The Influence of Polypropylene Fiber on the Working Performance and Mechanical Anisotropy of 3D Printing Concrete

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Abstract

The paper aims to clarify the influence of fiber properties on the working performance and mechanical properties of 3D printing concrete (3DPC). This paper investigates the effects of polypropylene fiber content and length on the working performance and mechanical anisotropy of 3DPC. The research results show that with the increase of polypropylene fiber content, the static yield stress, and the dynamic yield stress of 3DPC increase, the extrudability decreases. The buildability first increases and then decreases. As the length of polypropylene fiber increases, the static yield stress and dynamic yield stress increase, and the extrudability decreases. The buildability first increases and then decreases. The printability of 3DPC with 9 mm length fiber is better than that with 6 mm and 12 mm. Through the compressive strength and flexural strength tests of 3DPC, it was found that both the compressive strength and flexural strength have obvious anisotropy. The addition of fiber has a positive effect on the improvement of the compressive strength in three directions, and the flexural strength in the vertical and transverse directions is improved. Through work performance and mechanical anisotropy testing, it can provide a reference for optimizing the use of fibers in 3DPC.

1. Introduction

3D printing technology has received great attention in the construction industry. This method was introduced into the construction industry to construct free-form concrete structures digitally (Tay et al. 2017; Wu et al. 2016). Some researchers call it “3D printing” technology or some researchers call it “digital manufacturing”. 3D printing concrete (3DCP) technology can bring significant benefits to the construction industry, such as reducing construction time, manpower, and construction costs (Ovarlez and Roussel 2006).

Since 3DPC does not use formwork, the moisture is more likely to evaporate. The ratio of aggregate to cementitious material is low, and it contains many fine powders. It is susceptible to plastic shrinkage and cracking (Le et al. 2012a; Schutter et al. 2018). Since the 1990s, fiber reinforced concrete has been extruded through a simple extrusion process to improve the strength and toughness of structural members (Abdelrazik and Khayat 2020; Kassimi and Khayat 2020). In the process of extrusion, the orientation of the fibers is affected to a certain extent (Qian et al. 2003; Takashima et al. 2003; Hambach and Volkmer 2017). However, after adding fibers, the rheological properties of the paste change greatly, and the “extrudability” and “buildability” are affected (Zhang et al. 2020). “Extrudability” is 3D printing concrete to be “printed” by a nozzle and can form a continuous, uniform strip performance. “Buildability” is 3D printing concrete after extruding due to its own gravity and subsequent printing capacity without deformation. The influence of fibers on the working performance and mechanical properties of 3DPC has been studied by scholars at home and abroad.

With the addition of fiber, the rheological parameters of 3DPC change, and it affects the working performance. Work performance mainly refers to the rheological properties of 3D printing concrete, which specifically refers to slump flow, dynamic yield stress, and static yield stress. Mixing the proper amount of fiber material can optimize work performance. Hambach and Volkmer (2017) increased the fiber volume content to 1.5% in 3D printing fiber-reinforced Portland cement paste and found that the nozzle was frequently blocked during extrusion. When the fiber is 1% by volume, the printability is the best. “Printability” mainly refers to the extrusion ability, buildability and mechanical properties of 3D printing concrete. Qutaifi et al. (2018) added 1% steel fiber to the geopolymer mixture and found that the working performance was reduced by 4%. Adding 0.5% of polypropylene fiber reduces the processability by
about 33%. The reason is that these fibers absorb a large amount of geopolymer paste. The results of Nematollahi et al. (2018) show that adding polypropylene fibers to 3D printing geopolymers improves the ability for shape retention of the sample, and it can optimize the printability. Le et al. (2012a) found that the shear strength in the range of 0.3 to 0.9 kPa was the best for printability. This shear strength could be controlled by the amount of superplasticizer. Weng et al. (2018) established a prediction model for the rheology of 3DPC, and carried out experimental verification.

