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# An Experimental Investigation of Tensile Fracturing Behavior of Natural and Artificial Rocks in Static and Dynamic Brazilian Disc Tests

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**Abstract**

In this work, 3D printing (3DP) technology is applied to study rock fracturing behaviors in Brazilian disc tests. First, uniaxial compression tests were performed to identify the most suitable 3DP material from five available 3DP materials, i.e., ceramics, gypsum, PMMA (poly methyl methacrylate), SR20 (Acrylic copolymer) and resin (accura® 60), to simulate hard and brittle rocks. The experimental results demonstrated that the transparent resin produced via Stereolithography (SLA) was the best 3DP material for mimicking rocks. Then, static and dynamic Brazilian disc tests were carried out on the resin-based 3DP rocks and the corresponding prototype rocks. The testing results show that the fracturing behaviours of the 3DP rocks agreed well with those of the prototype rocks, which confirms the feasibility and validity of using 3DP to study rock fracturing behaviors in tensile tests. This work facilitates the application of 3DP to rock mechanics.

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*Keywords:* Tensile fracturing; Brazilian disc test; 3DP

## 1. Introduction

Rock fracturing has been traditionally studied in the laboratory using natural rocks. However, at present, the experimental study of rocks is encumbered by three problems: (1) rocks are both heterogeneous and unrepeatable; (2) rock cores collected from deep underground are difficult and expensive; and (3) manmade rock

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specimens with internal structures are difficult to fabricate. To solve these problems, identifying and developing some alternative materials and techniques are needed.

Three-dimensional printing (3DP), also called additive manufacturing, may help to address the rock sample preparation problem. 3DP has advantages over conventional manufacturing in fast and flexible preparation, high repeatability, and preparation of complex internal defects [1]. Due to these benefits, 3DP has been widely applied in biomedicine [2] and materials science [3] etc.

However, the application of 3DP in rock mechanics is in its infancy. By combination of the CT scan, 3D reconstruction and 3DP technologies, Ju et al. [4] produced a physical model to replicate natural coal rock. Jiang and Zhao [5] produced 3DP samples with polylactic acid (PLA) using fused deposition manufacturing (FDM) technique. Fereshtenejad and Song [6] studied the means of enhancing the compressive strength of the 3D printed gypsum samples. However, in these studies, the 3DP samples failed/yielded with low compressive strength, i.e., between 1 to 30 MPa, exhibiting ductile behavior. Therefore, a more brittle and strengthened 3DP material should be used to effectively mimic hard and brittle rocks.

In this study, laboratory tests conducted on five available 3DP materials are presented. Based on the test results, analysis of identifying a superior 3DP material to effectively replicate rocks was performed. Then, static and dynamic Brazilian disc tests were carried out to evaluate the feasibility of using the 3D printed samples produced with the identified 3DP material to study tensile failure problem.

## 2. Experimental setup

### *2.1. Specimen preparation*

In this study, three mainstream-printing techniques, i.e., the FDM, Stereolithography (SLA) and powder-based 3DP methods are used to prepare 3DP samples. Although each 3DP method has its unique principle, all these methods share the common principle of sequential-layer material joining throughout a 3D work envelope under automated control [7]. Five 3DP materials including ceramics, gypsum, PMMA (poly methyl methacrylate) produced by the powder-based 3DP for those three, SR20 (acrylic copolymer) fabricated by the FDM and resin (accura® 60) manufactured by the SLA were selected to prepare 3DP samples. Each specimen has a nominal size of 50 mm in diameter and 100 mm in length.

### *2.2. Testing apparatus*

Uniaxial compression tests were carried out to obtain the basic mechanical properties of the 3DP samples. The VJ Tech machine with a loading capacity of 100 kN was used to test the powder-based 3DP samples, i.e., ceramic sample, gypsum and PMMA. The other two samples, i.e., SR20 and resin, were tested with a Matest loading machine whose maximum loading capacity is 3,000 kN. All of the samples were tested at a loading rate of 2 mm/min.

## 3. Results and Analysis

### *3.1. Identification of a suitable 3DP material*

Table 1 shows the mechanical properties of the 3DP samples determined from compression tests, in which $\sigma_c$ is the peak stress, $\varepsilon_A$ and $\varepsilon_L$ are axial and lateral strains at the peak stress, $E$ and $\upsilon$ are Young's modulus and Poisson's ratio, respectively. Figure 1. displays stress-strain curves and the 3DP samples after tests.

