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Research Article

Study and Application of Similar Material Ratio in Collapsible Loess

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The similar material of collapsible loess is the basis and premise of the experimental study on the surface movement and deformation law of coal seam mining in collapsible loess-covered areas. The orthogonal experiment is used to make up similar material with different proportions using river sand and barite powder as aggregate, clay and gypsum as cementing material, and diatomite as adjusting material. The reasonable proportion of similar material in collapsible loess is studied by using range analysis, similar simulation, and field measurement. The results show that the content of diatomite plays a leading role in the collapsibility coefficient of similar material, and the collapsibility coefficient is positively correlated with the content of diatomite; moisture content is the main control of the cohesion of the material, and cohesion is negatively correlated with the moisture content; the ratio of bone-to-glue has the most significant effect on the internal friction angle, and the internal friction angle is positively correlated with the ratio of bone-to-glue. The reasonable ratio of the similar material in collapsible loess is 8 : 2 of the ratio of bone-to-glue, the ratio of clay-to-gypsum is 9 : 1, the barite powder content is 6%, the diatomite content is 23%, and the moisture content is 13%, and the mechanical parameters of the collapsible loess are 5.3%–6.3% different from the target value of similar material through laboratory tests, which can meet the experimental requirements. It is verified by a similar simulation experiment that the maximum surface subsidence value and the surface fracture width in the simulation results are 6.9% and 7.8% different from the field measured results, indicating a high degree of agreement. The results of the study have important references and guiding significance for the preparation of similar material with similar models.

1. Introduction

Collapsible loess is a kind of typical aeolian deposits; the internal loose metastable structure is the main cause of its produce wet fall [1–3]. In the mining area covered by collapsible loess, there are significant surface cracks in the mining of coal seams, causing soil erosion and deterioration of the ecological environment [4]. Therefore, it is necessary to study the reasonable ratio of collapsible loess similar material for the use of a physical similar simulation experiment to study the surface subsidence law of coal seam mining in collapsible loess covered areas.

At present, scholars have conducted a lot of research on similar material of loess, there are mainly, Xu et al. [5] and Liu et al. [6] by controlling the on-site sampling and the compactness and moisture content of remolded loess in the laboratory to simulate surface loess for model experiments; Zhang et al. [7] developed collapsible loess-like materials with similar properties to the natural collapsible loess by using the air free-fall method; Chen et al. [8] prepared artificial structural loess by adding CaO, $CaCl_2$, cement, kaolin, and CO_2 to the undisturbed loess with a certain moisture content in sequence; Jiang et al. [9] added $CaCO_3$ to the undisturbed loess to prepare collapsible loess with large pores and internal connections, and through the collapsibility test, pressure and wetting can reduce the internal pores of the loess and cause collapsibility; Hu et al. [10] prepared structural loess with properties similar to the undisturbed loess by adding 0.7% $Ca(OH)_2$ and CO_2 gas to the air-dried undisturbed loess, and using triaxial shear and other experimental studies, it is concluded that the collapsibility and deformation of structural loess are directly related to the failure of structural strength; Zhao et al. [11] used real-time field observation method to the study and concluded that the collapsible deformation of loess soil without seepage holes was closely related to the vertical and lateral diffusion of water in the soil layer; Zhang et al. [12] studied the distribution of collapsibility grades of loess at different buried depths through indoor experiments and mathematical statistics, and concluded that the loess collapsibility coefficient decreases with the increase of natural moisture content.

The abovementioned research results mainly focus on the preparation of loess similar material and qualitative analysis of the influence of various factors on the mechanical properties of loess and its similar material. The lack of quantitative research and the method to determine the reasonable proportion of similar material leads to the difficulty to determine the proportion of similar material in the model experiment. Combining previous research results, the selection of river sand, barite powder, clay, gypsum, and diatomite as similar material's raw materials, which are studied with orthogonal test and extreme difference analysis method to determine the reasonable proportion of collapsible loess similar material, and applied to the similar simulation experiment, for the preparation of the loess similar material and reasonable proportion of research to provide the reference.

