Study on Mechanical Properties and Constitutive Relationship of Recycled Large Aggregate Concrete

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Abstract: In this paper, two C25 strength grades of natural aggregate concrete (NAC) and recycled aggregate concrete (RAC) were prepared, and the compressive strength, splitting tensile strength and anti-wear strength were studied. And analyzing the two kinds of concrete under uniaxial compressive and tension state of the constitutive relation, the corresponding constitutive equation is established. The research results showed that: compared with NAC, the compressive strength of RAC at 7d, 28d and 56d decreased by 3.17%, 6.68% and 8.42% respectively, and the splitting tensile strength of RAC at 7d, 28d and 56d decreased by 4.76%, 6.67% and 5.48% respectively, the anti-wear strength decreased 59.02%, and the wear rate of specimens increased by 157.87%; the stress-strain curves of two kinds of concrete under uniaxial compression and tension were fitted, and the related constitutive equations were established. Although the mechanical properties of RAC are lower than that of NAC, they are not much different and can be used to replace NAC to some extent.

1. Introduction

Traditional concrete consists of cement, water and natural sandstone materials. Cement concrete has become one of the most widely used building materials due to its advantages of low cost, simple manufacture, good plasticity, firmness, durability and abundant resources, and is widely used in civil buildings, water conservancy projects, underground projects and road and bridge projects [1]. However, with the rapid development of urbanization, a large number of old buildings and projects are demolished every year. China alone produces about 200 million tons of construction waste every year, and only 10% of the waste is recycled [2]. Most of the construction waste is still in a simple landfill state, which not only wastes resources but also pollutes and damages the ecological environment. The research and development of recycled aggregate and recycled aggregate concrete can effectively alleviate a series of problems such as waste concrete treatment, waste of natural aggregate resources, environmental pollution, etc.

Recycled aggregate can be obtained by crushing, removing impurities and screening the construction waste after dismantling the waste concrete. Compared with natural aggregate, recycled
aggregate has rough and uneven surface, many edges and corners, high silt content and high needle and flake content [3], low apparent density and bulk density, high water absorption rate, large mass loss rate, high crushing value and wear value, which affect the strength and durability of aggregate itself [4,5]. Recycled concrete refers to concrete made by crushing, cleaning and grading waste concrete blocks and mixing them with gradation according to a certain proportion to partially or completely replace natural aggregate. The mechanical properties of recycled concrete will be affected by the aggregate state, type, particle size, dosage and service life [6]; the increase of aggregate content will reduce the compressive strength, tensile strength and flexural strength of recycled concrete [7]; different aggregates and replacement ratios have different effects on the mechanical properties of concrete. The mechanical properties of concrete can be improved by appropriate aggregate size and content [8].

According to the Recycled Coarse Aggregate for Concrete (GB/T 25177-2010), the recycled coarse aggregate whose particle size is larger than 4.75mm is called recycled coarse aggregate. The research on recycled coarse aggregate is mostly concentrated below 40mm. Compared with conventional recycled coarse aggregate, recycled coarse aggregate with particle size over 40 mm has the advantages of simple crushing, low energy consumption and easy acquisition, but the related research is relatively few. Bo Wu etc. [9,10] of South China University of Technology simply crushed waste concrete blocks to form recycled large aggregate, which can reach 167mm; in size when applied to concrete. Jianzhuang Xiao, Shicong Kou, Zongping Chen, Gaiwei Peng and other scholars [11-14] respectively studied the mechanical properties of various recycled concrete, including various recycled concrete with different strength grades and different service life as recycled coarse aggregate.

In this paper, recycled aggregate concrete is prepared by using aggregates with a particle size of more than 40mm and a maximum particle size of 80 mm. Firstly, the mechanical properties of two kinds of concrete are studied, including compressive strength, splitting tensile strength and impact and abrasion strength, and the effects of two kinds of aggregates on the mechanical properties of concrete are compared and analyzed. Secondly, non-dimensional analysis is carried out for concrete under uniaxial compression and tension. The full stress-strain curves of natural concrete and recycled concrete under different load conditions are fitted, and the related constitutive equations are established.

