Effect of different blending ratio of waste polypropylene hybrid fiber on crack resistance of recycled concrete beams

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Abstract. In order to improve the reuse efficiency of construction waste, industrial waste and textile waste, this study mixed the waste polypropylene fiber with polyacrylonitrile fiber in a certain proportion, and studied the influence of different blending ratio of hybrid fiber on crack resistance of recycled concrete beams. The experimental results showed that the mixing of hybrid fibers not only improves the basic mechanical properties and strength of recycled concrete test blocks, but also effectively inhibits the generation and development of cracks, and improves the crack resistance of recycled concrete beams. The article proposes the formula of maximum crack width in the limit state of normal use of hybrid fiber recycled concrete beams by theoretical analysis.

1. Introduction
With the rapid development of construction industry, many old and low utilization buildings have been demolished and rebuilt, resulting in large amounts of construction waste, most of which are waste concrete. The proportion of waste concrete in China is about 48.4% [1-2] of domestic total construction waste, but only a small amount of recycled aggregate is used for the use of roads. The rational treatment and reuse of construction waste is one of the effective ways to save energy and reduce the shortage of resources.

In recent years, scholars at home and abroad have made a exhaustive research on the reuse of abandoned concrete in the construction industry. It has been found that replacing some or all of the natural aggregates with recycled aggregate significantly reduces the tensile strength, crack resistance, etc. of the concrete. Adding proper amount of fiber to recycled concrete can make up for its deficiency and reduce the cost of concrete at the same time. According to correlative data[3-5], most of the waste and discarded textile fibers and their products in China each year are non-degradable polyester, polypropylene, and so on. Incineration or landfill not only wastes resources, but also destroys the ecological environment. Therefore the waste polypropylene recycled concrete has become a new research direction. At present, the research on waste textile fiber at home and abroad is limited to the basic mechanical property of concrete specimen[6-8], and the research of waste hybrid fiber to recycled concrete structure is relatively few.

In order to improve the reuse rate of construction waste, industrial waste and textile waste, fly ash is used to replace part of cement in concrete and recycled aggregate to replace part of natural aggregate. The effects of different blending ratio of polyacrylonitrile fiber and waste polypropylene fiber on crack resistance of recycled concrete beams were studied.
2. Test content and methods

2.1. Experimental design

The water-binder ratio used in the test was 0.4, in which 20% fly ash (FA) was used as the cementing material instead of some cement, and 30% of the recycled recycled concrete aggregate replaces part of the natural aggregate. Sand rate is 0.4. According to the results of the previous basic tests, the optimum combination of the two fibers is that the volume ratio of polyacrylonitrile fiber to waste polypropylene fiber is 1: 3. By changing the total incorporation rate of hybrid fiber 0.5% and 0.10% and 0.15% to 0.20%, analyze its effect on the crack resistance of recycled concrete beams through experiments. The design of test blending ratio is shown in Table 1.

Six groups of beams are designed. Beam length is 1500mm, section sizes are 120mm × 180mm. The tensile steel bars in the beam are 2B14(HRB335). The steel bar is 2B8(HRB335) and the stirrups are φ8@100(HPB300). Section size and reinforcement diagram of beam are shown in Fig.1.

| test number | cementing material | aggregate | blending ratio | type of fiber | length of fiber |
|-------------|--------------------|-----------|----------------|---------------|----------------|
| NR0         | 80                 | 20        | 100            | 0             | 0              |
| RC0         | 80                 | 20        | 70             | 30            | 0              |
| RC05        | 80                 | 20        | 70             | 30            | 0.05           |
| RC10        | 80                 | 20        | 70             | 30            | 0.10           |
| RC15        | 80                 | 20        | 70             | 30            | 0.15           |
| RC20        | 80                 | 20        | 70             | 30            | 0.20           |

plain: 1) NR0 is ordinary concrete;
2) RCX is recycled concrete, Subscript x as fiber content;
3) Fibre A represents polypropylene fine fiber, Fibre B represents regenerated waste polypropylene fiber.

![Fig.1 Section size and reinforcement drawing of Beams](image)

2.2. Materials

The cementing materials used in this experiment are ordinary Portland cement with the strength grade of 42.5 in Jilin Province, the second grade FA with a density of 2200kg/m3 produced by a thermal power plant in Yanji and its moisture content is 1%. The recycled coarse aggregate was broken and formed by laboratory crusher, and its diameter was 5-25mm. The fine aggregate is natural sand with a fine modulus of 3.23 and a density of 2650 kg/m3. The natural coarse aggregate is a continuous grained stone with a diameter of 5-25mm. Its density is 2700 kg/m3, and its moisture content is 2.0%. Polyacrylonitrile fiber (fiber A) is supplied by a Construction Engineering Co., Ltd .in Changsha, Hunan Province, its length is 19 mm, as shown in Fig.2(a).

