Experiment on Tension-compression Ratio of Hybrid Fibers Reinforced Recycled Aggregate Concrete

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Abstract. The cubic compressive and splitting tensile strength of recycled aggregate concrete reinforced with hooked-end steel and macro-polypropylene hybrid fibers (HFRRAC) was investigated through an orthogonal experiment. The results show that the replacement ratio of RCA has little effect on the tension-compression ratio. And the volume percentages of HES fiber are the most significant influencing factor in terms of fibers. The specimens reinforced with fibers fail in a ductile manner and are enhanced in the energy absorption capacity. The proposed prediction models for cubic compressive and splitting tensile strength of HFRRAC are adopted to predict the experimental results and meet the engineering application accurately.

1. Introduction

In the few decades, a large amount of waste concrete from the urbanization and demolition of old buildings has been produced worldwide. From an environmental perspective, the widespread application of recycled aggregate concrete (RAC) made of partially or fully replace natural coarse aggregate (NCA) with recycled coarse aggregate (RCA) is an effective method to alleviate the depletion of natural resources and landfilling issues [1]. However, the higher porosity and absorption of RCA as compared to NCA negatively affect the mechanical and durability properties of RAC [2,3]. To improve the performance of RAC, many researchers have focused on fibers reinforced RAC (FRRAC). The hybridization of two or more fibers can obtain optimal performance of concrete, which exceeds the sum of individual fibers performances [4]. The tension-compression ratio of concrete is defined as a ratio of the splitting tensile strength to the cubic compressive strength, which presents the brittleness index of concrete. Yan et al. [5] indicated that the tension-compression ratio of ultra-high-strength concrete is improved with the increase in the steel fiber volume percentages and increases by 24.08\% – 73.46\%. Zhang et al. [6] concluded that the polypropylene fibers can effectively enhance the tension-compression ratio and toughness of concrete. Liu and Xu [7] indicated that adding proper volume percentages of hybrid fibers to ultra-high-performance concrete can increase tension-compression ratio, as well as toughness.

The investigation on the tension-compression ratio of hybrid fibers reinforced RAC with Hooked-end steel (HES) and macro-polypropylene (MPP) fibers (HFRRAC) remains to be inadequate. The relation of cubic compressive strength and splitting tensile strength to the reinforcing index of fibers and replacement ratio of RCA needs to establish. Based on the experiment's orthogonal design, this study aims to analyze the effect of HES and MPP fibers and the replacement ratio of RCA on the tension-compression ratio and propose the prediction models of the cubic compressive strength and splitting tensile strength.
2. Methods and materials

2.1. Materials and mixture proportions
In this study, the river sand with a fineness modulus of 2.9 and Ordinary Portland Cement 42.5 was used as the fine aggregate and cementitious material, respectively. NCA and RCA with a continuous gradation of 5-20 mm were used as coarse aggregates. RCA was obtained from a recycling company located in Xi’an and classified as category II according to the Chinese code [8]. Table 1 presents coarse aggregates’ physical properties determined by experiments based on the test methods suggested in the Chinese code [9]. HES and MPP fibers were adopted in this research. Each type of fiber contains two different lengths, and the characteristics of fibers are shown in Table 2.

| Coarse aggregate type | Apparent density (kg/m³) | Bulk density (kg/m³) | Water absorption (%) | Crushing index (%) | Voidage (%) |
|-----------------------|--------------------------|----------------------|---------------------|-------------------|-------------|
| NCA                   | 2705                     | 1514                 | 0.40                | 10.2              | 44.0        |
| RCA                   | 2569                     | 1371                 | 4.53                | 15.8              | 46.6        |

Table 2. Geometry and properties of HES and MPP fibers.

| Fiber type | Equivalent diameter d (mm) | Length l (mm) | Aspect ratio d/l | Density (kg/m³) | Tensile strength (MPa) | Young modulus (GPa) |
|------------|-----------------------------|---------------|------------------|-----------------|------------------------|---------------------|
| HES I (II) | 0.75                        | 35 (60)       | 47 (80)          | 7800            | 1120                   | 200.0               |
| MPP I (II) | 0.94                        | 28 (47)       | 30 (50)          | 920             | 580                    | 5.5                 |

