Effect of Hybrid Fiber on Early Mechanical Properties of High Performance Concrete

Tusheng He, Qidong Chen, Zaibo Li*, Yang Liu, Sanyin Zhao, Xuguang Zhao
School of Chemistry and Civil Engineering, Shaoguan University, Shaoguan 512005, Guangdong, China
*Corresponding author’s e-mail: lizaibo@sgu.edu.cn

Abstract: The early mechanical properties of hybrid fiber reinforced concrete were studied by orthogonal test, the factors of steel fiber content, polypropylene fiber content and length on compressive strength and splitting tensile strength of concrete for 3d ages were investigated, the test results were analyzed by range analysis, variance analysis and performance index analysis. The results show that the hybrid fiber has a negative hybrid effect on the compressive strength of concrete for 3 days, a positive hybrid effect on the splitting tensile strength of concrete for 3 days. When the volume fraction of polypropylene fiber is 0.1%, the length is 12mm, and the volume fraction of steel fiber is 1.5%, the compressive strength of concrete is the largest. When the volume fraction of polypropylene fiber is 0.15%, the length is 18mm and the volume fraction of steel fiber is 1.5%, the splitting tensile strength of concrete is the largest.

1. Preface
Fiber can improve the tensile, flexural, impact and explosion resistance of concrete[1]. Due to the disordered distribution of fiber in the cement matrix, the friction and sliding between the fiber and the matrix can effectively prevent the formation and expansion of cracks, inhibit the accumulation and development of damage, and ease the stress concentration at the crack tip, so as to improve the toughness of concrete[2]. Adding a specific fiber alone can only improve one aspect of concrete performance[3]. For example, the addition of steel fiber can improve the tensile strength, impact resistance and toughness of concrete, but steel fiber has the disadvantages of easy corrosion, high bulk density, poor performance and so on. Polypropylene fiber can improve the tensile capacity and deformation capacity of concrete, but the elastic modulus and compressive capacity of concrete usually decrease slightly[4]. Mixing two or more kinds of fibers into concrete to make hybrid fiber concrete can effectively solve the above problems, and has better economic benefits[5].

2. Experiment

2.1. Raw materials
The cement (C) is P-O42.5R cement, the density is 3.05 g/cm³, the specific surface area is 385 m²/kg, and a flexural / compressive strength of 6.2 MPa/29.1 MPa and 8.5MPa / 49.1MPa for 3d and 28d ages, respectively; Coarse aggregate (G) is 4.75mm-26.5mm continuous graded limestone gravel with apparent density of 2.733 g/cm³; Fine aggregate (S) is river sand, apparent density is 2.692 g/cm³, the fineness modulus is 3.02; Additives (A) is polycarboxylate superplasticizer (ES-600WH, the solid content is 20%); The specific surface area is 400 m²/kg and the density is 3.40 g/cm³ of SS; The density of GBFS with S95 grade is 2.89 g/cm³; The basic properties of polypropylene fiber and steel
fiber are shown in Table 1.

Table 1 Basic properties of polypropylene fiber

| Type             | Appearance shape | Length /mm | Equivalent diameter /mm | Density /g/cm³ | Elongation rate /% | Tensile strength /MPa |
|------------------|------------------|------------|--------------------------|----------------|-------------------|-----------------------|
| Polypropylene fiber | Monofilament bundle type Y | 5-18       | 0.045                    | 0.91           | 16                | 370                   |
| Steel fiber      | Wave shape       | 38         | 0.8                      | 7.8            | /                 | 486                   |

2.2. Orthogonal test design

Three factors were identified: (1) Volume fraction of polypropylene fiber (A); (2) Polypropylene fiber length (B); (3) Volume fraction of steel fiber (C). According to the orthogonal test method, L16(4^5) orthogonal table is used to arrange the test, and the orthogonal test factors and levels are shown in Table 2.