When the paste is extruded from the nozzle, the fiber arrangement direction will be affected to a certain extent. A weak bonding surface will be formed at the same time, which will affect the mechanical properties. 3DPC components have mechanical anisotropy (Feng et al. 2015; Le et al. 2012a). The addition of fibers greatly improves the bending performance of the printed samples, and the fracture energy is significantly higher (Hambach et al. 2016; Al-Qutaifi et al. 2018; Behzad et al. 2018). However, the increase of fiber content results in a slight decrease in the bonding strength between layers (Behzad et al. 2018; Ding et al. 2020). By adding fibers, the compressive strength of printed specimens can be obviously improved (Soltan and Li 2018; Ogura et al. 2018; Le et al. 2012b), Ma et al. (2019) developed basalt fiber concrete. By testing the mechanical properties of the printed specimens in different directions, it is found that the 3D printing samples have obvious mechanical anisotropy. These studies focus on the actual workability of 3DPC, and the quantitative indicators are not comprehensive. There are few studies on the influence of fibers on the rheological properties and mechanical anisotropy of fresh 3DPC.

This paper selected polypropylene fibers with different dosages and lengths to explore their effects on the working performance and mechanical anisotropy of 3DPC. By optimizing the proportion of 3DPC, it has good printability. The load was applied from three orthogonal directions to explore the mechanical anisotropy of printed specimens.

### 2. Materials and methods

#### 2.1 Raw materials

The raw materials used in this test included the following: ordinary Portland cement (PO 42.5) with a specific surface area of 348 m²/kg, sulphoaluminate cement (SAC) with a specific surface area of 408 m²/kg, silica fume (SF) of SiO₂>90%, quartz sand of which the particle size was 40-80 mesh, the water content of 0%; dispersible latex powder (FX), point-400s type polycarboxylic acid superplasticizer (HRWRA) with 0.8% in content and 30% of the water reduction rate, and polypropylene fiber (PP) shown in Fig. 1(a). The properties of PP fiber are shown in Table 1. The particle size distribution curve of the cementitious material is shown in Fig. 1(b).

#### 2.2 Preparation of 3D printing concrete

PO, SAC, SF, sand, and FX were put into the mixing pot of UJZ-15 mortar mixer, then mixed for 5 minutes. Thereafter, water and superplasticizer were added and mixed for 5 minutes. Finally, PP fiber was added then mixed 5 minutes. It took a total of 15 minutes. After mixing, the paste was taken out and put into the silo. This process took 5 minutes. The water-binder ratio (w/b) was 0.33. See Table 2 for the blending ratio. By changing the content and length of polypropylene fiber, the effect of polypropylene fiber properties on the rheological properties, extrudability, buildability and mechanical anisotropy of 3DPC was studied.

#### 2.3 Flowability

Flowability is an important reference index for evaluating the printability of 3DPC. The 3DPC fluidity deter-
mination method was carried out according to the Chinese Standard GB/T 2419-2005. In this study, the fluidity test of 6 groups of paste with 15 minutes of water addition was carried out.

2.4 Rheological test
A rheometer (MCR302) was used to test the rheological properties of 3DPC. After mixing the raw materials evenly, the mixed 3DPC was divided into 4 parts. The divided 3DPC was poured into the test cylinder according to the 4 time periods of 15, 20, 25 and 30 minutes after adding water. The rheometer was automatically operated, and the test results were recorded. A concrete rheometer was used to systematically test the rheological properties of the test group. The 3DPC was regarded as Bingham fluid (Zhang et al. 2013; Feys et al. 2007). The typical test result is shown in Fig. 2(a). The static yield stress was taken as the peak value, and the dynamic yield stress was taken as the downward intercept.

The rheological curve test procedure is as follows: 1) 0 to 30 s, pre-cutting, 2) the speed was uniformly accelerated from 0 to 30 rpm in 60 to 90 s, and the speed dropped to 0 rpm in 90 to 120 s, as shown in Fig. 2(b), 3) after 3 minutes, the test cylinder was changed to the next set, and this test procedure was repeated for a total of 4 times. If the yield stress value of the rheological curve exceeded 1400 Pa, the procedure was finished.

