Test research on mechanical properties of engineered cementitious composites

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Abstract: Taking engineered cementitious composites (ECC) as the research object, the effects of sand particle size (A), total fiber volume content (B) and fiber types (C) (single, double or triple blending) on the flexural strength, compressive strength and tensile strength of ECC were studied by orthogonal test. The results show that the total fiber volume content has the greatest influence on the three mechanical properties of ECC, and the three mechanical properties are improved with the increase of total fiber volume content. Followed by the influence of fiber types, the flexural and compressive strength of single doped PVA is higher than single doped PP and the two mixed, steel fiber can improve the flexural and tensile strength. The influence of sand particle size on the three mechanical properties of ECC is the least. After comprehensive consideration, in the range considered in this study, the optimal scheme is 600 μm grain size, 2% fiber volume content and triple blending (PP0.5% + PVA1% + S0.5%).

1. Introduction

After Portland cement was invented by J. Aspdin in 1824, concrete has gradually become the most important material in the engineering field, which has a history of 200 years. With the further expansion of urbanization demand, buildings tend to be large-span and high-rise structures, but the ordinary concrete is brittle and easy to crack under tension, which is difficult to meet the performance requirements of modern buildings. The disadvantage of concrete is that it is difficult to solve this problem by changing its nature. We can only seek to achieve this goal by means of "compound" technology, among which the most representative is engineered cementitious composites (ECC). ECC are formed by adding non oriented fibers [1], which will lead to strain hardening and multi crack development. On the one hand, ECC can absorb energy and improve its seismic performance. On the other hand, it can improve the durability of the structure in normal use and extend its service life [2].

Victor C. Li and Leung [3] of the University of Michigan in the United States added polyvinyl alcohol fiber to cement-based materials and carried out relevant experimental research, and the first to put forward the basic theory of ECC materials. Deng et al. [4-6] set up orthogonal test to observe the compressive failure process of ECC, focusing on the influence of water binder ratio, fiber content, fly ash content and sand binder ratio on the size effect of ECC cube compressive strength. Li [7] tested the static properties of ECC, and proposed a constitutive equation suitable for high ductility concrete. Yang et al. [8] studied the effect of mixing two kinds of fibers with different elastic modulus. The
results showed that when the total content of two kinds of fibers was less than 1.0%, the compressive strength of ECC increased by 20%, and the effect was better than that of steel fiber with only 1.0%.

In recent years, ECC has not been widely used in the engineering field due to the insufficient experimental research and theoretical analysis on the influencing factors of mechanical properties of ECC in China. Therefore, it is of great value to continue to carry out relevant experimental research. Based on the above research, orthogonal test method was used to analyze the influence of the maximum sand particle size (150μm, 300μm, 600μm), total fiber volume content (0%, 1.5%, 2.0%) and fiber types (single, double and triple blending) on the flexural, compressive and tensile strength of ECC. At last a matching scheme with excellent mechanical properties was obtained.

2. Experimental procedure

2.1. Materials and mixing ratios

(1) Cement: P·O42.5 ordinary Portland cement (Taiyuan Zhihai Commercial Concrete Co., Ltd.). (2) Emulsion powder: white powder with water solubility, redispersibility and fluidity. (3) Fly ash: grade I fly ash (Taiyuan thermal power plant). (4) Fine aggregate: three kinds of high quality river sand with maximum particle size of 150μm, 300μm and 600μm respectively. (5) Water: tap water in Taiyuan. (6) Water reducer: yellow-brown viscous liquid, full name polycarboxylate high performance water reducer, water reducing rate of 25%, solid content of 28%. (7) Fiber: polyvinyl alcohol fiber (PVA), polypropylene fiber (PP) and steel fiber (S). The performance indexes are shown in table 1.

| Fiber     | Diameter/μm | Length/mm | Density/(kg/m³) | Elastic modulus/GPa | Tensile strength/MPa |
|-----------|-------------|-----------|-----------------|---------------------|----------------------|
| PVA       | 24          | 8         | 1300            | 25                  | 1580                 |
| PP        | 48          | 8         | 910             | >3.5                | >400                 |
| S         | 75          | 13        | 7850            | 180                 | 3000                 |

The physical pictures of some raw materials are shown in figure 1.

![Image](image1.jpg)

Figure 1. Part of raw materials.

The test mixing ratios are shown in table 2. The data in the table are all mass percentages. The total fiber content was determined according to the volume percentage of cement-based composite material, and the specific values were 0%, 1.5% and 2.0%.

| Cement/% | Emulsion powder/% | Fly ash/% | Sand binder ratio | Water binder ratio | Water reducer/% |
|----------|-------------------|-----------|-------------------|-------------------|-----------------|
| 64       | 6                 | 30        | 0.3               | 0.26              | 0.3             |
2.2. Design of orthogonal test scheme

