Experimental Analysis on Flexural Performance of Fair-faced Recycled Concrete Beams

Xiaojun Fang¹, Guangxiu Fang¹*, Pengjie Hu¹, Xiaoxu Liang¹
¹ Department of Civil Engineering, Yanbian University, Yanji, China, 133002
²*E-mail of corresponding author: gxfang@ybu.edu.cn

Abstract. This paper mainly studies the mechanical properties of fair-faced recycled concrete beams when different recycled aggregates replace natural aggregates and fly ash replaces cement in equal amounts. Through experiments, the crack development law and failure mode of fair-faced recycled concrete beams are first studied. Secondly, the curve equation of load and deflection and the relation curve of load and stress are obtained. Finally, the normal section bearing capacity obtained from the test is compared with the normal section bearing capacity calculated according to the current national code for concrete structure design, and the correction coefficient of the code formula is proposed, which provides reference for the research and engineering application of similar fair-faced recycled concrete beams in the future.

1. Introduction and Research Background

In recent years, as a new type of environmentally friendly concrete, fair-faced concrete has received social attention. Not only in foreign countries, but also in many large cities in China, there are many buildings using fair-faced concrete[1]. However, with people's living conditions getting better and better, only the pillars and walls made of fair-faced concrete can no longer meet people's needs. There are churches made entirely of fair-faced concrete abroad, but such buildings are rare in China. With the increasing scale of the utilization of fair-faced concrete, many related papers have been published in China. However, these papers are basically related to construction technology and mix proportion design, and there are few researches on mechanical properties related to flexural properties[2]. Therefore, this paper mainly studies and analyzes the flexural behavior of fair-faced recycled concrete beams.

When making fair-faced concrete, waste aggregate is used instead of natural aggregate to realize waste reuse. However, with the different replacement rates of waste aggregate and fly ash, it will have certain influence on the mechanical properties of fair-faced recycled concrete beams[3-7]. In this test, crack development law and failure mode, load-mid-span deflection curve equation, load-strain curve and ultimate bearing capacity calculation of fair-faced recycled concrete beam are taken as the main objects for analysis, and finally the calculation formula of normal section bearing capacity suitable for fair-faced recycled concrete beams are proposed for research purposes.

2. Test Parameters and Component Design

2.1. Selection of raw materials
(1)Cement: Using the low-hydration heat "Yatai brand" P·O42.5 ordinary silicate cement produced by Jilin Yatai Cement.
Fine aggregate: Fine aggregate is made of river sand and produced by Yanji, with a fine modulus of 2.5 and the grade area is Area II.

Coarse aggregate: Granite macadam with continuous gradation of 5 ~ 25 mm produced by Yanji.

Recycled aggregate: Crushed and sieved into particle sizes of 5-15 mm and 15-20 mm from the waste test pieces transported from the construction bureau, and replace the coarse aggregate with a ratio of 3: 1.

Fly ash: Fly ash of Grade I produced by Yanji Power Plant is selected.

Foaming agent: Industrial foaming agent is selected.

Water reducer (water reducing rate is 37%).

2.2. Mix design

| Group | Cement / (kg) | Fly ash / (kg) | Water / (kg) | Send / (kg) | Stone / (kg) | Recycled coarse aggregate / (kg) | Recycled fine aggregate / (kg) | Water reducer / (kg) | Foaming agent / (kg) |
|-------|---------------|----------------|--------------|-------------|--------------|-------------------------------|-------------------------------|-------------------|-------------------|
| N1    | 450           | 0              | 148          | 717.2       | 1568.3       | 0                             | 0                             | 1.7168            | 0                 |
| N2    | 406.8         | 45.2           | 148          | 717.2       | 940.98       | 470.49                        | 156.83                       | 1.7168            | 2.22              |
| N3    | 406.8         | 45.2           | 148          | 717.2       | 784.15       | 588.12                        | 196.04                       | 1.7168            | 2.22              |
| N4    | 406.8         | 45.2           | 148          | 717.2       | 627.3        | 705.75                        | 235.25                       | 1.7168            | 2.22              |
| N5    | 361.6         | 90.4           | 148          | 717.2       | 940.98       | 470.49                        | 156.83                       | 1.7168            | 2.22              |
| N6    | 316.4         | 135.6          | 148          | 717.2       | 940.98       | 470.49                        | 156.83                       | 1.7168            | 2.22              |

