Strength and fiber synergy effect of steel-polypropylene hybrid fibre-reinforced concrete

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Abstract: The strength calculation models and dependence relations for compressive strength, splitting strength and axial tensile strength of hybrid steel-polypropylene fiber-reinforced concrete are proposed based on the theory of composite material strength and the experimental observations. The parameters unfixed in the models are solved by means of statistical method, and the synergy effects of fibre are quantified related to the volume fraction and aspect ratios.

1. Introduction
There are many kinds of fibers, no matter metallic or polymeric, widely used in concrete engineering for their attractive advantages. In most cases, fiber reinforced concrete (FRC) contains only one type of fiber. It has been shown that polypropylene fibers (PPF) have good ductility, fineness, and dispersion so they can effectively restrain the plastic cracks resulting from shrinkage and differential settlements during the fresh state. However, as a consequence of low Young’s modulus, PPF cannot prevent the formation and propagation of cracks at high stress level, and neither can they bridge large cracks [1, 2]. On the other hand, steel fibers (SF) have a considerably larger length, higher Young’s modulus and stiffness as compared to PPF, so they can improve crack control and mechanical properties of concrete. Nevertheless, the addition of SF at high dosages has potential disadvantages in terms of poor workability and increased cost. In addition, micro-defects such as voids and honeycombs might form during placing as a result of improper consolidation at low workability levels [3-5].

According with the known conclusions, it is impossible that using only one type of fiber can contribute entire advantages to perfect properties of concrete. Therefore, hybrid fiber systems, such as in case of PPF and SF two complementary fibers with proper proportion in concrete, maybe provide optimization design of concrete [6-10]. Focusing on mechanical properties, the purpose of this paper is to evaluate the synergy effect of PPF and SF in hybrid fiber-reinforced concrete and present appropriate strength calculation model.

2. Experimental program
2.1 Materials and mix proportion
Trial mixtures were prepared to obtain target strength of 50MPa at 28 days. The raw materials used include tap water, local ordinary Portland cement of grade 425. River sand with a fineness modulus of 2.5 was used as the fine aggregate, while crushed limestone with the grading 5~20mm was used as coarse aggregate. For reasonable workability, the matrix was mixed with carboxylic acid X404 high...
efficiency water reducing agent, dosage of 0.8% of the cementitious material.

The mix proportion of normal concrete (NC) without fiber is listed in Table 1, and the physical and mechanical characteristic parameters of SF and PPF are provided in Table 2 and 3 respectively.

Table 1. Mix proportion of the matrix

| NC  | Cement grade (kg/m³) | Water (kg/m³) | Cement (kg/m³) | W/C ratio | Sand (kg/m³) | Gravel (kg/m³) | sand ratio | Water reducing agent (kg/m³) |
|-----|----------------------|---------------|----------------|-----------|--------------|---------------|------------|----------------------------|
| C50 | P.O.42.5             | 175           | 486            | 0.36      | 746          | 1038          | 42%        | 3.9                        |

Table 2. Characteristic parameters of steel fibers

| Length (mm) | Diameter (mm) | Aspect ratio L/D | Shape | Density (g/cm³) | Tensile strength (MPa) | Type |
|-------------|---------------|------------------|-------|-----------------|------------------------|------|
| 30          | 0.75          | 40 (30/0.75)     |       |                 | ≥1100                  | ZP308|
| SF          | 30            | 0.55             | 55    (30/0.55) | Hooked-end      | 7.8                    | ZP305|
| 60          | 0.75          | 80 (60/0.75)     |       |                 |                        | RC-80/60|

Table 3. Characteristic parameters of polypropylene fibers

| Length (mm) | Diameter (µm) | Aspect ratio L/D | Type         | Density (g/cm³) | Tensile strength (MPa) | Modulus (GPa) | Elongation ratio (%) |
|-------------|--------------|------------------|--------------|-----------------|------------------------|---------------|---------------------|
| PPF         | 19           | 30               | 633          | Monofilament    | 0.91                   | ≥500          | >3.5                | 15~35               |

2.2 Test procedures

In this investigation, the maximum range of fiber dosage needed for producing SPHFRC mixtures was identified for acceptable workability characteristics. Table 4 shows the number and types of specimens with different volume fraction and aspect ratio of fibers prepared for tests. According to Table 4, steel fiber dosages were defined from 0.4% to 1.2% in volume, and polypropylene fiber dosages were defined from 0.05% to 0.15% in volume.

