

Development and Application of a New Type of Geomechanical Similar Materials

Daohong Qiu, Yiguo Xue*, Maoxin Su, Nan Zhang, Xinwei Mu

*Research Center of Geotechnical and Structural Engineering,
Shandong University, Jinan 250061, China*

Abstract

Field exploration of steep rocky slope of Zengziyan suggests that the proposed similar materials of the rock possess fluid-solid coupling property and are similar to limestone. It requires that the materials have similar mechanical properties of limestone, such as high density and strength which will be basically unchanged after immersion, and homogeneous particle gradation. Through numerous tests of different proportion combinations, the materials were prepared by applying normal sand and fly ash as aggregate, ordinary portland cement and high purity vaseline as coagulant, and stirring them with appropriate water. Then by carrying out lots laboratory tests, the influences of different proportions on material parameters were systematically investigated and the main components which influence the properties of the similar materials were determined. The similar materials have been successfully applied to the geomechanical model experiments of steep rocky slope of Zengziyan. Mechanical and water physical properties of the materials satisfy the test requirements; therefore proper materials are provided for obtaining favorable experimental results.

Key words: ROCK SLOPE, SIMILAR MATERIALS, MODEL TEST

1. Introduction

Underground mining disrupts original stress equilibrium within the surrounding rock of mining area, leading to strata movement, deformation and damage. When mining area reaches certain scope, the movement taken place in surrounding area of slope will extend to ground and cause disasters such as surface deformation and ground settlement and mountain landslide. Such issues damage ecological environment, and directly threaten human safety. Underground mining caused geological hazards, including mountain

landslide and collapse, particularly in central and western mountainous areas of China, have produced huge losses to China. For instance, in 1982, the Yanchihe collapse in Hubei Province resulted by mining phosphate rock caused 284 death and destroyed the whole mine. To reduce the damage of Xiangshan landslide in Hancheng in 1985, 40 million RMB was spent in taking ground antiskid measures. On June 5, 2009, the huge landslide-debris flow of Jiweishan in Wulong, Chongqing, which was 2,150 m in length and 7 million m³ in volume, caused 74 death and

8 hurt. However, the law of mountain instability induced by mining has not been sufficiently studied. It is still difficult to warn and prevent landside disasters early [1, 2, 3, 4, 5]. Therefore, it is of vital theoretical and social significance in carrying out research on the stability evaluation of mining influenced steep slope and on disaster evolution mechanism.

The stability of steep slope is mainly investigated through theoretical research, physical model and numerical analysis. With the ongoing innovation and development of model test relevant technologies, laboratory physical model test presents unique advantages [6, 7, 8]. The key to a successful model test lies in whether various properties of model materials are similar to mechanical properties of rock and soil mass. Numerous studies have been carried out on the development of similar materials. Main research directions are as follows: 1) based on subsea tunnel, similar materials for fluid-solid coupling of underground engineering have been studied by utilizing materials of sand, barite powder, and iron powder; 2) based on underground reserve storage, similar materials of salt rock creep have been investigated by using materials of fine iron powder, barite powder, sand, and rosin; 3) based on the stability of the surrounding rock of highway tunnel, similar materials of the surrounding rock have been researched; 4) based on treating underground radioactive nuclear waste, similar materials of buffer and backfill materials have been investigated mainly applying the mixture of bentonite and sand[9,10,11,12]. However, the similar materials of steep rocky slope under special geological conditions are seldom studied in the research mentioned above, without significant achievements.

Field exploration of steep rocky slope of Zengziyan suggests that the proposed similar materials of the rock possess fluid-solid coupling property and are similar to limestone. It requires that the materials have similar mechanical properties of limestone, such as high density and strength which will be basically unchanged after immersion, and homogeneous particle gradation. By referring previous research achievements and based on similar theory of fluid-solid coupling, the paper developed a new kind of fluid-solid coupled similar materials for experiments by carrying out lots tests of different proportions. And the material was successfully applied to the model test of Zengziyan steep rocky slope.

2. Similarity theory of fluid-solid coupling

Similarity principles of model test require that the geometric size, boundary conditions and

load of the model and the bulk density, strength, deformation and water physical properties of similar materials have to follow certain similarity laws. Based on elasticity equation, dimensional analysis, and combined with fluid-solid coupling theory, the following similar relations are deduced [13, 14, 15].