2. Selection of Similar Raw Materials

2.1. Mechanism of Collapsible Loess. At present, scholars at home and abroad have many different arguments on the cause and mechanism of loess collapsibility, which can be summarized in two aspects: On the one hand, its internal porous structure and material composition (composition of particles, mineral composition, etc.); on the other hand, the special granular overhead structure system existing in the loess internal structure is destroyed mainly by the external water and pressure so that the pores in the overhead structure system and the intergranular void are destroyed, and the original equilibrium state between particles is broken, and the loess collapse is finally induced [13].

2.2. Selection Principles of Raw Materials. The key to the success of a similar simulation experiment is the selection of similar material [14]. Based on the mechanism of loess collapsibility and the previous research results [15–18], the preparation of similar material should follow the following principles:

(1) The material is composed of granular particles and must have a dense structure after mixing and stirring evenly

(2) Similar material has larger bulk density and smaller porosity, so materials with larger density and smaller particle size should be selected

(3) The cementation material should be selected with weak cementation to reduce the strength of the mixed material, and the performance is stable

(4) The material itself must have a large pore or porous structure, which can simulate the collapsible loess similar to the collapsible material of the characteristics

(5) In order to meet the requirements of different similarity ratios, the variation range of mechanical parameters of similar material can be adjusted by changing the proportion of similar material

2.3. Determination of Raw Materials

(1) *Aggregate*. ① River sand: The selected river sand with the same particle size can provide certain strength and permeability for similar materials. ② Barite powder (325 mesh): With low hardness and high density, it can be used as a counterweight material to adjust the bulk density of similar materials as shown in figures 1(a) and 1(b).

(2) *Cementing materials*. ① Clay: Clay with uniform particles is chosen after the screening, which has a certain degree of water absorption, low strength, low permeability, and moderate cohesiveness. ② Gypsum: Stable performance, with a certain strength and adhesion [19] as shown in figures 1(c) and 1(d).

(3) *Regulating material.* Diatomite: After encountering water, the strength is significantly reduced, and the number of microscopic surface pore structure units is large, which shows the characteristics of small pores and a large number of pores in the macroscopic view [20], it can be used to adjust the collapsibility of similar material as shown in figure 1(e).

3. Orthogonal Test Scheme for Similar Materials

3.1. Orthogonal Experimental Design. The orthogonal test design selects the collapsibility coefficient, cohesion, and internal friction angle of similar material of collapsible loess as the inspection indicators, and selects the following five factors (mass ratio) as the influencing factors of the orthogonal test: bone-to-glue ratio (aggregate/cement material), clay-to-gypsum ratio (clay/gypsum), barite powder content (barite powder/aggregate), diatomite content (diatomite/total mass), and moisture content (water/total mass), each factor is designed with 5 levels. The experiment selects the orthogonal experiment table L25 (5^5) of "5 factors and 5 levels" to design the orthogonal experiment. In order to highlight the uniformity and uniformity of the points selected in the test, each factor is designed with an equal interval of changes in the test plan [21]. The orthogonal design level is shown in Table 1.

3.2. Determination of Mechanical Parameters of Similar Materials. After the selected materials are dried, the materials are weighed in proportion according to the

River sand (a) Barite powder (b) Clay (c) Plaster (d) Diatomite (e)

Figure 1: Similar raw materials: (a) river sand, (b) barite powder, (c) clay, (d) plaster, and (e) diatomite.

Table 1: Orthogonal design level of similar materials.

Level	Influencing factors				
	Bone-to-glue ratio	Clay-to-gypsum ratio	Barite powder content (%)	Diatomite content (%)	Moisture content (%)
1	5 : 1	5 : 5	0	5	7
2	7 : 1	6 : 4	6	10	11
3	9 : 1	7 : 3	12	15	15
4	11 : 1	8 : 2	18	20	19
5	13 : 1	9 : 1	24	25	23

orthogonal experiment design scheme shown in Table 1, mixed and stirred evenly, and then loaded into the $\varphi 61.8 \times 20$ mm specimen to prepare the similar material samples. After the production is completed, in order to prevent the evaporation of water, a sealed bag is used to store, as shown in Figure 2, and in accordance with GB/T 50266-2013 "Engineering Rock Mass Test Method Standard" [22] to test the mechanical parameters of the specimen.

Figure 2: Similar material samples.