Table 4. Volume fraction and aspect ratio of fibers used in the study

| Volume fraction of SF (Vᵢᶠ, %) | Volume fraction of PPF (Vᵢᵖ, %) | SF Aspect ratio | PPF Aspect ratio |
|--------------------------------|-------------------------------|----------------|-----------------|
| 0.4%                          | 0.05%                         | 40             | 633             |
| 0.8%                          | 0.10%                         | 55             | 633             |
| 1.2%                          | 0.15%                         | 80             | 633             |

2.3 Testing SPHFRC mechanical properties

After 28 days’ curing from casting, mechanical properties tests on SPHFC specimens were carried out. A universal testing machine of capacity 3000kN was used for determining the compressive strengths and split tensile strengths of 150mm*150mm*150mm cubic specimens at a loading rate of 20kN/s and 2kN/s respectively, as shown in Figs. 1(a) and (b). In testing, the cube is turned over 90° with respect to casting direction and the compressive and splitting planes are the vertical central section of the cube. Specimens for axial tensile tests were prisms, with cross-section 100mm*100mm in the middle section and broadened tension zone in the end of specimens, as shown in Fig. 1(c). Axial tensile tests were operated with a force controlled testing instrument of capacity 300kN, and loading procedure at a
rate of 0.04kN/s.

![Image](a) (b) (c)

**Fig. 1.** Mechanical properties tests of SPHFRC: (a) Compressive strength test (b) Splitting tensile strength test (c) Axial tensile strength test

3. Results and analysis

3.1 Compressive, split tensile and axial tensile strength

Results for compressive, split tensile and axial tensile strength for all mixtures are presented in Table 5.

As demonstrated in paper [6], the strengths of mono-steel fiber-reinforced concrete (SFRC), ranging from 0.4% to 1.2% in volume fractions, are obviously improved in almost linear growth with the increase of volume fraction of SF, and larger aspect ratio has greater effect on mechanical properties of SFRC. However, the strengths of mono-polypropylene fiber-reinforced concrete (PPFRC), ranging from 0.05% to 0.15%, present similar change laws, which first increase slightly and then decline, with the increase of the dosage of polypropylene fiber. Although PPF added in concrete may not enhance the strength of concrete, it can benefit the deformation property of concrete from brittle fracture to ductile fracture as reported previously.

As for SPHFRC, a substantial increase of about 25% was observed in compressive strength, a 27% gain in splitting tensile strength, and a 39% gain in axial tensile strength. While regarding to SFRC, with the same steel fibers volume fraction, a pronounced increase of about 12% was observed in compressive strength, a 15% in splitting tensile strength, and an 18% in axial tensile strength. There is a synergy effect in the hybrid fibers system for the hybrid fibers concrete with good general mechanical properties, which could be further fortified by optimization using larger aspect ratio of steel fibers [11]. The improved strength of such SPHFRC mixtures can substantially increase the energy-absorbing capacity of concrete structures, so as to improve the ratio of the axial tensile strength to the compression strength.

| Specimen Series No. | Compressive strength (MPa) | Split tensile strength (MPa) | Axial tensile strength (MPa) | Au/Cu |
|---------------------|-----------------------------|-----------------------------|-----------------------------|-------|
|                     | Mean | $R_{p/nc}$ | Mean | $R_{p/nc}$ | Mean | $R_{p/nc}$ | |
| R40                 | 55.78 | 1.13 | 3.57 | 1.09 | 4.19 | 1.29 | 0.075 |
| P0.05%              | 52.46 | 1.06 | 3.50 | 1.07 | 3.76 | 1.16 | 0.072 |
| R55                 | 55.56 | 1.13 | 3.72 | 1.14 | 3.92 | 1.21 | 0.071 |
| R80                 | 58.96 | 1.19 | 3.69 | 1.13 | 3.86 | 1.19 | 0.066 |
| S0.4% P0.10%        | 59.72 | 1.21 | 3.77 | 1.15 | 4.32 | 1.33 | 0.072 |
| R55                 | 56.24 | 1.14 | 3.80 | 1.16 | 3.87 | 1.19 | 0.069 |
| R80                 | 51.62 | 1.05 | 3.56 | 1.09 | 3.72 | 1.15 | 0.072 |
| R0.15%              | 60.56 | 1.23 | 3.73 | 1.14 | 4.01 | 1.24 | 0.066 |
| R55                 | 57.57 | 1.17 | 3.60 | 1.10 | 3.74 | 1.15 | 0.065 |
| R80                 | 59.93 | 1.13 | 3.71 | 1.13 | 4.05 | 1.25 | 0.072 |
| P0.05%              | 59.94 | 1.21 | 3.70 | 1.13 | 4.53 | 1.40 | 0.076 |
| R55                 | 57.68 | 1.17 | 3.77 | 1.15 | 4.07 | 1.25 | 0.071 |
| R80                 | 57.60 | 1.17 | 3.75 | 1.14 | 3.87 | 1.19 | 0.067 |
| S0.8% P0.10%        | 58.02 | 1.18 | 4.01 | 1.22 | 4.10 | 1.26 | 0.071 |
| R55                 | 62.47 | 1.27 | 3.97 | 1.21 | 4.55 | 1.40 | 0.073 |
3.2 Strength calculation model