The regenerated polypropylene fiber (fiber B) is made of waste polypropylene carpet, which is cut manually and is 19mm in length, as shown in Fig.2(b). The properties of fiber A and fiber B are shown in Table 2. The liquid polycarboxylic acid high-efficiency water reducing agent is provided by a
Building Materials Co., Ltd. in Jilin Province, and the water reducing rate is 20%. And the mechanical properties of steel bars are shown in Table 3.

![Fiber configuration](image)

**Fig. 2 Fiber configuration**

| fiber | density/(g/cm^3) | tensile strength /Mpa | modulus of elasticity /Mpa | elongation at break /% |
|-------|------------------|-----------------------|---------------------------|----------------------|
| A     | 1.18             | ≥450                  | ≥3000                     | ≥10                  |
| B     | 0.91             | ≥270                  | ≥3000                     | ≥7                   |

| bar diameter /mm | design value of strength /Mpa | yield strength /Mpa | ultimate strength /Mpa |
|------------------|--------------------------------|---------------------|------------------------|
| B14              | 300                            | 390                 | 554                    |
| B8               | 300                            | 314                 | 466                    |
| A8               | 270                            | 338                 | 446                    |

### 2.3. Methods

The slump test, cube compressive strength and split tensile strength test, and prism elastic modulus test were carried out in this experiment, according to the GB/T 50081-2002 "test method of mechanical properties on ordinary concrete standard" and CECS 13:89 “steel fiber concrete test method of concrete block” [9-10]. The cube adopts the standard test size of 150mm × 150mm × 150mm, and the prism adopts the standard specimen size of 150mm × 150mm × 300mm. In order to prevent the concentration stress from affecting the test results, rigid iron blocks were placed at the loading point and the constraint point. All test operations meet the GB/T 50152-2012 "standard for test methods for concrete structures” [11].

### 3. Fundamental mechanical properties

#### 3.1. Slumps

The slump of recycled concrete with different blending ratios of hybrid fibers is shown in Fig. 3. It can be seen from the diagram that the slump of RC0 is obviously higher than that of the standard group NR0. The main reason is that the pore of recycled coarse aggregate is larger than that of natural aggregate, and the surface of recycled aggregate is attached to cementing materials such as cement, so its water absorption is higher. In the experimental design, considering the water absorption of recycled aggregate, the calculation of water consumption consists of two parts: additional water and free water. However, in the process of mixing and filling, the recycled aggregate can’t fully absorb water in a short period of time, so the slump of the mixture can be greatly improved. With the increase of hybrid fiber, the slump of concrete decreases gradually due to the bond effect of fiber.

#### 3.2. Compression strength

The 28d compressive strength of recycled concrete with different blending ratio of hybrid fibers is shown in Fig. 4. The results show that the compressive strength of RC0 is 19.6% lower than that of NR0. This is due to the adhered and hardened paste on the surface of recycled aggregate, and some
cracks will inevitably occur during the process of preparation and production of recycled aggregate, resulting in damage and performance degradation[12]. But with the increase of hybrid fiber incorporation rate, compressive strength gradually increased. This is mainly due to fiber incorporation into concrete, reduce or eliminate the early emergence and development of concrete primary cracks, and reduce the number and scale of micro cracks. Thus the stress concentration at the tip of the primary fracture is passivated[13], and the stress field in the base is more continuous and uniform.

3.3. Split tensile strength
The 28d Split tensile strength of recycled concrete with different blending ratio of hybrid fibers is shown in Fig. 5. It is known that the splitting strength of the concrete specimen is reduced by 7.1% by the addition of the recycled aggregate. However, the splitting tensile strength of recycled aggregate increased with the addition of hybrid fiber, and the splitting tensile strength of recycled aggregate concrete increased with the increase of fiber content. With the change of fiber content, the splitting tensile strength of group RC05, RC10, RC15 and RC20 was increased by 7.6%, 24.7%, 18.8% and 32.3% in comparison with that of RC0, respectively. It is because the fiber forms a tri-vera junction system in the concrete matrix, which plays a more important role in pulling than the crack loss caused by the uneven dispersion. So the splitting tensile strength of recycled concrete specimen can be improved significantly.