In powder-based 3DP samples, i.e., ceramics, gypsum and PMMA, the strength and Young's modulus are much lower than those of the common natural rocks. Though the strain at the peak stress of the ceramics and gypsum samples is comparable to that of some brittle rocks such as porous sandstone [8], they did not fail with sharp stress drop after the peak stress. Instead, the gypsum sample failed with swelling, exhibiting ductile property (Fig. 1c). Therefore, it is believed that the powder-based 3DP samples are unsuitable to mimic brittle and hard rocks.

With regard to the SR20 sample, it exhibited typical elastoplastic behavior, i.e., SR20 showed elasticity in pre-yield stress region and exhibited plastic behavior in post-yield stress region (Fig. 1b). In addition, the SR20 sample swelled by approximately 7.5% in the post-yield stress region. Hence, the FDM-fabricated SR20 material is also considered inappropriate for simulating brittle rocks.

For the SLA-fabricated resin sample, its strength and stress evolution process agreed well with those of some hard rocks, e.g., fine-grained sandstone [9], and it deformed without significant swelling in the post-peak stress region. In addition, the transparent feature makes researchers possible to directly monitor the crack evolution during the fracturing, which could facilitate understanding rock failure mechanisms. Consequently, it is believed that the SLA-fabricated translucent resin is the best 3DP material among five available 3DP materials to mimic rocks.

Table 1 Mechanical property of 3DP samples

| Sample | $\sigma_c$ (MPa) | $\varepsilon_A$ (%) | $\varepsilon_L$ (%) | $E$ (GPa) | $\upsilon$ |
|---|---|---|---|---|---|
| Ceramics | 2.9 | 1.83 | -0.64 | 0.2 | 0.20 |
| Gypsum | 3.8 | 3.07 | -1.28 | 0.4 | 0.29 |
| PMMA | 3.5 | 5.87 | -4.36 | 0.2 | 0.33 |
| SR20 | 105.6 | 12.23 | -10.05 | 2.7 | 0.36 |
| Resin | 110.3 | 3.60 | -1.75 | 3.8 | 0.40 |

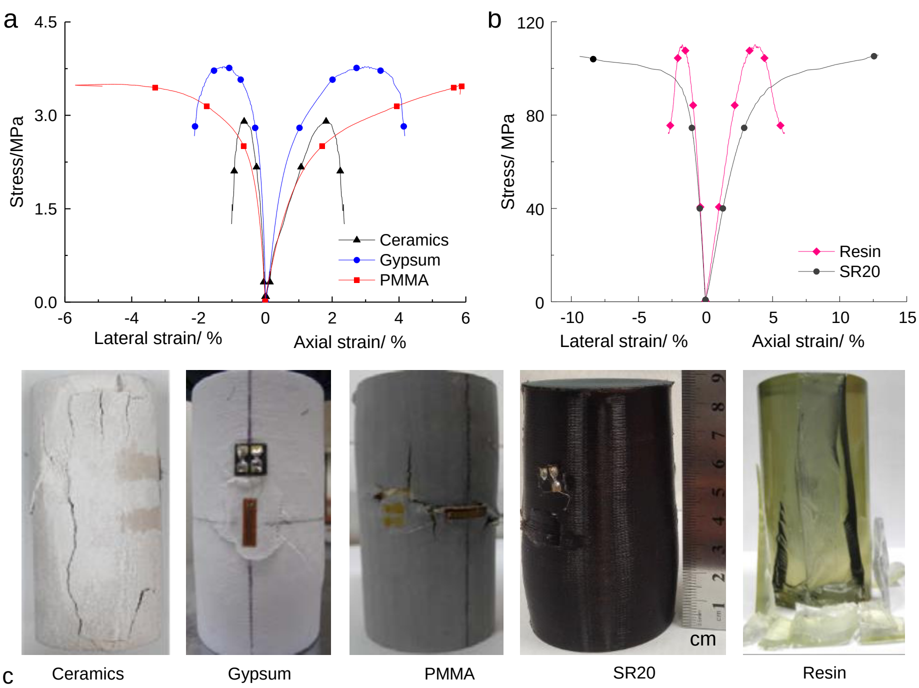


Fig. 1. stress-strain curves and the failure patterns of 3DP samples in uniaxial compression tests.

### 3.2. Brazilian disc tests

To evaluate the feasibility of using resin-based 3DP samples to study tensile failure problem, Micro-CT scan, 3D reconstruction and SLA technologies were together employed to produce resin-based artificial rocks with identical micro-defects as those found in the prototype volcanic and red sandstone rocks, respectively.

