Study on fractured rock-like materials for geomechanical model test based on 3D printing technology

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Abstract. The geomechanical model test has been verified to be an important way to solve some puzzling geotechnical issues. So far, there are mainly three methods used to construct geological models: pouring, tamping, and small block masonry. However, several disadvantages arise when using these artificial methods, including consuming too much time and cost, difficulty in guaranteeing uniformity of the density of different layers, most importantly, being unable to simulate detailed tectonic discontinuities, like faults or fissures. In view of the fact that three-dimensional printing (3DP) technology can easily produce complex fractured structures, 3DP technology is introduced to the research of the geomechanical model test. However, what kind of material is suitable to simulate rock mass and how to fabricate fractured rock-like material specimens are still two complicated problems. In this paper, a cement-based material is used to simulate fractured rock-like material specimens. This kind of material is proved to reach low strength and low elastic modulus by adjusting the mix ratio. What’s more, a method to fabricate small block masonry used in geomechanical model test with 3D printing fracture network is proposed. A series of tests are conducted for these 3DP fractured models, and the corresponding results show that their mechanical properties and failure characteristics are consistent with experimental results of other rock specimens with certain similarity, and geomechanical model test. These fundamental experimental investigations demonstrate the potential feasibility and prospects of 3DP technology in geomechanical model test.

1. Introduction

There are a large number of primary and structural joints in engineering rock mass. The directly facing problem in geotechnical engineering is mainly rock masses with certain structural characteristics composed of structural bodies (rocks) and complex structural surfaces (faults, fissures, etc.) [1]. Many studies showed [2-4] that the geometrical morphology of fissures and joints contained in engineering rock mass had significantly impacts on its mechanical properties and failure modes. Therefore, further research in this field had vital theoretical and practical importance to ensure the stability and safety of rock engineering.

Currently, the geomechanical model test has been verified to be an important way to solve some puzzling geotechnical issues [5-7]. So far, there are mainly three methods used to construct geological models: pouring, tamping, and small block masonry [6,8]. However, there are some disadvantages in these artificial methods, including being unable to simulate detailed tectonic discontinuities [8], difficulty in guaranteeing uniformity of the density of different layers and consumption of too much labor.

3D printing technology can provide a feasible method to print complex structures with fine nozzles [9,10]. Some scholars have conducted tentative experiments to introduce 3DP technology into aspects of rock mechanics research. Jiang et al. [11] tried to print specimens using polylactic acid material (PLA) and found that this material is not suitable for directly simulating rock materials. Ju et al. [12] combined CT imaging and 3D printing technology and used photosensitive resin materials to print coal and rock models. Jiang [13] used powdered gypsum as a 3D printing substrate to produce model specimens with
holes and cracks. What’s more, Feng [5] and Song [14] studied the possible use of the cement-based 3D printed materials in fabrication of a 3D structure. Li [15] and Fan [16] study the mechanical properties of 3D printed concrete through laboratory experiments and DIC technology. However, most of the aforementioned studies focused on the 3DP of rock models with the normal strength and elastic modulus. According to Principles of similitude, the target experimental materials must be low Young's modulus and low strength [6]. So, the feasibility of 3DP technology for the geomechanical model test has rarely been discussed.

In this paper, a cement-based material is used to simulate fractured rock-like material specimens. This kind of material is proved to reach low strength and low elastic modulus, which can be used in geomechanical model test. What’s more, a method to fabricate small block masonry used in geomechanical model test with 3D printing fracture network is proposed. A series of tests are conducted for these 3DP fractured models, and the corresponding results show that their mechanical properties and failure characteristics are consistent with experimental results of other rock specimens with certain similarity, and geomechanical model test. These fundamental experimental investigations demonstrate the potential feasibility and prospects of 3DP technology in geomechanical model test.

2. Fracture model generation and 3D printing
2.1 Fracture model generation
In order to explore the influence of fissures on the mechanical properties of rock-like material, a fissure generation program was compiled based on Matlab, which can generate random fissures of different lengths, inclination angles and numbers. Monte Carlo simulation was used in the program. Length variable was generated by a log-normal distribution, so that random fissures were generated in a certain range. The specific steps to generate the fracture model are as follows (figure 1):

1. Run the Matlab program to generate the fissure coordinates with the average length equal to 5, the standard deviation 10, and the inclination angles of 0°, 30°, 45°, 60°, and 90°, then export the coordinate information to an LSP file.

2. Import the *.LSP file into AutoCAD, then widen the fracture network, and draw the outer boundary of the model. Because the width of the fracture will affect the mechanical properties of the specimen, the width of the fracture in this test was uniformly set to 1.5 mm. Then use the Region command to generate the fracture network area and the outer boundary area of the model respectively, and obtain the 2D digital model of the fracture network.

