Experimental study on static and dynamic properties of similar materials for engineering rock mass

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Abstract. To determine the static and dynamic properties of similar materials for engineering rock mass, static and dynamic triaxial tests were conducted on similar engineering rock mass materials. The materials comprised barite powder, quartz sand, gypsum powder, water, and laundry detergent, based on an optimal design. The relationship between deviator stress and an axial strain was investigated under various loading and confining pressure. The test results reveal that the deformation characteristics of similar materials gradually develop from brittleness to ductility with an increase in applied confining pressure, and the static and dynamic elastic moduli show an increasing trend. The hysteresis loop area of similar materials becomes larger with an increase in dynamic stress, suggesting a greater damping ratio of similar materials. The results of this study provide a basic reference for the characteristics model test, and the findings can guide the numerical simulation of the stability analysis of super large-span flat cavern in future studies.

1. Introduction

The geomechanical model test is an indoor test method based on the similarity principle. It reflects the real physical and mechanical laws of rock and soil media, comprehensively and truly reproduces the instability and failure phenomena of complex underground engineering in the construction process, and provides solutions to engineering problems in the imperfect geotechnical mechanics theory situation. It has the advantages of low cost, convenient measurement, and reliable results. Thus, this method has been widely accepted by researchers in the underground engineering field for decades and is continuously developed and improved [1][2][3][4].

The selection of similar engineering rock mass materials is the key to the success of the test model. Domestic and foreign scholars have made unremitting efforts and achieved some research progresses. A mix ratio test of similar materials was conducted based on the specific types of rock and soil properties. Zhang et al. [5] used barite powder, sand, industrial salt, gypsum, and bentonite as raw materials and adopted the free-falling method in air to develop similar materials for a collapsible loess model test by numerous direct shear tests. In addition to the study of similar materials in soft soil, many scholars have developed similar materials for hard engineering rock mass. Further, some
scholars have prepared similar materials of sandstone with cement and sand as the main raw materials [6][7].

Alternatively, multifaceted research must be conducted before building large-scale underground projects due to their complexities. Moreover, another challenge is the lack of practical engineering geological conditions. Thus, it is necessary to perform a geological mechanics model test to determine solutions to the problems that may occur when building large-scale underground projects. The prepared similar materials should meet the similarity ratio requirements. Domestic scholars selected the physical and mechanical parameters of engineering rock mass based on highway tunnel design specification [8], to further select similar materials’ condition parameters. Mechanical oil or washing liquid with water were often used as binders [9]. Currently, there are several studies on the proportion of similar materials of class IV–V weak engineering rock mass. However, studies on similar materials of class III engineering rock mass are limited.

Similar materials ratio research methods aforementioned were designed using the orthogonal design method. The physical and mechanical parameters, such as cohesion, internal friction angle, elastic modulus, and compressive strength, of similar materials with different ratios were measured via several direct shear and uniaxial compression tests. However, the rock mass in practical engineering is in a three-dimensional stress state (Figure 1), and the excavation of underground engineering will cause the stress redistribution of the engineering rock mass. The rock and soil are not static under this situation. Thus, the authors conducted several matching tests with barite powder, quartz sand, gypsum powder, water, and washing liquid as raw materials. After selecting the best ratio for simulating grade III engineering rock mass, the static and dynamic triaxial shear tests of similar materials were conducted. The materials were prepared using the best ratio scheme. The test result is aimed at obtaining the materials’ mechanical characteristics under different stress paths. It can also provide a more reliable reference for model test results and numerical simulation in future studies.

