Study on Bending Strength of Cementitious Composites Based on Fiber Alignment

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Abstract: The traditional cement-based composites can’t meet the needs of actual 3D printing, people are committed to get breakthroughs in printing materials and extrusion process. This paper introduces the preparation of fiber-reinforced concrete materials, determining the optimum content of glass fiber in composite cement-based materials, and studying the fiber alignment during extrusion. From the bending strength, the performance of 3D printed fiber concrete materials are comprehensively analyzed. As a result, the bending strength of the sample does increase to the fiber volume ratio. The composite cement-based material with 2 vol.-% aligned fiber can have an excellent flexural strength of 12.05MPa, and the samples along the extrusion direction are more excellent than that along the transverse direction.

1. Introduction
3D printing concrete technology is a new kind of concrete moldless forming technology, through the printer material layer by layer is accumulated to realize the free design of the building. At present, though there is a major breakthrough made in the 3D printing equipment, the printing materials are still limited to the traditional ordinary concrete which only show good compressive strength, and it is slightly insufficient in flexural properties respects.

In the 1970s, R.F.Zollo et al [1] reported that a mortar containing high-performance synthetic fibers (glass fiber or carbon fiber) was added to the concrete, and the obtained cementitious composites exhibited a flexural strength of 50MPa. Le T T et al [2] produced a high-performance fiber-reinforced fine aggregate concrete getting the 28d compressive strength of cast samples up to 107MPa and the flexural strength up to 11MPa, while the 28d compressive strength of the samples printed with the composite concrete was from 75 to 102MPa and had a flexural strength from 6 to 17MPa in 2012. Effects on different kinds of fibers of the mechanical properties of 3D printed cement-based materials were studied by Hambach M [3]. It was found that cement-based materials admixed 1 vol.-% of carbon fiber showed a tremendous increase of its flexural strength upon 30MPa and the compressive strength up to 82.3MPa. Admixing 1% (by vol.) of basalt fibers, the flexural strength could reach 13.8MPa and the compressive strength advanced 85MPa. 1 vol.-% percent glass fibers had the flexural strength of 12.4MPa and the compressive strength of 84.5MPa. Although adding the fibers to the cement-based materials would directly improve the ductility of the printing construction, the fact that fibers randomly dispersed in fiber-reinforced cementitious materials fabricated by traditional methods(e.g. casting) was wasting much of their potential on flexural strength. During the 1990s, in order to increase the density
of the cement slurry and affect the fiber orientation, people had made lots of attempts to extrude fiber-reinforced cement mortar by using a simple extrusion process [4]. B.Mu [5] introduced fly ash in a glass fiber extruded composite as the replacement of 70% volume of the cement increased the strength by 10% and the toughness by 50% in 2002. To 2006, experiments had shown that fibers could be aligned as a reinforcing agent for cement substrates by extruding, and the toughness of aligned fiber composites was higher than the equal volumes of randomly distributed fiber cement mortar [6]. Manuel Hambach et al [7] had put forward the aligned reinforcing cement slurry having the alignment of carbon fibers guided by the nozzle got a high flexural strength up to 100MPa in 2016. Jong-Han Lee [8] developed a nozzle with blades called the B-nozzle improving the fiber orientation and distribution in fiber-reinforced cement-based materials. Differ from conventional circular nozzles, the B-nozzles increased the mean fiber orientation coefficients by approximately 31–39% and the fiber distribution coefficients by 3–23% in 2019.

The essence of fiber alignment process forced the fibers aligned in the concrete material along the stress direction by the high shear force which was generated from the extrusion process to improve the tensile properties and thereby take full advantage of the toughness of the fibers [9]. Based on the research about extruded fiber-reinforced composites, the mechanical properties of 3D printing fiber reinforcement specimen by controlling fiber volume and alignment were studied in this paper.