Note: In Table 1, the design strength grade of fair-faced recycled concrete is C35; N1 is ordinary concrete with recycled aggregate replacing natural aggregate by 0%, fly ash replacing cement by 0%, and no foaming agent is added. N2, N3 and N4 are fair-faced recycled concrete in which fly ash replaces cement with 10% and foaming agent with 1.5%, while recycled aggregate replaces natural aggregate with 40%, 50% and 60% respectively. N2, N5 and N6 are the mix proportions of fair-faced recycled concrete mixed with 1.5% foaming agent and recycled aggregate to replace 40% of natural aggregate, while fly ash to replace 10%, 20% and 30% of cement respectively.

2.3. Dimension Design of Beam Components

For the beam members designed by experiment, the diameter of the tensile steel bar at the bottom is 14mm, the diameter of the upper frame force bar is 12mm, and HRB400 grade steel bars are adopted. The diameter of stirrup is 6mm and HRB335 grade steel bar is adopted. The whole beam member is 1500mm long, 120mm wide, 200mm high and the thickness of the protective layer is 25 mm. Encrypted areas are set at both ends of the beam, with stirrup spacing of 100mm and stirrup spacing of 200mm in unencrypted areas, which is shown in Figure 1.

Figure 1. Size Design and Reinforcement of Beam Components

The mechanical property test of reinforcement is shown in Table 2, and the test beam parameters are shown in Table 3.
Table 2. Testing of Mechanical Properties of Rebar

| Type of reinforcement | Diameter / (mm) | Density / (kg/m³) | Design value of yield strength / (Mpa) | Tensile strength / (Mpa) | Elastic modulus / (Gpa) | Poisson's ratio |
|-----------------------|----------------|-------------------|---------------------------------------|-------------------------|------------------------|----------------|
| Tensile reinforcement | 14             | 7850              | 360                                   | 400                     | 200                    | 0.3            |
| Erect reinforcement   | 12             | 7850              | 360                                   | 400                     | 200                    | 0.3            |
| Stirrup               | 6              | 7850              | 360                                   | 400                     | 200                    | 0.3            |

Table 3. Parameter Design of Test Beam

| Width×Height×Length (mm×mm×mm) | Thickness of the protective layer / (mm) | Shear span ratio | Area of bar section / (mm²) | Reinforcement ratio / (%) |
|--------------------------------|-----------------------------------------|-----------------|-----------------------------|--------------------------|
| 120×200×1500                   | 25                                      | 2.38            | 308+226=534                 | 2.2                      |

2.4. Charger
The loading device is schematically shown in Figure 2.

![Figure 2](image)

Figure 2. Schematic diagram of loading device

In this experiment, six fair-faced recycled concrete beams with a dimension of 120×200×1500mm and a reinforcement ratio of 2.2% were fabricated. According to the current code, three-point loading, i.e. four-point bending test, is carried out. The type of steel strain gauge used in the test is 120-10AA and the type of concrete strain gauge is 120-10AA. The data acquisition system is a static strain test and analysis system.

2.5. Loader
According to GB/T 50152-2012 "Standard for Test Methods of Concrete Structures"[8], the loading procedure of this research test is divided into pre-loading and formal loading.

Pre-loading in the first stage: the pre-loading speed is 10N/s, the load is 5kN, and each load stays for at least 15 minutes.

Formal loading in the second stage: Before the specimen cracks, the load value applied in each stage is increased by 3kN, on the basis of the load value of the previous stage. After the specimen is cracked, the load value applied in each stage is increased by 5kN on the basis of that of the previous stage. After reaching 90% of the estimated value, each load applied is increased by 5kN until the component completely loses its bearing capacity. Each load applied stays on the secondary load for 15 minutes.

