{7}$$

The response parameters modulus-strength ratio and tensile-compression strength ratio are substituted into $\boldsymbol{Y}$ in the calculation process. The linear equations are solved with different levels of proportioning factors, and the coefficients are shown in Table 8.

Table 7 Normalized proportions in orthogonal design

Group number	Water-binder ratio	Sand-binder ratio	Microsilica-cement ratio
2	0.100	0.325	0.325
3	0.100	0.550	0.550
5	0.100	1.000	1.000
7	0.325	0.325	0.550
12	0.550	0.325	0.775
17	0.775	0.325	1.000
21	1.000	0.100	1.000

Table 8 Coefficients of multivariate polynomial equations

Index	b_0	b_1	b_2	b_3	b_4
E/σ_c	395.48	–216.29	58.84	–16.48	–2.81
σ_c/σ_t	18.41	8.18	–6.02	0.04	–3.17

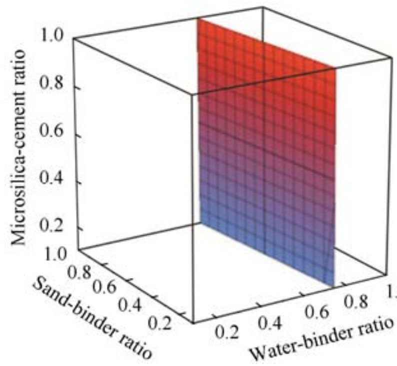
The calculated values, the measured values, and the errors between E/σ_c and σ_c/σ_t for seven groups of orthogonal tests using the polynomial relationship are shown in Table 9.

Table 9 Error between the calculated values and the measured values of E/σ_c and σ_c/σ_t

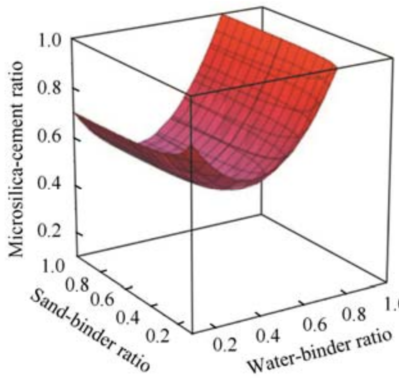
Index		2	3	5	7	12	17	21
E/σ_c	Measured	412.7	368.1	390.7	397.5	333.5	333.4	231.1
	Calculated	392.9	388.6	379.9	384.9	354.9	303.0	233.6
	Error	–0.05	0.06	–0.03	–0.03	0.06	–0.09	0.01
σ_c/σ_t	Measured	16.6	18.1	14.2	12.8	18.5	14.2	18.0
	Calculated	17.0	16.2	14.8	15.7	15.3	15.6	17.8
	Error	0.02	–0.10	0.04	0.23	–0.17	0.10	–0.01

The error between the calculated value of the deformation index and the measured value is relatively small. Therefore, the obtained relationship can be used to determine the proportion of rock-like materials that meets the selected sandstone deformation index. Compared with the deformation index, the error between the calculated value of the brittleness index and the measured value is slightly larger. When the solution is solved, the range of rock-like material proportion can be further adjusted through the range analysis diagram. By substituting the index values of the natural sandstone, $E/\sigma_c = 316.9$, $\sigma_c/\sigma_t = 15.7$, and coefficients listed in Table 8, into Eq.(1), equivalent surfaces of E/σ_c and σ_c/σ_t which meet the selected sandstone indexes can be obtained as shown in Fig.6. The coordinates on the curved surface in the figure are the proportion values of the index equal to the values of the selected natural sandstone.

The proportions are selected from the curved surface in Fig.6 to ensure that the material indexes obtained are similar to the natural sandstone to the greatest extent. According to the surface shown in the figure, the normalized value of water-binder ratio is selected as 0.73 and substituted into Eq. (1). The obtained proportions of the rock-like material are shown in Table 10.



(a) E/σ_c equivalent surface



(b) σ_c/σ_t equivalent surface

Fig. 6 Equivalent surfaces of E/σ_c and σ_c/σ_t

Table 10 Proportions of the rock-like material

Factor	Normalized value	Actual value
Water-binder ratio	0.73	0.39
Sand-binder ratio	0.23	0.78
Microsilica-cement ratio	0.90	0.36

3.4 Test inspection

According to the determined proportion, the corresponding test specimens are made, and their physical and mechanical properties are investigated to verify the correctness of the multivariate polynomial solution. In order to verify whether the deformation and brittleness characteristics of the rock-like material meet the requirements of the selected sandstone, a uniaxial compression test was carried out on the rock-like material with the above-mentioned proportion. E/σ_c and σ_c/σ_t were used as indexes to validate the accuracy of the proportioning process in this study. A triaxial compression test was performed on the prepared rock-like material to determine whether the plastic deformation characteristics of the rock-like material are similar to the selected sandstone. The cohesion and internal friction angle are used as indicators to analyze the similarity between the rock-like material and sandstone in terms of plastic deformation. Figure 7 visually shows the uniaxial compression and triaxial compression stress–strain curves of the rock-like material prepared according to the above method. It can be seen that the rock-like material has stress–strain characteristics similar to those of natural rocks: (1) under the uniaxial compression stress, brittle failure occurs in the rock-like specimen when the deformation is not large; (2) as the confining pressure increases, the total strain of the rock-like material increases before failure, which is mainly manifested as an increase in plastic strain; (3) the triaxial compressive strength of the rock-like material increases significantly with the increase of confining pressure, and the post-peak deformation gradually transits from brittle to plastic deformation.