2. Experiment

2.1. Raw materials and mix design

The basic materials used in this investigation were: Portland cement, water reducing agent, silica fume, glass fiber (see Table 1), water. Among them, the rapid hardening Portland cement P.O.42.5 were obtained from Lanke Environmental Water Purification Material Factory(Zhengzhou, China). The polycarboxylate superplasticizer was purchased from Suzhou Xingbang Enterprise, as cement dispersing agent to improve the dispersion of cement particles and reduce the slump loss. The high-performance silicon powder could increase the fiber-cement bond strength in cement matrix [10,11], which was got from Sichuan Langtian Company.

In addition, Glass fibers were pre-chopped having an average length of 12 mm and they were obtained from Yongxing Glass Fiber Factory. Water was ordinary drinking water.

| Density (g/cm³) | Tensile strength (MPa) | Elastic modulus (MPa) | Length (mm) | Elongation at break (%) | Melting point (°C) | Color |
|----------------|-----------------------|----------------------|-------------|------------------------|-------------------|-------|
| 0.91           | 346                   | 4286                 | 12          | 36.4                   | 169               | White |

There were four groups prepared in the experiment: Group 1 was plain cement composite, fabricated by casting. Group 2 was 1 vol.-% of glass fiber cementitious composites fabricated by conventional mold-casting. Group 3 and Group 4 were fiber-reinforced cement extrudates with fiber volume ratio of 1%, 2%, respectively. The mix proportions were listed in Table 2. By controlling the fiber volume content and alignment, the mixing ratio of Group 2, Group 3 and Group 4 were obtained on the basis of the G1. It was used to test the bending strength of ordinary concrete materials as the compared group to the other groups. While comparing the results of specimens of G1 and G2, the flexural properties of randomly distributed fibers in concrete materials could be analyzed. Furthermore, comparing G2 and G3, the mechanical properties of different fiber alignment in the cementitious composites could be found. And then, we could investigate the influence of different fiber volume which the fibers were aligned along the stress direction between the G3 and G4.
### Table 2 Mix proportions

| Mix ID | Cement | Water reducing agent | Silica fume | water | Fiber (%) | result                        |
|--------|--------|----------------------|-------------|-------|-----------|-------------------------------|
| G1     | 0.53   | 0.17                 | 0.26        | 0.02  | 0         | Flow state                    |
| G2     | 0.53   | 0.17                 | 0.26        | 0.02  | 0.01      | Viscous mortar                |
| G3     | 0.53   | 0.17                 | 0.26        | 0.02  | 0.01      | Squeeze easily                |
| G4     | 0.53   | 0.17                 | 0.26        | 0.02  | 0.02      | Squeeze difficultly and block the nozzle |

#### 2.2. Specimen preparation

After all solid materials, apart from glass fibers, were mixed in dry state, 20 g water were added every time and mixed until a homogeneous cement mixture was obtained, the glass fiber was added and the mixture was stirred for 150s to get the fiber-reinforced cement paste. The prepared mixed mortar was directly poured into a mold with the dimensions of 40×40×160 mm for 3-point-bending test and 50×50×50 mm for compressive strength test, and the surface of the mortar composites became smooth using the spatula. The mold was placed on a vibrating table when the filling was completed. After shaken to 30S, it was taken down and sealed with plastic wrap. The group was placed in the standard curing room as a G2 group. The preparation of the G3 and G4 groups required a simple injection technique that injected the cement paste containing admixed chopped fibers in a specific mold and extruded mixed cement paste through a smaller nozzle. Since the nozzle diameter was smaller than the average length of fibers, when the specimens were fabricated by a sample extrusion technique through high compression and high shear, the fibers within the mixed mortar in the extrusion process would be aligned along the stress direction [12]. The mold taken in this study was a disposable syringe having a nozzle diameter of 10 mm along with 12 mm fibers, as illustrated in Fig 1. And in the same way, the samples were placed on a vibrating table, shaken for 30 s, and sealed with plastic wrap, which were placed in a standard curing room as the G3 and G4 groups.