3. Use the command Extrude in AutoCAD to stretch the fracture network area to the positive direction of the Z axis by 110 mm, while the outer boundary area of the model was stretched to the negative direction of the Z axis by 0.5 mm, which was functioned as a base platform to fix the fracture network. Then a 3D digital model of the fracture network was obtained.

4. Output the 3D digital model completed above as a *.STL format file, and then import it into the 3D printing software ideaMaker to obtain a 3D printing model, which can be sliced and printed by importing it into a 3D printer.

Fig.1. Fracture network model and 3D printing procedure
2.2 3D printing of fissures model

The 3D printer model used in this article is Raise3D Pro2 Plus. As is shown in figure 2, the 3D printer is equipped with 2 nozzles with a diameter of 0.4 mm and an accuracy of 0.01 mm. The maximum size of printing space is 300mm×300mm×300mm. Several materials can be used for this printer, including polylactic acid (PLA), acrylonitrile-butadiene-styrene (ABS) and polyvinyl alcohol (PVA, a commonly used water-soluble polymer). PVA water-soluble material was used in this test, and the printing method was fusion accumulation. As is shown in figure 3, fissures with different inclination angles were printed. The layer thickness for printing is an important factor. Too thin layer thickness will cause the printing time to increase, while too thick layer thickness will affect the accuracy of the model. Hence, after several trials, the layer thickness of this test was set to 0.25 mm. Some related printing parameters are set as follows:

(1) Calibrate and level the printing platform, then clean the debris on the probe and nozzle in time.
(2) Place the PVA wire material in the heating box, setting the temperature to 45°C and the humidity to 24%.
(3) Set the appropriate print head and platform temperature. The nozzle temperature was about 215 °C, while the platform temperature was about 50 °C, which can basically ensure that the PVA material can obtain enough plasticity and fluidity after the nozzle was heated.
(4) Lastly, set the filling rate and method. The general filling method was divided into linear filling and grid filling. This experiment was to make a fracture network model, which means the line width was very thin, so it was set to no filling, that is, the filling rate was 0.

3. Preparation for rock-like material specimen with 3D printing fissures

In this paper, cement, sand, fly ash and admixtures were selected as the basic materials of the mortar. In order to blend a cement-based similar material with low strength and low elastic modulus suitable for 3D printing, a series of orthogonal tests were conducted. As is shown in table 1, the strength of rock-like material specimens ranges from 1.32MPa to 25.95MPa, while the elastic modulus of rock-like material specimens ranges from 160MPa to 1214MPa. It indicates that cement-based materials can satisfy the requirement of low strength and low elastic modulus for geomechanical model test.

The water-cement ratio is an important factor affecting the strength of concrete. It directly affects the process of cement hydration reaction and the bonding strength between raw materials. Based on group A, after increasing the water-cement ratio from 0.4 to 0.6 while controlling other variables unchanged, the compressive strength dropped from 25.95MPa to 10.20MPa while elastic modulus dropped from 1214MPa to 0.619GPa. On the other hand, replace cement with fly ash can reduce the heat of hydration of cement and adjust the hardening process. At the same time, the silica in fly ash can also combine with free lime to form a cementitious substance to fill the internal pores. Based on group B, after replacing...
cement with the same amount of fly ash, the compressive strength dropped from 19.45MPa to 5.11MPa while the elastic modulus dropped from 1.105GPa to 0.563GPa. In all, increasing the water-cement ratio and reducing the proportion of cement can significantly reduce the strength and elastic modulus of rock-like material specimens.