Based on the Chinese code [10], the mixture proportion of natural aggregate concrete (NAC) was designed and used as a control group. The mixture proportion of NAC is shown in Table 3. To compare the effect of fibers and RCA, the mixture proportion of HFRRAC was the same as NAC. The percentage of NCA content was replaced by RCA in RAC, while the total coarse aggregate weight remained the same. In this study, RCA was soaked in water for 10 min and drained for another 10 min to achieve a saturated surface dry condition before mixing.

| Cement (kg/m³) | Fine aggregate (kg/m³) | Coarse aggregate (kg/m³) | Water (kg/m³) |
|----------------|------------------------|--------------------------|---------------|
| 467            | 639                    | 1043                     | 251           |

2.2. Specimens
For each group, six cubic specimens with dimensions 150×150×150 mm were adopted for cubic compressive strength and splitting tensile strength tests. The demolded specimens were cured in the standard curing room at (20±2) °C and 95% RH for 28 days.

2.3. Test description
According to Chinese code [11], the servo-hydraulic compression test machine with a load capacity of 2000 kN was adopted for all specimens. $f_{cu}$ and $f_t$ of cubic specimens were tested under loading control with a rate of 0.5 MPa/s and 0.05 MPa/s, respectively.

2.4. Orthogonal design of experiment
The orthogonal design of the experiment is used to analyze experiments with factors and levels through the orthogonal table. In this study, the influence of hybrid fibers and the replacement ratio of RCA on the tension-compression ratio was evaluated through the orthogonal experiment. The influence factors incorporate Factor A, B, C, D, E, and interactions. Table 4 lists the factors and levels following the $L_{16}(2^{15})$ orthogonal array design. Besides, there are three RAC mixtures with the replacement ratio of RCA of 0%, 50%, and 100%, respectively, as shown in Table 5.
Table 4. Factors and levels.

| Factor ID | Factor description | Level 1 | Level 2 |
|-----------|--------------------|---------|---------|
| A         | Volume percentages of HES | 0.5%   | 1.0%   |
| B         | Aspect ratio of HES | 47      | 80      |
| C         | Volume percentages of MPP | 0.5%   | 1.0%   |
| D         | Aspect ratio of MPP | 30      | 50      |
| E         | Replacement ratio of RCA | 50%    | 100%   |

3. Results and discussions

3.1. Analyses of variance for the tension-compression ratio of HFRRAC

Table 5 lists the experimental results of HFRRAC, and all values listed are the averaged test results from three specimens. The order of significant factors and interactions will be found out by analyses of variance in the following.

Table 5. Experimental results of HFRRAC.

| Test ID | A | B | C | D | E | f_{cu} (MPa) | f_t (MPa) | f_{cu} / f_t |
|---------|---|---|---|---|---|-------------|-----------|-------------|
| G0      | 0 | 0 | 0 | 0 | 0 | 37.72       | 3.42      | 0.0907      |
| G9      | 0 | 0 | 0 | 0 | 0 | 34.30       | 2.71      | 0.0790      |
| G10     | 0 | 0 | 0 | 0 | 0 | 34.27       | 2.60      | 0.0759      |
| G11     | 1 | 1 | 1 | 1 | 1 | 43.25       | 3.35      | 0.0775      |
| G12     | 1 | 1 | 1 | 1 | 2 | 41.11       | 3.34      | 0.0812      |
| G13     | 1 | 1 | 1 | 2 | 2 | 41.52       | 3.20      | 0.0771      |
| G14     | 1 | 1 | 2 | 2 | 2 | 43.08       | 3.57      | 0.0829      |
| G15     | 1 | 2 | 1 | 2 | 1 | 39.53       | 3.26      | 0.0825      |
| G16     | 1 | 2 | 1 | 1 | 2 | 43.36       | 3.04      | 0.0701      |
| G17     | 1 | 2 | 2 | 2 | 1 | 43.36       | 3.48      | 0.0803      |
| G18     | 1 | 2 | 2 | 2 | 2 | 41.56       | 3.36      | 0.0808      |
| G19     | 2 | 1 | 2 | 1 | 2 | 42.46       | 3.77      | 0.0888      |
| G20     | 2 | 1 | 2 | 1 | 2 | 43.32       | 3.59      | 0.0829      |
| G21     | 2 | 1 | 2 | 2 | 1 | 43.87       | 3.87      | 0.0882      |
| G22     | 2 | 1 | 2 | 2 | 2 | 42.63       | 3.50      | 0.0821      |
| G23     | 2 | 2 | 1 | 1 | 1 | 47.70       | 3.92      | 0.0822      |
| G24     | 2 | 2 | 1 | 1 | 2 | 42.34       | 4.18      | 0.0997      |
| G25     | 2 | 2 | 1 | 2 | 2 | 43.98       | 4.59      | 0.1044      |
| G26     | 2 | 2 | 1 | 2 | 1 | 45.55       | 4.54      | 0.0997      |