![Figure 1 Fibers are aligned by extrusion to produce solid samples containing oriented fibers.](image)

#### 2.3. Flexural strength measurements

The three-point bending test was carried out, according to GB/T 17671-1999, to determine the flexural tensile strength in a 3-point bending test setup. The testing machine was a Micro servo hydraulic universal testing machine with a 100kN load cell attached. The size of prism specimens was 40×40×160mm with 3 specimens for each testing series. Both the mid-bearing part and the bottom support were made of round steel with a radius of 1 cm as sketched in Fig. 2b. Besides, the free span l between supports was equal to 100 mm. In the bending test, the self-made bracket was placed in the center of the lower plate, adjusting the position of the test block and then placing the pressure-bearing round steel on the mid-span of the test block. Additionally, the pressure-bearing round steel was compacted by the upper dial compact before formal measurement. The samples were loaded from 0kN...
and the speed was set as 1mm/min until to the failure. By measuring the maximum force $F$ the flexural strength $f_s$ could be determined through:

$$f_s = \frac{3}{2} \times \frac{F \times l}{b \times h^2}$$  

(1)

Where $l$ represents the distance between the supports (100 ± 0.1 mm for specimens 160 mm in length), $b$ is the specimen's width, here equal to 40 mm, and $h$ is specimen's height, here equal to 40 mm. Before the measurement, the specimen's dimensions were determined within an accuracy of about 0.1 mm. The fiber orientation of samples containing aligned glass fibers and the testing setup can be seen in Fig. 2a.

![Figure 2](image)

**Figure 2** (a)Schematic illustration of aligned fiber-reinforced cement test specimens used in 3-point bending tests. (b) Photograph of three-point bending test in actual experiment.

### 3. Results and discussion

For the comparison purpose, the group of plain cement composite fabricated by casting and 1% randomly distributed glass fibers composites were placed together as the fiber content control group. The group of 1% randomly distributed glass fibers composites and the glass fiber-reinforced cement extrudates with fiber volume ratio of 1%, 2% are placed together as a control group for fiber alignment.

Table 3 showed the average strength of different fiber volume content and fiber alignment samples. As the measured results, when the fibers of the test samples were aligned, the bending strength was increased from 1 to 12MPa. In addition, samples prepared by conventional mold-casting achieving excellent compressive strength up to 24.63MPa were higher than extrusion processing of fiber reinforced cementitious composites samples G4 in the test direction II achieving 17.7MPa. It is obvious that compressive strength values were slightly decreasing, if fibers were admixed to the prepared cement paste samples, this was attributed to fiber induced damage effects leading to a composite with higher porosity. At least 3 specimens were tested for each three-point bending test and compression test.

| Sample               | Flexural strength (MPa) | Compressive strength (MPa) |
|----------------------|-------------------------|----------------------------|
|                      | Test direction I | Test direction II | casting | Test direction II |
| G1 (without fibers)  | 1.61±0.3               | -              | 24.63±0.1 | -               |
| G2 (1 vol.% glass fibers) | 5.28±0.2             | -              | 20.32±0.2 | -               |
| G3 (1 vol.% aligned glass fibers) | 9.38±0.1             | 17.34±0.2     | 19.32±0.1 |             |
| G4 (2 vol.% aligned glass fibers) | 12.05±0.2            | 16.30±0.1     | 17.70±0.3 |             |

Typical concrete exhibited the high compressive property, the poor flexural and tensile strength. Generally speaking, in order to improve the overall bending performance of the buildings, the corresponding steel bars were arranged at the specific position to exert the flexural properties in practical engineering. However, for 3D printed buildings, the technical craft of adding steel directly while houses
were printed had been realized difficultly. Therefore, it was acknowledged that fibers had taken the place of bars to play a tremendous role in the printing material. This was likely a result of the fiber reducing the occurrence of micro cracks on the concrete surface, decreasing the brittleness of concrete, improving the ductility and having an active influence on the fiber bridging strength to affect the mechanical properties of samples. In order to determine the effect of fiber volume fraction on the mechanical properties and the gain of strength, 3-point bending and compressive strength tests were performed. The bending strength-deflection curve was obtained, as shown in Fig. 3.

