

Article

Investigation of Sandstone-like Material for Damaged Rock Mass Based on Orthogonal Experimental Method

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Abstract: The investigation of the mechanical properties of rock mass can be effectively carried out through rock-like material experiments. In this study, polystyrene foam particles were utilized as a novel material for simulating initial damage within rocks. Our research involved the development of sandstone-like materials with comparable mechanical properties to actual sandstone. These materials were then subjected to orthogonal mechanical tests, allowing us to identify the key factors that have a substantial impact on the mechanical parameters of sandstone-like rocks. The influencing factors considered in the orthogonal mechanical tests were the proportion of aggregate and binder, the proportion of polystyrene foam in the entire model, the proportion of binder and regulator, and the size of polystyrene foam. Five levels were set for each factor, and mechanical parameters such as compressive strength, tensile strength, elastic modulus, axial strain, and Poisson's ratio were tested for each group of samples. The changes in mechanical parameters with the levels of the above four factors were studied. The study found that modifying the proportion of aggregate to binder can alter the elastic modulus, tensile strength, and compressive strength values of sandstone-like material. The size of polystyrene foam can be modified to alter the axial strain values of sandstone-like materials. Additionally, adjusting the ratio of binder and regulator can modify the value of Poisson's ratio. The comparison of mechanical parameters between sandstone-like samples and sandstone reveals that sandstone-like materials can better simulate the deformation and failure mechanisms of sandstone. The error in the main mechanical parameters, such as modulus of elasticity, strength, and Poisson's ratio, is less than 7%, indicating a greater resemblance between sandstone-like materials and sandstone. Therefore, sandstone-like materials can be used to investigate the deformation law, damage evolution law, and failure mechanism of sandstone. This can help alleviate the difficulty of obtaining specimens of deep damaged rock and the high cost of testing.

Keywords: damaged rock mass; sandstone-like material; orthogonal test; mechanical property



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1. Introduction

In recent years, deep rock engineering has faced numerous challenges, including rock bursts and large deformation of surrounding rock, which pose a serious threat to the safety of deep engineering. However, due to the difficulty in obtaining samples of deep rock mass, there have been limited studies on deep rock mass mechanics tests, and the mechanical properties, deformation, and failure mechanism of deep rock mass remain unclear. Moreover, it has not been established that the mechanical theory of deep rock mass is based on the deformation law and failure mechanism.

As rock-like materials and rock mass have similar mechanical properties and failure mechanisms, many scholars have conducted experimental studies on rock-like materials to investigate the mechanical properties of rock mass. These studies have enabled the deformation law and failure mechanism of different types of rock mass to be mastered and corresponding theoretical models to be established.

Yang [1] took barite powder and iron concentrate powder as aggregate, quartz sand as a regulator, and quicklime and gypsum as cementing agents and studied the effects of four factors on the mechanical properties of similar materials. Hu [2] studied the effects of four factors, namely the water–binder ratio, the ratio between binder components, the ratio between aggregate components, and the particle size of pottery sand, on the mechanical properties of rock-like specimens. Gong [3] investigated the mechanical properties of rock mass with different geological structures with rock-like material consisting of pulverized coal, sand, cement, water, gypsum, soil, and sodium chloride. Zhang [4], Liu [5], Ning [6], and Dai [7] studied the influence of composition on the compressive strength, density, elastic modulus, and permeability coefficient of rock-like materials. Wang [8] studied the influence of the sand–binder ratio and residual water content on the uniaxial compressive strength, elastic modulus, and Poisson’s ratio of rock-like specimens consisting of river sand and gypsum. Liu [9] prepared rock-like specimens with gypsum, yellow sand, quartz, and barite powder and investigated the effects of molding pressure, compaction rate, and repeated stirring times on the mechanical properties of rock-like materials. Liu [10] made rock-like material specimens with sand, cement, gypsum, diatomite, red clay, and marl powder to study the mechanical properties of rocks with different weathering degrees.

Klammer [11] investigated the influence of grain-scale heterogeneity on strainburst proneness using rock-like material. Cao [12] made a multi-scale model of plasticity and damage for rock-like materials with pores and inclusions. Ma [13] investigated the behaviors and mechanisms of rock-like specimens with two circular holes under compression. Zhao [14] investigated fracture mechanisms of intact rock-like materials under compression. Zhang [15] investigated the damage characteristics and fracture behavior of rock-like materials with weak interlayer zones. Ding [16] investigated the shear performance of anchored jointed rock-like mass under different corrosion levels. Fan [17] carried out an experimental and numerical investigation of the crack mechanism of folded flawed rock-like material. Hou [18] studied the excavation unloading response of cylindrical rock-like specimens with axial joints. Huang [19] investigated damage mechanisms under high pressure with a plastic damage model for rock-like materials. Jia [20] investigated the initiation and propagation of embedded three-dimensional parallel cracks in transparent rock-like material. Li [21] investigated the acoustic emission and mechanical characteristics of rock-like material containing a single crack. Meng [22] carried out experimental and numerical studies on the anisotropic mechanical characteristics of rock-like material. Pan [23] established a damage constitutive model of rock-like materials under the action of chemical corrosion and uniaxial compression. Teng [24] investigated the shear failure modes and acoustic emission characteristics of rock-like materials. Tian [25] investigated the multi-angle Effects of micron-silica fume on the micro-pore structure and macroscopic mechanical properties of rock-like material. Wang [26] investigated the mechanical properties and failure mechanism of rock-like specimens. Wang [27] investigated the strength and failure characteristics of a layered composite rock-like sample with a single hole. Wang [28] used the phase-field method to make a model with damage and cracking in heterogeneous rock-like materials. Yu [29] used a double-phase-field method to make a model with mixed cracks in rock-like brittle materials under compressive stresses. Zhao [30] established a new discrete element model for rock-like materials. Deng [31] explored the internal relationship between pore structure and mechanical properties of sandstone-like materials. Gao [32] studied the dynamic fracture mechanism of rock under high in situ stress with rock-like material.

However, most studies on rock-like materials focused on undamaged specimens, neglecting the impact of initial damage on the mechanical properties of rock mass. As there are random distributions of original defects in deep rock mass, such as holes, cracks, and joints, these defects cannot be ignored when conducting experimental research on the mechanical properties of deep rock mass. Consequently, we investigated the impact of the composition and proportion of sandstone-like material on its mechanical parameters with the orthogonal test method. The objective was to comprehend the correlation between the mechanical parameters of sandstone-like material and the component proportions. By

altering the composition proportion of sandstone-like material, the mechanical parameters of sandstone-like material were adjusted. This allowed for the establishment of a preparation method for sandstone-like material that is appropriate for simulating damaged rock mass. In order to determine the main composition of deep rock mass, X-ray diffraction analysis was performed on deep rock mass to determine its main components. Based on the components determined for rock mass, the authors designed a set of orthogonal tests to confirm the suitable component ratio of sandstone-like materials applicable to deep damaged rock.