Table 2 Test factors and levels

| Levels | Factor A /% | Factor B /mm | Factor C /% | Error D | Error E |
|--------|-------------|--------------|-------------|---------|---------|
| 1      | 0.05        | 5            | 0.5         | 1       | 1       |
| 2      | 0.10        | 6.5          | 1.0         | 2       | 2       |
| 3      | 0.15        | 12           | 1.5         | 3       | 3       |
| 4      | 0.20        | 18           | 2.0         | 4       | 4       |

2.3. Concrete mix proportion

16 groups of hybrid fiber concrete and 1 group of reference concrete were designed. Because of the low volume content of fiber, it has little effect on the volume fraction of the original components of concrete, so when the concrete is formed, other components are the same as the reference concrete except fiber. According to the relevant regulations of mix proportion in JGJ55-2011 code for design of mix proportion of ordinary concrete and the results of previous tests, the final benchmark concrete mix is shown in Table 3 (X0), and the concrete mix based on L16(4^5) orthogonal design and strength test are shown in Table 4.

Table 3 Reference concrete mix proportion and test results

| Number | Concrete mix proportion /kg/m³ | Test result for 3d |
|--------|--------------------------------|---------------------|
|        | C     | SS | GBFS | S     | Water | G     | A | Compressive strength /MPa | Splitting tensile strength /MPa |
| X0     | 288   | 57.6 | 134.4 | 734   | 135   | 1102  | 7.20 | 41.6 | 3.25 |

Table 4 Concrete mix proportion and test results

| Number | Factor A | Factor B | Factor C | Test result for 3d |
|--------|----------|----------|----------|---------------------|
|        | Level    | Content /kg | Level | Length /mm | Level | Content /kg | Compressive strength /MPa | Splitting tensile strength /MPa |
| X1     | 1        | 0.455    | 1      | 5         | 1     | 39        | 37.6 | 3.30 |
| X2     | 1        | 0.455    | 2      | 6.5       | 2     | 78        | 33.2 | 3.32 |
| X3     | 1        | 0.455    | 3      | 12        | 3     | 117       | 37.2 | 3.29 |
| X4     | 1        | 0.455    | 4      | 18        | 4     | 156       | 36.2 | 3.33 |
| X5     | 2        | 0.91     | 1      | 5         | 2     | 78        | 39.5 | 2.96 |
2.4. Test method
The samples shall be made in accordance with the relevant provisions of CECS13:2009 standard for test methods of fiber reinforced concrete, the sample specification is 100mm × 100mm × 100mm test block, and the formwork shall be removed 24 hours after the test block is made, and the standard curing shall be 3 days. The compressive strength and splitting tensile strength shall be determined in accordance with GB/T 50081-2002 standard for mechanical properties of ordinary concrete.

3. Test results and analysis
3.1. Range analysis
According to the orthogonal test method, taking the compressive strength and splitting tensile strength of concrete curing for 3 days as the indexes, a visual analysis table is made, as shown in Table 5. K₁, K₂, K₃ and K₄ in the table respectively represent the sum of corresponding test results when each factor is taken as level 1, 2, 3 and 4. k₁, k₂, k₃ and k₄ represent their average values. The influence of each factor on the index can be judged by the size of the range, and the factor corresponding to the maximum range is the factor that has the greatest influence on the test results, that is, the most important factor.

| Index               | Factors | K₁    | K₂    | K₃    | K₄    | k₁    | k₂    | k₃    | k₄    | RangeR |
|---------------------|---------|-------|-------|-------|-------|-------|-------|-------|-------|--------|
| Compressive strength| A       | 144.2 | 160.0 | 146.9 | 150.4 | 36.05 | 40.00 | 36.72 | 37.60 | 3.94   |
| f_c/MPa             | B       | 150.1 | 149.2 | 151.9 | 150.2 | 37.53 | 37.31 | 37.98 | 37.55 | 0.66   |
| Splitting          | C       | 149.7 | 148.0 | 150.5 | 153.2 | 37.43 | 37.00 | 37.62 | 38.31 | 1.31   |
| tensile strength   | A       | 13.2  | 12.9  | 13.3  | 12.7  | 3.31  | 3.23  | 3.32  | 3.17  | 0.15   |
| f_t/MPa             | B       | 12.7  | 13.2  | 12.8  | 13.4  | 3.19  | 3.30  | 3.19  | 3.35  | 0.17   |
|                     | C       | 12.8  | 12.6  | 13.5  | 13.1  | 3.20  | 3.16  | 3.38  | 3.29  | 0.22   |