According to reference [12], two kinds of strength calculations models of SPHFRC are presented. One is considering of fiber hybrid interaction, and the other is not:

\[ f_f = f(1 + \alpha \lambda_{sf} + \beta \lambda_{pf}) \]  

Or

\[ f_f = f(1 + \alpha \lambda_{sf} + \beta \lambda_{pf} + \gamma \lambda_{sf} \lambda_{pf}) \]  

Where, \( f_f \), \( f \) denote the strength of SPHFRC and NC; \( \alpha \), \( \beta \), \( \gamma \) denote the influence factor of SF, PPF and hybrid interaction; \( \lambda_{sf} \), \( \lambda_{pf} \) denote the reinforcement index of SF and PPF; \( \lambda_{sf} = v_{sf} l_{sf} / d_{sf} \), \( \lambda_{pf} = v_{pf} l_{pf} / d_{pf} \); \( v_{sf} \), \( v_{pf} \) are the volume fraction of SF and PPF; \( l_{sf} / d_{sf} \), \( l_{pf} / d_{pf} \) are the aspect ratio of SF and PPF.

Strength calculation model of SPHFRC are shown in Table 6. In this table, \( f_{cu}, f_{s}, f_{t} \) represent compressive strength, splitting tensile strength, axial tensile strength of SPHFRC, \( f_{cu}, f_{s}, f_{t} \) represent that of NC.

| Strength calculation model | \( R^2 \) |
|-----------------------------|---------|
| Compressive strength        | 0.884   |
| \( f_{fcu} = f_{cu} (1 + 0.196 \lambda_{sf} + 0.136 \lambda_{pf}) \) |         |
| Split tensile strength      | 0.914   |
| \( f_{fs} = f_{s} (1 + 0.170 \lambda_{sf} + 0.093 \lambda_{pf} + 0.137 \lambda_{sf} \lambda_{pf}) \) |         |
| Axial tensile              | 0.857   |
| \( f_{fa} = f_{a} (1 + 0.219 \lambda_{sf} + 0.166 \lambda_{pf}) \) |         |
|                            | 0.867   |
| \( f_{ft} = f_{t} (1 + 0.203 \lambda_{sf} + 0.138 \lambda_{pf} + 0.089 \lambda_{sf} \lambda_{pf}) \) |         |
|                            | 0.847   |
| \( f_{fa} = f_{a} (1 + 0.314 \lambda_{sf} + 0.14 \lambda_{pf}) \) |         |

Note: S, P and R: steel fiber, polypropylene fiber and aspect ratio of steel fiber; \( R_{sec}: \) ratio of the SPHFRC strength to NC strength; \( \text{At/Cu}: \) ratio of the axial tensile strength to the compression strength.
strength \[ f_\text{fr} = f_i (1 + 0.277\lambda_{sf} + 0.077\lambda_{pf} + 0.202\delta_{pf}) \] 0.879

Note: \( R^2 \): coefficient of multiple determinations.

It is observed from the corresponding parameters in the above calculation model that the decision roles are volume fraction and aspect ratio of SF with high elastic modulus, whereas PPF with low elastic modulus and high ductility plays a secondary role. PPF mainly constraints the early primary micro-cracks under the condition of low tensile stress, and SF have the obvious effect in blocking of macro-cracks of concrete. By comparing the experimental and predicted values, it is demonstrated that the proposed model provides a reasonable estimation of the experimental values.

3.3 Strength relationships
Based on the experimental results, it is noted that compressive, split tensile and axial tensile strength of SPHFRC have good correlation, thus it is reasonable to establish a relation between the various strengths. According to the experimental values of statistical analysis, the power function expressions are used to reflect relationship of strengths in this paper.

\[ f_{sp,ts} = 0.254 f_{sp,cu}^{2/3} \] (3)

Integral absolute error \( IAE=3.93\% \), variation coefficient of test value to calculate value is \( \delta = 0.049 \).

\[ f_{sp,ax} = 0.195 f_{sp,cu}^{3/4} \] (4)

Integral absolute error \( IAE=4.02\% \), variation coefficient of test value to calculate value is \( \delta = 0.051 \).

Integral absolute error calculated as:
\[ IAE = \frac{\sum (o_i - p_i)^2}{\sum o_i} \times 100 \] (5)

where: \( o_i \) denote actual value of test, \( p_i \) denote calculate value by the power function.

