Experimental Study on Cracking Resistances of RAC Beams with Polypropylene Fibers and Steel Fibers

Jiajun Tang¹ and Changchun Pei¹, *

¹ Department of Structural Engineering, College of Engineering, Yanbian University, Yanji, Jilin, 133000, China
* Corresponding author’s e-mail: peicc@ybu.edu.cn

Abstract. The recycled coarse aggregate has poor mechanical properties and cracking resistances due to its own defects, which hinders the application of recycled aggregate concrete (RAC) in practical engineering. In this paper, the cracking resistances of RAC beams were studied by changing the volume incorporation rates and mixing methods of polypropylene fibers and steel fibers. The results show that the cracking width of RAC beams decreases, but the number of cracks is relatively larger when they are destroyed, compared with RAC beams. The ductility of RAC beams with fibers is relatively better. Through the experimental study and theoretical analysis, the formula for calculating the maximum cracking width of RAC beams with hybrid fibers is derived.

1. Introduction
With the rapid development of the construction industry, the old buildings were demolished, and a large amount of construction waste was produced. According to the data, the total amount of construction waste in 2015 in China is more than 70 million tons, but its comprehensive utilization rate is less than 5% at present[1]. In order to save energy and improve the reuse rate of waste, the waste concrete is processed into recycled coarse aggregate instead of part of natural coarse aggregate[2-5]. However, the recycled coarse aggregate has poor mechanical properties and cracking resistances because of the interface is relatively weak and easier to produce cracks[6-9], which hinders the application and popularization of recycled aggregate concrete (RAC) in practical engineering. Therefore, the cracking resistances of RAC beams are studied in this paper by adding polypropylene fibers and steel fibers, and it also provides technical reference for the practical application of RAC.

2. Test content and method

2.1. Design of test scheme
In this paper, 8 RAC beams are designed by changing the volume incorporation rates and mixing methods of polypropylene fibers and steel fibers. The ratio of water to cement is 0.4, 15% fly ash (mass percentage in gelatin) is used to replace part of cement, and 30% recycled coarse aggregate (mass percentage in total coarse aggregate) is used to replace part of natural coarse aggregate. The length of the beams is 1500mm, the span is 1200mm, and the section size is 150mm×250mm. The longitudinal tensile steel bar adopts 2 φ 14 (HRB400 grade steel), the reinforcement ratio is 0.96%, the frame reinforcement adopts 2 φ 14 (HRB400 grade steel), and the stirrup adopts φ 6@100 (HPB300 grade steel, double limb hoop). In order to exclude the influence of the shear stress on the force performance of the normal section of the specimen, there is a pure bending section of 400mm length in
the middle span of the beam. In this paper, the strain of longitudinal tensile steel bar in the middle span, load-deflection curve, and development of cracks are tested under the condition of the beam specimens. And the formula for calculating the maximum cracking width of RAC beams with hybrid fiber is derived by theoretical analysis. The design of test scheme and concrete mix ratio are shown in table 1, and the structure of the beam is shown in figure 1.

Table 1. Design of test scheme and concrete mix ratio (material per cubic meter)

| Test NO. | cement (kg) | fly ash (kg) | polypropylene fiber (kg) | steel fiber (kg) | water reducer (kg) | water (kg) | sand (kg) | natural coarse aggregate (kg) | recycled coarse aggregate (kg) |
|----------|-------------|--------------|--------------------------|-----------------|-------------------|-----------|---------|-------------------------------|-------------------------------|
| RC       | 393.1       | 69.4         | -                        | -               | 6.9               | 190       | 625.9   | 657.2                         | 281.6                         |
| S0P1     | 393.1       | 69.4         | 0.9                      | -               | 6.9               | 190       | 625.9   | 656.5                         | 281.4                         |
| S1P0     | 393.1       | 69.4         | -                        | 39.0            | 6.9               | 190       | 625.9   | 629.9                         | 269.9                         |
| S2P0     | 393.1       | 69.4         | -                        | 58.5            | 6.9               | 190       | 625.9   | 616.2                         | 264.1                         |
| S3P0     | 393.1       | 69.4         | -                        | 78.0            | 6.9               | 190       | 625.9   | 602.6                         | 258.2                         |
| S1P1     | 393.1       | 69.4         | 0.9                      | 39.0            | 6.9               | 190       | 625.9   | 615.6                         | 263.8                         |
| S2P1     | 393.1       | 69.4         | 0.9                      | 58.5            | 6.9               | 190       | 625.9   | 601.9                         | 258.0                         |
| S3P1     | 393.1       | 69.4         | 0.9                      | 78.0            | 6.9               | 190       | 625.9   | 601.9                         | 258.0                         |

Note: 1) RC represents the concrete specimen with recycled coarse aggregate; 2) P0, P1: the volume incorporation rates of polypropylene fibers are 0% and 0.1% respectively; 3) S0, S1, S2, S3: the volume incorporation rates of steel fibers are 0%, 0.5%, 0.75% and 1% respectively.

