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Development of epoxy-silicone rubber-based geotechnical similar material and its engineering application

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Proper selection of similar materials is the key to the simulation of engineering prototypes. According to the similarity theory of geomechanical model tests, a novel similar material was developed after a great number of mixture ratio tests. The similar material consisted of barite powder and sand as the coarse aggregates, epoxy resin, polyamide, silicone rubber and a silicone rubber curing agent as the adhesive, and gasoline as the solvent. The mechanical tests on this similar material indicated that the material properties were stable and the manufacturing process was simple. Hence, the similar material can meet the requirements of large-scale model tests. The similar material was applied in the model test on a deep-buried tunnel under high *in-situ* stresses. The deformation and failure process of the tunnel were successfully simulated, and the failure pattern of the tunnel was obtained, which can provide an efficient basis for tunnel design and construction.

Keywords: Similar material, Model test, Deep-buried tunnel, Epoxy resin, Silicone rubber

Introduction

Many problems, such as strength, deformation, failure and reinforcement, of geotechnical materials are involved during tunnel excavation and lining. These issues can be studied by theoretical and numerical methods; on the other hand, they can be investigated by geotechnical model tests.[1,2]

The basis of model tests is the similarity theory. Similarity theory requires that the model and the prototype be similar, so the model can reflect the properties of the prototype. According to the similarity theory, a similar material should be adopted to prepare the model. The selection of materials and the mixture ratio greatly affect the physical and mechanical properties of the similar material. In the model tests, proper selection of model material and the mixture ratio is of great significance.[3]

In traditional model tests, a similar material with gypsum as the adhesive is commonly used worldwide, as its brittleness is close to rocks and it has a large adjustment range of elastic modulus and compressive strength. Moreover, the manufacturing process is simple and the material is conveniently available.[4] However, as gypsum is a water-soluble material, the properties are greatly influenced by temperature and humidity. In addition, its drying process is very slow. If gypsum is adopted as the similar material for large-scale model tests, the test duration will be increased considerably.

In this study, a new type of similar material was developed after a great number of mechanical tests. This similar material consists of barite powder and sand as the coarse aggregates, epoxy resin, polyamide, silicone rubber and a silicone rubber curing agent as the adhesives, and gasoline as the solvent.

Similarity theory

In order to produce similar physical phenomena in a model to the prototype, the model material, configuration and loading process should follow the similarity theory. As for the geomechanical model test, the model should follow the consistency of the equilibrium equation, the compatibility equation, the geometric equation, the physical equation and the boundary condition between the model and the prototype. Furthermore, the same strain and similar strength criterion and constitutive model are required. Therefore, the geometric dimensions, boundary conditions, loading process, bulk density, strength and deformation properties of the model should satisfy the similarity theory.

According to the similarity theory, the model test should satisfy the following criteria:

(i) The relationship between the stress similarity ratio C_σ, the bulk density similarity ratio C_γ and the geometric similarity ratio

$$C_l{:}C_\sigma = C_\gamma C_l \qquad (1)$$

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(ii) The relationship between the displacement similarity ratio C_δ, the geometric similarity ratio C_l and the strain similarity ratio

$$C_\varepsilon{:}C_\delta = C_\varepsilon C_l \tag{2}$$

(iii) The relationship between the stress similarity ratio C_σ, the elastic modulus similarity ratio C_E and the strain similarity ratio

$$C_\varepsilon{:}C_\sigma = C_\varepsilon C_E \tag{3}$$

(iv) In the model tests, the similarity ratio for all the dimensionless parameters (such as strain, internal friction angle φ, friction coefficient f and the Poisson's ratio μ) are required to be 1.

Furthermore, the similarity ratio for the physical quantities having the same dimension (such as the cohesion c, the tensile strength σ_t and the compressive strength σ_c) shall be the same. That is

$$C_\varepsilon = C_f = C_\phi = C_\mu = 1 \tag{4}$$

$$C_\sigma = C_E = C_c = C_{\sigma_c} = C_{\sigma_t} \tag{5}$$

Development of the similar material

Principles for selection of similar material

According to the experiences of numerous experiments, the similar material should satisfy the following principles:

(i) Specific properties of the material shall be similar to the rock under study.
(ii) The material shall be electrically insulated, and not affected by temperature and humidity (the mechanical properties of the material shall be relatively stable during tests).
(iii) The mechanical properties of the material can vary in a broad range by changing the mixture ratio.
(iv) The manufacturing process should be simple and the drying process shall be fast.

As a large-scale model test was to be conducted in this study, the material had to be dried in a short time. According to the above principles, tests were conducted on samples with different mixture ratios of barite powder and sand as the coarse aggregates, epoxy resin, polyamide, silicone rubber and silicone rubber curing agent as the adhesives, and gasoline as the solvent.

