Influence of Replacement Level of Recycled Coarse Aggregate on Fracture Properties of Recycled Aggregate Concrete

Kaiyun Wu¹, Surong Luo¹*

¹ College of Civil Engineering, Fuzhou University, Fuzhou, P.R.China
* E-mail: 344623785@qq.com, lsr@fzu.edu.cn

Abstract. recycled aggregate concrete made with recycled aggregate was one of the effective ways to reuse the construction and demolition waste. Due to the weak complex interface transition zone of recycled aggregate concrete, the defect had great effect on the bearing capacity and durability of recycled aggregate concrete. The fracture performance of recycled aggregate concrete was studied, which was of great practical significance and engineering value. The wedge splitting test of 200mm x 200mm x 230mm specimens was carried out using the fatigue testing machine (MTS). The elastic modulus of the specimens were measured and calculated by strain gauge and dynamic resistance strain gauge, and the elastic modulus was about 4GPa lower than that of standard test. Based on double-K fracture model of recycled aggregate concrete, the crack initiation fracture toughness and the unstable fracture toughness was obtained. The test results show that the replacement level of recycled aggregate is not obvious to the crack initiation fracture toughness, and the unstable fracture toughness is lower than that of natural concrete. Using the exponential function to fit the tail of the P-H-COMD curve of the wedge splitting test, it is found that the fracture energy of the recycled aggregate concrete is not reduced with the increase of the replacement level of the recycled aggregate.

1. Introduction

Large quantities of construction and demolition waste (C&DW) have caused serious environmental problems. An increased interest was focused on the recycled aggregate concrete (RAC), which is an effective way to reuse C&DW. Compared with natural aggregate, recycled aggregate has higher water absorption porosity, and more micro cracks. The concrete with recycled aggregate exhibits considerably complicated structure because it contains dual interfacial transition zones (ITZ) [1-3], and the fracture behaviour of RAC becomes more complicated. In order to widen the application of RAC, it is necessary to study the fracture properties and propose effective measures to improve its anti-cracking performance [4-7]. The further study about the fracture mechanics of RAC can be the reference for the practical application in the future.

At present, there only have been a few researches on the fracture performance of RAC. Wang [8] found that the fracture energy of RAC had no linear relationship with tensile compressive strength, and the fracture energy did not increase with the replacement level of recycled aggregate (or decrease), according to the experiment on shear fracture of RAC under 4-point loading. Huang [9] concluded that with the increased of the maximum particle size of recycled aggregate (5-25mm), the fracture energy increased, based on three-point bending fracture tests. And the fracture energy of RAC increased with the decreased of water-binder ratio. Shen [10] suggested that the fracture energy of RAC decreased with the increased of the replacement level of recycled aggregate. With the improvement of water-binder ratio, the difference between natural concrete and recycled aggregate concrete fracture
decreased gradually. Several attempts have been made to research the mechanical properties of RAC, such as compressive strength, flexural strength, and elastic modulus, with different recycled coarse aggregates replacement level [11-13]. But seldom research about the influence of different replacement level on the fracture mechanics of RAC have been done.

In this paper, wedge splitting method was used to conduct fracture tests on RAC, with 0%, 50%, 70% and 100% recycled coarse aggregate replacement percentages. The fracture properties were estimated in terms of double-K fracture parameters. The $F_{th}$-CMOD curve was fitted by exponential function and the fracture energy was calculated. The influence rules of replacement level of recycled coarse aggregate on fracture performance of RAC were analysed accordingly.

2. Experiment

2.1. Materials

The recycled coarse aggregate (RCA) was derived from the abandoned concrete of the road surface in Sanming, Fujian province, and the strength grade of the original concrete was C18. The grain size range of the recycled aggregate was 5-20mm after crushing and screening. The natural coarse aggregate (NC) used was gravel measuring 5-20mm. According to Chinese Code [14], the performance indexes of recycled coarse aggregate and natural coarse aggregate were tested, which is shown in Table 1. Using P.O 42.5 Portland cement (C), 372m$^2$/kg specific surface area; natural river sand as fine aggregate (S), fineness modulus was 2.33, apparent density was 2655kg/m$^3$. The chemical component of cement is shown in Table 2.