2. Experiment Design

The mechanical properties of rock-like materials are significantly influenced by the materials' components. XRD analysis was conducted on damaged sandstone to determine its main components. The similarity criterion for deep damaged rock mass was then determined based on the main mechanical parameters of the rock, including strength, strain, elasticity modulus, and Poisson's ratio. The method for creating sandstone-like specimens was determined based on the compositions and similarity criteria of the damaged sandstone. The specific implementation methods are outlined below.

2.1. Detection of Deep Rock Composition

The specimens examined in this research were obtained from Sichuan, China, at a depth of approximately 300–700 m. The predominant rock type is sandstone. To prepare the test sample for XRD analysis, the sandstone specimen was ground into a fine powder. X-ray diffraction analysis was performed on rock samples using the TD-3500 X-ray diffractometer (Figure 1). The performance parameters of the TD-3500 are shown in Table 1, and the analysis results are displayed in Figure 2.



Figure 1. X-ray diffractometer TD-3500.

Table 1. The performance parameters of TD-3500.

Index	Diffraction Radius	Scanned Range of 2θ	Scanning Speed	Repeated Accuracy of 2θ	Minimum Step Angle	Accuracy of Measurement
Performance Parameter	185 mm	$-35\sim 170^\circ$	$0.006\sim 120^\circ/\text{min}$	$\leq 0.0005^\circ$	0.0001°	$\leq 0.001^\circ$

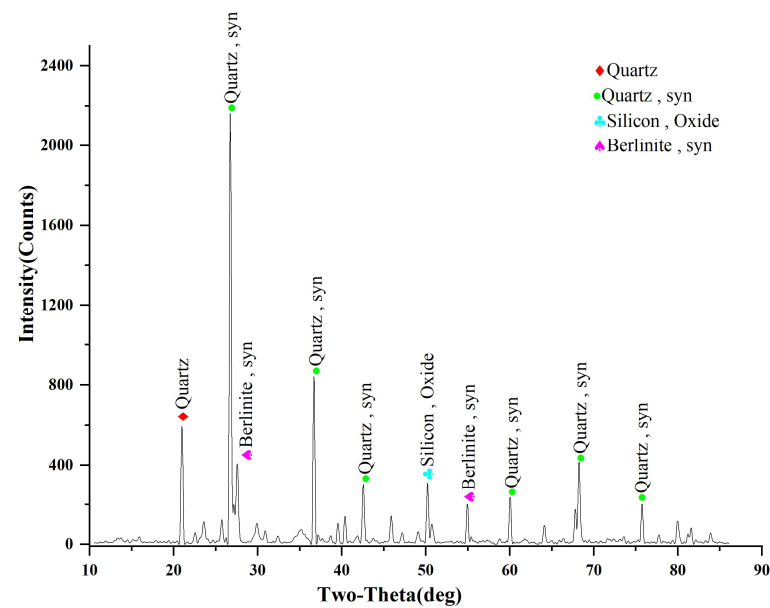


Figure 2. XRD composition detection of sandstone.

The XRD analysis shows that the sandstone is composed mainly of quartz, silicon oxide, and berlinite. Therefore, the appropriate components for creating sandstone-like materials are river sand as the raw material, cement as the binding agent, and gypsum powder as the regulator.

2.2. Similarity Criterion

The variable C has been assigned to denote the similarity ratio between the physical quantities of protolith (P) and sandstone-like material (M) in accordance with the similarity criterion. The required outcome can be obtained by applying the following formula:

$$C_{\varphi} = \frac{\varphi_P}{\varphi_M}, C_{\mu} = \frac{\mu_P}{\mu_M}, C_{\sigma} = \frac{\sigma_P}{\sigma_M}, C_{\varepsilon} = \frac{\varepsilon_P}{\varepsilon_M}, C_E = \frac{E_P}{E_M}, C_{\eta} = \frac{\eta_P}{\eta_M}, C_{C_F} = \frac{C_{FP}}{C_{FM}}$$

$$C_{\sigma_s} = \frac{\sigma_{sP}}{\sigma_{sM}}, C_{\gamma} = \frac{\gamma_P}{\gamma_M}, C_L = \frac{V_P}{V_M}, C_F = \frac{F_P}{F_M},$$

where C_{φ} is the similarity constant of the internal friction angle, C_{μ} is the similarity constant of Poisson's ratio, C_{σ} is the similarity constant of stress, C_{ε} is the similarity constant of strain, C_E is the similarity constant of the elasticity modulus, C_{η} is the similarity constant of the viscosity coefficient, C_{C_F} is the similarity constant of cohesion, C_{σ_s} is the similarity constant of yield strength, C_{γ} is the similarity constant of unit weight, C_L is the geometric similarity constant, and C_F is the similarity constant of force.

Based on the initial similarity criterion, which suggests that comparable phenomena share equivalent criteria of similarity and corresponding similarity index values measuring 1, we can establish relationships between equivalent constants.

$$C_{\varepsilon} = C_{\mu} = 1 \quad (1)$$

$$C_{\sigma} = C_{\eta} = C_{C_F} = C_{\sigma_s} = C_E \quad (2)$$

$$C_{\gamma} = \frac{C_F}{C_L^3} \quad (3)$$

Given the differential scales between the engineering rock mass and the laboratory test rock specimen, a geometric similarity constant of 20 was established in order to ensure

geometric equivalence. Consequently, it can be obtained from the above formula that $C_\sigma = C_\eta = C_{C_F} = C_E = C_\gamma \times C_L = 20$.

2.3. Orthogonal Test of Rock-like Material

This paper examines the constitution of sandstone-like material by considering two factors. Firstly, the composition of sandstone is examined to ensure that sandstone-like material has a comparable composition. Secondly, the physical and mechanical parameters of sandstone are assessed to ensure that they are within the same range for both sandstone-like material and sandstone.

The study employs river sand with a diameter of 30~40 mesh as the aggregate, Portland cement P.O42.5 as the binder, and gypsum powder as the regulator. Figure 3 illustrates all the aggregates used. To replicate the effects of internal structural damage on the mechanical characteristics of rocks, researchers used polystyrene foam, also known as EPS, to simulate the initial damage sustained by rocks located deep. The polyethylene foam is approximately spherical in shape and has lower strength than rock mass. To replicate the irregular distribution of damage inside the rock, the random filling technique was employed.