It can be seen from the range values of various factors of compressive strength in Table 5, when the volume fraction of polypropylene fiber is 0.05% - 0.20%, the length of polypropylene fiber is 5.0mm-18mm, and the volume fraction of steel fiber is 0.5% - 2.0%, (1) The volume fraction of polypropylene fiber has the greatest influence on the compressive strength of concrete, followed by the volume fraction of steel fiber, and finally the length of polypropylene fiber. The latter two have
little influence and are close to each other; (2) It can be seen from the range value of various factors of splitting tensile strength that the volume fraction of steel fiber has the greatest influence on the splitting tensile strength of concrete, followed by the length of polypropylene fiber, and finally the volume fraction of polypropylene fiber. The three factors have little influence and are close to each other.

3.2. Variance analysis
The variance analysis of the test results of compressive strength and splitting tensile strength of hybrid fiber reinforced concrete curing for 3 days is shown in Table 6. If $F_{0.01}(f_1,f_2)<F$, the influence of representative factors on the test results is "extremely significant", indicated by "***"; If $F_{0.05}(f_1,f_2)<F<F_{0.01}(f_1,f_2)$, it indicates that the influence of factors on the test results is "significant", which is indicated by "**"; If $F<F_{0.05}(f_1,f_2)$, it indicates that the influence of factors on the test results is "no significant". When the factor has little influence on the test results, the factor and error are combined into a new error $e\Delta$.

| Index                  | Difference source | Sum of deviation squares (SS) | Freedom (df) | Mean square (MS) | $F$ value | F distribution value | Saliency       |
|------------------------|-------------------|-------------------------------|--------------|------------------|-----------|----------------------|----------------|
| Compressive strength   |                   |                               |              |                  |           |                      |                |
| $f_c$/MPa              | A                 | 35.64                         | 3            | 11.88            | 6.75      | **                   |                |
|                        | $B$               | 0.93                          | 3            |                   |           | $F_{0.01}(3,12)=5.95$|                |
|                        | $C$               | 3.55                          | 3            | 1.34             |           | $F_{0.05}(3,12)=3.49$|                |
|                        | Error             | 16.64                         | 6            |                   |           |                      |                |
| Splitting tensile      |                   |                               |              |                  |           |                      |                |
| strength $f_t$/MPa     | $A$               | 0.114                         | 3            | 0.0380           | 1.34      | no significant       |                |
|                        | $B$               | 0.062                         | 3            |                   |           | $F_{0.01}(3,12)=5.95$|                |
|                        | Error             | 0.081                         | 3            | 0.341            | 0.0300    | $F_{0.05}(3,12)=3.49$|                |

It can be seen from Table 6 that: (1) the volume fraction of polypropylene fiber has a "extremely significant" effect on the compressive strength of concrete for 3 days; The influence of polypropylene fiber length is the second, the influence of steel fiber volume fraction is the least (the new error $e\Delta$ is combined with the error column), which is consistent with the result of range analysis. (2) The influence of volume fraction of polypropylene fiber, length of polypropylene fiber and volume fraction of steel fiber on splitting tensile strength of concrete for 3 days is "no significant"; However, the volume fraction of steel fiber is the main factor affecting the splitting tensile strength of concrete, followed by the length of polypropylene fiber, and the volume fraction of polypropylene fiber has the least influence, which is consistent with the results of range analysis.

3.3. Factor index analysis
In order to analyze the relationship between the factors and the performance indexes of concrete curing for 3 days, the average index value of each factor at different levels is calculated from the visual analysis table, as shown in Figure 1 ~ Figure 2.
It can be seen from Figure 1 and Table 5 that: (1) when the volume fraction of polypropylene fiber is increased from 0.05% to 0.2%, there is the optimum content (0.1%), that is, the maximum value of compressive strength of concrete for 3 days; However, compared with the reference concrete (X0), the compressive strength of the concrete decreased by 3.85% under the optimum dosage, so the early compressive strength of the concrete showed negative hybrid effect. The main reason is that after adding the fiber, the concrete has "initial defect". Because of the air entrainment of polypropylene fiber, the binding force between the cementitious material and the aggregate of the concrete decreases, resulting in the reduction of the compressive strength of the concrete. (2) When the length of polypropylene fiber increases from 5mm to 18mm, the range of splitting tensile strength of concrete for 3 days is 0.66MPa, that is to say, changing the length of polypropylene fiber has little effect on the early compressive strength of concrete; According to the analysis of variance in Table 6, the effect of polypropylene fiber length on the early compressive strength of concrete is "no significant". (3) When the volume fraction of steel fiber is increased from 0.5% to 2.0%, the compressive strength of concrete has the maximum value, that is, the content of steel fiber is 2.0%, and the compressive strength of concrete for 3 days is 38.3MPa, which is increased by 4.2%. Compared with the reference concrete, the compressive strength decreased by 7.91%.