2.5 Extrudability evaluation methods
During the printing process, the paste was squeezed out of the nozzle head under the pumping action of the screw shaft. 3DPC must have good fluidity. Its static yield stress should not be too high (about 1000 Pa). Otherwise, it can cause pumping difficulties, and the paste will be difficult to extrude (Ketel et al. 2019). The test method of extrudability referred to the method in the patent application of Yang et al. (2014). Corresponding improvements had been made to the test method by combining the printers in this project group: before the test, the silo, the mixing pump, and the nozzle were wetted with water; after the water was completely drained, the well-mixed 3DPC was loaded into the 3D printer. The diameter of the circular nozzle was 15 mm, as shown in Fig. 3. The manual speed magnification was set to 100%; that was, the stirring axis speed was 11.6 rpm, then the mixing pump was started. After the 3DPC was uniformly and continuously extruded from the print nozzle, the time was recorded for 60 seconds using a stopwatch. The extruded mass M of 3DPC within 60 seconds was weighed accurately to 0.1 g. The extrusion quantity M was used to characterize the extrudability of 3DPC. The 3DPC was tested once for 5 minutes and tested 4 times.

![Fig. 2 (a) Results of typical rheological tests; (b) The test program of rheological curve.](image)
2.6 Buildability evaluation methods

Buildability refers to the ability of the 3DPC material to bear its own gravity and the gravity of the subsequent printed upper layer paste. After the 3DPC material is extruded and the shear thinning effect disappears, it does not deform and flow (Wang and Yang 2020). Since the paste has a relatively large static yield stress (about 800 Pa) after extrusion, it can resist the deformation caused by gravity (Long et al. 2019; Nerella et al. 2018; Wangler et al. 2019).

To study the influence of polypropylene fiber on the buildability of 3DPC, the height of the printed structure was used to evaluate the buildability. To maintain their shape and position, 3D printing structures usually must not collapse. In this study, the length of the printed specimen is 250 mm, the width is 20 mm, the number of layers is eleven, and the height of each layer is 8 mm. Imported the processed print file into the printer, set the nozzle moving speed to 3600 mm/min, stirring shaft speed was set to 6.6 rpm, then started printing. After printing, the total height of the printed structure was measured, as shown in Fig. 4. In this study, due to the large differences in the open time for printability of the 6 groups of materials, only the buildability of the 6 groups of materials with water for 15 minutes was tested.

2.7 Mechanical performance test

The strength of 3D printing concrete was tested in accordance with GB/T17671 (SAC 1999). According to the previous extrudability and buildability tests, it was found that the printing effect of the PP0.8-9 mm group was the best. Through the mechanical anisotropy test of the PP0-9 mm group without fiber and the PP0.8-9 mm group with the best printing effect, the influence of polypropylene fiber on the anisotropy of 3DPC was explored. The length of the print is 250 mm, the width is 160 mm, the number of layers is eleven and the height of each layer is 8 mm. The specimens were put in a room at 20±2°C and 65% relative humidity for curing. After curing for one day, they were cut. The sample size for the compressive strength test is 40×40×40 mm³. The size of the sample used for the flexural strength test is 40×40×160 mm³. The printing test piece and cutting method are shown in Figs. 5(a) and 6(a). There are three directions for samples, which are transverse X, longitudinal Y, and vertical Z, and longitudinal Y is the printing direction. The surface of the printed test pieces was polished to smooth and flat. Then the printed samples were cured for 7 days. Compressive strength test specimens and flexural strength test specimens were tested for compressive strength and flexural strength in transverse X, longitudinal Y, and vertical directions Z, respectively,

![Fig. 3 HC1009 frame printer; round nozzle 15 mm in diameter.](image)

![Fig. 4 Stacking performance test.](image)
as shown in Figs. 5(b) and 6(b). The strengths in the X, Y and Z directions are represented by the symbols $F_x$, $F_y$, and $F_z$, respectively. The test in each direction was performed 3 times, and the average value was taken.

3. Results and discussion

3.1 The influence of polypropylene fiber on the extrudability

The paste was subjected to the shearing force of the stirring blade in the silo to overcome the yield stress and flow. Under the pumping action of the screw column, the paste was pumped to the nozzle to be extruded. The amount of extrusion in this process is related to the dynamic yield stress. The greater the dynamic yield stress, the less likely the paste was to be extruded.