Based on dimensional analysis, physical quantities of all dimensions are 1 and similarity ratios of equal dimensional physical quantities are equal. Therefore, we obtain

$$C_\varepsilon = C_\varphi = C_\mu = 1 \quad (1)$$

$$C_\sigma = C_{\sigma_c} = C_{\sigma_t} = C_E = C_c \quad (2)$$

According to physical equation, the similar relation among similarity ratio of displacement (C_δ), geometric similarity ratio (C_L), and strain similarity ratio (C_ε) is:

$$C_\delta = C_\varepsilon C_L \quad (3)$$

Based on dimensional analysis, the similar relation among stress similarity ratio (C_σ), similarity ratio of bulk density (C_γ), and geometric similarity ratio (C_L) and such relation among stress similarity ratio (C_σ), similarity ratio of elastic modulus (C_E) and strain similarity ratio (C_ε) are respectively expressed as

$$C_\sigma = C_\gamma C_L \quad (4)$$

$$C_\sigma = C_\varepsilon C_E \quad (5)$$

According to the fluid-solid coupled mathematical model of continuous and homogeneous medium, the similarity theory of fluid-solid coupling is deduced. And the similar relation among similarity ratio of permeability coefficient (C_K), geometric similarity ratio (C_L) and similarity ratio of bulk density (C_γ) is

$$C_K = \frac{\sqrt{C_L}}{C_\gamma} \quad (6)$$

In Equations (1)~(6), γ is bulk density, L is length, δ denotes displacement, ε denotes strain, E refers to elastic modulus, σ is stress, σ_t denotes tensile strength, σ_c is compressive strength, c denotes cohesion, φ is internal friction angle, μ refers to poisson ratio, and K is permeability coefficient.

3. Preparation of similar materials

3.1. Selection of original materials

Field exploration of steep rocky slope of Zengziyan suggests that the proposed similar materials of the rock possess fluid-solid coupling property and are similar to limestone. It requires that the materials have similar mechanical properties of limestone, such as high density and strength which will basically unchange after

immersion, and homogeneous particle gradation. By referring relevant literatures, different materials put forward in literatures were tested. After grasping related mechanical properties of the materials, according to test requirements, ordinary abrasive sand and fly ash were selected as aggregate, and ordinary portland cement and

high-purity vaseline were adopted as coagulant. After adding suitable amount of water in the above materials, the mixture was stirred. The basic components of the similar materials are illustrated in Figure 1.



Figure 1. Basic ingredient of limestone similar materials

In the preparation of similar materials, the particle diameter of standard sand is less than 1 mm and the sand is of homogeneous gradation. In addition, the finenesses of fly ash and barite powder are 1,250 and 625 mesh respectively; the cement is high-quality P.O.32.5 portland cement; and the vaseline is of high purity.

3.2. Preparation of samples

Based on the properties of material components, the steps of preparation are presented below.

(1) Aggregates and coagulants were weighed according to the proportions of test materials.

(2) Four fine materials: sand, barite powder, fly ash, and cement, were mixed and stirred uniformly.

(3) Vaseline was heated on alcohol burner and poured in the stirred materials to uniformly mix with other materials after melting.

(4) Suitable amount of water was weighed according to the proportions of test materials and then sufficiently stirred with the materials.

(5) The materials were poured in the mould for rapid compression moulding as long as they were uniformly mixed.

(6) The materials were demoulded and maintained at room temperature after moulding.

3.3. Tests of basic mechanical parameters

3.3.1. Test for the density of the sample

Following the weighing of each group of samples, the heights were measured using vernier caliper. Based on the bottom area of the mould, the corresponding densities were calculated. Considering the characteristics of limestone in the unstable rock mass of Zengziyan in Chongqing, in the model test, the corresponding orthogonal test was designed. By adjusting the proportions of different components, the density and strength of the similar materials were changed correspondingly. The parameters of several test samples are presented in Table 1.

Table 1. The basic parameters of the statistical test block

Specimen No.	Height (cm)	Quality (g)	Volume (cm ³)	Density (g/cm ³)
1	10.15	430.25	199.19	2.16
2	10.05	431.93	197.23	2.19
3	10.20	422.38	200.18	2.11
4	10.00	386.61	196.25	1.97
5	10.10	422.19	198.21	2.13
6	10.10	408.31	198.21	2.06
7	10.15	440.21	199.19	2.21
8	10.10	414.26	198.21	2.09

The above data suggest that the density of the similar material of limestone ranges from 1.97 to 2.25 g/cm³; the prepared similar materials are lighter than that of the similar materials of the original rock. However, based on similar formula, test requirements can be satisfied through conversion calculation.