The contribution ratio, \( \rho_i \), determines the influence of factor \( i \) and error on the total fluctuation and is expressed as equations (1) and (2).

\[
\rho_i = \frac{(SS_i - DF_i \cdot MS_i)}{SS_T} \quad (1)
\]

\[
\rho_i = \frac{DF_i \cdot MS_i}{SS_T} \quad (2)
\]

Where, \( DF_i \) and \( SS_i \) are the degree of freedom and sum of squares of factor \( i \), respectively; \( DF_T \) is the sum of \( DF_i \); and \( SS_T \) is the sum of \( SS_i \); \( MS_i \) is the mean square of error.

Table 6. Analyses of variance table of tension-compression ratio.

| Source | DF | SS             | F-value | Significance criterion | \( \rho_i \% \) |
|--------|----|----------------|---------|------------------------|----------------|
| A      | 1  | 0.000559       | 105.76  |                        | 45.02          |
| B      | 1  | 0.000009       | 17.03   |                        | 6.89           |
| A\(\times \)B | 1 | 0.000144       | 27.24   |                        | 11.28          |
| C      | 1  | 0.000062       | 11.73   | \( F_{9.7} \) = 12.25 \( F_{10.7} \) | 4.61           |
| A\(\times \)C | 1 | 0.000009       | 1.70    |                        |                |
| B\(\times \)C | 1 | 0.000063       | 11.92   |                        | 4.69           |
| D\(\times \)E | 1 | 0.000018       | 3.41    |                        |                |
As shown in Table 6, one can observe that the listed factors are highly significant effects on the tension-compression ratio, but the contribution of some factors is less than that of the error. It can be seen that the volume percentages of HES fiber is the most significant influence on the tension-compression ratio among all factors, followed successively by the interaction between volume percentages of HES fiber and aspect ratio of HES fiber, the interaction between volume percentages of MPP fiber and replacement ratio of RCA, and the aspect ratio of HES fiber. As shown in Table 5, when \( r_g = 50\% \), hybridization of 0.5% HES fiber and 0.5% MPP fiber have a negative effect on the tension-compression ratio compared to mix G9. When \( r_g = 100\% \), all combinations of two fibers positively affect the tension-compression ratio compared to mix G10. The tension-compression ratio of mix G26 increases by 26.2% compared to mix G9; the tension-compression ratio of mix G25 increases by 37.5% compared to mix G10. It indicates the fibers more evidently improve the tension-compression ratio of RAC than NAC, which is in accordance with previous research [12].

3.2. Cubic compressive and splitting tensile strength

![Figure 1. Failure mode of mixes for cubic compressive strength of (a) G0; (b) G23.](image1)

![Figure 2. Failure mode of mixes for splitting tensile strength of (a) G0; (b) G21.](image2)

Failure modes of cubic specimens under compression are shown in Figure 1. During the cubic compressive strength tests, the outer walls of specimens without fibers occur in the sizeable spalling area accompanied by the crackling sounds. Their failed modes present the typical shape of an hourglass or cone. In contrast, the specimens with fibers remain good integrity in the compression test since the fibers generate the bridging and interlocking effect in restraining the crack extension. Besides, the specimens expand and fail in a ductile manner, and the sound of fibers pull-out can be heard obviously. This is because the hybridization of two fibers builds a skeleton structure and forms the synergy effect in crack propagation resistance.
Failure modes of cubic specimens in splitting tensile strength tests are shown in Figure 2. The specimens without fibers present brittle failure and are split into two halves with a loud bang when the specimen loses bearing capacity. The failure models of the specimens reinforced with fibers are markedly different from that of the control specimens. The first crack initiates at the center of the surface of cubic specimens and propagates rapidly through the whole cross-section with the increase of applied load. And the fibers can prevent the specimens from splitting completely. It is also observed that multiple small cracks distribute on the surface of the specimen. Due to the addition of fibers, the strong bonds between fibers and cement paste result in the ductile failure of HFRRAC specimens before they ultimately failed [13].