3.2.1. Test of Loess Collapsibility. The collapsibility of loess is mainly reflected by the collapsibility coefficient, according to the "Building Standards for Collapsible Loess Areas" [13], the WG type single lever consolidation instrument is used to carry out the collapsibility consolidation test to determine the collapsibility coefficient of each group of similar material. The calculation method of collapsibility coefficient is as

$$\delta_s = \frac{h_p - h_p'}{h_0}. \tag{1}$$

In the formula, δ_s is the collapsibility coefficient; h_p is the height when the sinking is stable after pressurizing 200 KPa, mm; h_p' is the height when the sinking is stable after immersion (saturation), mm; and h_0 is the original height of the sample, mm.

It can be seen from the "Building Standards for Collapsible Loess Areas" [13], $\delta_s \leq 0.03$ is weakly collapsible loess; $0.03 < \delta_s \leq 0.07$ is moderately collapsible loess; $\delta_s > 0.07$ is strongly collapsible loess, the deformation failure and mechanical strength attenuation of collapsible loess are particularly significant after soaking in water.

3.2.2. Loess Direct Shear Test. A strain-controlled direct shear tester is used to perform shear tests on each group of similar materials. The shear stress and normal stress of each group of specimens are measured separately, and then the cohesive force c and internal friction angle φ of each group of materials are determined according to the Coulomb criterion.

$$\tau = c + \sigma \tan \phi. \tag{2}$$

In the formula, τ is the shear stress, KPa; σ is the normal stress, KPa; c is the cohesion, KPa; and φ is the internal friction angle, °.

4. Analysis of Orthogonal Test Results

Through collating and analyzing the test results of mechanical parameters of similar materials, the collapsibility coefficient, cohesive force, and internal friction angle of the materials with similar proportions are obtained, as shown in Table 2. Further analysis of the data in Table 2 shows that the mechanical parameters of similar materials with different ratios have a wide distribution range, the collapsibility coefficient is distributed between 0.01 and 0.087, the cohesive force is between 0.05 KPa and 18.41 KPa, and the internal friction angle is between 3.49° and 30.01°. When conducting similar material simulation experiments, appropriate similarity constants can be selected according to the mechanical parameters of the prototype loess on the surface, and the mechanical parameters of similar material can be within the test range by adjusting the ratio of similar material.

Table 2: Orthogonal test results.

Test number	Influencing factors					Inspection index		
	Bone-to-glue ratio	Clay-to-gypsum ratio	Barite powder content (%)	Diatomite content (%)	Moisture content (%)	δ_s	c (KPa)	φ (°)
A1	5 : 5	5 : 1	0	5	7	0.056	10.31	28.41
A2	5 : 5	7 : 1	6	10	11	0.051	18.41	23.76
A3	5 : 5	9 : 1	12	15	15	0.068	0.64	9.94
A4	5 : 5	11 : 1	18	20	19	0.072	5.97	8.21
A5	5 : 5	13 : 1	24	25	23	0.053	7.85	3.49
A6	6 : 4	5 : 1	6	15	19	0.054	6.94	16.13
A7	6 : 4	7 : 1	12	20	23	0.049	0.98	7.18
A8	6 : 4	9 : 1	18	25	7	0.087	13.95	15.43
A9	6 : 4	11 : 1	24	5	11	0.046	13.56	13.85
A10	6 : 4	13 : 1	0	10	15	0.066	4.65	27.64
A11	7 : 3	5 : 1	12	25	11	0.076	13.58	28.95
A12	7 : 3	7 : 1	18	5	15	0.032	0.12	25.98
A13	7 : 3	9 : 1	24	10	19	0.059	0.29	10.03
A14	7 : 3	11 : 1	0	15	23	0.046	8.69	22.34
A15	7 : 3	13 : 1	6	20	7	0.075	7.51	27.68
A16	8 : 2	5 : 1	18	10	23	0.024	0.09	16.24
A17	8 : 2	7 : 1	24	15	7	0.068	8.43	28.49
A18	8 : 2	9 : 1	0	20	11	0.074	0.57	29.68
A19	8 : 2	11 : 1	6	25	15	0.080	15.30	18.96
A20	8 : 2	13 : 1	12	5	19	0.032	0.68	30.01
A21	9 : 1	5 : 1	24	20	15	0.044	0.75	24.89
A22	9 : 1	7 : 1	0	25	19	0.058	4.68	16.31
A23	9 : 1	9 : 1	6	5	23	0.010	0.05	28.75
A24	9 : 1	11 : 1	12	10	7	0.060	4.65	29.64
A25	9 : 1	13 : 1	18	15	11	0.068	0.42	27.85

5. Sensitivity Analysis of Various Factors

The extremum difference analysis method is to determine the degree of influence of the factor on the inspection index when different levels of the factor are selected by analyzing the extreme difference of each factor [23]. According to the orthogonal experiment theory, the average value of the results of the same level of each factor is taken, the extreme difference is obtained by subtracting the minimum value from the maximum value in the average value. The impact of the test results is relatively large, which is an important factor, and vice versa is relatively small [24, 25]. The sensitivity of the influencing factors of each index is analyzed by the range analysis method.