3.4. Modulus of elasticity
The modulus of elasticity of recycled concrete at different blending rates for hybrid fibers is shown in Fig. 6. It can be seen that the elastic modulus of concrete specimen is reduced by 19.1% with the addition of recycled aggregate. The incorporation of hybrid fiber to make up for the defects caused by recycled concrete, so the elastic modulus of recycled concrete increases with the increase of the blending ratio of hybrid fibers. And the elastic modulus of recycled concrete increased by 22.8% and 28.5% in comparison with RC0 when the blending ratio of hybrid fibers was 0.15% and 0.2% respectively.
4. Analysis of cracking and ultimate load of beam

4.1. Analysis of destructional form of specimen beam
In the process of loading, the first crack appears in the middle and lower part of the beam span, and then, with the increasing of load, the number of cracks in the surface layer of the beam increases and the width of the crack increases gradually. For ordinary concrete beams and recycled concrete beams without fiber, debris will fall and even collapse will occur with the increase of load. For the beams mixed with hybrid fibers, the cracks mainly occur around the main cracks, and the cracks are not broken, and there is almost no collapse phenomenon.

As the load continues to increase, the deflection of the specimen beam increases gradually, and the strain of the steel bar increases obviously. When the tensile steel bars yield, the deflection of the beam develops rapidly, and cracks appear in the concrete compression zone and are crushed quickly. The ultimate load of specimen beam with hybrid fiber is larger than that of ordinary concrete beam and regenerated concrete beam without fiber.

![Fig. 7 Failure mode of hybrid fiber beams](image)

4.2. Development of cracks
The cracking load and inclined crack cracking load of the specimen beam are shown in Fig. 8. It can be seen that the cracking load and oblique crack cracking load of the RC0 test beam with recycled aggregate is obviously lower than that of the NR0 beam without recycled aggregate, mainly because of the cracks in the recycled aggregate itself. When mixed with hybrid fiber, the cracking load of concrete beams are higher than that of RC0 beam, and the crack load of RC10 and RC15 are the largest, which are 11.1% higher than that of RC0. The results show that the hybrid fibers increase the cracking load of concrete beams and delay the development of cracks. Moreover, the load of inclined crack of concrete beams mixed with hybrid fiber is higher than that of RC0 beams, and the load of inclined cracks in group RC15, RC20 increases obviously. Compared with the RC0, the increase was 25% and 75%, respectively. Because of the three-dimensional disorderly distribution of hybrid fiber in recycled concrete, the effect is similar to that of steel bar, which absorbs some energy and shares the internal stress[14-15], and effectively prevents the occurrence and development of the crack. Therefore, the mixing of hybrid fibers contributes to the diagonal crack cracking of concrete beams.

![Fig.8 Cracking load and inclined crack load of beams](image)
4.3. Relationship of Load-crack

The load-crack width curve of concrete beams is shown in Fig. 9. It can be seen that the addition of recycled aggregate obviously reduces the ultimate bearing capacity of concrete beams, and the maximum crack width also increases obviously. Under the same load, the maximum crack width of hybrid fiber concrete beams decreases to some extent than that of RC0 with the increase of hybrid fiber. The crack width of concrete beams with hybrid fiber is similar with the development trend of load increase. When the load reaches 100 kN, the crack width of RC0 is 0.7mm. The crack width of concrete beam with hybrid fiber is basically 0.18 mm, and reduced by 74.3 %. The slope of load-crack width curve and the maximum load of linear growth of hybrid fiber reinforced concrete beams are obviously larger than that of RC0, which indicates that hybrid fiber blocks the development of cracks and slows down the damage process of matrix. It has good toughening effect on concrete[16].

The development of the number of cracks in beams subjected to various loads is shown in Fig. 10. It can be seen that in the initial stage of loading, the number of cracks of each specimen beam is basically the same, that is, the hybrid fiber has no obvious effect on the initial crack development. With the increase of load, the influence of hybrid fiber on the number of cracks in beam becomes more and more obvious. When the mixing ratio of hybrid fiber is 0.1%, the number of cracks in concrete beams develops most slowly with the increase of load, and the number of cracks under the same load is the least, which has obvious contribution to the crack resistance of concrete beams.