The porosities of the nature volcanic rock and red sandstone are 7.2% and 5%, respectively. The preparation details of resin-based 3DP rock can be found in Zhou and Zhu [10]. Subsequently, static and dynamic Brazilian disc tests were carried out on these resin-based artificial rocks and prototype rock samples. The static Brazilian disc tests were conducted in a TAW-2000 electro-hydraulic servo controlled machine with a loading rate of 2 mm/minute and the dynamic Brazilian disc tests were performed in the split Hopkinson pressure bar (SHPB) with a loading rate of approximately 500 GPa/s. During testing, a high-speed camera (FASTCAM SA1.1) was used to monitor the fracturing process with a frame rate of 100,000 frames per second.

*Static Brazilian disc test*

The static Brazilian disc test results are shown in Fig. 2, in which the tensile strain was measured by the strain gauge pasted on the back surface of the sample (Fig. 2c). It can be seen that the tensile strain of the 3DP samples is approximately twice of that of the prototype rocks, and the tensile strength is higher by about one-third than that of the prototype rocks. Two factors can be used to explain this discrepancy. On the one hand, the lower stiffness (~ 4 GPa) of the 3DP resin results in a larger deformation of the resin-based artificial specimens. On the other hand, the high tensile strength of the 3DP resin (~ 22 MPa) makes the tensile stress of the resin-based artificial rocks still higher than that of the prototype rock samples. However, the tensile stress-strain curves of the 3DP samples and their prototype rocks both exhibited almost linear behaviour prior to the sharp drop of the force at the peak stress. The high-speed photography images in Fig. 2c demonstrate the fracturing process of each sample. Generally speaking, the fracturing process and the failure pattern of the 3DP samples agreed well with those of the prototype rocks, i.e., the cracks generated near the top loading point, then propagated along the loading plane, and finally split the sample into two halves. In addition, we observed that new cracks generated at the pre-existing defects in 3DP samples due to its transparency, whereas we cannot observe this phenomenon in prototype rocks because of its opaque nature. Consequently, it can be concluded that the 3DP samples fabricated with the accura® 60 resin can be used to study fracturing properties in static tensile tests, although its mechanical properties, i.e., tensile stress and strain, need to be improved to well mimic prototype rocks.

*Dynamic Brazilian disc test*

Figure 3 shows the results in dynamic Brazilian disc tests. It needs to be noted that it is difficult to measure tensile strain in dynamic tests, thus we compared the dynamic tensile stress evolution in 3DP rocks with that in prototype rocks. Although the post-peak stress evolution of the 3DP samples were different from that of prototype rocks, the dynamic tensile strengths and the pre-peak stress behaviours agreed well with those of the prototype rocks. It indicates that the 3DP resin can well mimic the mechanical properties, i.e., dynamic tensile strength and pre-peak stress behaviour, of the prototype volcanic rock and red sandstone under dynamic loading conditions. There are two explanations for this phenomenon: first, the brittleness of the 3DP samples was enhanced by increasing loading rate which render the pre-peak stress behaviour of the 3DP rocks are comparable to that of the prototype rocks; and second, the strain rate effect is more significant for prototype rock materials.

Figure 3c presents the fracturing process of the prototype rocks and the 3DP samples in dynamic Brazilian disc tests. The fracturing behaviours in dynamic tests are consistent with the results in static ones, i.e., the fracturing process and failure pattern of 3DP samples are similar with those of prototype rocks. However, the new crack generation in 3DP rocks was slower by approximately 20 μs than that in prototype rocks. It is mainly due to the larger elastic deformation at the beginning of the loading stage in 3DP rocks. Thus, the crack evolution in 3DP rocks was delayed and the whole failure process was also prolonged. This phenomenon also explains why the post-peak stress of the 3DP rocks dropped slowly. In view of this, it can be concluded that the approach of incorporating micro-CT scanning and 3DP can be applied to study dynamic behaviours of rocks in dynamic tensile tests.

## 4. Conclusions

This paper reports application of 3DP on studying fracturing behaviours of rocks in Brazilian disc tests. The main conclusions are as follows:

(1) The SLA-fabricated resin material is the best for mimicking brittle and hard rocks, although its brittleness is not exactly the same as brittle rocks.

(2)The resin-based 3DP rocks can well replicate the mechanical properties, i.e., dynamic tensile strength and pre-peak stress behaviour, in dynamic Brazilian disc tests, but the results are poor for static Brazilian disc tests.
(3)The fracturing behaviours, i.e., fracturing process and failure patterns, of the 3DP rocks agreed well with those of the prototype rocks, which confirms the feasibility and validity of using 3DP to study rock fracturing behaviours in tensile tests.
(4)The transparent 3DP resin could be adopted to directly observe and analyse the internal crack evolution during rock fracturing, which may help better understand the failure mechanisms.