| Table 1. Properties of coarse aggregate |
|----------------------------------------|
| Properties                          | Natural aggregate (NCA) | recycled coarse aggregate (RCA) |
|---------------------------------------|-------------------------|---------------------------------|
| Apparent density (kg/m$^3$)           | 2695                    | 2506                            |
| Stacking density (kg/m$^3$)           | 1590                    | 1302                            |
| Voids ratio (%)                       | 41.0                    | 48.0                            |
| Water absorption in 10 min (%)        | 0.7                     | 4.9                             |
| Water absorption in 30 min (%)        | 0.9                     | 5.6                             |
| Water absorption in 24h (%)           | 1.0                     | 6.1                             |
| Crushing value (%)                    | 7.9                     | 13.2                            |
| Flat-elongated particles (%)          | 4.0                     | 3.2                             |

| Table 2. The chemical component of cement (%) |
|-----------------------------------------------|
| Moity | SiO$_2$ | Al$_2$O$_3$ | Fe$_2$O$_3$ | MgO | CaO | SO$_3$ | Na$_2$O | K$_2$O | f-CaO | CL |
|-------|---------|-------------|-------------|-----|-----|--------|---------|-------|-------|----|
| Cement| 17.64   | 4.89        | 3.83        | 2.41| 59.45| 2.99   | 0.3     | 0.44  | 0.35  | -  |

2.2. Concrete mixtures

Because of the high water absorption of recycled coarse aggregate, and the great difference between recycled coarse aggregate from different sources, the additional water was considered in the mixture...
proportion design of RAC, without prewetting treatment. With the reference to the Chinese Code [15, 16], several trial tests were conducted to determine the proportion. The concrete mixtures were designed to produce C40. Four mixes were made using the replacement level of recycled coarse aggregate of 30%, 50%, 70% and 100%. And the water to cement ratio w/c=0.38, sand percentage was 35%. The concrete slump of recycled aggregate concrete was between 140-180 mm, and the flow property was good enough to meet the test requirements. The details of mix proportion and the basic properties in mechanics of the concrete are shown in Table 3.

Table 3. The mix proportion and slump of concrete

| Code  | Mix proportion (kg/m³) | Slump (mm) | Compressive strength (MPa) | Axial compressive strength (MPa) | Elastic modulus (MPa) |
|-------|------------------------|------------|-----------------------------|----------------------------------|----------------------|
|       | RCA | NCA | S | C | W | SP |                      |                        |                      |                     |
| NAC   | 0   | 1106 | 597 | 474 | 180 | 1.5 | 177                  | 53.06                 | 43.80                | 30.47               |
| RAC50 | 553 | 553 | 597 | 474 | 180 | 1.9 | 173                  | 48.13                 | 42.10                | 29.49               |
| RAC70 | 774 | 332 | 597 | 474 | 180 | 2.3 | 165                  | 54.90                 | 47.10                | 32.78               |
| RA100 | 1106 | 0 | 597 | 474 | 180 | 3.4 | 169                  | 54.73                 | 48.30                | 32.27               |

Note: NAC mean ordinary concrete; RAC means recycled aggregate concrete; RACX means the replacement level is X, the value of X are 50%, 70%, 100%.

2.3. Wedge splitting test

2.3.1. Specimens preparation: According to Chinese Code [17], 20 standard wedge splitting specimens were prepared, with the dimension of 200mm×200mm×230mm, as shown in Figure 1. The classification of the specimens is listed in Table 3. All the specimens were cast in steel molds and compacted using a vibration table. The test of specimens was cured at 20±2 ℃ and relative humidity of 95% until the age of testing.

2.3.2. Test set-up: The loading device of the test was 250kN MTS fatigue testing machine (as shown in Figure 2), and the transmission device consisted of a wedge loading rack, a transmission plate and a base. Wedge-shaped loading frame was welded with two wedge-shaped steel plates, and the wedge angle was 15 degrees. The transmission plate was composed of a cover plate and two rollers, and a ball bearing was fitted on both sides of the plate to minimize the influence of friction. The measuring system included load measuring device, displacement measuring device, variable measuring device and COD measuring device. Load measurement and displacement measurement were measured by measuring system inside the pressure testing machine. The strain measurement was based on the 8-channel IMC dynamic strain data acquisition system. The measurement of COD was carried out with a clip extension meter.
3. Results and discussion