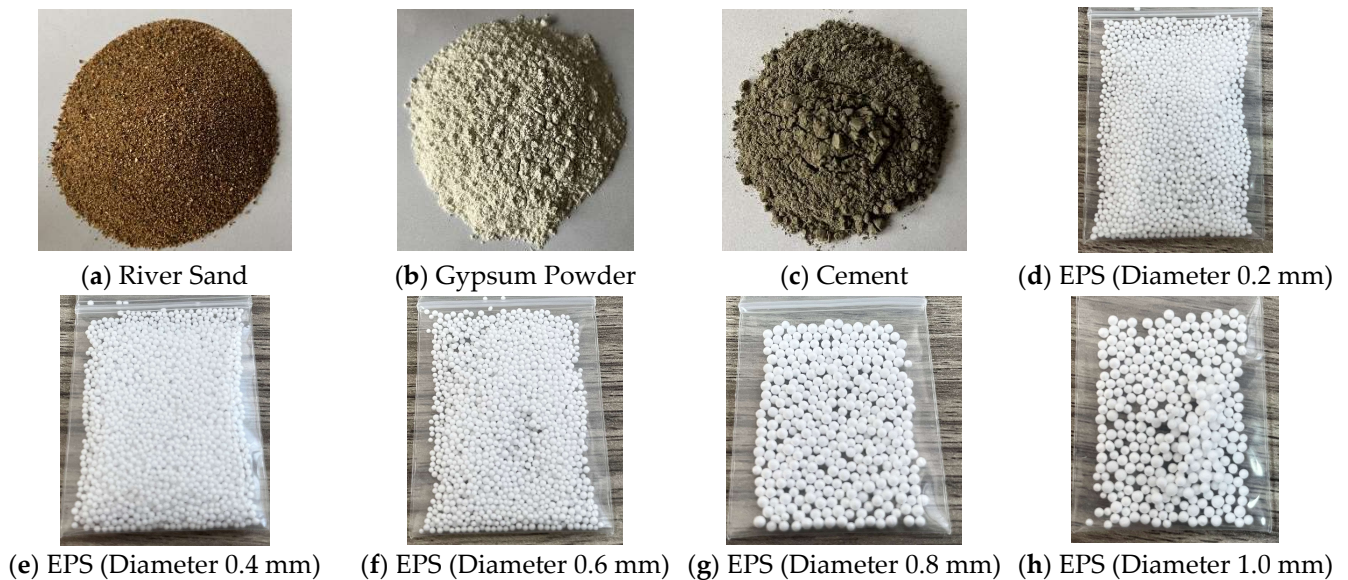


Figure 3. Components of sandstone-like material.

To investigate the impact of the component ratio on the mechanical properties of sandstone-like materials and develop a method for controlling these properties, we selected four factors that may significantly affect parameters such as strength and deformation. Factor A denotes the proportion of aggregate and binder, whereas factor B signifies the proportion of polystyrene foam in the entire model. Moreover, factor C denotes the proportion of the binder and regulator, and factor D is the size of the polystyrene foam. To ensure a clear understanding of the influence of each factor on the mechanical factors, we divided each factor into five grades. We combined this with the orthogonal test scheme used in previous investigations on rock-like materials [33,34]. Table 2 presents the orthogonal test scheme for the sandstone-like material ratio, while Table 3 shows the orthogonal test scheme for four factors and five levels.

Table 2. Sandstone-like material ratio of four factors.

Level	Factor A	Factor B	Factor C	Factor D
		%	%	mm
1	2:1	1.0	25	0.2
2	3:1	1.5	30	0.4
3	4:1	2.0	35	0.6
4	5:1	2.5	40	0.8
5	6:1	3.0	45	1.0

Table 3. Orthogonal test scheme of four factors and five levels.

Number	Factor			
	A	B (%)	C (%)	D (mm)
1	3:1	1.5	40	0.4
2	6:1	1.0	30	0.4
3	5:1	1.0	35	0.6
4	2:1	1.5	45	0.6
5	4:1	1.0	40	0.8
6	3:1	2.0	35	0.8
7	5:1	1.5	30	1.0
8	6:1	1.5	25	0.8
9	6:1	2.5	40	0.6
10	5:1	2.5	45	0.8
11	4:1	2.5	25	1.0
12	3:1	2.5	30	0.2
13	3:1	1.0	45	1.0
14	5:1	2.0	25	0.4
15	2:1	2.0	40	1.0
16	2:1	1.0	25	0.2
17	4:1	1.5	35	0.2
18	6:1	3.0	35	1.0
19	2:1	2.5	35	0.4
20	4:1	3.0	45	0.4
21	3:1	3.0	25	0.6
22	5:1	3.0	40	0.2
23	6:1	2.0	45	0.2
24	2:1	3.0	30	0.8
25	4:1	2.0	30	0.6

3. Specimen Preparation and Test Process

Sandstone-like specimens were prepared based on the composition and ratio of sandstone-like materials determined in this paper. Uniaxial compressive tests were conducted on the specimens to measure their compressive strength, tensile strength, elastic modulus, Poisson's ratio, and strain. We analyzed the factors that influence the mechanical properties of the sandstone-like specimens.

3.1. Specimen Preparation

This manuscript adhered to the directives delineated in the Standard [35] by utilizing a cylindrical sample with dimensions of $\Phi 50 \times 100$ mm. The non-parallelism error of the two end faces of the specimen was contained within a range of ± 0.05 mm, while the diameter error along the height of the specimen was controlled within a range of ± 0.3 mm. Additionally, the deviation between the end face and the axis of the specimen was limited to $\pm 0.25^\circ$. To create the specimen, a cylindrical split mold, as depicted in Figure 4, was employed.



Figure 4. Specimen mold.

Initially, we weighed the aggregate, binder, and regulator following the orthogonal test scheme and then mixed all components. Once the ingredients were mixed evenly, water was added and stirred in until a consistent mixture was achieved. The uniform mixture was then filled into a split mold, and the polystyrene foam (EPS) was equally divided and mixed in accordance with the predetermined proportion. In order to reduce the effects of stratification, a stratified compaction methodology was employed. Additionally, prior to packing, the surface of the specimen was intentionally scratched. In order to guarantee consistent density and strength across all specimens, the compaction pressure was set to 2 kN. Once the specimens were assigned identification numbers, they underwent a drying process lasting 12 days in a well-ventilated environment, thus guaranteeing uniform drying throughout. A temperature and humidity chamber was used to dry all specimens at 80 °C to eliminate any moisture content differences that could affect the specimens' mechanical properties. The mass of the specimens was measured every two hours, and the drying process ceased once the mass difference was less than 0.1 g for two consecutive measurements. Some of the test specimens are shown in Figure 5.



Figure 5. Part of the sample.

3.2. Test Process and Results

Laboratory mechanical tests were conducted on sandstone-like specimens to obtain the main mechanical parameters of the material. The compressive strength, tensile strength, and elastic modulus of the sandstone-like material were determined. The axial and radial deformation of the material was used to calculate the axial strain, radial strain, and Poisson's ratio of the material. Table 4 shows the results of measurements conducted in accordance with the Standard [35] for the compressive strength, tensile strength, elastic modulus, axial strain, and Poisson's ratio of the sandstone-like specimens.

Table 4. Test results of physical and mechanical parameters of sandstone-like materials.