By conducting rheological tests on different groups, the rheological curves were obtained. Figure 7 shows the rheological test curve of the first group over time. The shear stress changes with the change of the shear rate. According to the rheological curve, the static yield stress and dynamic yield stress can be calculated (Zhao et al. 2021). The dynamic yield stress test results of different groups are shown in Fig. 8. The dynamic yield stress gradually increases with the increase of the time of adding water. Different amounts of polypropylene fibers have a great influence on the rheology of 3DPC. As shown in Fig. 8(a), in the 4 groups PP0-9 mm, PP0.4-9 mm, PP0.8-9 mm, PP1.2-9 mm, the dynamic yield stress improves with the improvement of fiber content. The fiber content improved from 0.8% to 1.2%, and the dynamic yield stress increased the most. As shown in Fig. 8(b), in the three groups of PP0.8-6 mm, PP0.8-9 mm, PP0.8-12 mm, the fiber content remains unchanged, and the dynamic yield stress increases with the increase of fiber length. When the water was added for 15 minutes, the dynamic yield stress increased from 370.63 Pa to 559.65 Pa, and the paste was difficult to be squeezed out.

![Fig. 5](image1.png)

Fig. 5 (a) Compressive strength test specimen cutting method; (b) Anisotropic mechanical property measurement by loading the 3D printed cubic samples from three orthogonal directions - i.e., load in x, y and z directions.

![Fig. 6](image2.png)

Fig. 6 (a) Flexural strength test specimen cutting method; (b) Anisotropic mechanical property measurement by loading the 3D printed prism specimens from three orthogonal directions - i.e., load in x, y and z directions.
It can be seen that the dynamic yield stress enlarges with the increase of fiber content and length.

The effect of polypropylene fiber on the extrudability of 3DPC is shown in Fig. 9. In the extrudability test of six groups of 3DPC, the printer used a 15 mm diameter nozzle, in manual adjustment mode, fixed to the stirring axis speed of each set of tests of 11.6 rpm. The amount of extrusion decreased with the increase of the time of adding water. It can be seen from Fig. 9 that the extrusion volume of 3DPC decreases with the increase of fiber content and length.

3.2 The influence of polypropylene fiber on the buildability

After the paste was extruded, it was stacked in layers in strips. The larger the static yield stress, the less likely it is to flow and the better the buildability. The static yield stress test results are shown in Fig. 10. It can be seen from the rheological data in Fig. 10 that the static yield stress gradually increases with the increase of the time of adding water. Different dosages of polypropylene fibers have a great influence on the rheological properties of 3DPC. As shown in Fig. 10(a), in the 4 groups PP0-9 mm, PP0.4-9 mm, PP0.8-9 mm, PP1.2-9 mm, the static yield stress increases with the increase of fiber content. The fiber content increased from 0.8% to 1.2%, and the static yield stress increased the most. When the water was added for 15 minutes, the static yield stress increased from 690.1 Pa to 1134.4 Pa. And in the case of the stirring shaft rotation speed, the shear force by the slurry was smaller than the static yield stress of the slurry itself.
The slurry did not flow, failed to be extruded, the slurry lost printability. As shown in Fig. 10(b), in groups PP0.8-6 mm, PP0.8-9 mm, PP0.8-12 mm, the fiber content remains unchanged, and the static yield stress increases with the increase of fiber length. The shorter the fiber, the easier it is to disperse the fiber. During the mixing process, the longer the fibers, the easier they are to overlap each other, forming a “three-dimensional network structure”. The “three-dimensional network structure” reduces the flow performance and increases the static yield stress.

In the 6 sets of constructive tests, in order to achieve the lateral contrast between the test group, the 3D printer had a 15 mm nozzle, and the nozzle movement speed was set to 3600 mm/min, and the stirring shaft rotational speed was set to 6.6 rpm. The results of the buildability and slump flow of the 6 test groups are shown in Fig. 11. The static yield stress increases with the increase of fiber content. At the same time, the slump flow decreases from 248 mm to 190 mm. As shown in Fig. 11(a), the accumulation layer height of PP0-9 mm, PP0.4-9 mm, PP0.8-9 mm group gradually increases, and the buildability gradually improves. Behzad et al. (2018) also find that increasing the fiber content can obtain better shape retention. In the PP1.2-9 mm group, the fiber content is 1.2%, the extrudability of the paste is poor, the nozzle was blocked, and the uniform and continuous strip cannot be extruded, and it is not constructive.