Table 1. Mechanical parameters of specimens with different proportions

| Group | Water-cement ratio | Cement: Fly Ash: Sand | Proportion of admixtures | Strengtha (MPa) | Elastic modulusa (MPa) |
|-------|--------------------|-----------------------|--------------------------|-----------------|------------------------|
| A     | 0.4                | 1:0:1                 | 10%                      | 25.95           | 1214                   |
| A1    | 0.5                | 1:0:1                 | 10%                      | 19.45           | 1105                   |
| A2    | 0.6                | 1:0:1                 | 10%                      | 10.20           | 619                    |
| A3    | 0.5                | 5:2:7                 | 10%                      | 8.67            | 604                    |
| B     | 0.5                | 4:3:7                 | 10%                      | 6.52            | 489                    |
| B1    | 0.5                | 3:4:7                 | 10%                      | 5.11            | 563                    |
| B2    | 0.5                | 1:0:1                 | 1%                       | 22.71           | 1067                   |
| B3    | 0.5                | 1:1:2                 | 10%                      | 25.95           | 1214                   |
| C     | 0.4                | 1:0:1                 | 10%                      | 3.99            | 176                    |
| C1    | 0.5                | 1:1:2:8               | 10%                      | 3.61            | 208                    |
| C2    | 0.5                | 1:1:4                 | 10%                      | 1.84            | 168                    |
| D     | 0.5                | 2:5:7                 | 10%                      | 1.65            | 172                    |
| D1    | 0.5                | 0:1:1                 | 10%                      | 1.32            | 160                    |
| D2    | 0.5                | 1:0:1                 | 5%                       | 17.21           | 875                    |
| D3    | 0.5                | 1:0:1                 | 15%                      | 18.04           | 832                    |
| E     | 0.5                | 1:6:7                 | 10%                      | 1.32            | 160                    |
| E1    | 0.5                | 2:5:7                 | 10%                      | 1.65            | 172                    |
| E2    | 0.5                | 0:1:1                 | 10%                      | 1.32            | 160                    |
| E3    | 0.5                | 1:0:1                 | 10%                      | 17.21           | 875                    |
| F     | 0.4                | 1:0:1                 | 5%                       | 18.04           | 832                    |

a Both strength and elastic modulus are the average value of at least 3 tests.

Furthermore, in order to test the mechanical properties of rock-like material specimen with 3D printing fissures, the water-cement ratio was selected as 0.5 and the admixture content was 10%. The mixing ratio of cement, fly ash and sand was 4:3:7 (B2 in table 1). The uniaxial compressive strength of this kind of material was 6.52MPa after curing for 5 days under standard conditions, and the elastic modulus was 489MPa.

The rock-like specimens were poured in a triple mould of 100mm×100mm×100mm. First, put the printed fracture model into the triple mould, making sure that the bottom plate of the fracture model was completely attached to the bottom of the triple mould. Then, pour the well-stirred mortar into the triple mould, calibrating that the angle of the fracture model was still correct after vibrating (figure 4). During the curing process, the specimens were allowed standing and covered with plastic wrap to keep water. When the specimen is initially solidified, remove the specimen from the mould, and put it in water for 48 h until PVA fissures are dissolved (figure 5). The specific pouring process is as follows:

1. Place the 3D printing model in a steel mould, and the inner size of the model is 100mm ×100mm × 120mm (length × width × thickness).
2. In this test, the high-strength white Portland cement, quartz sand and water are fully stirred at 1:2:0.5 (mass ratio), and then poured the mixtures into the steel mould, fully shaking to make the cement mortar evenly fill the entire mould.
3. After 48 hours from pouring, remove the mould and place specimens in a curing box for 12 days under the standard curing conditions. Then put specimens in clean water for 48 hours to dissolve the PVA fissure network by itself. Finally, use tweezers to remove the remaining PVA material in the fissures.
4. 48 hours later in the room temperature and humidity, the upper and lower surfaces of specimens were smoothed.
4. Uniaxial compression mechanical properties

4.1. Experimental Setup and method

As is shown in figure 6, the uniaxial compression test was carried out on YZW 1000 multi-field coupling rock fracture direct shear apparatus (figure 6). The maximum normal force of the loading module is 1000KN while the maximum tangential force is 500kN with an accuracy of 1%. In this test, the displacement control is adopted with a rate of 0.005 mm/s and the loading process was continued until the specimen was completely destroyed. Stress-strain curve was recorded with a displacement resolution of 0.001mm. Experimental method for rock-like material specimens with different inclination fissures is shown in table 2. The inclination angles of fissures are measured anticlockwise from the horizontal line.
Table 2. Experimental method for rock-like material specimens with different inclination fissures

| Group | Water-cement ratio | Cement: Fly Ash: Sand | Proportion of admixtures | Inclination angle | Material of fissures |
|-------|--------------------|-----------------------|--------------------------|------------------|---------------------|
| a     | 0.5                | 4:3:7                 | 10%                      | 0°               | PVA                 |
| b     | 0.5                | 4:3:7                 | 10%                      | 30°              | PVA                 |
| c     | 0.5                | 4:3:7                 | 10%                      | 45°              | PVA                 |
| d     | 0.5                | 4:3:7                 | 10%                      | 60°              | PVA                 |
| e     | 0.5                | 4:3:7                 | 10%                      | 90°              | PVA                 |

4.2 Experimental results and discussion

4.2.1 Mechanical properties of rock-like specimens with 3D printing fissures

As is shown in figure 7, the curve has obvious elastic phase, plastic phase, peak strength, strain softening and residual phase, which is very similar to the behaviour of real rock specimens. In the initial stage of loading, the stress increases linearly with the strain as the axial load increases, with obvious linear elastic deformation characteristics. After that, the stress-strain curve deviates from the linear relationship and enters the plastic deformation stage. The rate of stress increase gradually decreases with the increase of strain, and then the stress reaches the peak. Then, the stress gradually decreases with the increase of strain, and enters the post-peak deformation stage, showing the characteristics of strain softening. Finally, the stress-strain curve gradually becomes flat and enters the residual deformation stage.