Development of similar material

The model preparation process tended to be as simple as possible, and the model was dried rapidly after moulding so as to speed-up the model test process. After various ingredients were mixed evenly at a certain ratio, they were poured into a mould immediately and tamped to the required dimensions. The dimensions of the cylindrical specimen were 50 mm in diameter and 100 mm in height (Fig. 1). During model preparation, it was ensured that all the procedures were the same so as to ensure stable performance of the material. The specimens were first dried for about 24 hours in room temperature (25°C) and then kept in a drying room with a constant temperature of 30°C. The test results indicated that the specimen became thoroughly dry in 48 hours (Fig. 2).

1 Experimental model

During the mixture ratio tests, the main parameters including the bulk density, uniaxial compressive strength and deformation modulus were measured. As a considerable amount of work would be involved in specimen preparation and testing, an optimised design method with quadratic orthogonal combinations was utilised for the mixture ratio tests in the primary stage and only the bulk density and uniaxial compressive strength were measured. In the later fine-tuning stage after the essential components and the approximate mixture ratio were determined, the tensile strength, Poisson's ratio, cohesion and internal friction angle were measured in addition to the bulk density and the uniaxial compressive strength.

The uniaxial compression test and tensile tests were performed using a hydraulic universal testing machine. The cylindrical specimen for uniaxial compression test had dimensions of 50 mm in diameter and 100 mm in height, and those for the split test were 50 mm in diameter and 30 mm in height. The direct shear test was conducted by a self-designed shear test platform, and the specimen dimensions (length × width × height) were 70 mm × 120 mm × 160 mm. The tests strictly followed the standards of rock mechanical tests. During the uniaxial compression test, the strain was mainly measured by the electrical-resistance strain gauges affixed on the specimen sides. During the shear test, the strain was measured by a dial indicator.

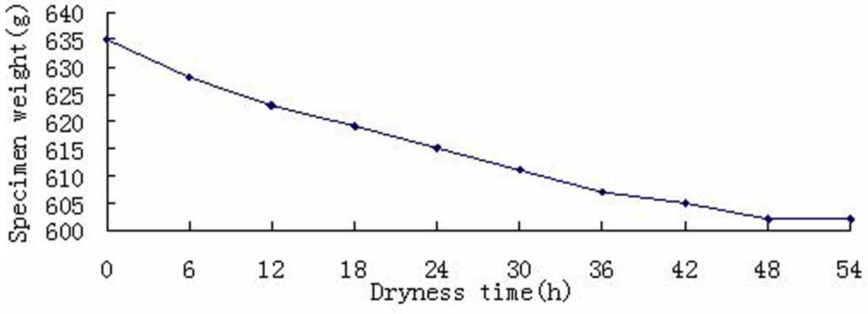
Through a generous amount of mixture ratio tests, the effects of various components on the properties of the similar material were obtained:

(i) The higher the content of adhesives composed of epoxy resin, polyamide, silicone rubber and silicone rubber curing agent, the higher the compressive strength and elastic modulus of the specimen. (Figs. 3 and 4).
(ii) The higher the content of sand, the lower the compressive strength and elastic modulus of the specimen (Figs. 5 and 6).
(iii) If the content of barite powder was high, the specimen density increased accordingly.