Number	Compress Strength (MPa)	Tensile Strength (MPa)	Elastic Modulus (GPa)	Axial Strain ($\times 10^{-3}$)	Poisson's Ratio
1	2.43	0.39	0.24	14.97	0.29
2	2.93	0.52	0.13	19.19	0.19
3	3.12	0.54	0.22	23.78	0.26
4	2.22	0.45	0.29	10.81	0.33
5	3.80	0.55	0.25	18.63	0.26
6	2.22	0.42	0.24	19.51	0.19
7	4.34	0.62	0.24	14.99	0.34
8	7.75	0.85	0.34	18.01	0.19
9	4.31	0.60	0.21	15.64	0.31
10	3.86	0.55	0.33	11.73	0.36
11	4.17	0.52	0.34	22.26	0.21
12	3.92	0.54	0.43	7.37	0.29
13	5.20	0.64	0.37	15.13	0.22
14	3.05	0.49	0.36	10.92	0.27
15	3.93	0.54	0.41	19.84	0.38
16	2.80	0.45	0.38	12.56	0.27
17	3.39	0.65	0.34	11.39	0.26
18	2.42	0.66	0.29	14.09	0.33
19	2.97	0.43	0.35	10.51	0.34
20	3.53	0.56	0.32	10.73	0.36
21	2.90	0.40	0.32	13.29	0.21
22	4.25	0.59	0.33	16.12	0.27
23	4.93	0.71	0.27	14.14	0.35
24	3.66	0.50	0.36	16.27	0.27
25	3.24	0.47	0.29	15.47	0.23

4. Results and Discussion

The range analysis method was used to calculate the range for each physical and mechanical parameter of sandstone-like material based on measurements obtained from mechanical tests. The degree of influence of factors A to D on the parameters was established by comparing the range size. A greater range indicates a stronger impact of the factor on the parameter, indicating higher sensitivity to the factor. Conversely, parameters with a smaller range are less sensitive to the factor in question.

4.1. Analysis of Factors' Sensitivity to Parameters

Sandstone-like materials were prepared using an orthogonal design scheme to determine the proportion of each material. The sandstone-like specimens were prepared in accordance with the Standard [35], and material ratio tests were carried out. The primary mechanical parameters were obtained for different levels of factors. These mechanical parameters are shown in Table 4. In order to assess the effect of different factors on the main mechanical parameters of the sandstone-like materials, an intuitive parameter analysis table was constructed. This table contained the physical and mechanical parameters for each factor level, allowing the parameter values to be compared. The range was calculated as the difference between the maximum and minimum values of the mechanical parameters within each factor level. The range serves as an indicator of the influence of the factors on the mechanical parameters. A larger range indicates a greater influence of the factors on the mechanical parameters of the sandstone-like materials.

This paper presents an analysis of the effect of factors A, B, C, and D on the elastic modulus, with a focus on observing the change in the elastic modulus as the levels of these factors vary. Figure 6 illustrates the variation in the elastic modulus with respect to the levels of factors A, B, C, and D. In addition, Table 5 provides a visual analysis table of the elastic modulus. Based on the analysis shown in Figure 6, it is evident that the elastic

modulus gradually decreases as the level of factor A increases, exhibits an initial decrease followed by an increase with the levels of factors C and D, and gradually increases with the level of factor B. Moreover, the analysis in Table 5 reveals that the largest range of elastic modulus is observed under different levels of factor A, which measures 0.11. Cui et al. [36] found that the elastic modulus of rock-like materials decreases with the ratio of aggregate and binder and that this ratio has the most significant effect on elastic modulus, which is consistent with the pattern presented in this paper. This indicates that factor A has the greatest degree of influence on the elastic modulus, and there is a negative correlation between the elastic modulus and the level of factor A.

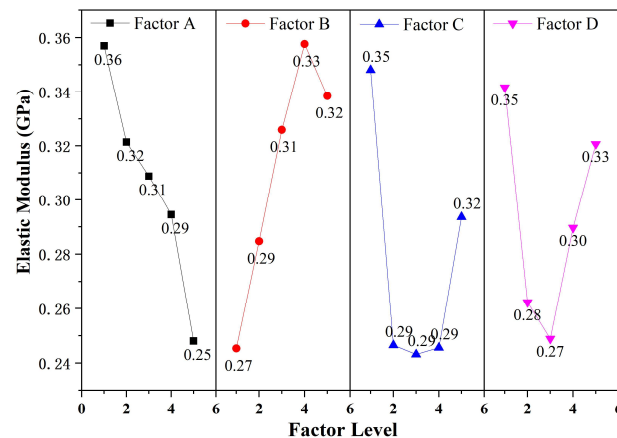


Figure 6. Elastic modulus analysis of sandstone-like materials.

Table 5. Range analysis of elastic modulus.

Factor Level	Elastic Modulus (GPa)			
	Factor A	Factor B	Factor C	Factor D
1	0.36	0.27	0.35	0.35
2	0.32	0.29	0.29	0.28
3	0.31	0.31	0.29	0.27
4	0.29	0.33	0.29	0.30
5	0.25	0.32	0.32	0.33
Range	0.11	0.06	0.06	0.08

Simultaneously, an investigation was carried out to assess the effect of variations in factors A, B, C, and D on key mechanical properties including compressive strength, tensile strength, Poisson's ratio, and strain. The analysis of factors A, B, C, and D on compressive strength, tensile strength, Poisson's ratio, and strain follows an analytical process similar to that for the modulus of elasticity. For the sake of brevity, this paper will not reiterate the entire process but rather provide the analysis results. The analysis, as shown in Figures 7–10, shows that the influence of factor A on compressive strength is the most significant, with a range reaching 1.35. This suggests that factor A has the greatest effect on compressive strength, and as the level of factor A increases, the compressive strength shows a gradual increase. The variation in tensile strength across different levels of factor A is the most significant, with a magnitude of 0.20, suggesting that factor A has the greatest impact on tensile strength. Furthermore, the tensile strength increases gradually as the level of factor A increases. A similar phenomenon was observed in similar material tests by Yang et al. [37], where compressive strength and shear strength increased with the gypsum content. Similarly, the range of the Poisson's ratio across different levels of factor C is the largest at 0.09, suggesting that factor C has the most pronounced effect on the Poisson's ratio. Furthermore, as the level of factor C increases, the Poisson's ratio gradually increases as well. Yang et al. [38] found that the Poisson's ratio increases with the

increase in the water–cement ratio, a trend similar to that shown in this paper, which may be due to the fact that both factors can change the deformation of the material during the loading process, which leads to the change in Poisson’s ratio. Finally, the strain is mainly influenced by factor D, as indicated by the largest range of 4.95. Correspondingly, as the value of factor D increases, there is a gradual increase in the strain. This is consistent with the phenomenon found in the experiment that the strain in the rock gradually increases with the amount of damage [39].