As shown in Fig. 11(b), for the PP0.8-6 mm, PP0.8-9 mm, PP0.8-12 mm groups, the stacked-layer height first becomes higher and then becomes smaller as the fiber length increases. The static yield stress increases with the increase of fiber length, and the slump flow decreases with the increase of fiber length. Therefore, the construction of the PP0.8-9 mm group is better than that of the PP0.8-6 mm group. However, when 12 mm polypropylene fiber with 0.8% volume content is added, although the static yield stress of the paste is relatively large, the dynamic yield stress is also relatively large. Therefore, the extrudability is poor, and the extruded paste is small. The strip height formed by the slurry does not satisfy the design height (the design height is 8 mm), resulting in a decrease in buildability. The PP0.8-9 mm group is more buildable than the PP0.8-12 mm group. On the whole, at the 3D printer, a 15 mm nozzle is used, the nozzle movement is 3600 mm/min, and the stirring shaft rotational speed is 6.6 rpm. 3D printing concrete static yield stress should be controlled at 800 Pa, and the dynamic yield stress should be controlled at 400 Pa.

![Fig. 10 Influence of the volume (a) and length (b) of PP fiber on the static yield stress of 3D printing concrete.](image1)

![Fig. 11 Influence of the volume (a) and length (b) of PP fiber on the buildability and slump flow of 3D printing concrete.](image2)
3.3 The influence of polypropylene fiber on the anisotropy

Through preliminary experiments, it is found that the printing effect of PP0.8-9 mm group is the best. This mechanical anisotropy test was carried out on the printed specimens of the PP0-9 mm group without fiber and the PP0.8-9 mm group with the best printing effect. The compressive strength in three directions is shown in Fig. 12(a). The flexural strength in three directions is shown in Fig. 12(b). To better characterize the anisotropy of the specimens, the three-direction strength anisotropy coefficient $\delta$ is introduced.

The arithmetic average of the intensity in the three directions is calculated by Eq. (1).

$$F = \frac{F_x + F_y + F_z}{3}$$ \hspace{1cm} (1)

The strength anisotropy coefficient in three directions is given by Eq. (2).

$$\delta = \sqrt{\frac{(F_x - F)^2}{F^2} + \frac{(F_y - F)^2}{F^2} + \frac{(F_z - F)^2}{F^2}} / 3$$ \hspace{1cm} (2)

where $F$ is the average value of intensity in three directions, $F_x$, $F_y$ and $F_z$ represent the strength values in three directions.

It is used to describe the degree of strength anisotropy in the three directions. When the value is larger, the anisotropy is stronger.

The three-direction compressive strength anisotropy coefficient of the PP0.8-9 mm group is 0.176. The compressive strength anisotropy coefficient of PP0-9 mm group is 0.125. This shows that the two sets of specimens have obvious anisotropy. After adding polypropylene fiber, the degree of anisotropy of the printed specimens becomes stronger. At the same time, after adding polypropylene fiber, the compressive strength in the three directions of X, Y, and Z are all increased. The reason is that the fiber crack bridge mechanism effectively inhibits the development of microcracks, thereby increasing the energy absorption capacity and compressive strength of the printing test piece. The failure state of the test piece in three directions is shown in Fig. 13. The compressive strength in the vertical direction (Z) is increased the most. The average compressive strength of the PP0.8-9 mm cube specimens in the vertical direction is about 26 MPa, which is much greater than the longitudinal and transverse compressive strengths. The reason is that as the 3DPC is extruded, the arrangement direction of the fibers is affected and tends to be arranged in parallel along the printing direction. When a load is applied in the vertical direction, the fibers play a bridging role and inhibit the occurrence of cracks. Figure 13(a) shows the failure mode of the PP0.8-9mm printed specimens after the load in the Z direction. Although the specimens have been damaged, they are bridged by the fibers to give them

