Study on mechanical properties of 3D printed rock mass samples with photosensitive resin material

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Abstract. 3D printing technology can provide an effective method for specimen preparation of rock mass, but the mechanical properties of 3D printed rock mass still need to be further studied. In this paper, uniaxial compression tests are carried out on the intact and jointed rock mass models which are printed by laser rapid prototyping printer with photosensitive resin materials, stress-strain curve and fracture propagation are obtained, and the mechanical properties of 3D printed rock mass are studied. The results show that the intact model of the photosensitive resin material has greater plasticity and stress hardening after the peak strength, while the jointed models have obvious brittle mechanical characteristics, but in general, plastic deformation occurs before brittle failure; that the joint dip angle has an important influence on the physical parameters such as the peak strength of the model, strain at brittle fracture, elastic modulus, and the crack propagation; and that photosensitive resin material can simulate rock fracture, but it is not as good as natural rock or rock-like material. The research results can be used for reference in the study of mechanical properties of photosensitive resin and its application in 3D printing for rock mass.

1. Introduction

Rock mass widely exists in nature, and the spatial distribution of its internal structure is complex [1]. It is difficult to make rock mass samples with the same spatial distribution as the real joints, which is one of the problems that puzzles the in-depth study of rock mechanics. In 2015, the State Council issued "Made in China 2025" to encourage additive manufacturing and develop 3D printing industry. 3D printing technology is widely used in many fields such as aerospace, industrial design, construction engineering, machine manufacturing and medical industry [2-4]. And it also provides an effective method for making rock mass samples, and then the failure mechanism of rock mass is studied.

At present, the application of 3D printing joint rock mass technology is gradually developed [5-7], different researchers use different printing materials and corresponding printing technology to realize the printing of jointed rock mass. Ju Y. et al. earlier carried out research on 3D printing technology of photosensitive resin materials in rock mass. MIMICS® Program was used to process CT scanning images of coal rock, STL format files of joints and rock blocks were output, and then it is imported into Objet Studio program to build 3D network jointed rock mass model. Joints and rocks were
respectively made of different photosensitive materials which are solidified into three-dimensional rock mass models by spraying stack and laser irradiation [8]. Zhou T. et al. printed the Brazilian splitting test of sample by melt deposition molding, powder layer and inkjet head technology and stereolithography technology. The photosensitive resin samples printed by stereolithography technology have good brittleness, but they are still insufficient compared with natural rocks [9]. In addition, Wang P. T. et al. selected green environmental protection polylactic acid polymer engineering plastic to print joint model [10]. Liu H. B. et al. and Jiang Q. et al. used gypsum materials for printing, and the research shows that due to the use of glue, 3D printing gypsum specimen has lower density, lower strength, and larger plastic deformation [11-12]. Zhao H. et al. used gypsum, cement, and water with different proportions for 3D printing [13]. Tian W. et al. printed samples by 3DP process with coated sand material which are closer to physical and mechanical properties of natural sandstone than SLS process [14].

In conclusion, a variety of printing materials and printing technologies have been applied in 3D printing rock mass technology. Photosensitive resin material has brittle mechanical properties and is one of the main materials for 3D printing rock specimen. However, mechanical properties of 3D printing rock mass with photosensitive resin need to be further studied. In this paper, SolidWorks software is used to establish model, and photosensitive resin material is used to accurately print rock mass through 3D printing technology of light curing technology, and the problem of joint rock sample preparation is explored. At the same time, mechanical properties of rock mass are deeply studied, and the suitability of characterizing mechanical properties of rock mass is discussed, which provides a reference for the study of mechanical behaviour of photosensitive resin materials and the 3D printing technology of rock mass.

2. Making rock mass model by 3D printing material

2.1. Main raw materials and equipment
In this experiment, SPR6000B photosensitive resin material is produced by Zhuhai Zhengbang Technology Co., Ltd. SPR6000B laser rapid prototyping printer (as shown in figure 1) and GHX700 curing box are used to print model. The forming thickness is 0.05-0.2mm, and the printing accuracy is 0.1mm. MTS CMT5105 electronic universal testing machine with a range of 100kN is selected for uniaxial compression test, as shown in figure 2.