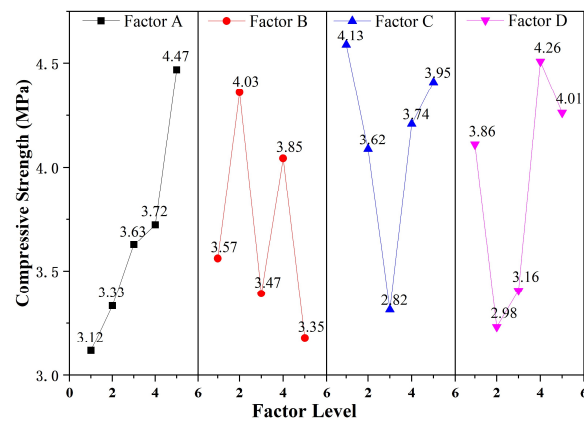


Figure 7. Compressive strength analysis of sandstone-like materials.

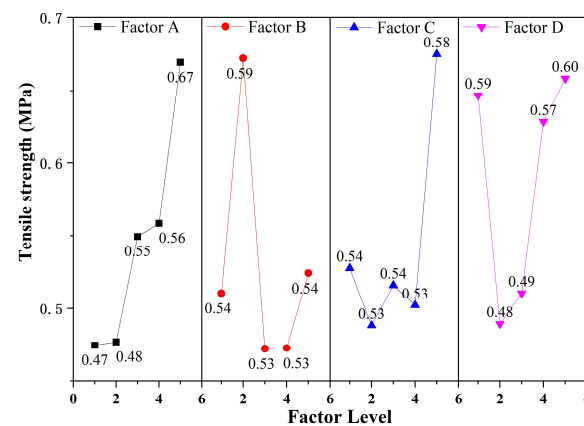


Figure 8. Tensile strength analysis of sandstone-like materials.

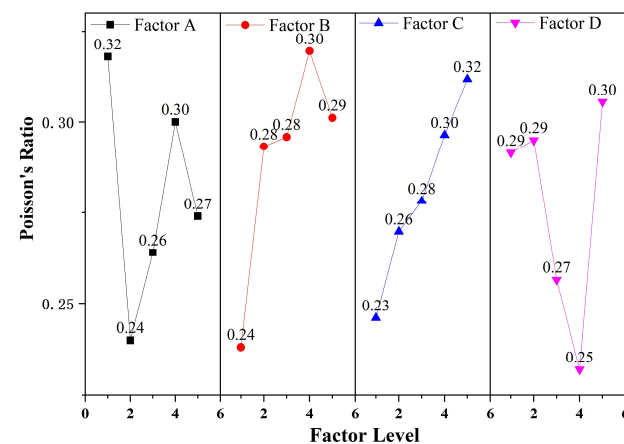


Figure 9. Poisson's ratio analysis of sandstone-like materials.

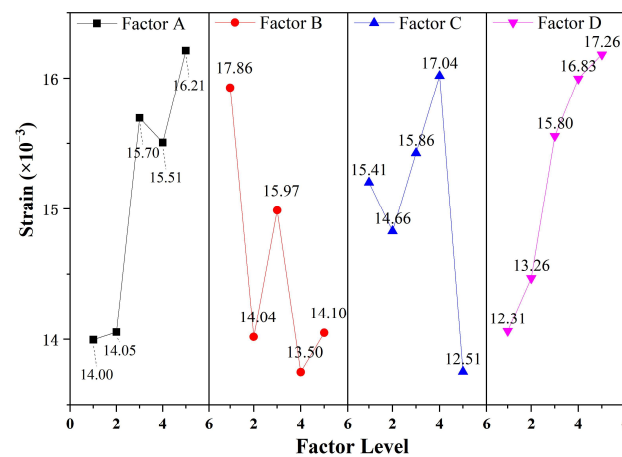


Figure 10. Strain analysis of sandstone-like materials.

In summary, the elastic modulus, compressive strength, and tensile strength of sandstone-like materials are primarily influenced by changes in factor A. By adjusting the level of factor A, the values of the elastic modulus, compressive strength, and tensile strength of sandstone-like materials can be changed. The level of factor C has the most significant effect on Poisson's ratio in sandstone-like materials, and by adjusting the level of factor C, the value of Poisson's ratio can be changed. In addition, changes in the level of factor D have a large effect on the strain value in sandstone-like materials. By adjusting the level of factor D, the strain value can be changed, allowing the physical and mechanical parameters of the sandstone-like material to be matched to those of the target rock. Polystyrene foam is available in different sizes ranging from 0.1 mm to 1 mm. Therefore, it is possible to simulate different sizes of damage in the sandstone-like specimen by selecting polystyrene foam particles with different diameters, thus changing the deformation during loading and adjusting the axial strain of the sandstone-like specimens.

A rigorous methodology has been used in this work to accurately elucidate the relationship between the constituent proportions of sandstone-like materials and their mechanical parameters. First, factor A, which was identified as the most influential variable on elastic modulus, compressive strength, and tensile strength, was selected as the independent variable. Consequently, a correlation equation was formulated between the elastic modulus, compressive strength, tensile strength, and factor A. Additionally, factor C, which was identified as the primary driver of Poisson's ratio, was designated as an independent variable, leading to the establishment of a correlation equation between Poisson's ratio and factor C. In addition, factor D, which was found to have the greatest influence on strain, was selected as the independent variable, resulting in the formulation of a correlation equation between strain and factor D. The equations and fit curves derived from this study are shown in Figures 11–15, while Table 6 shows the correlation equations between mechanical parameters, such as elastic modulus, and factor levels for sandstone-like materials.

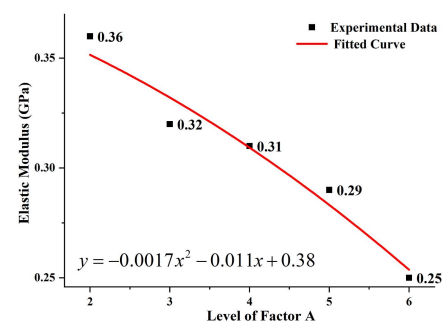


Figure 11. Fitting curve of elastic modulus.

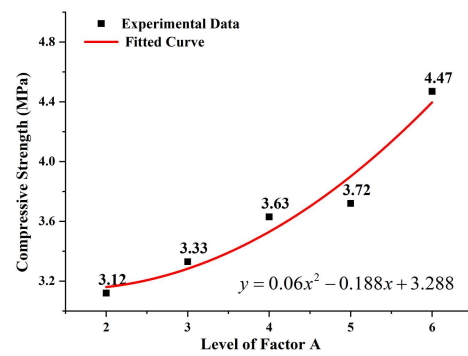


Figure 12. Fitting curve of compressive strength.