![Figure 1. Three-dimensional stress diagram of engineering rock mass](image)

2. Experimental program
2.1. Raw materials and sample preparation

The similar materials of engineering rock mass are composed of aggregate, binder, and regulator. In this experiment, barite powder and quartz sand were used as the main aggregates, gypsum powder and water were used as binders, and washing liquid was used as a regulator. Notably, the grade III engineering rock mass has better physical and mechanical parameters than weak rock mass. The author prepared similar materials by increasing the mesh number of fine aggregate barite powder to 1250 mesh based on class IV–V engineering rock mass to increase the materials’ density. To significantly increase the friction angle of similar materials, 8–16 mesh quartz sand was selected as coarse aggregate after repeated attempts. Mixing high-strength gypsum powder and water as similar materials binder can obtain a wide range and convenient adjustment of cementation ability. Gypsum is an air-hard material that can improve the elastic modulus of similar materials. Choosing washing liquid as the regulator can slow down gypsum powder’s setting time and improve samples’ uniformity. The raw materials selected in this experiment are easy to obtain, cheap, and reusable.

After several previous proportioning experiments, this study used the proportion of barite powder: quartz sand: gypsum powder: water: laundry liquid = 29: 29: 3: 4: 1 as the proportion of sample
preparation in the triaxial test. Figure 2 shows the sample preparation process. When preparing the samples according to the proportioning scheme, barite powder, quartz sand, and high-strength gypsum powder were put in a container and stirred uniformly. The well-weighed laundry solution and water were mixed and poured into the container, with continuous stirring to obtain a uniform mix. The materials were subsequently poured into a 50 mm × 100 mm three-lobe mold dividedly four times; each layer was hammered about 20 times using a compaction instrument to achieve the maximum density of the samples. The demoulding was conducted after 30 min, and the samples were wrapped with a layer of polyethylene film for 24 h, and then the test was conducted.

![Figure 2. The process of sample preparation: (a) Raw materials and mixing (b) Sample compaction (c) Sample demoulding and maintenance](image)

2.2. Test equipment

The triaxial tests in this study were conducted on the GDS(Global Digital System) dynamic triaxial testing system of Tongji University. The experimental equipment is mainly composed of a three-axis pressure chamber, confining pressure controller, back pressure controller, and computer (Figure 3). This equipment is a high-precision triaxial apparatus developed by the GDS Company. Its basic functions include the following: 1) It can conduct unidirectional axial compression cyclic loading in the range of 5 Hz; 2) Cyclic axial deformation can be applied to the samples in the range of 5 Hz; 3) Conventional triaxial shear tests can be conducted and controlled by stress and strain. Its main technical parameters are as follows: 1) The maximum load is 10 KN; 2) The maximum displacement is ± 25 mm and the maximum frequency is 5 Hz. The maximum confining pressure is 1 MPa and the strain range is 10⁻⁴–10⁻². The vibration waveforms are simple harmonic and custom random vibrations, and the vibration direction is vertically unidirectional.

2.3. Test scheme

The test in this study is an unconsolidated and undrained triaxial test, and static and dynamic triaxial tests were conducted, respectively. The range of confining pressure can be divided into three types: 1) The low confining pressures are 0, 6, 10, and, 16 KPa, which were used to study the stress and strain variation of similar materials of engineering rock mass in the model test under self-weight stress field. 2) The medium confining pressures are 20, 40, 60, and 80 KPa, and the stress–strain law of similar materials of engineering rock mass was analyzed for the test model in the case of the tectonic stress field. 3) The high confining pressures are 100, 200, 300, and 400 KPa following the Chinese Geotechnical test method standard [10], which can also provide more comprehensive information for the characteristics of similar materials. The loading methods employed in the test are as follows:

1) Static triaxial test. The target confining pressure was applied using a confining pressure controller, and the test was conducted at the shear rate of 1.0%/min. The test was stopped when the strain of the samples reached 15%, and the stress–strain curves of similar materials under corresponding working conditions were obtained.

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2) Dynamic triaxial test. Similarly, the target confining pressure was applied using the confining pressure controller, and the vibration triaxial test was performed. The vibration frequency was 0.33 Hz, and the vibration waveform was a simple harmonic wave. The test was conducted in the dynamic load control procedure. According to the static triaxial test results, different initial loads and load amplitudes were applied under various confining pressures.