![Figure 1. SPS600B laser rapid prototyping printer.](image1)

![Figure 2. MTS CMT5105 electronic universal testing machine.](image2)

2.2. Specimen preparation
The basic principle of three-dimensional laser rapid prototyping (also known as stereolithography technology) is that YAG laser with 355 nm wavelength is selected by low-pressure mercury lamp to generate 254 nm spectrum in laser, then two orthogonal galvanometers swing harmoniously to irradiate the viscous photosensitive resin surface, finally the liquid resin material polymerizes and
solidifies layer by layer to obtain the required samples. Based on this principle, the main steps of specimen making are as follows:

1. Firstly, the liquid photosensitive resin was filled into the liquid tank of SPS600B printer.
2. The photosensitive resin was scanned and cured through. Ultraviolet with 300-500mv beam power irradiate a plane controlled by computer, and the scanning speed of contour and filling part was 2000-8000 mm/s and 3000-8000 mm/s, respectively.
3. Then the working platform was lowered by 0.1 mm, a layer of photosensitive resin was coated on the cured section by vacuum coating system, and then scanning and curing was carried out. (2) and (3) were repeated until the specimen was printed.
4. After printing, the specimens were cleaned and put into the curing box with six 25W UV lamps. After 20 minutes of rotary irradiation, the specimens were made.

Based on the above principles and steps, six specimens of cylinder with Φ39.1mm×80mm were prepared with an average density of 1159.92kg/m$^3$. No. 1 (R1) is a jointless cylinder shown in figure 3 (a). The specimens from No. 2 to 6 (JRM2-JRM6) with the joint of the length of 0.5 times of diameter, thickness of 1 mm, and dip angles of 0°, 30°, 45°, 60° and 90° are made, as shown in figure 3 (b). In addition, to test the influence of different loading speed on the mechanical properties of 3D printing rock, two specimens of cylinder (CR1 and CR2) with Φ 25 mm×50 mm were made.

![Figure 3](image1.png)  
(a) The intact specimen.  
(b) Specimens with different dip angles.  

Figure 3 3D printed rock mass specimens using photosensitive resin material.

![Figure 4](image2.png)  
Figure 4. The intact specimen after uniaxial compression.

3. Mechanical properties of 3D printed rock mass specimens under uniaxial compression

3.1. Mechanical properties of intact specimens under uniaxial compression with different loading rates

To test mechanical properties of the jointless specimens of photosensitive resin and determine the reasonable loading rate, uniaxial compression tests were carried out on CR1 and CR2 specimens with loading rates of 0.1mm/min and 1mm/min respectively, and R1 specimen with 0.1 mm/min. Figure 4 shows the compression specimen of jointless specimen R1, and figure 5 shows the stress-strain curves of three jointless specimens.

It is shown in figure 4 that the specimen is not cracked under large compression deformation but has large transverse deformation and drum shape. This phenomenon is similar to the uniaxial compression phenomenon of photosensitive resin in reference [15]. It indicates that the jointless photosensitive resin specimen has strong plastic deformation ability and is quite different from that of intact rock sample.

As can be seen from figure 5:

1. With the increase of loading rate, the peak strength and elastic modulus increase. And the peak strength and elastic modulus of different sizes specimens with the same loading rate and are close to each other.
2. The uniaxial compression of photosensitive resin specimens can be divided into elastic deformation, plastic deformation before peak strength, softening, plasticity after peak strength and
In the plastic stage after the peak strength, the stress softens to a certain value, there is an obvious yield plateau, and the transverse deformation of the specimen is obvious. In the hardening stage, the specimen is compacted, and the stress increases significantly with the increase of strain, which is higher than the peak strength.

In view of the high efficiency of 1 mm/min loading rate test, so the uniaxial compression test of photosensitive resin rock mass is carried out with 1 mm/min loading rate.

Figure 5. Stress-strain curves of intact specimens with different loading rates.

Figure 6. Stress-strain curves of rock mass with different dip angles joint under uniaxial compression.