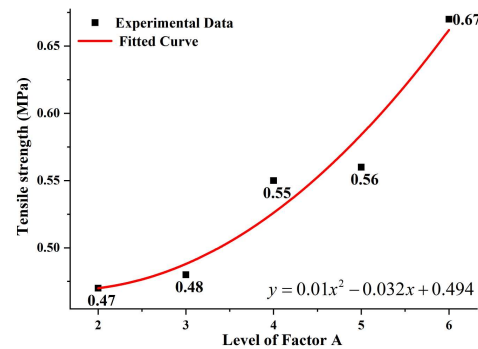


Figure 13. Fitting curve of tensile strength.

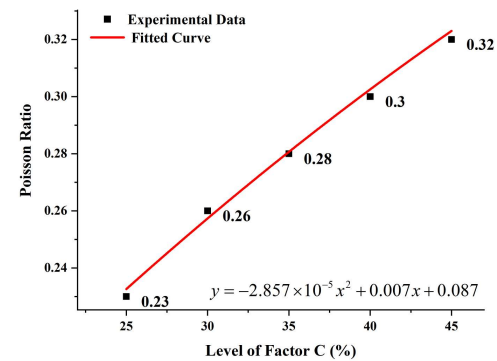


Figure 14. Fitting curve of Poisson's ratio.

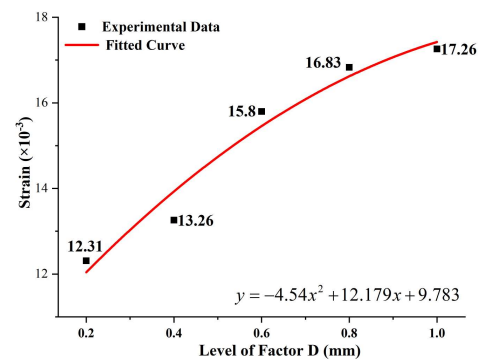


Figure 15. Fitting curve of strain.

Table 6. Fitting equations of parameters of sandstone-like materials.

Mechanical Parameter	Equation	R ²
Elastic Modulus	$y = -0.0017x^2 - 0.011x + 0.38$	0.95184
Compressive Strength	$y = 0.06x^2 - 0.188x + 3.288$	0.90189
Tensile Strength	$y = 0.01x^2 - 0.032x + 0.494$	0.90047
Poisson Ratio	$y = -2.857 \times 10^{-5}x^2 + 0.007x + 0.087$	0.97146
Strain	$y = -4.54x^2 + 12.179x + 9.783$	0.92684

Based on the results of the correlation equations presented in Table 6, it can be observed that the elastic modulus of the sandstone-like material has a negative correlation with factor A. On the other hand, the compressive and tensile strengths of these materials have a positive correlation with factor A, with their fitting equations being quadratic functions. The R² values for the fitting equations of the elastic modulus, compressive strength, and tensile strength are 0.95184, 0.90189, and 0.90047, respectively. These high R² values indicate a strong agreement and correlation between the fitting equations and the mechanical parameters of the materials. Additionally, the Poisson's ratio of sandstone-like materials is found to be positively correlated with factor C, and the fitting equation between these two variables is also a quadratic function. The R² value for this fitting equation is 0.97146, further supporting the high degree of fit and correlation with the test data. Similarly, the strain of sandstone-like materials is positively correlated with factor D, with the fitting equation also being a quadratic function. The R² value for this fitting equation is 0.92684, indicating a well-fitted curve and a strong correlation with the test data. Overall, the obtained fitting equations for the physical property parameters of sandstone-like materials allow for the preparation of specimens with different mechanical parameters by adjusting the levels of different factors within a certain range. This allows the simulation of real rocks and the study of their mechanical behavior and failure mechanisms through mechanical testing.

4.2. Discussion and Verification Test

In this paper, we have analyzed the effects of the proportions of aggregate and binder (factor A), the proportion of polystyrene foam in the entire model (factor B), the proportion of the binder and regulator (factor C), and the size of the polystyrene foam (factor D) on the elastic modulus, compressive strength, tensile strength, Poisson's ratio, and strain of sandstone-like materials, as well as the changing trends of the levels of the main influencing factors on each mechanical parameter.

Based on the analysis of the test results, it has been observed that the proportions of aggregate and binder (factor A) significantly influence the elastic modulus, compressive strength, and tensile strength of sandstone-like materials. The elastic modulus of these materials exhibits a gradual decrease as factor A increases. This trend can be attributed to the fact that the stability of the aggregate-supported structure is critical for sandstone-like materials. The cementing agent serves the purpose of bonding aggregates and enhancing the relative stability of the aggregate structure. As the proportion of aggregates in sandstone-like materials increases, the cohesion between the aggregates weakens, leading to a reduction in their resistance to elastic deformation and consequently a reduction in the elastic modulus. The elastic modulus changes little with factor B and factor C; the range is only 0.06, and this change is not significant for rock materials. Therefore, it is shown that factors B and C do not have a significant effect on the change in the value of the elastic modulus and are not suitable to be used as the main factor to regulate the elastic modulus of sandstone-like materials. The elastic modulus first decreases and then increases with the change in factor D. This may be due to the fact that the ability of the sandstone-like material to resist elastic deformation decreases as the damage size increases, but when the damage size exceeds the critical threshold, the sandstone-like material is destroyed at smaller deformations, which may instead lead to an increase in the calculated elastic

modulus due to the method used for the calculation of strain of the sandstone-like material in this paper, and the strain is also relatively small at small deformations.

Both the compressive and tensile strengths show a progressive increase as factor A is increased. This observation can be attributed to the use of 30 mesh river sand as the selected aggregate in this study, which has a larger size compared to the cement particles and therefore has a higher strength. Increasing the proportion of aggregate in sandstone-like materials strengthens the internal structural support within these materials, increasing their structural stability and consequently their overall strength. This, in turn, results in an increased resistance to destructive forces. The compressive and tensile strengths are not significantly affected by factor B. This may be due to the chosen damage percentage ratio in this paper, which does not significantly impact the strength values of sandstone-like materials at this ratio. The compressive strength exhibits a tendency of decreasing initially and then increasing with the increase in factor C. This suggests that the regulator has a significant impact on the compressive strength when it accounts for a larger proportion of factor C. Additionally, the gypsum powder exhibits strong plastic deformation after hardening, which causes the compressive strength to decrease as the level of factor C decreases. Increasing factor C enhances cohesion between components, leading to increased friction and compressive strength of the sandstone-like materials. However, the effect on tensile strength is not significant, except for a sudden increase at level 4, which may be due to the insignificant effect of cohesion on tensile strength in the sandstone-like material splitting test. Under the influence of factor D, the compressive and tensile strengths of the materials showed a trend of decreasing and then increasing, and the reason for this may be that the increase in damage size will make the strength of sandstone-like materials decrease; however, when the damage size continued to increase, the strength of the specimen increased instead, which may be due to the fact that the polyethylene foam material, although easily deformed, is not easily ruptured, and thus it may lead to an increase in the strength instead of a decrease. However, the reason for this is still unclear, and further experiments need to be conducted to analyze the cause, which the authors will further analyze in subsequent studies.