3.1. Compressive strength, axial compressive strength and elastic modulus

From Table 3, when the replacement level of recycled aggregate is 50%, the compressive strength of concrete decreased, but when the replacement level is 70% and 100%, the strength does not decrease. The reason may be that the water absorption level of recycled aggregates is much higher than that of natural aggregates, and no additional water consumption is considered in the mix proportion. Therefore, with the increase of the replacement level of recycled aggregate, the actual water to cement would be reduced, enhancing the strength of recycled aggregate concrete (RAC). The axial compressive strength of RAC fluctuates with the replacement level of recycled aggregate. When the replacement level of recycled aggregate is 50%, the elastic modulus of concrete is lower than that of natural aggregate concrete (NAC), but when the replacement level is 70% and 100%, the elastic modulus is higher.

In summary, when the replacement level of recycled aggregate is 50%, the mechanical properties of concrete are worse than ordinary concrete, but the difference is not more than 10%. Instead, at a level of 70% and 100%, because of higher water absorption of recycled aggregates and no additional water in mix proportion, along with the increase of RAC actual water-binder ratio decreased, therefore, its mechanical properties compared with normal concrete does not decline.

3.2. Test phenomena

When the load reached the crack load, which provided by the loading tester, the specimen began to crack along the prefabricated crack. When the specimen reached the buckling load, the crack expands rapidly and became a macroscopic crack, and gradually expanded to the whole section. Due to the long period of complete destruction, this test stopped loading when the vertical load was reduced to 0.2kN. The crack trend of the specimen is shown in Figure 3, and the surface of fracture specimens are shown in Figure 4 and 5.

It shows that the crack developed along the direction of the precast crack. The fracture surface of RAC is quite different from that of NAC. The ITZ of RAC is relatively complicated and the strength of aggregate is lower. It is found that nearly half of the fracture surface of RAC is the fracture of coarse aggregate, and the other half is the fracture of cement stone. But in that of NAC, more fracture of cement stone and less fracture of natural coarse aggregate.
3.3 Double-K fracture parameters

3.3.1. Crack initiating load and maximum load: Using the IMC acquisition system to collect the strain of the specimen during the loading process, the collected vertical force $F_v$ value was converted to $F_H$ value, through the relationship between $F_v$ and $F_H$ (Formula (4)). The load of the linear-nonlinear point was obtained by $F_H-\varepsilon$ curve, which was the crack initiating load. The corresponding value of the maximum point was the maximum load. The crack initiating load, the maximum load and their ratios in each group are shown in Table 4. From Table 4, it can be seen that the crack initiating load is between 6.15 and 7.47, the maximum load is between 8.53 and 9.66, while their ratio is between 0.64~0.78 and the mean value is 0.73.

| Code  | Crack initiating load (kN) | Maximum load (kN) | Ratio |
|-------|-----------------------------|-------------------|-------|
| NC    | 6.15                        | 9.66              | 0.64  |
| RC50  | 6.41                        | 8.53              | 0.75  |
| RC70  | 5.92                        | 8.06              | 0.73  |
| RC100 | 7.47                        | 9.56              | 0.78  |

3.3.2. Elastic modulus, crack initiation fracture toughness and unstable fracture toughness

According to Xu [18], the elastic modulus ($E$) of wedge splitting test was obtained from Formula (1).

$$E = \frac{1}{t_0} \left[ 13.18 \times \left( 1 - \frac{a_0 + h_0}{h + h_0} \right)^2 - 9.16 \right]$$

Where $t$ is the thickness of specimen; $a_0$ is the initial crack length of the specimen; $h_0$ is the thickness of the blade on the specimen; $h$ is the height of specimen; $c_i = \frac{V_i}{F_i}$ is the initial flexibility, it means the inverse of the initial slope of the $F_H$-CMOD curve.