3. Test loading and failure mode
The cracking load and ultimate load testing are shown in Table 4.

Table 4. Crack cracking load and ultimate load

| Project | Cracking load (KN) | Ultimate load (KN) |
|---------|--------------------|--------------------|
| N-1     | 18.2               | 65                 |
|    |    |    |
|----|----|----|
| N-2| 18.8| 60.6|
| N-3| 19.4| 57.29|
| N-4| 19.8| 53.13|
| N-5| 20.4| 60.28|
| N-6| 20.9| 60.03|

(1) N-1 group of ordinary concrete beams: When the load is loaded to 18.2kN, the first crack is generated in the mid-span, and the direction is vertical upward. Then with the increase of the load, the deflection of the beam begins to increase, showing a linear growth. And the cracks also increase. When the load reaches 35.7kN, the initial crack in the mid-span slowly develops vertically upward and gradually widens, and develops in a T-shape at the top of the concrete beam. When the load reaches 43.5kN, oblique cracks have already begun to occur. At this time, the main cracks are visible and obvious, and there are few small cracks. Some cracks beside the main cracks are connected with the main cracks, and the cracks below the main cracks in the mid-span are obvious. Until the load reaches 65kN, the middle and upper part of the beam span is seriously damaged, the beam deformation is serious, and the test is finished, the failure mode of N1 is shown in Figure 3(a).

(2) Group N-2 of fair-faced recycled concrete beams: When the load is loaded to 18.8kN, the first slender crack is generated in the mid-span. When the load is loaded to 28.6kN, oblique cracks begin to appear in the beam. At this time, the compression area is intact, the length becomes longer, and the width is smaller. When the load reaches 46.6kN, the first crack starts to appear transverse crack and its width increases. As the load increases, it extends upward in a Y-shape and connects with No.2 crack and No.3 crack in the compression zone. When the load reaches 60.6kN, many small cracks begin to appear around the crack in pure bending section. At this time, the main change is the width of the first crack in the mid-span area until the load is broken; the failure mode of N2 is shown in Figure 3(b).

(3) Group N-3 of fair-faced recycled concrete beams: In the test, when the load is 19.4kN, the first slender crack appears. When it is loaded to 30.5kN, a second crack with the same width as the main crack but with a smaller length appears on the left side of the beam span. At this time, the main crack extends upward all the time. When the load reaches 42.8kN, the first crack develops to both ends at this time, and the third crack develops rapidly, showing a connection trend with the main crack. When the load reaches 57.29kN, the beam cracks, the concrete in the middle and upper part of the beam span has been crushed, the main crack has extended to the crushed area, and debris begins to fall, and the beam reaches the limit state, the failure mode of N3 is shown in Figure 3(c).

(4) Group N-4 of fair-faced recycled concrete beams: When the load reaches 19.8kN, the first crack, which is located in the middle of the beam span, appears when the load is 34.5kN, cracks 1 and 3 develop rapidly, not only the length becomes bigger, but also the width becomes longer, and the two cracks begin to close to the mid-span compression area. When the load is 46.3kN, a slight crack appears above the mid-span crack and an oblique crack appears at the same time, with a small amount of debris falling off. When the load reaches 53.13kN, the upper crack of the beam starts to appear transverse crack penetration, the concrete in the compression zone at the right end is seriously damaged, and a large amount of slag begins to fall off, thus the beam reaches the limit state, the failure mode of N4 is shown in Figure 3(d).