The main mechanical properties of ECC include flexural strength, compressive strength and tensile strength. In this paper, the effects of sand particle size, total fiber volume content and fiber types on the above properties of ECC were considered. In order to analyze the relationship between the mechanical properties and the influencing factors of ECC, the orthogonal test design method with three factors and three levels was used to determine the test scheme. The factors and levels of orthogonal test are shown in table 3, and the test combination scheme determined by orthogonal table L9 (3^4) is shown in table 4. Table 5 lists the specific situation of fiber types and amounts under different fiber content. In this paper, the effect of PP and PVA was mainly studied, and the effect of 0.5% steel fiber was only considered in the three dopants.

| Level | Sand particle size/μm (A) | Total fiber volume content /% (B) | Fiber types (C) |
|-------|--------------------------|---------------------------------|-----------------|
| 1     | 150                      | 0                               | Single blending |
| 2     | 300                      | 1.5                             | Double blending |
| 3     | 600                      | 2.0                             | Triple blending |

| Test serial number | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|--------------------|---|---|---|---|---|---|---|---|---|
| Influencing factor | A | 1 | 1 | 1 | 2 | 2 | 2 | 3 | 3 |
|                    | B | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 |
|                    | C | 1 | 2 | 3 | 2 | 3 | 1 | 3 | 1 |

| Fiber types | Total fiber volume content /% |
|-------------|-----------------------------|
| Single blending | 1.5%PP 2.0%PP |
|              | 1.5%PVA 2.0%PVA |
| Double blending | 1.0%PP+0.5%PVA 1.5%PP+0.5%PVA |
|              | 0.5%PP+1.0%PVA 1.0%PP+1.0%PVA |
| Triple blending | 0.5%PP+0.5%PVA+0.5%S |
|              | 1.0%PP+0.5%PVA+0.5%S |
|              | 0.5%PP+1.0%PVA+0.5%S |

2.3. Test block making and testing method

2.3.1. Size of test block.

The size of flexural and compressive test block: 40mm × 40mm × 160mm. The size of tensile test block: 78mm × 22.5mm × 22.5mm. The molds used for both are shown in figure 2.

(a) Flexural and compressive mold and test block  (b) Tensile mold and test block

Figure 2. Mold and test block.
2.3.2. Preparation of test block

2.3.2.1. Mixing process of composite materials:

2.3.2.2. Forming and curing of test block:

Flexural (compressive) test block: the mixture was poured in two layers, 50% was poured first, the other part was poured after vibrating for 30s, and then the other part was vibrated for 30s again. The surface was smoothed and covered with a layer of plastic film to prevent the moisture from evaporating too fast. After 24 hours, it was demolded and put into the curing pool.

Tensile test block: after pouring the mixture in one time, put it into the vibration table for 30s. The surface was covered with plastic film after leveling, and it was demoulded for curing after 24 hours.

Test block curing: standard curing conditions, temperature: 20±1℃, relative humidity: ≥95%, curing time: 28 days.

This study included 9 types of tests. It can be seen from table 5 that there are different combinations under the same fiber volume content and the same number of fiber types. In order to further study the hybrid effect of different fibers, a total of 15 groups of tests were designed. Each group had 3 flexural (compressive) test blocks and 3 tensile test blocks. The cured test blocks are shown in figure 2.

2.3.3. Determination of mechanical properties of test block.

The flexural strength and compressive strength were measured by the DYE-300S fully automatic computer constant stress press, and the tensile strength was measured by microcomputer controlled electro-hydraulic servo universal testing machine. The instruments are shown in figure 3.

3. Results and discussion of orthogonal test

3.1. Test phenomenon

Flexural test: at the beginning of loading, there was almost no deformation of the test block. With the gradual increase of load, weak sound would be generated inside the concrete, and small cracks would appear on the bearing surface. The main cracks appeared, which gradually expanded and extended, and finally reached the failure load. When the fiber was added, although the crack ran through the whole cross-section, there was still a large amount of fiber on the fracture surface, and the test block still had part of the bearing capacity.

Compressive test: compressive test was carried out with the flexural test block. When the load was gradually added to a certain level, a weak sound would be generated inside the concrete, and then...
many small cracks could be seen on its surface. When the load continued to increase, we could hear
the sound of breaking and the sound of sliding and collision of sheet concrete, and the cracks
expanded and finally crushed. The common specimens showed cone-shaped failure and ECC
specimens had small cracks on the surface.

Tensile test: in the process of loading, the test block appeared a weak fiber and concrete fracture
sound. When the load reached a certain extent, the test block would emit a very crisp fracture sound.
At this time the concrete was pulled into two parts. Brittle failure occurred, but the two ends were still
connected after the fiber was mixed, and it was difficult to break off by hand.

The failure modes of the test blocks are shown in figure 4.

(a) Test block after folding (b) Test block after pressing (c) Test block after pulling

Figure 4. Failure modes of test blocks.
3.2. Results and discussion

The mechanical property test results are shown in figure 5. When more than one sub test was included in a class of test, the sub test with the highest average strength value was selected and the combination was marked in the figure. P represents PP, a represents PVA and s represents steel fiber. The relationship between the levels of various factors and the mechanical properties of ECC was obtained by the range analysis method of orthogonal test, as shown in figure 6.