3.4 Synergy effect
The ratio method is adopted to define synergy effect coefficient, which can be described as:

\[ \beta_i = \frac{f_i}{f_m} \] (6)

\[ \alpha_{sp} = \frac{\beta_i}{\beta_p \beta_p} \] (7)

Where, \( \alpha_{sp} \) denote synergy effect coefficient of steel-polypropylene hybrid fibers; \( \beta_i \) denote strengthening coefficient; \( f_i \) denote the strength of FRC; \( f_m \) denote the strength of NC without fiber. When \( \alpha \geq 1 \), it is a positive synergy effect and when \( \alpha < 1 \), it is a negative synergy effect. Quantitative analysis of fibers effect on the properties of the matrix concrete can be easily explored by the synergy effect coefficient.

The synergy effect coefficients of compressive, split tensile and axial tensile strength are listed in Table 7, 8 and 9 respectively.

### Table 7. Synergy effect coefficient of compressive strength

|        | PPF 0.00% | R40C | SF 0.40% R55C | R80C | SF 0.80% R55C | R80C | R40C | SF 1.20% R55C | R80C |
|--------|-----------|------|---------------|------|---------------|------|------|---------------|------|
| \( \alpha_{sp} \) | \( \beta_{i} \) | \( \beta_{p} \) | \( \alpha_{sp} \) | \( \beta_{i} \) | \( \beta_{p} \) | \( \alpha_{sp} \) | \( \beta_{i} \) | \( \beta_{p} \) | \( \alpha_{sp} \) | \( \beta_{i} \) | \( \beta_{p} \) |
| 0.00%  | 1.06      | 1.01 | 1.00          | 1.07 | 1.10          | 1.07 | 1.11 | 1.07          | 1.18 |
| 0.05%  | 1.06      | 1.13 | 1.01          | 1.06 | 1.09          | 1.13 | 1.13 | 1.00          | 1.21 |
| 0.10%  | 1.02      | 1.19 | 1.11          | 1.21 | 1.18          | 1.17 | 1.07 | 1.27          | 1.12 |
| 0.15%  | 0.95      | 1.05 | 1.23          | 1.29 | 1.17          | 1.23 | 1.25 | 1.18          | 1.28 |

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It can be drawn from above: (i) in the test range \((V_{sf} =0.4\%-1.2\%, \ V_{pf} =0.05\%-0.15\%\), except several individual group, the synergy effect coefficient in compressive, splitting tensile and axial tensile strength of SPHFR C \(\alpha_{sp}\) were greater than 1, and showed a positive synergy effect; (ii) when \(V_{pf}\) was 0.05\%, the strengthening coefficient of polypropylene fiber concrete \(\beta_p > 1\), the synergy effect coefficient of SPHFR C \(\alpha_{sp}\) increases with the increase of \(V_{sf}\); When \(V_{pf}\) was 0.10\%, \(\beta_p > 1\), \(\alpha_{sp}\) has a tendency of decreases with the increase of \(V_{sf}\); When \(V_{pf}\) was 0.15\%, \(\beta_p < 1\), \(\alpha_{sp}\) also has a tendency of decreases with the increase of \(V_{sf}\); so all those phenomena illustrate that the volume fraction of SF to select 0.8\% is relatively appropriate; (iii) when \(V_{sf}\) is fixed at 0.4\%、0.8\%、1.2\% respectively, \(\beta_p\) reach to the minimum at \(V_{pf}=0.15\%, \) which demonstrate that \(V_{pf}\) should not be more than 0.10\%. Therefore, in terms of workability and economic benefits, SF with volume fraction 0.8\% and aspect ratio 80 combine to PPF with volume fraction 0.10\% can obtain optimum hybrid fiber concrete performance in this investigation.

Combining with high volume fraction of fibers is the main cause resulting in negative synergy effect. High volume fraction of fibers will reduce the slump of concrete mixture, affect the compactness of forming concrete and evenly dispersing of fiber in the matrix, decrease surface contact between the fiber and cement mortar, and weaken bond of fiber and matrix. In the macroscopic properties, the strengthening effect of fiber on concrete is weakened and even negative synergy effect produced.

4. Conclusion

(1) It is observed that the strengthening effects on concrete strength by steel-polypropylene hybrid fibers are more distinct than the effects caused by mono-steel fiber or mono-polypropylene fiber.

(2) Steel fiber was noted to be a major contributor to improve significantly strength of the composite. However, the polypropylene fiber was found to have no notable effect on the strength in all the loading situations in this investigation.

(3) Synergetic properties of steel-polypropylene hybrid fibers are closely related to volume fraction and aspect ratio of fibers. Among all hybrid fiber combinations, SF with volume fraction 0.8\% and aspect ratio 80 combine to PPF with volume fraction 0.10\% can obtain optimum hybrid fiber concrete.
performance in this investigation. Excessive contents of fibers may deteriorate the strength of SPHFRC.

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