(5) Group N-5 of fair-faced recycled concrete beams: When it is loaded to 20.4kN, the first crack appears at the mid-span position. When it is loaded to 33.3kN, several vertically upward developed cracks appear in the mid-span area, although the number is large, the crack width is small. When the load reaches 49kN, the number of cracks increases significantly and oblique cracks begin to appear in the shear-compression zone. At 58.1kN, the width of No.1 crack suddenly widens and the beam cracks. When the load reaches 60.28N, the main crack develops to both ends, the main crack becomes more and more obvious, some debris falls off, and the beam reaches the limit state, the failure mode of N5 is shown in Figure 3(e).
(6) Group N-6 of fair-faced recycled concrete beams: When the load reaches 20.9kN, the first crack appears in the mid-span. As the load increases gradually, the crack also increases gradually. When it is loaded to 32kN, a number of cracks occur in the beam and slowly extends upward. When the load reaches 46kN, oblique cracks begin to appear in the shear-compression zone, and when the load reaches 53kN, the cracks begin to penetrate from the upper part of the beam. At 56kN, the beam begins to drop some debris. When it is loaded to 60.03kN, the width of the main crack obviously begins to widen, the beam drops debris seriously, and the bending degree of the beam is extremely large, reaching the limit state, the failure mode of N6 is shown in Figure 3(f).

\[\text{Figure 3. Test loading and failure modes of test pieces}\]

4. Relation curve between load and mid-span deflection

The load-mid-span deflection of each group of specimen beams is shown in Figure 4. As it can be seen from Figure 4, when the load value is less than the cracking load, the deflection of N1 ~ N6 specimens all shows linear growth with the increase of the load. The slope of the relationship between the load and the mid-span deflection of N1, N2, N4, N5, N6 specimens is similar, but the slope of N3 is obviously large. When the load value is less than the failure load, the deflection of N1 ~ N6 specimens all shows a linear increase with the increase of load. The slope of the relationship between load and mid-span deflection of N1, N2, N3, N4, N5 and N6 specimens is similar, but the deflection of N3 under the same load is obviously large. When the load value is greater than the failure load and less than the limit value, the deflection of N1 ~ N6 specimens shows a curve growth with the increase of load. With the increase of load value, the deflection of specimens with different replacement rates of recycled aggregate is different. Compared with fair-faced recycled concrete, the deflection of ordinary concrete is smaller than that of fair-faced recycled concrete under the same load effect.

Different replacement ratios of fly ash affect the change of deflection. When comparing the curves of B, E and F, it can be seen that the deflection is the largest when the fly ash content is 20%, and the deflection is the smallest when the fly ash content is 10%. However, under the same load, the deflection of the three groups is greater than that of ordinary concrete.

When the load is in the stage of 0-15KN, the slope of group E suddenly increases, which is obviously larger than that of the other five groups, and then it slowly increases.

When the load is greater than 75% of the limit load, with the increase of the load, the slope of the six groups of concrete beams suddenly increases, indicating that the deflection of the beams is changed greatly at this time. When comparing Group B, Group C and Group D, it can be found that the more recycled stone content there is, the greater the slope change will be, indicating that the larger the beam deformation is. When comparing Group B, Group E and Group F, it can be found that the more the content of fly ash there is, the larger the deformation of the beam will be. Considering comprehensively, in this test, fair-faced recycled concrete beams of Group B have outstanding deformation resistance effect.
5. Relation curve between load and strain

Footnotes Relation curve between load and strain of reinforcement is showed in Figure 5.

Figure 5 is the load-strain curve of steel bar in the span of fair-faced recycled concrete beam. When the load is 0-20KN, the strain rate changes evenly. At this time, the lower concrete and the reinforcement bear the pulling force together, and the reinforcement is in the elastic deformation stage. When the load exceeds 20KN, the strain rate becomes significantly faster and the stress increases rapidly. At this time, cracks appear in the tensile failure of the lower concrete, and the steel bar bears the tensile force alone. When the load exceeds 40KN, the steel bar enters the yield stage, and the rate change is more obvious until the steel bar yields and fails.