(1) According to the range analysis in figure 6, within the different levels of various factors considered in this study, the order of influence on the three mechanical properties test results of ECC is as follows: total fiber volume content (B) → fiber types (C) → sand particle size (A). The results show that the influence degree of the three factors on the three mechanical properties of ECC has good consistency, which has a good starting point for improving the mechanical properties of ECC.

(2) It can be seen from figure 6(a) that the sand particle size has a relatively small effect on the flexural strength of ECC. The flexural strength of ECC increases linearly with the increase of total fiber volume content when the total fiber volume content is less than 2%. When the total fiber volume content is 2%, the flexural strength of ECC is 68% higher than that of cement-based materials without fiber. The flexural strength of single and triple doped fibers is better than that of double doped fibers, which indicates that PP and PVA have a negative hybrid effect for flexural strength, while the flexural strength of three doping is significantly improved due to the contribution of steel fiber, which is a positive hybrid effect[9]. In terms of flexural strength, A2B3C3 is the best combination, that is, the sand particle size is 300μm, the total fiber volume content is 2%, and triple blending (steel fiber 0.5%).

(3) It can be seen from figure 6(b) that the compressive strength of the test block with sand particle size of 600μm is higher than that of 150μm and 300μm. The compressive strength of 1.5% fiber is 42% higher than that of cement-based material without fiber. Then, with the increase of fiber, the improvement of compressive strength tends to be slow. The compressive strength of ECC decreases with the increase of fiber types. Although steel fiber has high elastic modulus, the incorporation of steel fiber will cause the increase of holes and defects in the test block, which will reduce the compressive strength[10]. In terms of compressive strength, A3B3C1 is the best combination, that is, the sand particle size is 600μm, the total fiber volume content is 2%, and single mixing. It can be seen from figure 5(b) that the effect of PVA alone is better than that of PP, because PVA is soluble in water and can be well combined with cement, so that there are fewer defects in the test block.

(4) It can be seen from figure 6(c) that the tensile strength of the test block with sand particle size of 150μm is slightly better than that of 300μm and 600μm. The tensile strength of ECC with 2.0% fiber volume content is 28% higher than that of cement-based materials without fiber. PP and PVA have a positive mixed effect on the tensile strength of ECC. Due to the incorporation of steel fiber in the three blending, the tensile strength of ECC is improved by placing a series of short steel bars in the
matrix. In terms of tensile strength, A1B3C3 is the best combination, that is, the sand particle size is 150μm, the total fiber volume content is 2%, and the triple blending. It can also be seen from figure 5(c) that the tensile strength value of A1B3C3 combination (test 3) is the highest, which is 5.9Mpa.

(5) It can be seen from figure 6 that considering the influence of various factors on the mechanical properties of ECC, within the level range considered in this study, the excellent scheme is A3B3C1, that is, the sand particle size is 600μm, the total fiber volume content is 2%, single mixing, and the effect of PVA is better than that of PP. Considering the good compressive properties of the cement-based material, in order to better improve its tensile and flexural strength, the best scheme is A3B3C3, which is sand particle size of 600μm, total fiber volume content of 2%, and three admixtures (PP0.5% + PVA1% + S0.5%). Secondly, considering the economy, the suitable mechanical properties can be obtained by reducing the total fiber volume content to 1.5%.

4. Conclusions
(1) In this experiment, the effects of various factors on the three mechanical properties of ECC are as follows: total fiber volume content → fiber types → sand particle size. The three mechanical properties of ECC all increase with the increase of the total fiber volume content. Compared with the cement-based materials without fiber, when the total fiber volume content is 2%, flexural strength, compressive strength and tensile strength of ECC increase by 68%, 44% and 28% respectively. The overall mechanical properties of single-doped PVA are better than those of single-doped PP and the mixture of both. Compared with 2% PVA, when 0.5% steel fiber is added for three blends, the flexural strength and tensile strength are increased by 3% and 19% respectively, and the compressive strength is reduced by 16%. The change of sand particle size has little effect on the three mechanical properties, and the strength change range is just between 10% and 15%.

(2) The failure of the test block mixed with fiber: The fracture of the flexure test block penetrated through the cross section, but a large number of fibers were bonded on the fracture surface, so that it still had the bearing capacity without rapid damage; there were small cracks on the surface of the compressive test block, but it was still a whole and had not been directly compressed into scattered pieces; after the through cracks appeared in the tensile test block, there were still fibers at both ends, which could continue loading and deforming. These phenomena show that the ductility of cement-based materials with fiber has been significantly improved.

(3) Within the range of the various factors considered in this study, considering that the cement-based material itself has good compressive performance, in order to improve the tensile and flexural strength, the best scheme is A3B3C3, that is, the sand particle size is 600μm, the fiber volume content is 2%, and the triple blending (PP0.5% + PVA1% + S0.5%).

Acknowledgments
This work was supported by the Innovation and Entrepreneurship Training Project for College Students (Project Nos. 2017074) and the Taiyuan University of Technology. The authors are very grateful for the support. In addition, the authors would like to thank technical staff in the College of Civil Engineering at the Taiyuan University of Technology for key support.

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