3.3.2 Test for uniaxial compressive strength and elastic modulus

To obtain the uniaxial compressive strength and elastic modulus of the similar materials, cylindrical samples of 5 cm in diameter and 10 cm in height were made according to the requirements of relevant standards. Afterwards, the samples were tested on the electrohydraulic servo tester for the rigid pressure of the rock. By collecting the complete stress-strain curve in the compression process, the typical stress-strain curve of the samples was obtained, as illustrated in Figure 2; while the field photograph is presented in Figure 3.

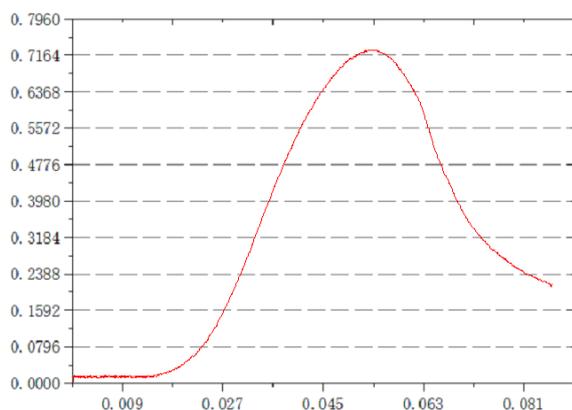


Figure 2. Limestone similar material stress - strain curves

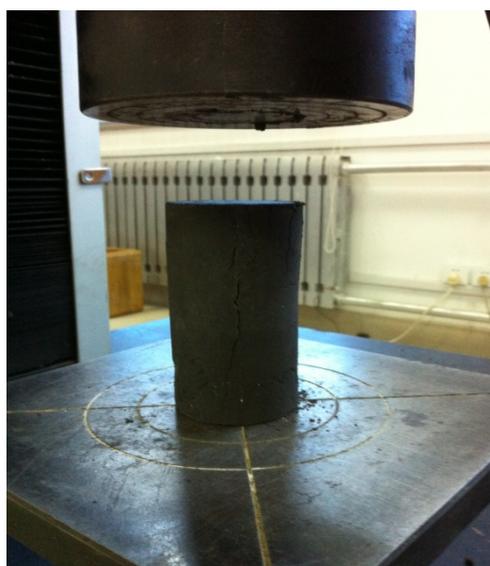


Figure 3. Uniaxial compression test photo

Test results reveal that the compressive strength and elastic modulus of the materials change from 0.96 MPa to 2.43 MPa and 120 MPa to 145 MPa respectively. The strength and elastic modulus of some samples are shown in Table 2.

Table 2. Compressive strength and elastic modulus of different specimens' ratios

Serial number	Material ratio (S:F:C:B:V:W)	Compressive strength σ_c /MPa	Elastic Modulus E/MPa
1	140:140:10:60:35:40	0.72	125

2	150:130:15:60:30:40	1.11	136
3	140:140:25:60:20:40	1.53	144
4	150:130:10:60:35:40	0.85	117

Note: S : F : C : B : V : W refer to normal sand, fly ash, cement, barite powder, vaseline, and water.

3.3.3. Test for permeability coefficient

In permeability test, the permeability coefficients of the materials were measured based on varying-head method. After sufficiently mixing the materials according to the proportioning scheme, the materials were put in the mould and hit solidly. Afterwards, the materials were sampled using ring knife, weighted, and then tested in the permeameter. After turning on the controlling switch of water, samples were immersed for one day, followed by permeability test with varying-head. The experimental data were recorded and calculated using the following equations.

$$k_t = 2.3 \frac{aL}{A(t_2 - t_1)} \lg \frac{H_1}{H_2}$$

Where k_t denotes the permeability coefficient of the samples at water temperature of $t^\circ\text{C}$ (cm/s);

a is the inner cross-section area of the varying-head pipe (cm²);

2.3 is conversion factor of \ln and \lg ;

L denotes seepage path, namely the height of the samples (cm);

t_1 and t_2 are the starting and ending times of measuring water head respectively (s);

H_1 and H_2 are the starting and ending water heads respectively;

A refers to the area of flow section of the samples.

In the end, it was calculated that the permeability coefficient was in the range of $6.28 \times 10^{-6} \sim 8.15 \times 10^{-6}$ m/s.

3.4. Factors influencing strength and elastic modulus

Among the components of the similar materials, the coagulants exert significant effects on the strength of the materials. Therefore, by adjusting mass fractions of cement and vaseline, the compressive strength and elastic modulus of the materials can be changed.