![Dynamic triaxial testing system: (a) Triaxial cell (b) Computer (c) Confining pressure controller and backpressure controller](image)

**Figure 3.** Dynamic triaxial testing system: (a) Triaxial cell (b) Computer (c) Confining pressure controller and backpressure controller

3. Experimental results and discussion

3.1. Analysis of static triaxial experiment results

In this experiment, 12 static triaxial tests were conducted under various confining pressures, as described in Section 2.3. These pressures were divided into three grades: low, medium, and high pressure. Figure 4 shows the triaxial compression stress–strain curves of similar material samples under different grades.

Under the low confining pressure condition, the stress–strain curve obtained from the test can be roughly divided into three stages (Figure 4 (a)), namely, linear growth stage, nonlinear growth stage, and nonlinear reduction stage. The stress–strain curve gradually enters the elastic stage (straight line), plastic stage (concave), and post-peak failure stage (strength gradually decreases), as axial compression increases. The curve reveals an obvious elasticity phase, which lasts the longest. The bearing capacity of the sample gradually declines after reaching the peak point, exhibiting softening characteristics. In addition, the peak strength of the samples gradually increases with the confining pressure, and the bearing capacity after the peak also increases.

Figure 4 (b) shows that the sample’s stress–strain curve reveals a linear growth stage, a nonlinear growth stage, and a stable or slightly decreasing stage. The stress–strain curve gradually progresses to the elasticity phase (straight line), the plastic stage (concave), and the post-peak stability stage (slightly decreased strength), as the axial pressure increases. The curve also reveals an obvious elasticity phase, which lasts the longest. The bearing capacity of the samples gradually stabilizes or decreases slightly after reaching the peak point. In addition, the peak strength of the samples increases gradually with the confining pressure, and the bearing capacity also increases after reaching the peak.

The stress–strain curve is roughly divided into three stages when the sample is subjected to high confining pressure, namely, linear growth stage, nonlinear growth stage, and stable or slightly upward stage. The stress–strain curve gradually enters the elastic stage (straight line), plastic stage (concave), and post-peak stability stage (strength slightly increased), with an increase in axial pressure. The identification degree of the elastic stage decreases, the elastic stage duration decreases, and the
nonlinear growth stage duration increases significantly. The bearing capacity of the samples remains unchanged after reaching the peak point, whereas that of some samples increases slightly, indicating hardening characteristics. In addition, the peak strength of the samples increases gradually with an increase in confining pressure, and the bearing capacity also increases after reaching the peak.

![Figure 4](image)

**Figure 4.** Stress–strain curve of static triaxial test: (a) Low confining pressure (b) Medium confining pressure (c) High confining pressure

According to the stress–strain curves of the static triaxial test under various confining pressures, the corresponding elastic modulus and peak stress distribution of each case are obtained (Figure 5). There is no obvious regulation under low confining pressure, but only the fluctuation of the change rule of elastic modulus of similar materials. This phenomenon is mainly affected by the samples’ production error and the equipment’s measurement error. The elastic modulus of the samples exhibits an increasing trend under medium and high confining pressures. The elastic modulus significantly increases with confining pressure. The peak strength of similar materials increases and the growth rate of peak stress increases gradually with the confining pressure.

![Figure 5](image)

**Figure 5.** Distribution of elastic modulus and peak stress

3.2. *Analysis of dynamic triaxial experiment results*

The dynamic triaxial test in this study was also conducted using the same method as the static triaxial test. The vibration triaxial tests were performed on several samples under various confining pressures, which were divided into three types: low, medium, and high pressure.