If only compressive strength of concrete is considered, when the volume fraction of polypropylene fiber is 0.1%, the length is 12mm, and the volume fraction of steel fiber is 1.5%, the compressive strength of concrete is the largest, and the better scheme is A2B3C4.
It can be seen from Figure 2 and Table 5 that: when the volume fraction of polypropylene fiber is between 0.05% - 0.20%, the length of polypropylene fiber is between 5.0mm-18mm, and the volume fraction of steel fiber is between 0.5% - 2.0%, the range of splitting tensile strength of hybrid fiber concrete for 3 days is less than 0.25MPa, that is to say, the change of three factors has little effect on the early splitting tensile strength of concrete; The results of variance analysis in Table 6 show that the three factors have no significant effect on the compressive strength of hybrid fiber concrete for 3 days.

When the volume fraction of polypropylene fiber is 0.15%, the length is 18mm and the volume fraction of steel fiber is 1.5%, the splitting tensile strength of concrete is the largest, which is 2.2%, 3.1% and 4.0% higher than that of reference concrete (X0); This shows that fiber hybrid can show positive hybrid effect and improve the early splitting tensile strength of concrete. This is because the hybrid fiber mainly blocks the generation and expansion of micro cracks in the concrete matrix, slows down the stress concentration at the crack tip in the concrete matrix, delays the time when the concrete reaches the ultimate stress, and improves the splitting tensile strength of concrete significantly. If only splitting tensile strength of concrete is considered, the better scheme is A_3B_4C_3.

4. Conclusion
(1) The significant influencing factor of compressive strength of concrete for 3 days is volume fraction of polypropylene fiber, while length of polypropylene fiber and volume fraction of steel fiber are not significant; The compressive strength of concrete for 3 days with polypropylene fiber shows negative hybrid effect.

(2) The influence of volume fraction of polypropylene fiber, length of polypropylene fiber and volume fraction of steel fiber on splitting tensile strength of concrete for 3 days is "no significant"; The splitting tensile strength of concrete for 3 days with hybrid steel fiber and polypropylene fiber show positive hybrid effect.

(3) When the volume fraction of polypropylene fiber is 0.1%, the length is 12mm, and the volume fraction of steel fiber is 1.5%, the compressive strength of concrete is the largest. When the volume fraction of polypropylene fiber is 0.15%, the length is 18mm and the volume fraction of steel fiber is 1.5%, the splitting tensile strength of concrete is the largest.

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References
[1] Wu, Z.; Shi, C.; He, W. (2016) Effects of steel fiber content and shape on mechanical properties of ultra high performance concrete. J. Constr. Build. Mater., 103: 8–14.
[2] Biao Li, Lihua Xu, Yuchuan Shi, et al. (2018) Effects of fiber type, volume fraction and aspect ratio on the flexural and acoustic emission behaviors of steel fiber reinforced concrete. J. Constr. Build. Mater., 181:474-48.
[3] Ali, M.A.E.M., Soliman, A.M., Nehdi, M. L. (2017) Hybrid-fiber reinforced engineered cementitious composite under tensile and impact loading. J. Mater. Design., 117:139-149.
[4] Zhang J, Wang Q, Wang Z. (2017) Properties of polyvinyl alcohol-steel hybrid fiber-reinforced composite with high-strength cement matrix. J. Mater. Civ. Eng., 29(7):04017026.
[5] Wang D, Ju Y Z, Shen H, et al. (2019) Mechanical properties of high performance concrete reinforced with basalt fiber and polypropylene fiber. J. Constr. Build. Mater., 197:464-473.