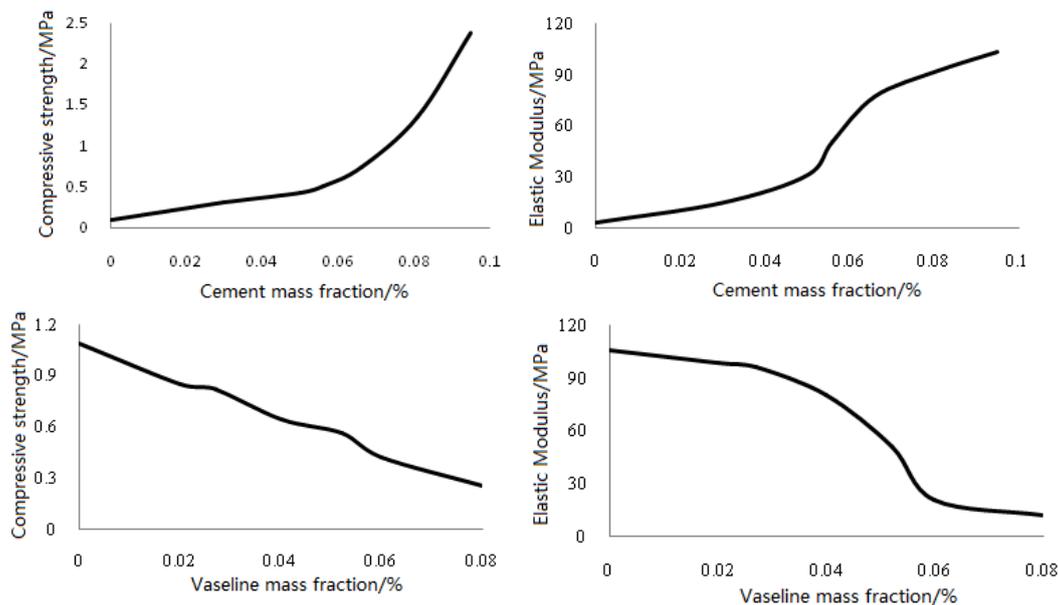


Figure 4. Affect curve of cement and vaseline on strength and elastic modulus

Figure 4 indicates that when the contents of other components are fixed, increasing cement content gradually increases compressive strength of the materials. When the cement is less than 5%, the increase of cement intensifies the strength slightly, because the strength is mainly produced by the cohesiveness of vaseline. When the mass fraction of cement is more than 5%, strength of

the materials is primarily influenced by cement; and the strength intensifies linearly with increasing amount of cement. Vaseline, as a plastic coagulant, the increase of its amount reduces the strength of the materials. Therefore, vaseline and the strength basically show linear relationship.

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When the cement is less than 5%, deformation property of the materials is mainly influenced by vaseline which is the plastic coagulant, and the material behaves large plastic and low elastic modulus. When the mass fraction of cement exceeds 5%, the deformation property of the materials is more significantly influenced by cement and the elastic modulus rapidly rises. When the mass fraction of cement is more than 8%, the elastic modulus rises slowly due to the influences of comprehensive component proportions of the materials. While plasticity of the materials increases and elastic modulus decreases significantly with increasing content of vaseline; in the case of over 6% of vaseline, the materials show obvious plasticity property and swelling failure without apparent shear failure surface.

4. Application of similar materials in model test of Zengziyan steep rocky slope

4.1. Experimental

Zengziyan in Nanchuan, Chongqing Province was applied as concrete engineering background in the model test to study the change trend and stability of the upper surrounding rocks after excavation of orebodies. The similar ratio of the test is 1/100, and the model size is 2.5 m×1.5 m×3 m. The model was filled with similar materials to 3 m and designed ore bed was excavated at the elevation of 0.5 m. Afterwards, water was injected in the upper fractures until the upper slump-mass deformed and collapsed. Physical and mechanical parameters and water physical property parameters of the original rocks, the fault and the similar materials are illustrated in Table 3.

Table 3. The original rock, faults and similar material parameters

	Severe $\gamma/g \cdot cm^{-3}$	Compressive strength σ_c/MPa	Elastic Modulus E/ GPa	Permeability coefficient $k/cm \cdot s^{-1}$
original rock	2.5~2.7	78~90	15.8~18.3	$3.69 \times 10^{-6} \sim 5.31 \times 10^{-6}$
Orebody	2.4~2.5	67~83	11~12.2	
Surrounding rock similar material	2.286	0.82	0.23	$6.28 \times 10^{-6} \sim 8.15 \times 10^{-6}$ m/s
Orebodies similar material	2.192	0.71	0.16	

4.2. Filling of the test frame

The compaction and layered filling were used in the filling of the test frame, and each layer was compacted. The basic filling process is shown below.