According to Feng et al. [14], the replacement ratio of RCA highly impacts cubic compressive strength but has little effect on the splitting tensile strength. In terms of the fibers, the volume percentages of HES fiber and the interaction between volume percentages and aspect ratio of HES fiber significantly impact cubic compressive and splitting tensile strength.

In this study, the mechanical properties of HFRRAC were evaluated using the reinforcing index \((RI_v)\) of fiber and \(r_g\). \(RI_v\) of hybrid fibers is defined as:

\[
RI_v = \sum_{i=1}^{n} k_i V_i \frac{l_i}{d_i}
\]

Where, \(V_i\) is the volume percentages of the \(i_{th}\) fibers; \(l_i\) is the length of the \(i_{th}\) fibers; \(d_i\) is the diameter of the \(i_{th}\) fibers. The values of bond factors, \(k_i\), for HES and MPP fibers in this study are set to 1 and 0.4.

The cubic compressive and the splitting tensile strength are calculated as:

\[
f_{cu} = \left(1 + 0.58RI_v - 0.32(RI_v)^2 - 0.10\left(r_g^{0.09}\right)\right) f_{cu0}
\]

\[
f_t = \left(1 + 0.34RI_v + 0.17(RI_v)^2 - 0.21\left(r_g^{0.06}\right)\right) f_{t0}
\]

The coefficients of determination of equations (4) - (5) are 0.87 and 0.82, respectively. It is also observed from Eq. (5) that there is a low correlation between \(r_g\) and splitting tensile strength. Table 7 shows the comparison between experimental and prediction results. The errors are within ±14.00%.

| Test ID | \(f_{cu}\) | \(f_t\) |
|--------|---------|---------|
| Exp. (MPa) | Pre. (MPa) | Error (%) | Exp. (MPa) | Pre. (MPa) | Error (%) |
| G0 | 37.72 | 37.72 | 0.00 | 3.42 | 3.42 | 0.00 |
| G9 | 34.3 | 35.89 | 4.64 | 2.71 | 2.74 | 1.17 |
| G10 | 34.27 | 33.83 | -1.28 | 2.60 | 2.71 | 4.33 |
| G11 | 41.25 | 41.25 | -4.61 | 3.35 | 3.13 | -6.48 |
| G12 | 41.1 | 39.76 | -3.29 | 3.34 | 3.16 | -5.25 |
| G13 | 41.52 | 40.02 | -3.60 | 3.20 | 3.20 | -0.13 |
| G14 | 43.08 | 43.06 | -0.05 | 3.57 | 3.35 | -6.03 |
| G15 | 39.33 | 41.27 | -4.40 | 3.26 | 3.37 | 3.30 |
| G16 | 43.36 | 43.73 | 0.86 | 3.04 | 3.47 | 14.00 |
| G17 | 43.36 | 43.92 | 1.29 | 3.48 | 3.50 | 0.59 |
| G18 | 41.56 | 42.51 | 2.28 | 3.36 | 3.62 | 7.64 |
| G19 | 42.46 | 41.95 | -0.21 | 3.77 | 3.49 | -7.45 |
| G20 | 43.32 | 44.34 | 2.36 | 3.59 | 3.59 | 0.02 |
| G21 | 43.87 | 44.50 | 1.43 | 3.87 | 3.63 | -6.27 |
| G22 | 42.63 | 42.95 | 0.75 | 3.50 | 3.75 | 7.13 |
| G23 | 47.70 | 45.61 | -4.39 | 3.92 | 4.17 | 6.39 |
| G24 | 42.34 | 43.56 | 2.88 | 4.18 | 4.23 | 1.18 |

4. Conclusions
The influence of five factors and interactions between each other on the tension-compression ratio of HFRRAC was studied through an orthogonal experiment. Some conclusions have been summarized:

(1) Based on the results of analyses of variance, the replacement ratio of RCA has little effect on the tension-compression ratio. And the volume percentages of HES fiber are the most significant influencing factor in terms of fibers.
(2) The addition of fibers changes the failure modes of concrete specimens. The specimens reinforced with fibers fail in a ductile manner and are enhanced in the energy absorption capacity.

(3) The regression models for cubic compressive and splitting tensile strength of HFRRAC were determined in this study. It is found that the proposed models can accurately predict the experimental results and meet the engineering application.

(4) The fibers more evidently improve the tension-compression ratio of RAC than NAC, and positively affect the seismic performance of the concrete structure.

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