According to the result of the orthogonal experiment, the extreme difference (R) of each factor level is obtained as shown in Table 3.

5.1. Sensitivity Analysis of Factors Affecting Collapsibility. From the data in Table 3, it can be seen that the extreme difference of diatomite content is the largest, followed by the moisture content, and the extreme difference of barite powder content is the smallest, indicating that the diatomite content plays a major role in controlling the collapsibility of similar material. The sensitivity of each factor to collapsibility in descending order is diatomite content, moisture content, bone-to-glue ratio, clay-to-gypsum ratio, and barite powder content. According to the results of the orthogonal experiment, the average value of the same level of each influencing factor is obtained, and the intuitive analysis diagram of the influence of each factor on the collapsibility is shown in Figure 3.

It can be seen from Figure 3 that the collapsibility coefficient is positively correlated with the diatomite content and the clay-to-gypsum ratio; it is negatively correlated with the moisture content and the bone-to-glue ratio; as the proportion of aggregate in the bone-to-glue ratio becomes larger and larger, the cement material accounts for the ratio is getting smaller and smaller, which causes the collapsibility coefficient to increase slowly with the increase of the clay-to-gypsum ratio. It is found from the visual diagram that the influence of barite powder content on the collapsibility coefficient of similar material is not obvious.

5.2. Sensitivity Analysis of Factors Affecting Cohesion. It can be seen from the data in Table 3 that the extreme difference of moisture content is the largest, followed by the bone-to-glue ratio, and the extreme difference of barite powder content is the smallest, indicating that the moisture content has the greatest influence on the cohesion of similar material and plays a major role in the cohesion. The sensitivity of each factor to cohesive force in descending order is moisture content, bone-to-glue ratio, diatomite content, clay-to-gypsum ratio, and barite powder content. According to the results of the orthogonal experiment, the average value of the same level of each influencing factor is obtained, and the intuitive analysis diagram of the influence of each factor on the cohesion is shown in Figure 4.

Table 3: Range analysis of each factor.

Material parameters	The extreme difference (R)				
	Bone-to-glue ratio	Clay-to-gypsum ratio	Barite powder content (%)	Diatomite content (%)	Moisture content (%)
δ_s	0.016	0.014	0.006	0.041	0.038
c (KPa)	6.53	5.41	3.74	6.13	6.67
φ (°)	10.73	4.73	8.50	8.77	10.33

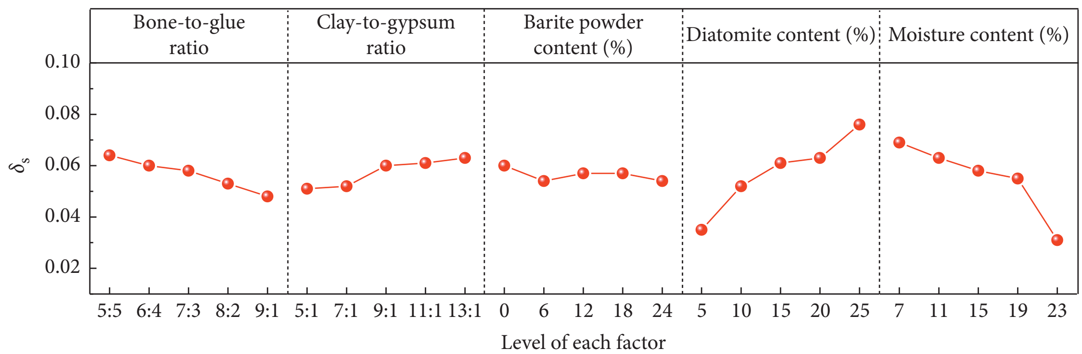


Figure 3: Intuitive analysis of collapsibility sensitivity.