The Poisson's ratio is mainly influenced by the ratio of the binder and modifier (factor C). As the level of factor C increases, the Poisson's ratio also increases. This suggests that a higher proportion of binder leads to a more pronounced transverse deformation in sandstone-like material. The reason for this is the stronger bonding force between internal components due to a higher proportion of binder. As a result, more deformation is necessary for the specimen to fail and separate these internally bonded components. The analysis of Poisson's ratio indicates that factors A and D have little influence on the Poisson's ratio of sandstone-like materials and that there is no discernible pattern. Under the influence of factor B, Poisson's ratio shows an increasing trend. Only a slight decrease occurs at level 5, indicating that Poisson's ratio gradually increases with the proportion of damage. This may be due to the fact that EPS materials deform with large transverse deformations. As the percentage of damage increases, it makes the sandstone-like material deform relatively more in the transverse direction, and the Poisson's ratio becomes larger accordingly.

Furthermore, the level of strain increases in proportion to the size of the polystyrene foam particles. The use of polystyrene foam can explain this, as it has low strength and high deformability. As the size of the polystyrene foam increases, the volume of low strength and high deformability within sandstone-like materials also increases. This makes the specimens more susceptible to significant deformation under axial load. Under the influence of factor A, the strain exhibits a gradual increase, which is similar to the change in the elastic modulus with factor A. The increase in the proportion of aggregates within the material reduces the bonding and cohesion between them, resulting in a decrease in the material's ability to resist elastic deformation. As a result, the specimen is more likely to deform after a load is applied. However, the range of change in factor A is relatively small, and its adjustability is limited, making it unsuitable for adjusting the strain value. Regarding the range of strain, although factors B and C have relatively large ranges, they

are not suitable as the primary factors for adjusting the strain due to the irregularity of the strain's change under their influence.

4.3. Comparison Test between Sandstone-like Specimen and Sandstone

We evaluated the applicability of the sandstone-like material ratio scheme for damaged rock mass proposed in this study. Three representative rock masses, namely sandstone 1, sandstone 2, and sandstone 3, were carefully selected. Similarly, sandstone-like material specimens, denoted as sandstone-like 1, sandstone-like 2, and sandstone-like 3, were prepared to possess comparable mechanical properties. Mechanical tests were then conducted on each specimen individually. A comprehensive comparison was made between the physical and mechanical parameters, deformation characteristics, and failure patterns of sandstone and sandstone-like materials. The sandstones, namely sandstone 1, sandstone 2, and sandstone 3, were obtained from Zigong City, Sichuan Province. The sandstone samples 1, 2, and 3 were converted using the same coefficients as previously mentioned to determine their physical and mechanical parameters. The conversion data can be found in Table 7.

Table 7. Mechanical properties parameters of sandstone and sandstone-like materials.

Parameters	Compressive Strength (MPa)	Tensile Strength (MPa)	Elasticity Modulus (GPa)	Poisson's Ratio
Sandstone 1	62.91	11.25	5.24	0.25
Similarity parameter * 1	3.16	0.56	0.31	0.25
Sandstone 2	78.53	10.12	6.85	0.32
Similarity parameter * 2	3.93	0.51	0.34	0.32
Sandstone 3	68.21	12.5	6.91	0.27
Similarity parameter * 3	3.41	0.63	0.35	0.27
Sandstone-like 1	3.36	0.53	0.29	0.24
Sandstone-like 2	4.17	0.49	0.33	0.31
Sandstone-like 3	3.64	0.66	0.36	0.26

* Similarity parameter is the value calculated based on the similarity theory of each kind of sandstone.

Sandstone-like 1 is used to illustrate the procedure for producing sandstone-like materials. Upon comparing the mechanical property parameters of sandstone 1 with those listed in Tables 4 and 7, it is evident that they are similar to the parameters of the No. 3 experiment in the orthogonal test. Therefore, a minor adjustment to the elastic modulus is required based on No. 3. The range analysis results indicate that reducing the level of factor A can increase the elastic modulus of sandstone-like materials. There is a negative correlation between the elastic modulus and factor A. Based on a comprehensive analysis of No. 3, it is recommended to cautiously increase the level of factor A to produce sandstone-like specimens. After preparing multiple groups of specimens and conducting mechanical tests, it was determined that the optimal ratio for sandstone-like materials meeting the established conditions is river sand/cement/gypsum powder/EPS = 5:1:0.35:0.06. Additionally, using the same preparation process, specimens with akin mechanical properties to rocks B and C were successfully created based on experiments No. 15 and No. 17, with the ratios being river sand/cement/gypsum powder/EPS = 2:1:0.05:0.07 and river sand/cement/gypsum powder/EPS = 4:1:0.05:0.08, respectively.

Upon analysis of the rock failure pictures and the stress–strain curve presented in Figure 16, it is evident that the stress–strain curve for rock mass can be categorized into three distinct stages: the damage compaction stage, the elastic deformation stage, and the failure stage. During the stage of damage compaction, axial load effectively compacts the

initial damage in the rock, such as voids, cracks, and holes. Consequently, the internal constituents of the rock become denser, resulting in significant strain experienced by the rock during this stage. During the elastic deformation stage, the rock's strain increases linearly with applied stress. Once the rock reaches its peak strength, it loses its bearing capacity, resulting in numerous cracks on its surface. The sandstone samples exhibit wing cracks, which originate from both ends of the rock and extend towards the middle along the direction of the principal stress. Brittle failure is evident in all three types of sandstones. Uniaxial compression tests on sandstone-like materials have shown that their stress–strain curves have distinct stages: damage compaction, elastic deformation, and failure. During uniaxial compression tests conducted on sandstone-like materials, it has been observed that the stress–strain curves of these materials also exhibit distinct stages, which are damage compaction stage, elastic deformation stage, and failure stage. Cracks in the specimens were observed to initiate from the top and propagate towards the middle along the principal stress direction, coinciding with the concentration of simulated material damage. The sandstone-like material exhibited clear signs of brittle failure, with a loss of bearing capacity occurring after reaching peak strength. Analysis of the failure patterns and stress–strain curves of both sandstone and sandstone-like materials indicates that they exhibit similar deformation characteristics and failure patterns.