4.4. Relationship of Load-deflection

The load-deflection curve of recycled concrete beams is shown in Fig.11. It can be seen from the figure that the deflection of the hybrid fiber recycled concrete beam is similar to that of the ordinary concrete beam according to the load variation trend. Compared with RC0 beams, the deflection of the beams with hybrid fibers does not change obviously at the initial loading stage, but when the load is reached the yield of steel bar, the rate of increase in deflection is accelerated significantly. The deflection of recycled concrete beams mixed with hybrid fiber decreases. The beams mixed with hybrid fiber reaches the ultimate bearing capacity basically when the deflection is 27mm, while that of RC0 beams is 30mm. The results show that hybrid fiber can inhibit the deflection development of recycled concrete beam and improve its ultimate bearing capacity. The main reason is that the stress is mainly borne by the longitudinal tensile steel bar before the yield strength of the steel bar in the concrete beam, so the mixing of the hybrid fiber has little effect on the deflection. But after the steel bar yield, the steel bar exits from work, the effect of hybrid fiber can be reflected, the uneven distribution of hybrid fiber in the beam plays the role of additional reinforcement. So after the yield of steel bar, the deflection of recycled concrete beam with hybrid fiber is obviously reduced. The crack resistance of beam is improved.

4.5. Analysis of steel bar strain

The load–strain curve of steel bar in concrete beams is shown in Fig. 12. It can be seen that the trend of variation of steel bar strain with load in hybrid fiber recycled concrete beams is similar to that of ordinary beam. In the early stage of loading, the variation of the strain of reinforcement in 6 groups of beams is not different. And the variation of the strain of reinforcing steel under the same load
gradually increases obviously after the crack of the beam. When the content of hybrid fiber is 0.1%, the strain of steel bar is minimum under the same load. Because hybrid fiber that mixed in the recycled concrete beams has a bonding effect with the concrete matrix, and can be used as additional reinforcing bar to share the partial tensile stress of concrete beams. So the stress on the longitudinal tensile steel bar is reduced, the deformation speed is slowed down, and the strain of the steel bar is reduced.

5. Calculation of crack width of Hybrid Fiber recycled concrete Beams

For the serviceability limit state, the maximum crack width check is calculated according to the formula of crack width in ‘Code for Design of concrete structures’ [17]. The maximum crack width \( \omega_{\text{max}} \) is determined by the method of multiplying the average crack width by the expansion coefficient for the normal concrete standard. The maximum crack width of normal concrete is calculated as equation (1):

\[
\omega_{\text{max}} = \alpha_{\text{cr}} \psi \frac{\sigma_{sq}}{E_s} (1.9c_s + 0.08 \frac{d_{eq}}{\rho_{te}})
\]

Where \( \alpha_{\text{cr}} \) is component stress characteristic coefficient. The age of this test is 28d, which belongs to the short term load, then this test takes \( \alpha_{\text{cr}} = 1.27 \);

\( \psi \) is nonuniform coefficient of the strain in the reinforcement. Calculation bases on empirical formula, \( \psi = 1.1 - 0.65f_{tk}/\rho_{te}\sigma_{sq} \). It takes \( \psi = 0.2 \) when \( \psi < 0.2 \), and \( \psi = 1.0 \) when \( \psi > 1.0 \).

\( \sigma_{sq} \) is stress of steel bar in crack section. For flexural members, \( \sigma_{sq} = M/0.87A_s h_0 \). \( A_s \) is the section area of the longitudinal reinforcement in tension zone, and \( h_0 \) is the effective height of the section.

\( E_s \) is the elastic modulus of steel bar
\( c_s \) is the distance from the outer edge of the outermost longitudinal tensile bar to the bottom of the tension zone. It takes \( c_s = 20\text{mm} \) when \( c_s < 20\text{mm} \), and \( c_s = 65\text{mm} \) when \( c_s > 65\text{mm} \).

\( d_{eq} \) is the equivalent diameter of longitudinal reinforcement in the tensile zone. \( d_{eq} = (\sum n_i d_i^2)/\sum (n_i n_i d_i) \), \( n_i \) is the number of longitudinal reinforcing bars of type \( i \) of the tensile zone, \( d_i \) is the nominal diameter of type \( i \) reinforcement in the tensile area;

\( \rho_{te} \) —Reinforcement ratio of longitudinal tensile reinforced bar with section area of effective tensile concrete. For rectangular sections \( \rho_{te} = A_s/0.5bh \).