① Weighing and processing of components: according to the component proportions of the similar materials, each component was weighed and treated. The sand was dried preliminarily, and vaseline was heated to melt before being added;

② Preparation of the similar materials: all components were added into the mixer according to their ratios in certain order and stirred uniformly; afterwards, similar materials of surrounding rocks and ore beds were developed;

③ Filling and compacting of similar materials: the model test frame was filled with developed similar materials immediately in each layer from top to bottom; after each layer was compacted, the compactness was tested;

④ Burying of monitoring elements;

⑤ Filling the test frame with similar materials to the designed elevation;

⑥ Separately preparing collapsing block.

The detailed process of the model test is demonstrated in Figure 5.





Figure 5. The model making process

4.3. Analysis of test results

On steep rocky slope of Zengziyan model, 7 monitoring points were established and their locations are listed in Figure 6. Three-step excavation was conducted to simulate the actual excavation of underground mine field. After the second step, water was injected into the fractures to simulate the influences of rainfall. The displacements of each monitoring point are shown in Figure 7. Following the three-step excavation and adding of water, failure occurred to collapsing block along weak structural plane. In the model test, the collapse of landslide soil mass was, to a great extent, associated with the joints and fracture within the rocks. In the excavation, as the inferior excavated area increased, the development of the fractures was accelerated, and therefore the upper fractures were widened. Besides, under the force of water, the strength of the fractures lowered gradually and the upper and inferior fractures connected. As a result, weak structural plane was formed. Under external forces, the unstable rock mass finally collapsed.



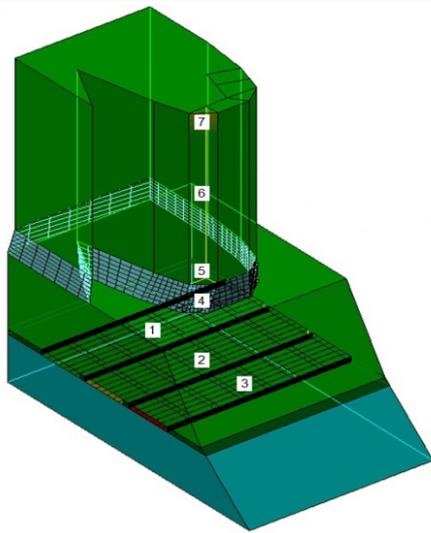


Figure 6. The main monitoring point space location map

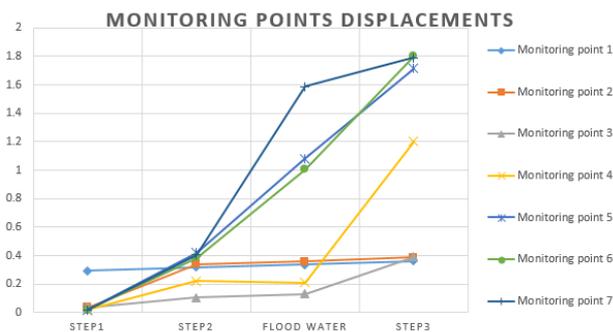


Figure 7. Each monitoring point displacements after three-step excavation

5. Conclusions

(1) By performing huge number of tests with different component proportions, the similar materials were prepared by applying normal sand and fly ash as aggregate and ordinary portland cement and high purity vaseline as coagulant, adding suitable amount water, and stirring these materials sufficiently. Consequently, the steep rocky slope of Zengziyan was simulated using the similar materials. The materials meet the requirements of strength, elastic modulus, permeability coefficient, etc. in the model test.

(2) The mechanical parameters and permeability coefficient of the materials vary in large ranges: the compressive strength ranges from 0.18 to 1.36 MPa, elastic modulus is in a range of 17~130 MPa, and permeability coefficient varies from 6.58×10^{-8} to 7.39×10^{-4} cm/s. Thus, the materials can simulate various rock materials with different permeabilities, and low or medium strengths.

(3) The similar materials have been successfully applied to the geomechanical model

experiments of steep rocky slope of Zengziyan. Mechanical and water physical properties of the materials satisfy the test requirements; therefore proper materials are provided for obtaining favorable experimental results.

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