Figure 6 plots the dynamic stress–strain curve of the samples under four low confining pressures of 0, 6, 10, and 16 KPa. The dynamic stress amplitude is 10, 20, 30, 40 kPa, respectively. The vibration is 10 times under each dynamic stress level, and the first stress cycle in the corresponding dynamic stress level is selected for comparative analysis. The figure shows that the sample’s stress–strain curves do not coincide, but form a closed hysteresis loop under periodic cyclic loading. The plastic deformation, hysteresis loop area, damping characteristics, and energy loss increases with dynamic stress under loading and unloading conditions. The sample’s hysteresis loop shows a “tip-leaf” at the load reversal. This implies that when the external load is reversed, the soft rock’s elastic
deformation response is rapid and plastic deformation is minimal. In addition, when the dynamic stress remains unchanged and the confining pressure increases in the low-pressure range, the area of the hysteresis loop does not significantly change.

![Graphs showing stress-strain relationship under different pressures](image)

**Figure 6.** Dynamic stress–strain curve of low confining pressure: (a) 0 kPa confining pressure (b) 6 kPa confining pressure (c) 10 kPa confining pressure (d) 16 kPa confining pressure

Figure 7 shows the test results under medium pressure. That is, the sample’s vibration triaxial test was conducted under four confining pressures of 20, 40, 60, and 80 KPa and the amplitudes of dynamic stress are 20, 40, 60, and 80 KPa, respectively. The samples were vibrated 10 times in each dynamic stress level, and a stress cycle in the corresponding dynamic stress level was selected for comparative analysis. The figure shows that under cyclic loading conditions, the stress–strain curve of the samples also forms a closed hysteresis loop. The plastic deformation, hysteresis loop area, damping characteristics, and energy loss increase with the dynamic stress during loading and unloading. The hysteresis loop of the samples shows a “tip-leaf” at the load reversal. The hysteresis loop area is significantly reduced with an increase in confining pressure under the same dynamic stress level, unlike the low-pressure situation. This implies that the confining pressure will reduce the plasticity and plastic deformation of the samples.

The dynamic characteristics of similar materials under high confining pressure were studied by increasing the confining pressure range (Figure 8). The samples were subjected to vibration triaxial tests under four confining pressures of 100, 200, 300, and 400 KPa. The amplitudes of dynamic stress are 40, 80, 120, and 160 KPa for four levels, and the samples were vibrated 10 times in each dynamic stress level. A stress cycle of corresponding dynamic stress levels was selected for comparative analysis. Figure 8 shows that under cyclic loading conditions, the stress–strain curve of the samples also forms a closed hysteresis loop. The plastic deformation, hysteresis loop area, damping characteristics, and energy loss increases with the dynamic stress. The hysteresis loop area decreased with an increase in confining pressure. The inclination angle of the hysteresis loop increases with the dynamic stress under the same confining pressure, unlike the medium-pressure condition. This implies that the dynamic elastic modulus of similar materials increases.
4. Conclusion

The static and dynamic triaxial tests of similar materials for simulating grade III engineering rock mass under various confining pressures were conducted using GDS dynamic triaxial apparatus. The stress–strain relationship, elastic modulus, damping characteristics, and variation characteristics of
plastic deformation were analyzed. Concurrently, the related phenomena in the test were analyzed and explained. The main conclusions drawn are as follows:

1) The stress–strain curve of the sample under static loading shows three stages: elastic increase, plastic increase, and post-peak softening under low confining pressure. Under medium and high confining pressures, the softening phenomenon disappears gradually and the stress tends to be stable after reaching the peak point. In addition, the elastic modulus of the samples exhibits no obvious variation pattern at low confining pressure. However, under medium and high confining pressures, the elastic modulus increases noticeably, and the peak stress of the samples is positively correlated with the confining pressure.

2) The stress–strain curve of the sample forms a closed hysteresis loop under dynamic loading. The plastic deformation, hysteresis loop area, and damping characteristics increase with an increase in dynamic stress. The hysteresis loop of the sample shows a “sharp leaf” at the load reversal. At constant dynamic stress amplitude and confining pressure increase in the range of medium and high pressures, the hysteresis loop area decreases gradually, indicating a decrease in the plastic deformation and damping characteristics. The hysteresis loop dip angle increases with the dynamic stress under the high confining pressure condition, suggesting an increase in dynamic elastic modulus.

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