3.2. Mechanical properties of jointed specimen with photosensitive resin

3.2.1. Stress-strain curves of specimen

Uniaxial compression test was carried out on 3D printed 5 photosensitive resin specimens (from JRM2 to JRM6), and the stress-strain relationship curve was drawn, as shown in figure 6. The curve ends with the sudden rupture of the specimen, in other words, the stress drops more than 70% in an instant, and the testing machine stops.

According to the different stages of stress change, the curves in figure 6 are divided into the following three categories:

1. Elastic-plastic-softening-plastic-hardening-britleness

The stress-strain curve of 0° angle joint belongs to this type, and the change trend of the curve is similar to that of the jointless specimen under compression, but the obvious difference is that when the strain of 0° dip angle joint is 0.412, the specimen is broken, and the stress drops sharply. The curves show brittle failure at last, but obvious plastic deformation and stress hardening appear in the process of stress development.

The 45° angle joint specimen also belongs to this type, but compared with the 0° angle joint specimen, the brittle fracture occurs in the stress softening stage, the stress decreases rapidly, and the stress hardening stage is not obvious.

2. Elastic-plastic-brittle

When the 30° angle joint specimen reaches the peak strength at the strain value of 0.033, the fracture at the joint penetrates and the instantaneous stress decreases by more than 70%. The specimen shows obvious brittle mechanical characteristics, and the plastic deformation is small, which is similar to the real jointed rock mass.

3. Elastic-plastic-softening-plastic-brittle

The 60° and 90° dip angles belong to this category, showing that there is a significant plastic deformation stage before brittle failure, especially for the 90° angle joint specimen.
3.2.2. Influence of dip angle on mechanical parameter

To study the relationship between the strain, peak strength, elastic modulus and dip angle, the fitting curves are drawn in figure 7, figure 8 and figure 9.

Figure 7 shows the curve of strain value and dip angle corresponding to the sudden stress drop (i.e. brittle failure time) of specimens with different dip angles, which is fitted by cubic polynomial of formula (1). The results show that the brittle failure of 30 ° angle joint specimen is in the extreme value of the curve at the lower strain value. With the increase of the inclination angle, the strain value corresponding to the brittle failure time increases.

\[ \varepsilon_c = 0.410 - 0.023\alpha + 4.235 \times 10^{-4}\alpha^2 - 2.002 \times 10^{-8}\alpha^3 \]  

Figure 8 shows the curve of peak strength and dip angle under uniaxial compression of specimens, which is fitted by cubic polynomial of equation (2). The uniaxial peak strength of specimens with 30 ° dip angle is low, which is in the extreme value of the curve. The uniaxial peak strength increases with the increase of dip angle from 30° to 90°.

\[ \sigma_p = 59.365 - 1.578\alpha + 0.031\alpha^2 - 1.435 \times 10^{-4}\alpha^3 \]  

Figure 9 shows the curve of the relationship between the elastic modulus and the dip angle. The elastic modulus is approximately expressed by secant modulus, and two curves are drawn from 0 to peak strength and to 80% peak strength. The plastic deformation of the specimen happens before the peak strength, so the stress-strain curve is close to a straight line from 0 to 80% of the peak strength, which the secant modulus is closer to the elastic modulus of the specimen. Linear correlation between the elastic modulus and the dip angle is high. The secant modulus calculated from 0 to 80% of the peak strength is fitted with equation (3), and the secant modulus calculated from 0 to peak strength is expressed in equation (4).

\[ E_1 = 1.155 + 4.51 \times 10^{-7}\alpha \]  
\[ E_2 = 1.017 + 3.48 \times 10^{-7}\alpha \]  

where \( \varepsilon_c \) is the strain corresponding to brittle failure time of specimens, and \( \alpha \) is the dip angle (°).

where \( \sigma_p \) is the peak strength of specimens (MPa).

\( E_1 \) and \( E_2 \) are to 80% of the peak strength secant modulus (GPa) and to peak strength secant modulus (GPa), respectively.