The mechanical properties of the fractured rock-like material specimens and the intact rock-like material specimens are compared in this paragraph. As mentioned in Section 3, the uniaxial compressive strength and elastic modulus of the intact rock-like material specimens are 6.25MPa and 489MPa respectively while the fractured rock-like material specimens are in the range of 0.6~2.57MPa and 16~106MPa, which indicates that fissures can significantly reduce the uniaxial compressive strength and elastic modulus of the rock-like material specimens. The results show that their mechanical properties are consistent with experimental results of other rock specimens with certain similarity.

Furthermore, changes in uniaxial compression strength and elastic modulus of rock-like material specimens with different inclination fissures are analysed in table 3 and figure 8. As the inclination angle increases from 0°, the uniaxial compressive strength and elastic modulus both decrease first and then increase. The uniaxial compressive strength decreased from 1.48MPa to 0.6MPa (45°) and finally...
increased to 2.57MPa (90°). The modulus of elasticity decreased from 59 MPa to 16 MPa (45°) and increased to 106 MPa (90°).

It can be concluded that, as the inclination angles increases from 0° to 90°, the uniaxial compressive strength and elastic modulus both decrease first and then increase. Specifically, both strength and elastic modulus reach the minimum at about 45°, decreasing from 0° to 45°, and conversely increase from 45° to 90°.

Table 3. Uniaxial compression strength and elastic modulus of rock-like material specimens with different inclination fissures

| Inclination angle | Material | UCS/MPa | E/MPa |
|------------------|----------|---------|-------|
| 0°               | PVA      | 1.48    | 59    |
| 30°              | PVA      | 1.10    | 29    |
| 45°              | PVA      | 0.60    | 16    |
| 60°              | PVA      | 0.96    | 29    |
| 90°              | PVA      | 2.57    | 106   |

Fig.8. Uniaxial compression strength and elastic modulus of rock-like material specimens with different inclination fissures

4.2.2 Failure modes analysis

The macroscopic mechanical properties of rock materials are closely related to their microscopic or mesoscopic characteristics. Rock failure is a gradual failure process, that is, the macroscopic failure of rock is evolved from microscopic fracture. The deformation of the rock-like specimens with fissures consists of two parts: ① Basic deformation of the rock. The rock-like specimens with fissures also go through two stages of compaction and elastic deformation; ② Destruction caused by localized internal slip or failure. The rock-like specimens reach the maximum local stress at the tip of fissures, and they will quickly fail through the fissures, leading to general failure.

In this paper, the failure process is roughly divided into two categories: one is the tension failure between fissures and fissures; the other is the tension-shear failure through fissures. When the inclination angle of the specimen is relatively small (0°, 30°), it is mainly tensile failure (figure 9a, b). When the inclination angle is 45° to 90°, the failure mode of the specimen is shear failure (figure 9c, d, e). The crack initiates at the position of the prefabricated fissures, propagating from the fissure tip, and finally the failure surface penetrates the entire specimen along the fissures (figure 9c, d, e). In all, regardless of the failure mode, it appears obvious brittle failure, which is consistent with the failure of rock materials.
5. Conclusions
In this paper, a cement-based material is used to simulate fractured rock-like material specimens. By adjusting the mix ratio, the mechanical parameters of this material can reach low elastic modulus, low strength required in geomechanical model test. What’s more, a method to fabricate small block masonry used in geomechanical model test with 3D printing fracture network is proposed. A series of tests are conducted for these 3DP fractured models, and the corresponding results show that their mechanical properties and failure characteristics are consistent with experimental results of other rock specimens with certain similarity, and geomechanical model test. Our work in this paper provide a solid foundation for the application of 3DP technology in geomechanical model test. The following conclusions can be drawn:

(1) Cement-based materials can satisfy the requirement of low strength and low elastic modulus for geomechanical model test. In our test, the minimum strength is 1.32MPa while the minimum elastic modulus is 160MPa.
(2) Increasing the water-cement ratio and reducing the proportion of cement can significantly reduce the strength and elastic modulus of rock-like material specimens.
(3) Fissures play an important role in strength and elastic modulus. With the increase of the inclination angles, the strength and elastic modulus are correlated, both decreasing first and then increasing, and the minimum is at 45°.
(4) The failure modes of fractured rock-like material specimens are all brittle failure, which is consistent with the failure of real rock materials.

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