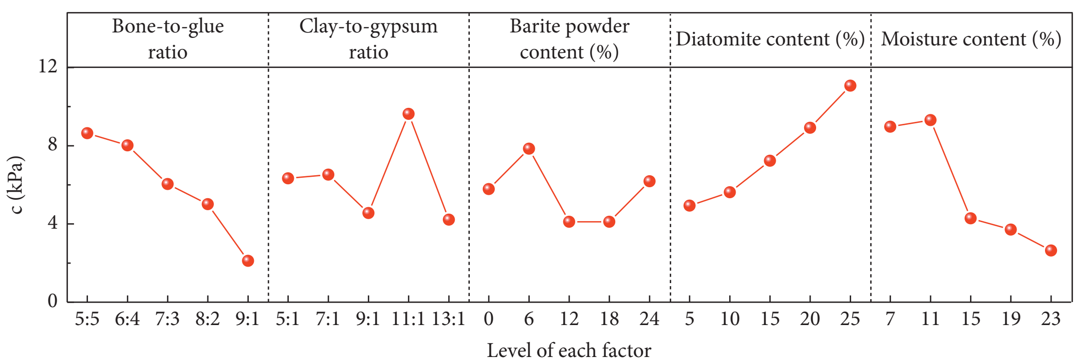


Figure 4: Intuitive analysis of cohesion sensitivity.

It can be seen from Figure 4 that the cohesive force of similar material is negatively correlated with the bone-to-glue ratio; it is positively correlated with the diatomite content. The higher the content of diatomite, the greater the cohesion and the more obvious the viscosity characteristics of similar material. The influence of moisture content on the cohesive force of similar material first increases and then decreases, and there is an optimal moisture content (about 11%) to maximize the cohesive force of the material, above this value, the similar material can show a certain fluidity due to excessive water, this is consistent with the research conclusions of the literature [15]. From the visual diagram, it is found that the clay-to-gypsum ratio and the content of barite powder have little effect on cohesion.

5.3. Sensitivity Analysis of Influencing Factors of Internal Friction Angle. From the data in Table 3, it can be seen that the extreme difference of bone-to-glue ratio is the largest, the extreme difference of barite powder content and diatomite content are similar, and the extreme difference of clay-to-gypsum ratio is the smallest, it shows that the bone-to-glue ratio plays a major role in controlling the internal friction angle of similar materials. The content of barite powder and the content of diatomite have the same effect on the internal friction angle of similar materials. The sensitivity of each factor to the angle of internal friction in descending order is the bone-to-glue ratio, moisture content, diatomite content, barite powder content, and clay-to-gypsum ratio. According to the results of the orthogonal experiment, the average value of the same level of each influencing factor is obtained, and the intuitive analysis diagram of the influence of each factor on the angle of internal friction is shown in Figure 5.

It can be seen from Figure 5 that the internal friction angle is positively correlated with the bone-to-glue ratio; it is negatively correlated with the moisture content, diatomite content, and barite powder content; due to the small particle size of the barite powder selected in the experiment, the sandy characteristics of the aggregate is weakened, and the internal friction angle decreases with the increase of the

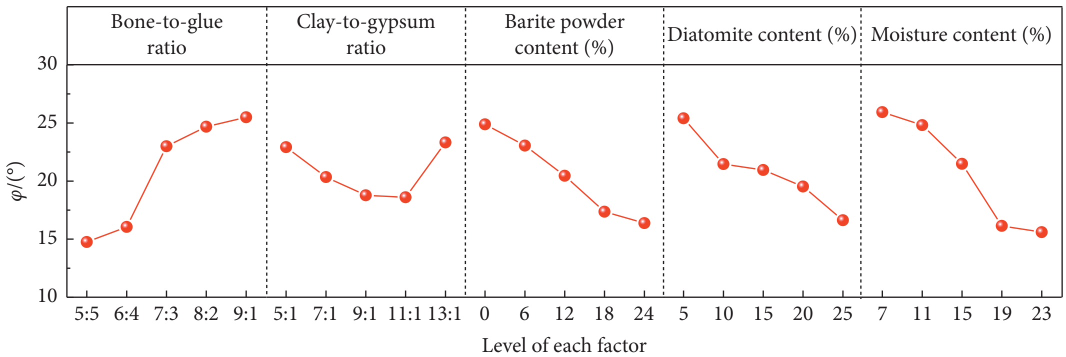


Figure 5: Intuitive analysis of the sensitivity of internal friction angle.

barite powder content. It is found from the visual diagram that the influence of the clay-to-gypsum ratio on the internal friction angle of similar material is not obvious.