Figure 1. Structure of specimen and layout of loading

2.2. Test loading method
The specimen is loaded with three equal points, and the loads are measured by the sensor. The layouts of the concrete strain gauge, steel strain gauge, displacement meter and the loading device are shown in figure 1. The test is carried out by step loading. It is necessary to check whether the support is stable, whether the instrument and loading equipment are normal before the start of the structure test. Specific test methods refer to Standard for test method of concrete structures (GB/T50152–2012)[10].

3. Analysis of cracking resistances

3.1. Analysis of the width of cracks
Figure 2 shows the widths of cracks under the different volume incorporation rates and the different mixing methods of polypropylene fibers and steel fibers. It can be seen from the figure that the cracking width of RAC beams with polypropylene fibers is smaller than that of RC beam, while the cracking widths of RAC beams with steel fibers are significantly smaller than that of RC beam under the same loads. The cracking widths become smaller and smaller with the increase of the content of steel fibers, and it indicates that the steel fibers can resist the development of the cracks obviously. Under the same loads, the cracking width of group S3P1 with hybrid fibers is the smallest. It means
that the synergistic effect of polypropylene fibers and steel fibers is better, which plays an effective role in the generation and development of cracks.

3.2. Analysis of the number of cracks
Figure 3 shows the number of cracks under the different volume incorporation rates and the different mixing methods of polypropylene fibers and steel fibers. It can be seen from the figure that the number of cracks in the RC beam is less, and the cracks are all through cracks. The number of cracks obviously increases when the fibers are added, but there are few through cracks. The number of cracks of beams with polypropylene fibers and steel fibers is more than that of the corresponding beams with single fibers. This is because the number of interface between the matrixes increases with the increase of the content of fibers, and the interface is a weaker area of concrete.

3.3. Analysis of load-deflection curves
Figure 4 shows the load-deflection curves under the different volume incorporation rates and the different mixing methods of polypropylene fibers and steel fibers. It can be seen from the figure that the deflections increase linearly when the load is small. With the increase of the load, it is different due to the difference of the materials mixed in the concrete. The deflections of RAC beams are improved by adding polypropylene fibers, while the deflections are obviously improved by adding steel fibers. The deflections of the beams decrease gradually with the increase of the amount of steel fibers, which indicates that the steel fibers can cooperate with the concrete to improve the ductility of RAC beams. According to the figure, the effect of group S1P1 is better. The deflections of RAC beams with polypropylene fibers and steel fibers are smaller than that of the corresponding RAC beams with single steel fibers under the same loads. It indicates that the simultaneous addition of steel fibers and polypropylene fibers in RAC can improve the ductility of RAC beams.

3.4. Analysis of load-strain curves
Figure 5 shows the load-strain curves of the longitudinal tensile steel bar in the middle span under the different volume incorporation rates and the different mixing methods of polypropylene fibers and
It can be seen from the figure that the deformation of the specimen is elastic, the strain of the longitudinal tensile steel is elastic, and the tensile stress is very small at the initial stage of loading. As the load increases, the curves’ slopes of RAC beam and RAC beam with single polypropylene fibers are constantly mutative, while the curves of RAC beams with single steel fibers and RAC beams with polypropylene fibers and steel fibers are relatively gentle. It shows that the tensile stress of RC beam is mainly borne by the reinforcement after cracking, and the stress changes faster with the increase of the load. The tensile stresses of beams with single polypropylene fibers are mainly borne by reinforcement and polypropylene fibers after cracking. The stress of reinforcement changes faster with the increase of the load, because polypropylene fibers bear limited tensile stress. While the tensile stresses of beams with steel fibers are mainly borne by reinforcement and steel fibers after cracking. The stress of the reinforcement increases steadily with the increase of the load.