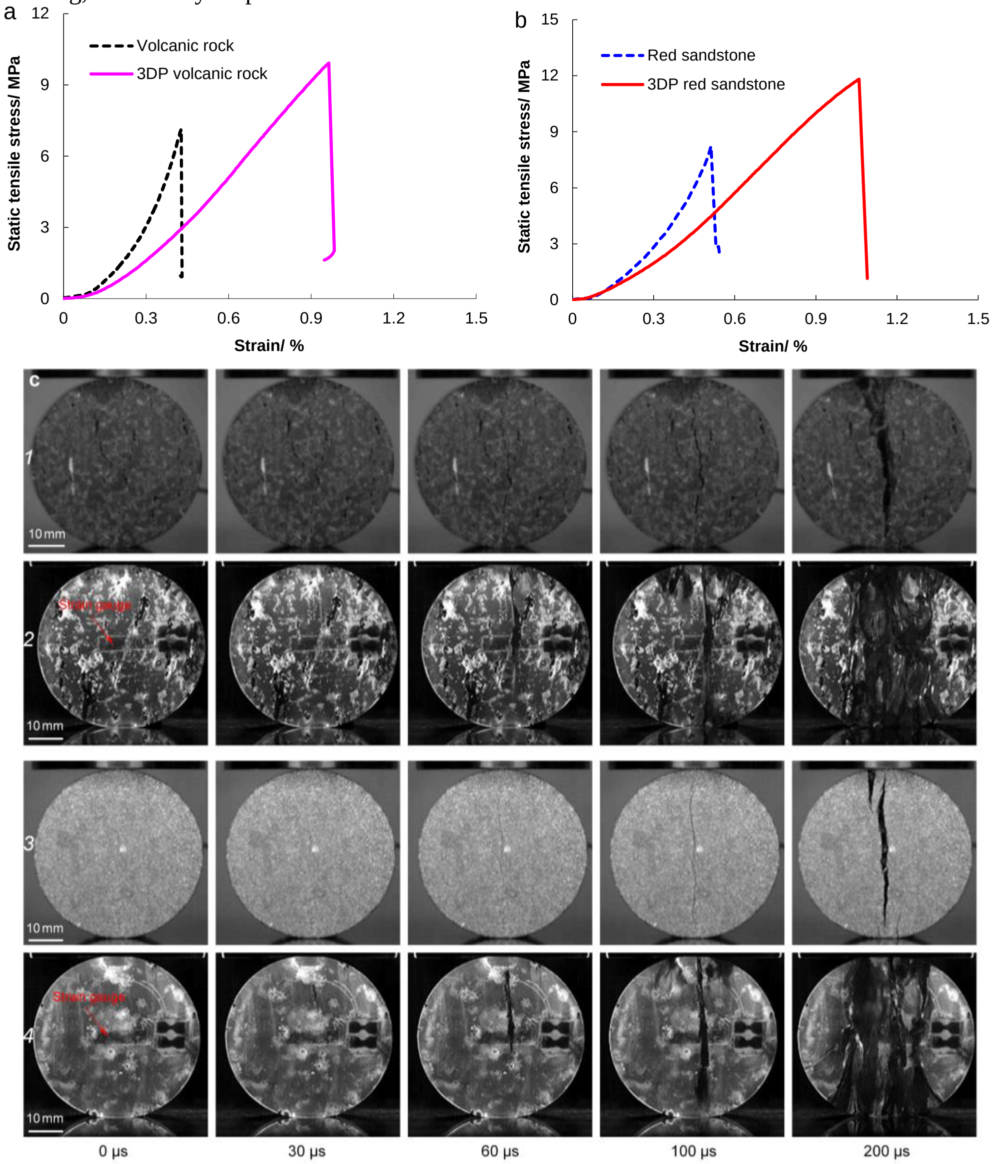


Fig. 2. (a) static tensile stress-strain curves of volcanic rock and 3DP volcanic rock; (b) tensile stress-strain curves of red sandstone and 3DP red sandstone; (c) fracturing processes of the prototype rocks and the corresponding 3DP rocks in static Brazilian disc tests. In (c), the first to fourth rows of the image are for volcanic rock, 3DP volcanic rock, red sandstone and 3DP red sandstone, respectively. The time at the bottom of the images is the absolute time of crack propagation sequence of each specimen.