![Figure 3 Stress-displacement plots of 3-point bending tests for plain cement paste, mold casted and nozzle-injected glass fiber-reinforced cement paste for 1 and 2 vol.-% glass fibers.](image)

What we could get from the bending strength-deflection plot was that the flexural performance was improved by increasing the fiber volume content (Fig. 3). Comparison of the spots 1 and 2, it was obvious that flexural properties of specimens exhibiting a remarkable improvement due to the increase of fiber volume content. The failure pattern of ordinary concrete composite without fiber can be seen in Fig. 4a. Plain cement composite reached the maximum strength of 1.61MPa and it exhibited obvious brittleness when broken. It can be seen from the experimental process that as the amount of load increased, several small cracks were generated on the surface of the test samples. With the load further increased, the cracks were continuously developed and extended. When the load was close to the ultimate bearing capacity, the specimens were disconnected from the middle part directly and there was no obvious sign before the failure. Then the curve fell in a straight leading to the bending strength dropped suddenly. However, when the fiber content was about 1%, the curve became very smooth and the bending strength was increased to 5.28MPa (relative enhancement of 340%). It was because the mechanical bonding between the matrix and the fibers would improve performance of fiber reinforcement composite showing a strong reinforcement mechanism. In order to restrict the deformation and cracks, a great number of energies were consumed in the fracture and pullout processes resulting in the mechanical capability thus being improved. Hence, due to the great anchor force generated by the fiber end hook bundled with the cement matrix, the ductility was enhanced in bending breakage. There were not collapse and directly break for samples after reaching the peak (Fig. 4b). G4, which fiber content was increased based on G3. In the loading process, the curve went up bit by bit before the bending strength up to 10.5MPa. There were no obvious deformation and small cracks generated on the surface. If the flexural performance achieved 10.5MPa, the mid-span portion displayed some deflection cracks which slowly expanded to the supports. When the maximum bending strength 12.05MPa was achieved, the specimen was broken and the curve began to drop, and then the bending
strength declined. After the samples losing effectiveness, it was observed that no large area of soil was falling off. Except for the main crack in the span, there wasn't other crack generating (Fig. 4d). Therefore, the addition of fiber improved the ductility and the plastic deformation property of concrete composites.

![Failure surface](image)

Figure 4 Failure pattern of (a) plain cement sample, (b) 1% randomly distributed glass fibers sample, (c) Aligned fiber-reinforced cement sample (1 vol.-% percent fibers), (d) 2 vol.-% aligned glass fibers sample.

4. Conclusion

In this paper, the effects of fiber alignment on the mechanical properties of concrete are analyzed by comparing the samples produced by extrusion process and conventional mold-casting. The following conclusions have been derived from this study:

(1) The extrusion process plays an important part in aligning the fibers along the stress direction in the concrete composites, especially for 1% volume of glass fibers. Moreover, when the fiber content exceeds 2%, the fiber reinforced mortar will become very viscous, resulting in nozzle blocked typically during extrusion, which will affect the performance of printed products.

(2) Compared with plain concrete paste, the flexural performance of samples with fiber alignment has been greatly improved. A net increase of flexural strength by 600% with the fiber content of 1 vol.-% percent fibers and an ultimate flexural strength of admixing 2% (by vol) of aligned fiber cement of about 12.05MPa can be reached.

(3) There are still different challenges to the current extruding fiber reinforced concrete technology. Because the fiber length is larger than that of the nozzle, it is easy to cause the conveying pipeline and the printing nozzle clogging in the printing process, which results in the condensation of the printed lower layer material, and the upper layer material has not yet been ejected, thus the bond between the layers is not tight, which affects the safety performance of the printing building. Additionally, it will be the key of 3D printing high-rise buildings to further study the method of reinforcing steel bar introduction combined with the concept of assembly building or to make breakthroughs in material mix ratio.
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