4. Crack propagation process of specimens with different dip angles under uniaxial compression

Due to the existence of joints, the mechanical properties of the fractural photosensitive resin material specimen are obviously different from that of the intact specimen. At the same time, crack propagation process of specimens is also different with different dip angles. The pictures of uniaxial compression test of fractural photosensitive resin with different dip angles are arranged in table 1, which can clearly show the crack propagation process. It can be seen from table 1 that:
(1) Different from the intact sample, the fractural specimens have obvious brittle failure accompanied by large fracture sound, especially for the 45° angle fractural specimen of which all the fragments fly out at the last moment of fracture. And the crack of fractural specimen with 30° angle develop rapidly to connect with each other, and the stress drops sharply, which shows a similar hard brittleness to rock.

(2) Except for the specimens with 30° dip angle, there is no obvious plastic deformation before the failure in the other specimens. The plastic deformation of the specimens with the angle of 0° is the largest, followed by 90°, 60° and 45° respectively. Bending failure occurs at the plastic deformation after crack propagation.

(3) The crack propagation of 90° angle fractural specimen gradually becomes parallel to the loading direction. The crack propagation of 30°, 45°, 60° angle fractural specimen is generally perpendicular to the fracture.

| Model | Initial state | Peak intensity moment | Crack growth moment 1 after peak strength | Crack growth moment 2 after peak strength | State of destruction | Broken fragments |
|-------|---------------|-----------------------|------------------------------------------|------------------------------------------|---------------------|-----------------|
| JRM2  |               |                       |                                          |                                          |                     |                 |
| JRM3  |               |                       |                                          |                                          |                     |                 |
| JRM4  |               |                       |                                          |                                          |                     |                 |
| JRM5  |               |                       |                                          |                                          |                     |                 |
| JRM6  |               |                       |                                          |                                          |                     |                 |

Note: the peak strength of JRM3 is instantaneous failure state.
5. Discuss
In this experiment, the mechanical properties of rock mass printed by photosensitive resin material are studied. To explore whether the jointed rock mass printed by this material is suitable for characterizing the mechanical characteristics of jointed rock mass, the law obtained from uniaxial compression test of rock made of cement mortar with water cement ratio of 0.65 in reference [16] is compared.

The compressive strength of 30° to 90° angle joint specimens increases with the increase of joint dip angle, which is consistent with the conclusion in reference [16]. However, the compressive strength of 0° angle joint specimen is significantly higher than that in reference [16], which is mainly due to the compaction of joints and 0° angle joint specimen shows the mechanical properties similar that of intact photosensitive resin specimen. In addition, the plastic deformation before brittle fracture is larger than rock. Photosensitive resin material used to print rock mass has shortcomings compared with rock-like material and needs to be further improved.

6. Conclusion
In this paper, the 3D printing technology of photosensitive resin is used to make rock mass specimens with different dip angles. Uniaxial compression tests are completed to study the mechanical properties of specimens. The conclusions are as follows.

(1) The uniaxial compression curve of intact photosensitive resin specimen shows the mechanical characteristics of elasticity - plasticity before peak strength - stress softening - plasticity after peak strength - stress hardening after peak strength. The plasticity after peak strength is significant, and stress hardening after peak strength is obvious, which is quite different from the mechanical characteristics of rock.

(2) The mechanical characteristics of jointed specimens are significantly different from those without joints, and the specimens with joints exhibit crack propagation until brittle failure. Generally speaking, the fracture is perpendicular to the joint surface first, and then the crack propagation gradually inclines to the loading parallel direction. At the same time, the joint dip angle has a significant effect on crack propagation, in which the 30° angle joint specimen exhibits the similar hard brittle mechanical properties of rock, while the other angle joint specimens exhibit brittle failure after partial plastic deformation.

(3) The strain value, peak strength, and elastic modulus of brittle failure of fractural specimens with different dip angles are different under uniaxial compression. The relationship between the first two and the dip angle can be expressed by a cubic polynomial equation, and the elastic modulus has a linear relationship with the obliquity. The three physical parameters of specimens from 30° to 90° angle increase with the increase of dip angle.

(4) In this experiment, photosensitive resin has obvious hardness and brittleness, and fracture propagation is helpful to study the law of rock crack propagation. But before brittle failure, plastic deformation is obvious, which is different from rock mechanical properties. If it is used as a printing material for rock sample, it needs to be further improved. In addition, this study provides a reference for the research and application of the mechanical properties of photosensitive resin materials.

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