6. Similar Simulation Experiment

6.1. Proportion of Similar Material. The experiment selected a mine in the Yushen mining area in northern Shaanxi as the research object. The coal seam mined in the mine is 2^{-2} coal seam with a simple structure, with a thickness variation of 0.5 m to 5.2 m, an average coal thickness of 4.5 m, and an inclination of 2 to 4°. It is a nearly horizontal coal seam. The buried depth of the coal seam is generally about 130 m. The 2304 fully mechanized mining face has been mined, the strike length is 1800 m, the inclined length is 270 m, and the roof is managed by all caving methods. The surface of the 2304 working face is Quaternary Malan.

Malan formation loess, and the underlying Lishi formation loess, both of which have typical collapsibility, with a total average thickness of about 21.4 m.

According to the aforementioned collapsible loess ratio scheme and sensitivity analysis results, the corresponding similar material is prepared and the mechanical parameter tests and model experiments are carried out. The similarity simulation experiment selects the geometrical similarity constant $\alpha_l = 150$. Through field sampling and testing in the laboratory, the mechanical parameters of prototype loess and the theoretical values of mechanical parameters of similar material are shown in Table 4.

Comparing Tables 2 and 4, the ratio of similar material should be appropriately increased on the basis of the no A18 of the orthogonal test to increase the cohesive force of the material and reduce the collapsibility coefficient and internal friction angle. The results of the range analysis show that increasing the moisture content on the basis of 11% can effectively reduce the values of the three at the same time. Increasing the content of barite powder can also reduce the internal friction angle of the material and increasing the content of diatomite can increase the cohesion of the material. Thus, on the basis of no A18 of the appropriate test ratio increase moisture content, the content of barite powder, and diatomite content, after many proportioning tests, it is finally determined that the proportions of similar material in the model are bone-to-glue ratio 8 : 2, clay-to-gypsum ratio 9 : 1, barite powder content 6%, diatomite content 23%, and moisture content 13%. The mechanical parameters of the similar material being tested, and the results are shown in Table 4. Among them, the mechanical parameters of similar materials are in good agreement with the target values, and the deviations are respectively 5.6% of the collapsibility coefficient, 6.3% of the cohesive force, and 5.3% of the internal friction angle, which meet the requirements of the experiment.

Table 4: Mechanical parameters of prototype loess and similar material.

Type	δ_s	c (KPa)	φ (°)
Prototype loess test value	0.071	95	27.13
Similar material target value	0.071	0.63	27.13
Similar material test value	0.075	0.59	28.57

6.2. Simulation Experiment. This similar simulation experiment uses a similar simulation experiment device based on curvature deformation independently developed by the Xi'an University of Science and Technology, as shown in Figure 6. The device uses a curvature deformation adjustment mechanism to adjust the curvature deformation of the rock and soil layer, instead of the manual mining process of the coal seam, has convenient operation, high experiment accuracy, and strong maneuverability, and avoids wastage of experimental materials and manpower.

A similar simulation experiment is used to simulate the surface movement and failure characteristics of coal seam mining in the rainy season. By wetting the loess from the top of the model, it is used to simulate the loess layer after rain in the rainy season. The experimental model is shown in Figure 7.

After the simulated excavation, the measured width of the surface crack is 0.1–2.3 mm (as shown in Figure 8(a)), which is located behind the open-off cut, and the maximum subsidence value of the surface is 2602 mm.

By arranging the surface movement and deformation observation station, the long-term observation of the surface movement of the 2304 working face showed that the maximum surface crack width is 0.32 m (as shown in Figure 8(b)), which is located behind the open-off cut of the working face, and the maximum surface subsidence value is 2435 mm.

The surface subsidence curve measured on-site and the experimental simulated surface subsidence curve is shown in Figure 9.

FIGURE 6: Similarity simulation experimental device.