The current 'Technical standard for Fiber reinforced concrete structures' (CECS38:2004) [18] in China, a comprehensive theoretical model based on the bond-slip theory is adopted to establish the formula for calculating the crack width of fiber reinforced concrete beams. In order to link up with the current calculation method, the formula for calculating the maximum crack width of reinforced steel fiber concrete flexural members with rectangular section is as equation (2):

\[
\omega_{f\text{max}} = \omega_{\text{max}} (1 - \beta_{\psi} \lambda_{\psi})
\]
Where $\omega_{\text{max}}$ is the maximum crack width calculated according to the current design specification of concrete structure without consideration of the effect of fiber;

$\beta_{cw}$ is influence Coefficient of Fiber on Crack Width of Reinforced Fiber Reinforced Concrete Members. It should be determined by test.

$\lambda_f$ is characteristic parameter of fiber, $\lambda_f = \rho_f l_f / d_f$, where $\rho_f$ is the volume fraction of fiber, $l_f$ is the length of fiber, $d_f$ is the diameter of fiber.

At present, there is no standard for calculating crack width of organic fiber concrete, and polyacrylonitrile fiber is mixed with waste polypropylene fiber in this experiment. In this paper, it is suggested that the influence coefficient of fiber on crack width of reinforced concrete members should be revised as equation (3):

$$\omega_{f,\text{max}} = \omega_{\text{max}}[1 - (\beta_1 \lambda_{f1} + \beta_2 \lambda_{f2})]$$

Where $\beta_1$ is the influence coefficient of polypropylene fiber on crack width of reinforced concrete members, and takes $\beta_1 = -0.731$ by fitting;  

$\lambda_{f1}$ is the characteristic parameters of polypropylene fiber;  

$\beta_2$ is the influence coefficient of waste polypropylene fiber on crack width of reinforced concrete members, and takes $\beta_2 = 0.423$ By fitting;  

$\lambda_{f2}$ is the characteristic parameters of waste polypropylene fiber

Therefore, the maximum crack width formula of the serviceability limit state of the hybrid fiber recycled concrete beam under short-term load can be calculated as equation (4):

$$\omega_{f,\text{max}} = \omega_{\text{max}}[1 - (0.731 \lambda_{f1} + 0.423 \lambda_{f2})]$$

The calculated values of the maximum crack width obtained from equation 4 are compared with the experimental values as shown in table 4. From the NR0 and RC0 in table 4, it can be seen that the crack width of concrete beams mixed with recycled aggregate and fly ash can be calculated according to the crack formula of ordinary concrete beams. The calculated value of crack width correction formula in the serviceability limit state after mixing hybrid fiber is in good agreement with the test value.

| Test Number | Test Value $\omega_{\text{f,exp}}$/mm | Calculated Value $\omega_f$/mm | $\omega_{\text{f,exp}}$/mm $\omega_f$ |
|-------------|--------------------------------------|-------------------------------|-------------------------------------|
| NR0         | 0.30                                 | 0.297                         | 1.010                               |
| RC0         | 0.28                                 | 0.268                         | 1.045                               |
| RC05        | 0.29                                 | 0.290                         | 1.000                               |
| RC10        | 0.28                                 | 0.276                         | 1.014                               |
| RC15        | 0.21                                 | 0.223                         | 0.942                               |
| RC20        | 0.25                                 | 0.240                         | 1.042                               |

6. Conclusion

By mixing polyacrylonitrile fiber with waste polypropylene fiber in a certain proportion, the effects of different blending ratio on the mechanical properties and crack development of recycled concrete beams are studied in this paper. The conclusions are as follows:

(1) The compressive strength of recycled concrete is increased with the addition of hybrid fiber, and the compressive strength increased with the increase of blending ratio.

(2) For the cracking load, inclined crack load and crack width of recycled concrete beams, the effect reaches the best when the mixing ratio of hybrid fiber is 0.1 %. But for the number of cracks under different loads, the incorporation rate is 0.15 %.

(3) The deflection of recycled concrete beams decreases with the increase of the mixing ratio of recycled fiber. Under the same load, the deflection of recycled concrete beams is the smallest when the incorporation ratio is 0.15 %.
(4) The strain of steel bar in hybrid fiber reinforcement concrete beams is similar to that of ordinary concrete, in which steel bar strain is the smallest when the mixing rate of hybrid fiber is 0.1%.

(5) The maximum crack width of concrete beams mixed with fly ash and recycled aggregate under the serviceability limit state can be approximately calculated according to the current code of China. The formula for calculating crack width of recycled concrete beam with different mixing ratio of hybrid fiber is fitted to the coefficients $\beta_1$ and $\beta_2$, and the formula for calculating maximum crack width of hybrid fiber recycled concrete beam under the serviceability limit state is put forward.

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