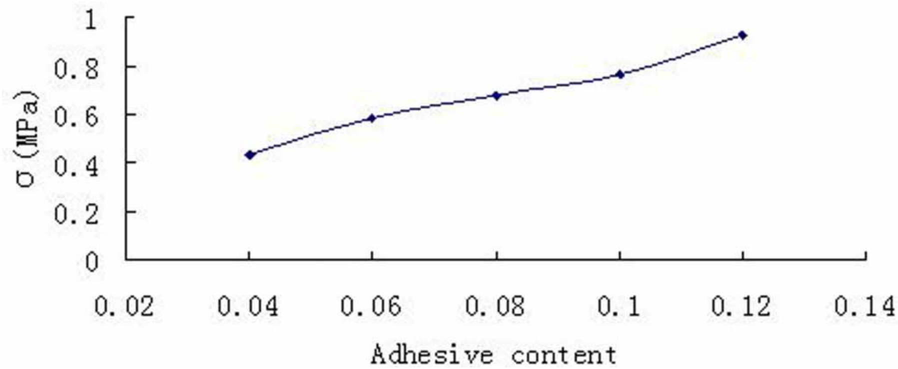
Engineering application

Project overview

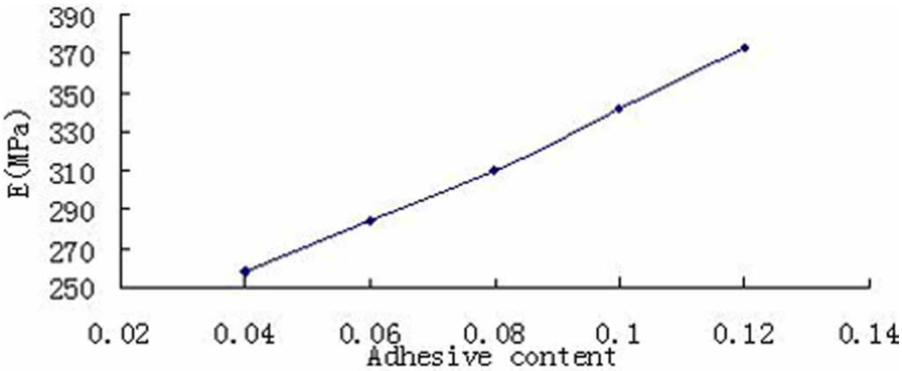
The Gonghe tunnel of the Chongqing–Changsha highway is a one-way double-hole tunnel. The left tunnel is 4741 m in total length, and the right tunnel



2 Specimen dryness time curves at temperature 30°C



3 Relationship between adhesive content and compressive strength



4 Relationship between adhesive content and *E*

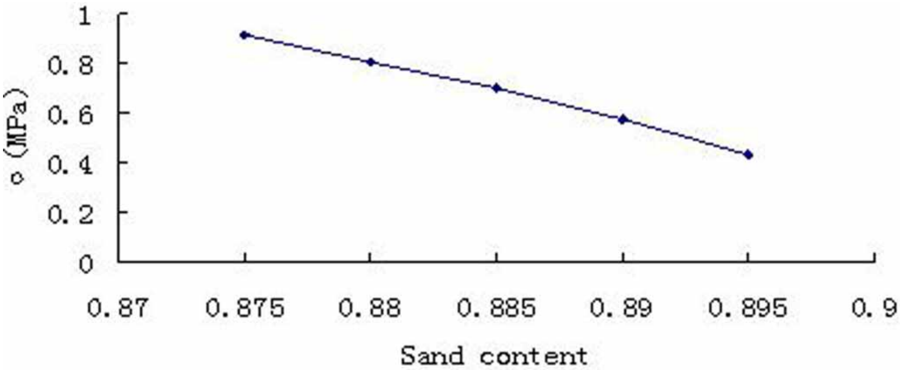
measures 4770 m. The distance between the tunnel axes is 20–23 m. The maximum cover depth is up to 1000 m. The shape of the tunnel cross-section is a three-centre circle with curvy side walls. The tunnel span is 12 m, and the height is 9·5 m. The strata along the tunnel alignment are the Luoreping groups with sandy shale, shale and local siltstone of the Silurian system. The *in-situ* stress measurement data indicated that the difference between the maximum horizontal stress and the vertical stress was quite small. Both of the stresses were about 20 MPa.

Model setup

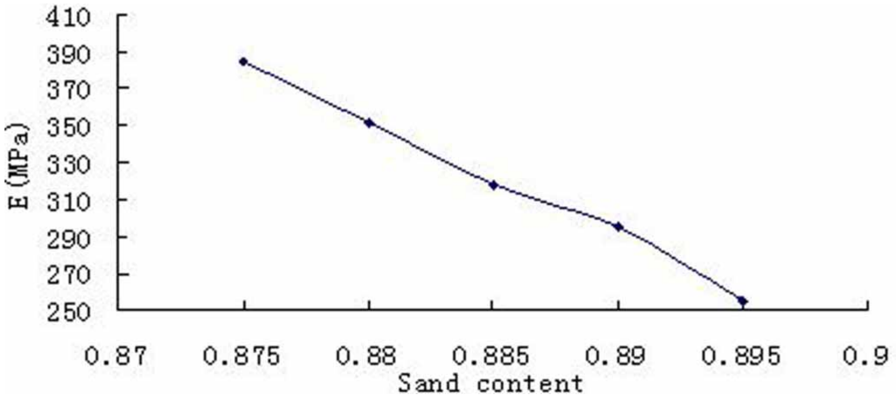
The experiment was conducted by a large-scale true triaxial physical model testing machine for geotechnical engineering. With consideration to the simulation range, the test site condition and other factors, a geometric similarity ratio of 200, a stress similarity ratio of 74 and a bulk density similarity ratio of 1·31 were adopted in this study. The model dimensions were 0·8 m × 0·8 m × 0·8 m. The tunnel span was 220 mm, and the tunnel height was 170 mm. The model consisted of two specimen layers. The dimensions of each specimen layer were 0·8 m × 0·8 m × 0·2 m. Two mortar pads with dimensions of 0·78 m × 0·78 m × 0·20 m were placed on the external sides of the two specimen layers (Fig. 7). The tests showed that the similar material adopted in this study reasonably satisfied the requirements of the similarity design (Table 1, as the prototype parameters divided by similarity coefficient is the theoretical value).