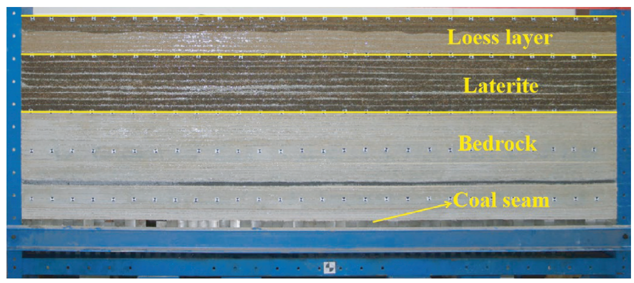
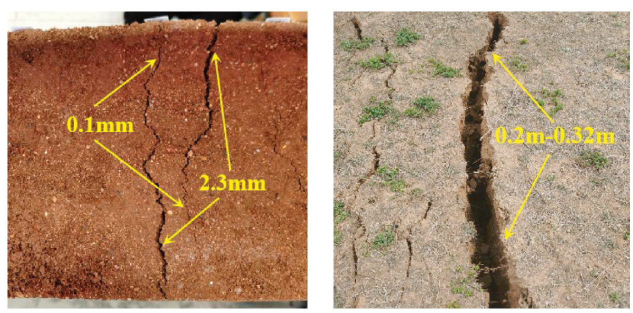


FIGURE 7: Similarity simulation experimental model.



Similarity simulation experiment

(a)

On-site measurement

(b)

FIGURE 8: Surface fracture diagram. (a) Similarity simulation experiment. (b) On-site measurement.

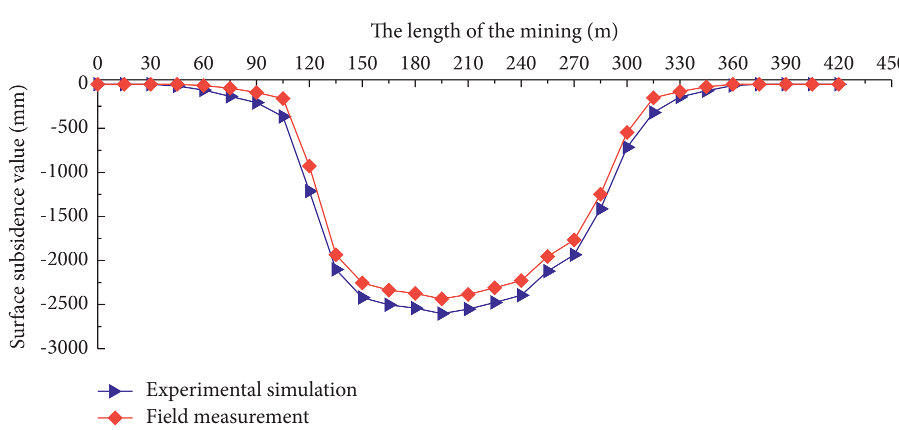


FIGURE 9: Surface subsidence curve.

The width of the surface cracks and the maximum surface subsidence in the field measured results are in good agreement with the results of the similar simulation experiment, and the deviations are 7.8% and 6.9%. It shows that the similar simulation material based on the orthogonal experiment design has good similarity with the ground prototype loess. The research results have a good reference significance for exploring the movement law of collapsible loess surface.

7. Conclusions

(1) The results of the range analysis show that the diatomite content plays a leading role in the collapsibility coefficient of the material, and the collapsibility coefficient is positively correlated with the diatomite content; the moisture content has the greatest influence on the cohesion of the material, and the cohesion first increases and then decreases with the increase of the moisture content; The main control effect of the internal friction angle is the bone-to-glue ratio, and the internal friction angle is positively correlated with the bone-to-gel ratio, and sorted the sensitivity of each factor.

(2) Based on the results of the range analysis and the similarity ratio of the similar simulation experiment, it is determined that the reasonable ratio of similar material in the model experiment is bone-to-glue ratio 8 : 2, clay-to-gypsum 9 : 1, barite powder content 6%, diatomite content 23%, and moisture content 13%, after laboratory tests, its mechanical parameters are in good agreement with the ground prototype loess.

(3) A reasonable proportioning scheme was used to prepare the similar material for collapsible loess and a similar simulation experiment is carried out, the simulation results of the experiment are basically consistent with the field measured results. The results of this study can provide a reference for the preparation of similar materials in similar model experiments.

Data Availability

The data used in the results of this study are included in the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

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