The six groups of strains A, B, C, D, E and F have obvious differences from the load of 25KN. When comparing the three groups of strain curves B, C and D, it can be seen that the slope of D is the largest. After the load exceeds 35KN, the strain rate becomes larger, and finally yield failure occurs after the strain reaches 2053με. However, Group B has the lowest initial velocity, which increases rapidly after the load exceeds 40KN, and finally reaches the maximum stress of 1800με before the beam is destroyed. The tensile reinforcement at the bottom of groups B, C and D are the same, and the fly ash content is also 10%, so the more recycled stone content there is, the greater the strain and the faster the change rate will be.
When comparing the three sets of strain curves of B, E and F, it can be seen that the slope of B is the largest. After the load exceeds 35KN, the strain rate becomes larger, and finally the strain reaches the maximum stress of 1800με before the beam is damaged. However, the early velocity of group f is the smallest, and increases rapidly after the load exceeds 35KN. Finally, the strain before failure reaches the maximum stress of 1723με. The tensile steel bars at the bottom of groups B, E and F are the same, and the content of recycled stone is also 40%, so the strain can be improved by adding fly ash appropriately.

6. Analysis of Bending Capacity of Normal Section

Each figure should have a brief caption describing it and, if necessary, a key to interpret the various lines and symbols on the figure.

6.1. Analysis on Test Results of Bending Capacity of Normal Section

The experimental results of flexural bearing capacity of the 6 groups of beams are shown in Table 5. The ultimate bearing capacity and the ultimate bending moment are respectively compared and analyzed as shown in Figure 5 and Figure 6 below.

| Project | Ultimate bearing capacity (KN) | Ultimate bending moment (MPa) |
|---------|-------------------------------|------------------------------|
| N1      | 65                            | 13.00                        |
| N2      | 60.6                          | 12.12                        |
| N3      | 57.29                         | 11.46                        |
| N4      | 53.13                         | 10.63                        |
| N5      | 60.28                         | 12.06                        |
| N6      | 60.03                         | 12.01                        |

6.2. Calculation of normal section bearing capacity

According to the Code for Design of Concrete Structures (GB 50010-2010) [9]

Basic Formulas for Calculating Rectangular Section with Single Rib

\[ \sum X = 0, \alpha_1 f_y b x = f_y A_s \]  \hspace{2cm} (4-1)

\[ \sum M = 0, M \leq M_y = \alpha_1 f_y b x \left( h_b - \frac{x}{2} \right) \]  \hspace{2cm} (4-2)

\[ M \leq M_{sy} = f_y A_s \left( h_b - \frac{x}{2} \right) \]  \hspace{2cm} (4-3)

In the formula: \( M \) —— Design bending moment;

\( \alpha_i \) —— When the concrete strength grade does not exceed C50, \( \alpha_i = 1 \); 

\( f_y \) —— Tensile design strength of reinforcement;  

\( A_s \) —— Sectional Area of Tensile Reinforcement; 

\( x \) —— The height of the compression zone after the stress graph is converted into a rectangle; 

\( h_b \) —— The effective height of the section, where the beam height is 200mm, so 

\[ h_b = h - a_s = 200 - 35 = 165 \text{ mm}. \]

In order to keep the designed interface within the scope of the beam suitable for reinforcement, the following two conditions should be met, that is, the conditions of using the three formulas above.
In the formula, $\xi_b$ —— The relative wire compression zone height of the beam shall be calculated according to Formula (4-6):

$$\xi_b = \frac{\beta_1}{1 + \frac{f_s}{E_s \varepsilon_{cu}}}$$  \hspace{1cm} (4-6)

$$\varepsilon_{cu} = 0.033 - \left(f_{cu,k} - 50\right) \times 10^{-5}$$  \hspace{1cm} (4-7)

In the formulas, $\beta_1$ —— Coefficient, when the concrete strength does not exceed C50, $\beta_1 = 0.8$; $E_s$ —— Elastic Modulus of Tensile Reinforcement; $\varepsilon_{cu}$ —— The ultimate compressive strain of the normal section of concrete is 0.0033 if the value calculated by formula (4-7) is greater than 0.0033; $f_{cu,k}$ —— Concrete cube compressive strength standard value.