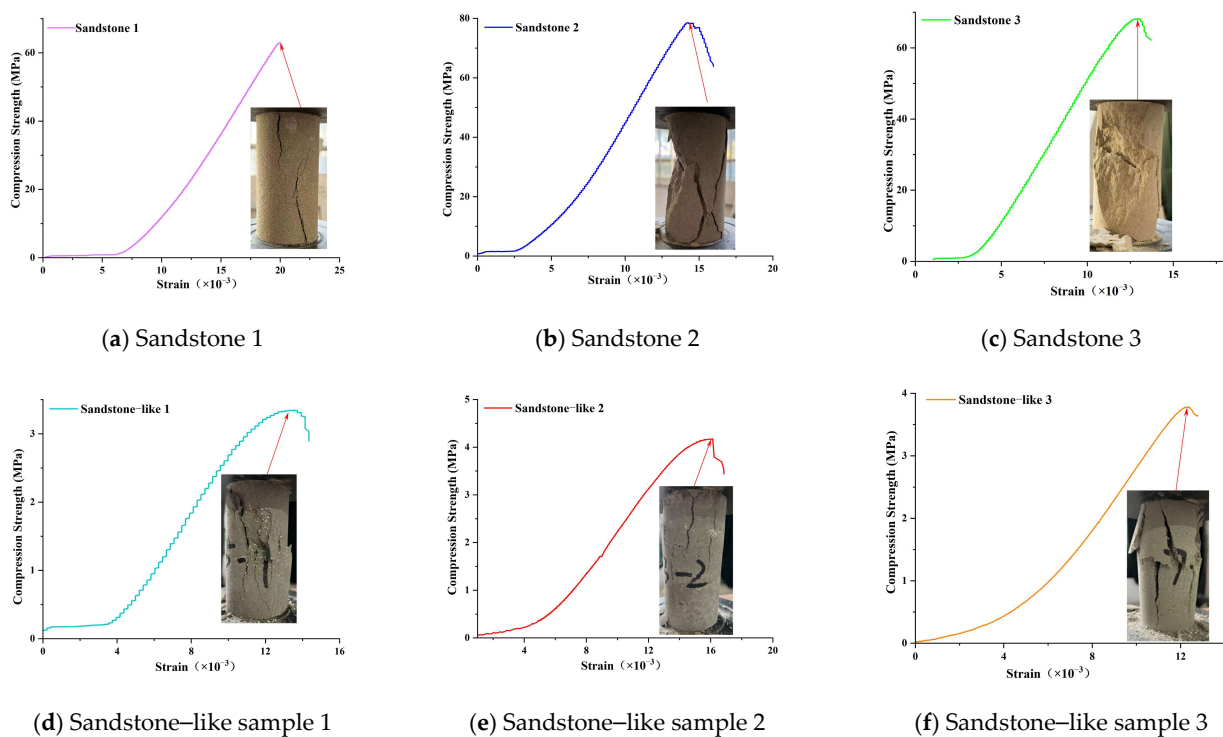


Figure 16. Comparison of failure patterns and stress–strain curves between sandstone and sandstone-like materials.

The mechanical parameters of the sandstone, calculated based on the similarity criterion, closely match those of sandstone-like materials from Table 7. The compressive strength, tensile strength, modulus of elasticity, and Poisson's ratio for sandstone 1 and sandstone-like 1 had errors of 5.9%, 5.7%, 6.9%, and 4.2%, respectively. The compressive strength, tensile strength, modulus of elasticity, and Poisson's ratio for sandstone 2 and sandstone-like 2 had errors of 5.8%, 4.1%, 3.0%, and 3.2%, respectively. Similarly, sandstone 3 and sandstone-like 3 had errors of 6.3%, 4.5%, 2.8%, and 3.8% in compressive strength, tensile strength, modulus of elasticity, and Poisson's ratio, respectively. Therefore, by comparing the failure modes, stress–strain curves, and mechanical parameters of sandstone-like materials and sandstone as mentioned above, it can be found that, based on the good simi-

ilarity between the sandstone-like materials and sandstone, sandstone-like materials can be used to replace sandstone in mechanical tests to investigate the mechanical properties and rupture modes of sandstone, which can alleviate the difficulties of obtaining sandstone materials in the deep part of the country, as well as the high cost of the tests.

5. Conclusions

In this study, the orthogonal test method was employed to prepare sandstone-like specimens for mechanical testing, which can serve as a substitute for deep damaged sandstone. River sand was used as an aggregate, and cement was used as a binder. An innovative approach was taken by using polystyrene foam (EPS) as a damage simulation material. The effect of four factors on the main mechanical parameters of sandstone-like materials was investigated. The findings indicate the following:

- (1) Polystyrene foam was chosen to simulate initial damage in sandstone due to its low strength and ease of deformation. The deformation and strain of sandstone-like materials can be adjusted by the use of different sizes of polystyrene foam, allowing for the characterization of the effect of initial damage on the strength and deformation of the rock mass. The use of polystyrene foam to simulate initial damage can better replicate the random and irregular distribution of damage.
- (2) The compressive strength, tensile strength, and elastic modulus of sandstone-like materials are mainly affected by the proportion of binder to aggregate (factor A). The compressive strength and tensile strength increase as factor A increases, while the elastic modulus decreases. Furthermore, the Poisson's ratio of sandstone-like material is predominantly affected by the proportion of binder to regulator (factor C), and the size of polystyrene foam (factor D) has the most significant impact on the strain. The strain of sandstone-like materials increases as factor D increases, while Poisson's ratio increases proportionally with the increase in factor C.
- (3) The mechanical test conducted on sandstone-like and sandstone specimens indicated that their mechanical parameters and failure modes are highly similar. The elasticity modulus, compressive strength, tensile strength, and Poisson's ratio of sandstone-like material and sandstone differ by no more than 7%. Both materials undergo three stages of damage: the compaction stage, the elastic deformation stage, and the failure stage. The broken specimens' surfaces display clear, extended cracks, indicating brittle and destructive characteristics. Sandstone-like materials may be a better alternative to sandstone for mechanical testing, studying the deformation law and failure mode of sandstone, and reducing the difficulty and high cost of obtaining damaged sandstone in large quantities.

The sandstone-like materials prepared in this paper can be used as a substitute for damaged rock mass in mechanical experiments. These tests can help to study the mechanical properties, deformation laws, and damage mechanisms of rock mass. By conducting mechanical experiments on sandstone-like materials, a constitutive equation can be established to describe the stress–strain relationship of the damaged rock mass. Creep tests can be used to establish a creep equation for sandstone-like materials. This equation can provide design and theoretical guidance for engineering practices such as the excavation of deep chambers and roadway perimeter rock support. However, the use of sandstone-like materials in theoretical research is limited. Substituting sandstone-like materials for rock mass can only be used to qualitatively analyze the deformation and failure mechanism of the rock mass, making it difficult to accurately quantify the deformation. Although the mechanical properties of sandstone-like materials are similar to those of rock mass, there is still a certain gap. The materials presented in this paper can be used to qualitatively analyze the deformation, destruction, and damage evolution of damaged rock mass. To conduct a quantitative analysis, it is essential to compare the mechanical parameters of sandstone-like material with those of sandstone. This comparison will help determine the range of error in the primary mechanical parameters of both materials, which can then be analyzed quantitatively.

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