4. Calculation and analysis of the maximum cracking width of RAC beams with hybrid fibers

According to the formula for calculating the maximum cracking width in the Code for design of concrete structures (GB 50010–2010)[11], the formula is as follows:

$$\omega_{\text{max}} = \alpha_{ce} \psi \frac{\sigma_{\text{sq}}}{E_s} \left( 1.9 c_s + 0.08 \frac{d_{eq}}{\rho_{\text{te}}} \right)$$

Where: $\alpha_{ce}$—component stress characteristic coefficient, take $\alpha_{ce} = 1.9$ for flexural members; $\psi$—strain inhomogeneous coefficient of longitudinal tensile reinforcement between cracks, $\psi=1.1-0.65f_{tk}/\rho_{\text{te}}\sigma_{\text{sq}}$, when $\psi<0.2$, take $\psi=0.2$ and take $\psi=1.0$ when $\psi>1.0$; $\sigma_{\text{sq}}$—stress of reinforcement in crack section, take $\sigma_{\text{sq}}=M_{\text{tk}}/0.87A_s h_0$ for flexural members; $E_s$—elastic modulus of reinforcement; $c_s$—the distance from the edge of the outermost longitudinal tensile reinforcement to the bottom of the drawing area, when $c_s<20\text{mm}$, take $c_s=20\text{mm}$ and take $c_s=65\text{mm}$ when $c_s>65\text{mm}$; $d_{eq}$—equivalent diameter of longitudinal reinforcement in the drawing area; $\rho_{\text{te}}$—effective reinforcement ratio of longitudinal tension reinforcement calculated according to the area of effective tensile concrete section, take $\rho_{\text{te}}=A_s/0.5bh$ for flexural members of rectangular section, when $\rho_{\text{te}}<0.01$, take $\rho_{\text{te}}=0.01$.

According to the formula for calculating the cracking width of steel fiber reinforced concrete members in the Technical specification for fiber reinforced concrete structures (CECS 38: 2004)[12], the formula is as follows:

$$\omega_{f,\text{max}} = \omega_{\text{max}} \left(1 - \beta_{cw} \lambda_f \right)$$

Where: $\beta_{cw}$—influence coefficient of steel fiber on crack width of reinforced steel fiber reinforced concrete members, take $\beta_{cw}=0.35$ for flexural members; $\lambda_f$—characteristic parameter of steel fiber content, $\lambda_f = \rho_f l_f / d_f$, $\rho_f$—volume incorporation rate of steel fiber, $l_f$—length of steel fiber, $d_f$—diameter of steel fiber, the ratio of length to diameter ($l_f/d_f$) of steel fiber in this test is 60; $\omega_{\text{max}}$—calculate by formula (1).

Considering the reduction of the cracking width is more obvious, the calculation formula of the maximum cracking width of RAC beams with hybrid fibers is corrected. In this paper, formula (3) is obtained by the fitting of the experimental data according to formula (1) and formula (2).

$$\omega_{f,\text{max}} = \omega_{\text{max}} \left(1 - \beta_f \lambda_f - \beta_p \lambda_p \right) = \omega_{\text{max}} \left(1 - 1.367\lambda_f + 0.681\lambda_p \right)$$

Where: $\beta_f, \beta_p$—influence coefficient of steel fiber and polypropylene fiber respectively; $\lambda_f$—characteristic parameter of steel fiber content; $\lambda_p$—characteristic parameter of polypropylene fiber content, $\lambda_p = \rho_p l_p / d_p$, $\rho_p$—volume incorporation rate of polypropylene fiber, $l_p$—length of polypropylene fiber, $d_p$—diameter of polypropylene fiber, the ratio of length to diameter ($l_p/d_p$) of polypropylene fiber in this test is 800; $\omega_{\text{max}}$—calculate by formula (1).
The results of comparison between the calculated values ($\omega_{f_{\text{max}}}^c$) and the test values ($\omega_{f_{\text{max}}}^t$) of maximum crack width of RAC beams with hybrid fibers show that the average value of the calculated values to test values ($\omega_{f_{\text{max}}}^c/\omega_{f_{\text{max}}}^t$) is 1.089, the standard deviation is 0.078, the coefficient of variation is 0.072. It shows that the calculated values are in good agreements with the test values. The formula can be used to calculate the maximum cracking width of RAC beams with hybrid fibers.

5. Conclusions
In order to improve the cracking resistances of RAC, the cracking resistances of RAC beams are studied by changing the volume incorporation rates and mixing methods of polypropylene fibers and steel fibers. The following conclusions are obtained:

1. Compared with the RC beam, the widths of cracks of RAC beams with fibers decrease, the number of cracks is relatively larger when they are destroyed, and the ductility is better. In this experiment, a better anti cracking effect is obtained in the S3P1 beam.

2. According to the load-strain curves, it is shown that the bond performances between fibers, reinforcement and recycled aggregate concrete are good, the deformation is coordinated during the loading process, so they can work together.

3. Considering the reduction of the cracking width is more obvious, the calculation formula of the maximum cracking width of RAC beams with hybrid fibers is corrected, and the correction formula is put forward: $\omega_{f_{\text{max}}} = \omega_{\text{max}}(1 - 1.367\lambda_f + 0.681\lambda_p)$.

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