6.3. Comparative Analysis of Bearing Capacity Calculation Value and Test Value

According to the above formulas (4-1) to (4-7), the flexural bearing capacity of the normal sections of the 6 groups of fair-faced recycled concrete beams can be theoretically calculated, and the experimental values are compared with the theoretical calculated values, the correction coefficient of bearing capacity is introduced $H_I$. The results are shown in Table 6. Among them,

$$H_I = \frac{M_{u2}}{M_{u1}}$$  \hspace{1cm} (4-8)

Table 6. Comparative Analysis of Bearing Capacity

| Project | Experimental value $M_{u1}$ (MPa) | Calculated value $M_{u2}$ (MPa) | $M_{u2}/M_{u1}$ | Calculated value $M_{u3}$ (MPa) | $M_{u3}/M_{u1}$ |
|---------|----------------------------------|-------------------------------|-----------------|-------------------------------|-----------------|
| N1      | 13.00                            | 15.45                         | 1.19            | 15.45                         | 1.19            |
| N2      | 12.12                            | 15.43                         | 1.27            | 14.37                         | 1.19            |
| N3      | 11.46                            | 15.43                         | 1.35            | 13.60                         | 1.19            |
| N4      | 10.63                            | 15.42                         | 1.45            | 12.67                         | 1.19            |
| N5      | 12.06                            | 15.43                         | 1.28            | 14.37                         | 1.19            |
| N6      | 12.01                            | 15.43                         | 1.28            | 14.37                         | 1.20            |

The replacement ratio of recycled aggregate has a significant effect on the compressive strength of concrete. When the replacement ratio of recycled aggregate to natural aggregate is 40%, 50% and 60% respectively, the ultimate bearing capacity of fair-faced recycled concrete beams is reduced by 6.8%, 11.9% and 18.3% respectively compared with ordinary concrete beams. It is proposed to revise the calculation of flexural bearing capacity by using the compressive strength ratio strength ($\eta$) of fair-faced recycled concrete and ordinary concrete[10]. Figure 6 is a graph showing the change of the specific strength value ($\eta$) of fair-faced recycled concrete and ordinary concrete with the replacement ratio ($r$) of recycled aggregate.
Figure 6. Relationship between specific strength $\eta$ and recycled aggregate replacement ratio $r$.

It can be seen from the figure that with the increase of the replacement ratio of recycled aggregate, the specific strength $\eta$ decreases and shows a parabolic curve decreasing trend. Fitting and analyzing the specific strength value $\eta$ helps to obtain the correction coefficient of the calculation formula of the ultimate bearing capacity of the fair-faced recycled concrete beam.

$$\eta = 1.00003 + 7.2 \times 10^{-1}r - 6.2 \times 10^{-5}r^2$$

Formula (4-2) is multiplied by the correction coefficient $\eta$ to obtain the ultimate bearing capacity calculation formula of the fair-faced recycled concrete beam.

$$M_u = \alpha \eta f'_{cx}b h \left( h - \frac{x}{2} \right)$$

The ultimate bearing capacity results of fair-faced recycled concrete beams calculated according to the above formula are shown in Table 6. The $Mu3/ Mu1$ value of the modified fair-faced recycled concrete beams is close to the $Mu3/ Mu1$ value of ordinary concrete beams. This shows that the revised calculation formula not only has certain calculation precision, but also improves the safety reserve of the flexural capacity of fair-faced recycled concrete beams, which can be used for calculating the ultimate flexural capacity of fair-faced recycled concrete beams.

7. Conclusion

(1) When fly ash replaces cement with 10% and foaming agent with 1.5%, and recycled aggregate replaces natural aggregate with 40%, 50% and 60% respectively, the ultimate bearing capacity of fair-faced recycled concrete beams is reduced by 6.8%, 11.9% and 18.3% respectively, and the number of cracks and mid-span deflection is significantly increased compared with that of ordinary concrete beams;

(2) The failure mode characteristics and load-deflection curves of fair-faced recycled concrete beams are similar to those of ordinary concrete beams;

(3) The formula for calculating the flexural ultimate bearing capacity of ordinary reinforced concrete beams is applicable to fair-faced recycled concrete beams. The safe reserve for calculating the ultimate flexural bearing capacity of fair-faced recycled concrete beams according to the current specifications is insufficient. Considering the replacement rate of recycled aggregate and other factors, the calculated values are very consistent with the experimental values, and the coefficient of variation is small.

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