![Fig. 12](image1.png)

**Fig. 12** (a) Compressive strength of 3D printing concrete; (b) Flexural strength of 3D printing concrete.

![Fig. 13](image2.png)

**Fig. 13** Failure modes after compressive strength test: (a) Direction Z; (b) Direction Y; (c) Direction X.
certain unity. From the perspective of the distribution of cracks, the failure mode of the specimen is a typical wedge failure. At the same time, due to gravity in the vertical direction, the paste is denser, and the printing tow has a stronger bonding force in the vertical direction. Therefore, the vertical direction (Z) has the highest compressive strength. When a load is applied in the longitudinal direction (Y), the strength of the specimen is higher than that in the transverse direction (X). The reason is that the specimen has a “short column effect”. The failure mode of the specimen is shown in Fig. 13(b). The crack is parallel to the direction of the load action. When a load is applied in the transverse direction (X), the printing tow is discontinuous in the vertical direction, and the horizontal bonding force is weak. In addition, the reinforcing effect of the fiber is difficult to play, so the specimen is more susceptible to damage. The failure mode is shown in Fig. 13(c), and the failure mode is also a typical wedge failure. However, during the process of applying a load, the cracks develop rapidly in the weak joint surface between the strips, so the strength in this direction is low.

The three-direction flexural strength anisotropy coefficient of the PP0.8-9 mm group is 0.265. The three-direction flexural strength anisotropy coefficient of the PP0-9 mm group is 0.193. The flexural strength of the specimens also shows obvious anisotropy. When 0.8% polypropylene fiber was added, the degree of anisotropy became larger. It can be seen from Fig. 12(b) that the flexural strength difference between the transverse (X) and the vertical direction (Z) is small. The flexural strength in the Y direction is greatly lower than the flexural strength in the other two directions. After the fiber is added, the flexural strength in the Z and X directions is improved, but the increase is not large. The reason is that although the addition of polypropylene fiber can inhibit the generation of cracks, it is more used to enhance the toughness of the component and has a small effect on the strength. The failure mode of the specimen is shown in Fig. 14. The reason for the lower flexural strength in the Y direction is that the bonding force of the printing tow in the horizontal direction is lower than that in the vertical direction. After adding fibers, the fluidity of the paste becomes worse, and the bonding force of the printing tow in the horizontal direction is further reduced. The structure is discontinuous against force, and it is more prone to damage when subjected to tension.

4. Conclusions

By exploring the influence of the content and length of polypropylene fiber on the working performance and mechanical anisotropy of 3D printing concrete, the following conclusions can be drawn.

(1) As the time of adding water increases, the static yield stress and dynamic yield stress of 3DPC increase. With the content or length of polypropylene fiber augments, the static yield stress and dynamic yield stress of 3DPC augment. When the fiber content increases from 0.8% to 1.2%, the static yield stress increases the most.

(2) When the 3D printer uses a 15 mm nozzle, the nozzle moving speed is 3600 mm/min, and the stirring shaft speed is 6.6 rpm with the content or length of polypropylene fiber raises, the extrudability of 3DPC decreases. The buildability first increases and then decreases with the increase of the content or length of polypropylene fiber. When the fiber volume content is 1.2%, the 3DPC is blocked at the nozzle, and it fails to extrude a continuous strip, which is not buildable. As the fiber length changes, the working performance of 3DPC changes. The working performance of 3DPC mixed with 9 mm length fiber is better than 3DPC mixed with 6 mm length fiber or 12 mm length fiber. The slump flow of the paste should be controlled at about 220 mm. The static yield stress should be controlled at 800 Pa, and the dynamic yield stress should be controlled at 400 Pa.

(3) The compressive strength and flexural strength of printed specimens have obvious anisotropy. The compressive strength in the vertical direction is greater than the compressive strength in the longitudinal and transverse directions. Both the vertical flexural strength and the transverse flexural strength are obviously greater than the longitudinal flexural strength. The addition of fiber has a positive effect on the improvement of the compressive strength in the three directions, and the flexural strength in the vertical and transverse directions is improved, but the increase is not large.

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