Table 11 compares the basic physical and mechanical parameters of the two materials. According to the data in the table, the errors between the deformation and brittleness indexes of the rock-like material made with the proportion obtained by the solution and the corresponding indexes of the natural rock are –0.0974 and –0.0115, respectively.

In tests to determine the proportions of the material using the orthogonal method, Shi et al.[19] determined that when the difference between the parameter value obtained by the regression ratio and that of the prototype is 20%, the obtained material is regarded as the rock-like material that meets the proportioning requirements. This proportioning standard is used to determine the applicability of the proportion of the rock-like material in this study. Based on Table 11, the rock-like material prepared according to the deform- ation index E/σ_c and the brittleness index σ_c/σ_t basically meets this standard. In addition, the cohesive force and internal friction angle of the rock-like material are within the statistical range of natural sandstone, and the strength-deformation characteristic under the triaxial compression is consistent with that of rock, which ensures the feasibility of using rock-like materials to replace natural rocks. In order to obtain the rock-like material for rock mechanical property tests, the proportion of the rock-like material can be further adjusted according to the change of parameters with the proportioning factors as shown in the range analysis diagram.

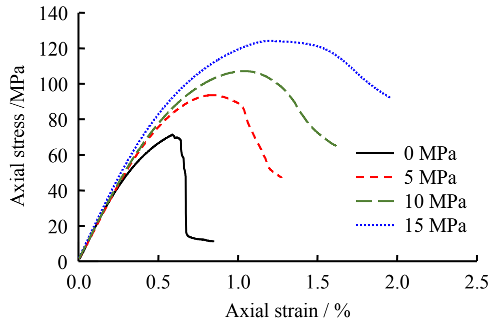


Fig. 7 Stress–strain curves of the rock-like material under different confining stresses

Table 11 Basic parameters of sandstone and the rock-like material

Material	ρ_0 / (g · cm^{-3})	σ_c / MPa	σ_t / MPa	E / GPa	μ	E/σ_c	σ_c/σ_t	c / MPa	φ / (°)
Sandstone	2.16	51.56	3.28	16.34	0.31	316.92	15.69	14.58	37.19
Rock-like material	2.06	70.92	4.57	20.28	0.28	286.06	15.51	19.02	34.57
Error	–0.046 3	0.375 5	0.393 3	0.241 1	–0.096 8	–0.097 4	–0.011 5	0.304 5	–0.070 4

4 Discussion

The rock-like material made according to the method described in this paper ensures that the rock-like material has similar deformation and brittleness characteristics to the selected natural sandstone. The problems of the blindness and the inconsistency of deformation and brittleness in previous proportioning of rock-like materials are overcome and the error in the laboratory test caused by replacing the rock with the rock-like material of different properties is also reduced. At the same time, the prepared rock-like materials and natural rock blocks have similar strength and deformation parameters to a certain extent, and the strength and elastic modulus of the rock-like material will not differ from the values of natural rocks by one to two orders of magnitude. Therefore, indoor mechanical tests on rocks and rock masses can be carried out with more accuracy with the help of rock-like materials

However, in some laboratory tests, such as shear tests of joints, if the shear constitutive relationship of natural rock mass is determined according to the test, deformation, brittleness characteristics, and some other mechanical parameters such as strength of the rock-like material should be similar to the natural rock, to ensure the accuracy of the joint wall strength in the test. Therefore, subsequent adjustment of parameter selection is required based on the method in this study. The parameter such as strength can be added as a response index to improve the proportion solution or fitting accuracy to obtain rock-like materials with strength and deformation parameters similar to the selected natural rock. The obtained rock-like material can be effectively used in the shear tests of joints for investigation of the mechanical properties.

5 Conclusions

A method for preparing rock-like materials is systematically developed, which ensures that the basic deformation and brittleness characteristics of the rock-like material are similar to those of the selected natural rocks in the laboratory tests of mechanical properties. In this paper, a specific sandstone is used as a prototype, and the deformation index E / σ_c and brittleness index σ_c / σ_t are selected as quantitative parameters to investigate the proportions of the desired rock-like material using the orthogonal test method. The preparation process of the rock-like material is introduced as follows:

(1) Based on the strength and deformation characteristics of sandstone, cement, microsilica, quartz sand, and water are used as raw materials to ensure that the materials have similar brittleness, dilatancy and strength to the ordinary sandstone. In addition, the uniformity of the internal structure of the rock-like material is also ensured.

(2) Specimens with different proportions are prepared by the orthogonal method and basic physical and mechanical parameters of specimens in each group are obtained in laboratory. The feasibility of using this material as a rock-like material can be determined by comparing the deformation index E / σ_c and brittleness index σ_c / σ_t of the rock-like material and natural sandstone. Moreover, changes in response indexes of the rock-like material with different levels of proportioning factors are determined by the range analysis method.

(3) In order to obtain the proportions of the rock-like material with similar deformation and brittleness characteristics to the selected sandstone, a multivariate polynomial solution method is used to establish a relationship between response indexes and proportioning factors. The specific proportions of the rock-like material are obtained by substituting the parameter values of the original sandstone into the regression equation.

(4) A set of specimens is made according to the proportions of the obtained rock-like material. It is verified that the strength and deformation properties of the material are consistent with those of the original sandstone by the uniaxial and triaxial compression tests, which demonstrates the feasibility of this method.

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DOI: 10.16285/j.rsm.2019.6711