The crack initiation fracture toughness of wedge splitting test was calculated by Formula (2), (3) and (4), according to Chinese Code [19].

$$K_{IC}^{ini} = \frac{F_{HQ} \times 10^{-3}}{th^{1/2}} f(a)$$

$$f(a) = \frac{3.675 \times \left[ 1 - 0.12(a - 0.45) \right]}{(1 - a)^{3/2}}$$

$$F_{HQ} = \frac{\left( F_0 + mg \times 10^{-2} \right)}{2 \tan 15^\circ}$$
Where $K_{IC}^{ini}$ is the crack initiation fracture toughness (MPa·m$^{1/2}$); $m$ is the weight of the wedge loading rack (kg); $F_{HQ}$ is the horizontal crack initiating load (kN); $F_{vQ}$ is the vertical crack initiating load (kN), corresponding to the turning point of the curve on the $f$-$v$ curve. In this test, the wedge loading rack is bolted to the test machine, so actually there is no ‘$mg$’ in the Formula (4).

The unstable fracture toughness was calculated by Formula (5), (6), (7) and (8).

$$K_{IC}^{un} = \frac{F_{Hmax} \times 10^{-3}}{th^{1/2}} f(\alpha) \quad \text{(5)}$$

Where $f(\alpha)$ and $F_{Hmax}$ are obtained by Formula (6) and (7) respectively.

$$f(\alpha) = \frac{3.675 \times [1 - 0.12(\alpha - 0.45)]}{(1 - \alpha)^{3/2}}, \alpha = \frac{a_c}{h} \quad \text{(6)}$$

$$F_{Hmax} = \frac{(F_{max} + mg \times 10^{-3})}{2 \tan 15^\circ} \quad \text{(7)}$$

Where $a_c$ is critical effective crack length and is calculated by formula (8); $F_{Hmax}$ is horizontal maximum load (kN); $F_{max}$ is vertical maximum load (kN).

$$a_c = (h + h_0) \left\{ 1 - \left[ \frac{13.18}{\left( \frac{V_c E_t}{F_{Hmax}} + 9.16 \right)^{1/2}} \right] - h_0 \right\} \quad \text{(8)}$$

Where $V_c$ is the critical value of the crack open mouth displacement, namely CMOD ($\mu$m) when the load reaches maximum.

The cohesive fracture toughness $K_{IC}^{c}$ reflects the aggregate cohesion in concrete. It is related to effective crack length $a_c$ and the softening curve of concrete. The relationship between cohesive fracture toughness, crack initiation fracture toughness and unstable fracture toughness is:

$$K_{IC}^{un} + K_{IC}^{c} = K_{IC}^{ini} \quad \text{(9)}$$

### 3.3.3. The influence of replacement level on the double K fracture parameters

The calculation results of the double K fracture parameters are shown in Table 5. Figure 6 shows the influence of the replacement level of recycled aggregate on cohesive fracture toughness, crack initiation fracture toughness and unstable fracture toughness. It can be obtained that the replacement level of recycled aggregates has little effect on crack initiation fracture toughness, but it has a great influence on the unstable fracture toughness and cohesion fracture toughness. When the replacement level of recycled aggregate is 50%, the unstable fracture toughness of RAC was the lowest, 0.43 lower than that of NAC, and the cohesive fracture toughness of RAC is the maximum, 0.53 higher than that of NAC. It is likely to indicate that the fracture performance of RAC is the worst when the replacement level of recycled aggregate is 50%.
Table 5. Double-K fracture parameters of concrete

| Code | Elastic modulus GPa | \(V_c\) \(\mu m\) | \(a_c\) m | \(K_{IC}^{ini}\) MPa·m\(^{1/2}\) | \(K_{IC}^{un}\) MPa·m\(^{1/2}\) | \(K_{IC}^{c}\) MPa·m\(^{1/2}\) |
|------|---------------------|-----------------|------|----------------|----------------|----------------|
| NC   | 25.94 | 203.00 | 0.138 | 0.4938 | 1.8611 | -1.3672 |
| RAC50 | 24.87 | 137.03 | 0.121 | 0.5963 | 1.4345 | -0.8382 |
| RAC70 | 23.56 | 177.54 | 0.125 | 0.6645 | 1.6880 | -1.0235 |
| RAC100 | 24.85 | 151.50 | 0.121 | 0.5465 | 1.5800 | -1.0334 |

Figure 6. Effect of replacement level of recycled concrete to fracture toughness

3.4. Fracture energy of recycled aggregate concrete (RAC)

3.4.1. Calculation of fracture energy: In the last section, fracture toughness was expressed through fracture toughness. But fracture energy is the parameter which is the most direct reflection of the concrete resistance to fracture ability. This test adopted the exponential function (Formula (10)) to fit the descending section of the \(F-V\)-CMOD curve, starting from the maximum loading point of the descending section 1/3, so as to calculate the fracture energy.