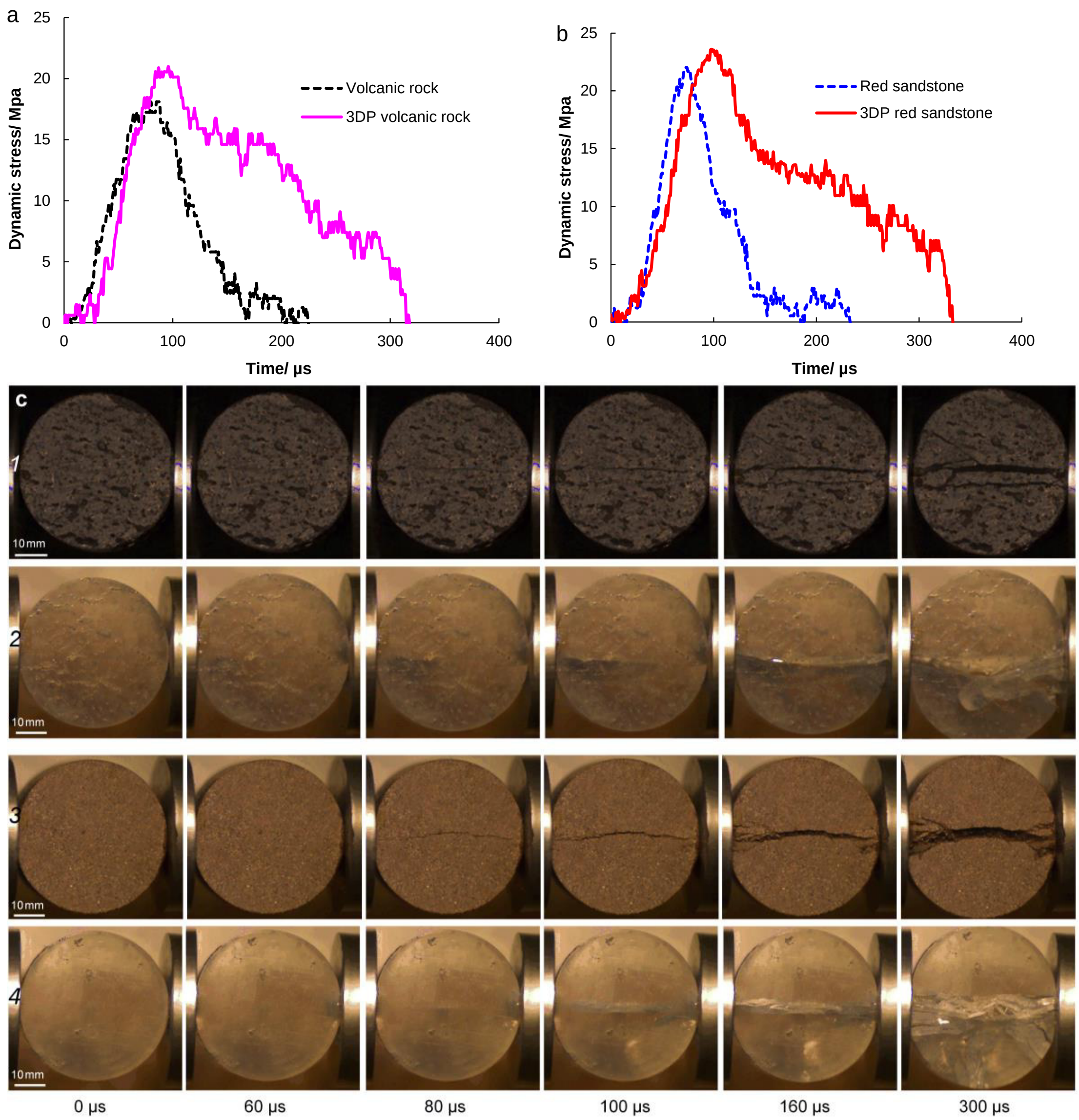


Fig. 3. (a) dynamic tensile stress-strain curves of volcanic rock and 3DP volcanic rock; (b) dynamic tensile stress-strain curves of red sandstone and 3DP red sandstone; (c) fracturing processes of the prototype rocks and the corresponding 3DP rocks in dynamic Brazilian disc tests. In (c), the first to fourth rows of the image are for volcanic rock, 3DP volcanic rock, red sandstone and 3DP red sandstone, respectively. The time marked below the images indicates the time recorded during the dynamic loading process.

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