Experiment procedures and instrumentation

The experiment was conducted by a large-scale true triaxial physical model testing machine for geotechnical engineering. The machine was equipped with true triaxial test



5 Relationship between sand content and compressive strength



6 Relationship between sand content and elastic modulus

functions. Axial loading could be applied independently along three directions, namely, the *X*-axis (left and right), the *Y*-axis (forward and backward) and the *Z*-axis (up and down). Through add different loads to research, the stress change law of surrounding rock with changed stresses.

After the model was placed in the specimen chamber of the testing machine (Fig. 7), horizontal and vertical loads were applied simultaneously until the model failed (the ratio between the horizontal and vertical loads was 1:1, and the loads were added at a rate of 30 kN per minute. The load transmission plates in the *Y*-direction were fixed so as to restrain the model in the *Y*direction). The load of 100 kN was equivalent to the geo-stress of the real tunnel (20 MPa) and in these experiments the final load was 200 kN.

7 Testing machine

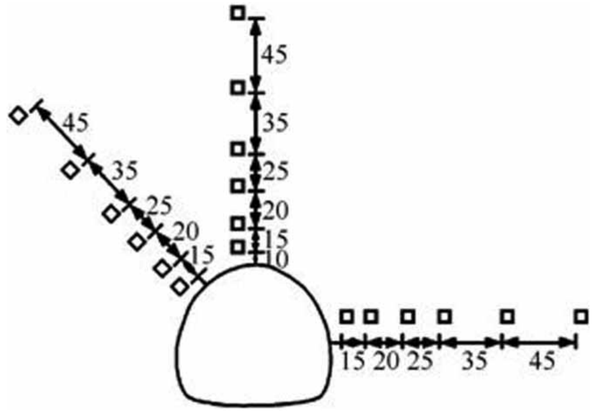
The strain in the surrounding rock mass and the failure process of the model were monitored during the experiment.

The strain in the surrounding rock mass was mainly measured by electrical-resistance strain gauges (Fig. 8). Measurement lines were set at the arch spring, spandrel and crown. Strain gauges were affixed at each measurement point to measure the radial and tangential strains. The strain gauges formed 1/4 bridges through computer data cables with a diameter of 0·2 mm and were connected to the DN3815N multi-channel high-speed static strain measurement system.

During the model test, a BT-688 pinhole camera was used to monitor the failure process in real time. The

Table 1 Physical–mechanical parameters of the similar material

Parameters	Elastic modulus *E* (MPa)	Compressive strength R_c (MPa)	Unit weight (kN m^{-3})	Poisson's ratio μ
Theoretical value	313·78	0·677	21·0	0·350
Measured value	310·00	0·684	21·0	0·331



8 Monitoring line (unit: mm)

image signals were transmitted to the CF-1701-4 data acquisition card installed in the computer for data conversion. In this way, the entire failure process of the tunnel could be displayed on the computer monitor.

Experiment results

As can be seen from the failure process monitored by the pinhole camera, the tunnel deformation can be divided into a few phases. At first, falling local debris occurred in the spandrel and other parts remained somewhat stable. When the loading increased at a constant loading rate, cracks occurred in the arch bottom and rock debris started to fall at the arch spring. When the load was increased further, cracks propagated to the entire tunnel wall, and large rock pieces fell from time to time. The loading interval became smaller, the breakdown speed tended to increase. Generally speaking, the tunnel failure process was progressive and non-continuous, which was intermittent and sporadic.

Conclusion

The mechanical properties of the similar material developed in this study can vary in a broad range by adjusting the mixture ratio. It can be used to simulate most rock types and is an ideal material for model tests.

The theoretical and measured values of the main physical and mechanical indexes of the similar material were close to each other. The properties were stable and the tests can be well repeated.

As gasoline is volatile, with a short drying time, the test preparation duration can be shorter. Hence, it can satisfy the requirement of large-scale model tests.

As the material is highly insulating, strain gauges can be affixed on the model directly without any other protective measure.

The material was applied to the model test on a tunnel. The results indicated that shear failure was the principal failure mechanism of the tunnel. The occurrence of initial cracks was the premise of the rapid failure at a later stage. The entire failure process was: local cracks – crack propagation – rapid coalescence of cracks – failure. Different tunnel parts exhibited distinctly different deformation characteristics. The formation and propagation of cracked zones led to the formation of the collapsed arch along the gravity direction in the tunnel arch and eventually to the failure of the entire tunnel. The observation was consistent with the engineering practices. The model test can provide an effective basis for tunnel design and construction.

Acknowledgements

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