The Formula (11) was used to calculate the fracture energy without considering the influence of the fixed wedge fixture and the weight of the specimens.

\[
F_V = a e^{b\delta}, \quad W_V = \int_a e^{b\delta} d\delta, \quad G_F = \frac{W}{A} = \frac{W_V + W_I}{A}
\]

(10)
(11)

Where \(W_V = \frac{W_{V}}{2g R}, \quad W_I = \frac{W_{I}}{2g R}\), and \(W_{V}\) and \(W_{I}\) respectively represent the area of the measured \(F-V\)-CMOD curve and the area of the fitting \(F-V\)-CMOD tail curve.

The reliability coefficient \(R^2\) was used to reflect the effect of exponential function fitting. From Table 6, the correlation coefficient \(R^2\) is between 0.957 and 0.993, which is close to 1, indicating good function fitting effect and high correlation.
Table 6. Correlation values of exponential function fittings

| Code  | The results of exponential function fitting | W_{1/2} |
|-------|---------------------------------------------|---------|
|       | R^2  | a(a>0) | b(b<0) |       |
| NC    | 0.9846 | 2.5839 | -0.881 | 0.3415 |
| RC50  | 0.9688 | 2.2007 | -1.4315 | 0.093  |
| RC70  | 0.9697 | 3.1289 | -1.32  | 0.1157 |
| RC100 | 0.9668 | 2.8331 | -1.5962 | 0.0746 |

Through the Origin software, the area of F_{H}-CMOD curve was calculated, and W_{0/2} was obtained. Figure 7 shows the F_{H}-CMOD curves of each group.

![F_{H}-CMOD curves](image)

(a) NC group  
(b) RAC50 group  
(c) RAC70 group  
(d) RAC100 group

Figure 7. F_{H}-CMOD curve

According to Formula (11), F_{H}-CMOD curve area W and fracture energy G_{F} were calculated, as shown in Table 7.

Table 7. Area of F_{H}-CMOD curves and fracture energy

| Code  | W (kN.m) | G_{F}(kN/m) |
|-------|----------|-------------|
| NC    | 14.241   | 593.627     | 281.295   |
| RC50  | 7.092    | 295.540     | 161.970   |
| RC70  | 8.789    | 366.219     | 224.166   |
| RC100 | 6.245    | 260.216     | 186.964   |
3.4.2. The influence of replacement level on fracture energy: From Figure 8, the effect of replacement level of recycled aggregate on fracture energy was studied. Whether the replacement level is 50%, 70% or 100%, the fracture energy of RAC is much lower than that of NAC. When the replacement level of recycled aggregate is 100%, the fracture energy of RAC is 94.3N/m lower than that of NAC (with exponential function).

![Figure 8](image.png)

**Figure 8.** Effect of recycled aggregate’s replacement level on fracture energy

4. Conclusions
Based on wedge splitting test and double-K fracture model, experimental study was carried out on the fracture parameters of recycled aggregate concrete, and the influence of replacement level of recycled aggregate on crack initiation fracture toughness, and unstable fracture toughness and fracture energy were analyzed.

(1) When the replacement level of recycled aggregate is 50%, the mechanical properties of RAC is worse than that of NAC, but no more than 10%.

(2) When the replacement level was 70% and 100%, the mechanical properties of RAC are not decreased compared with NAC. The reason may be that the high water absorption of recycled aggregate, the additional water was not considered in the mix proportion, and the actual water-binder ratio of RAC was reduced with the increase of the replacement level of recycled aggregate.

(3) The effect of replacement level on crack initiation fracture toughness of RAC is not obvious, but it has great influence on the unstable fracture toughness. When the replacement level of recycled aggregate is 50%, the fracture performance is the worst, 0.43 MPa·m$^{1/2}$ lower than NAC. When the replacement level is 50%, 70% and 100%, the fracture energy of NAC is 119.3N/m, 57.1N/m and 94.3 N/m respectively compared with the NAC.

(4) Regardless of the replacement level of recycled aggregate, the fracture energy of RAC can be lower than NAC.

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