2. Material and Methods

2.1. Raw Materials
Cement: cement is P·O 42.5 ordinary Portland cement, density is 3100 kg/m³, water consumption for normal consistency is 27.2%, 28d compressive strength and flexural strength are 47.6MPa and 8.2MPa;
Fine aggregate: fine aggregate is locally produced river sand with fineness modulus of 2.6, apparent density of 2640 kg/m³ and bulk density of 1600 kg/m³;
Coarse aggregate: Coarse aggregate includes natural limestone macadam with continuous gradation of 5-80mm and recycled coarse aggregate with particle size in the range of 5-80 mm. The apparent density of natural coarse aggregate is 2720kg/m³, bulk density is 1600kg/m³, water absorption rate is 0.22%, silt content is 1.44%, crushing value is 11%, apparent density of recycled coarse aggregate is 2490 kg/m³, bulk density is 1240kg/m³, water absorption rate is 4.48%, silt content is 5.32%, crushing value is 15.7%.

2.2. Test Mix Proportion
The test set the mass ratio of NAC as m (water): m (cement): m (sand): m (stone) =136: 317: 645: 1370; the mass ratio of RAC was m (water): m (cement): m (sand): m (stone) =134: 344: 577: 1226.

2.3. Test Methods
The test shall be conducted according to the Hydraulic Concrete Test Specification (SL352-2006).
(1) Compressive strength: Concrete specimens were cube specimens of 200 mm × 200 mm × 200 mm. All specimens were tested for compressive strength on a universal pressure testing machine. The loading rate of the press is (0.3~0.5) MPa/s, and the compressive strength test is carried out and the data are recorded when the concrete test block reaches the specified age.

(2) Splitting tensile strength: the splitting tensile test concrete specimens were cube specimens of 200mm × 200mm × 200mm, the mat strip was a steel square mat strip with a section of 5mm × 5mm and a length of 200 mm, the loading rate of the press was (0.04~0.06) MPa/s, and the splitting tensile strength test was carried out when the concrete reaches the specified age.

(3) Impact and abrasion strength: The cylinder with specimens size of φ300mm × 100mm required for impact and abrasion test shall be cured to the specified age for impact and abrasion test after forming. The test time was 72h and the motor stirring rate was 1200 r/min.

(4) Non-dimensional analysis is carried out on the stress-strain full curves under uniaxial compression and tension of the two kinds of concrete, and the full curves under uniaxial compression and tension of the two kinds of concrete are fitted to obtain the constitutive equation of the full curves.

3. Results and Analysis

3.1. Compressive Strength

Compressive strength tests were carried out on two kinds of concrete test blocks, and the compressive strength test results of 7d, 14d, 28d, 56d and 90d were obtained as shown in figure 1, and figure 2 is an SEM image of recycled aggregate.

As can be seen from figure 1, the compressive strength of RAC is lower than that of NAC at each age, and the decrease in compressive strength at the early 7d is the smallest. RAC is 3.17% lower than that of NAC, and the decrease in compressive strength at 56d is the largest. RAC is 8.42% lower than that of NAC, indicating that the increase in compressive strength of RAC is smaller than that of NAC with the increase of age. There are pores in recycled aggregate and a little cement paste in the aggregate. The weak interfacial transition zone between the new mortar and the old mortar in recycled concrete directly affects the compressive strength of concrete, but it is not much different from natural concrete as a whole. RAC can be used instead of NAC to some extent.

3.2. Splitting Tensile Strength

The splitting tensile strength test was carried out on two kinds of concrete test blocks. The test results are shown in figure 3, and the fracture surface morphology after splitting is shown in figure 4 and figure 5. After splitting the specimen, it can be seen from observation that the aggregate inside NAC is relatively compact in combination with cementing material, and the aggregate surface is relatively flat with high integrity. However, the aggregate distribution in RAC is scattered, and there are pores in RAC. RAC is not dense, and the fracture surface of recycled aggregate has defects such as pores and cracks.
Figure 3. Variation curve of NAC and RAC splitting tensile strength with age

Figure 4. NAC splitting surface

Figure 5. RAC splitting surface

As can be seen from figure 3, the splitting tensile strength of RAC at each age is lower than RAC, and the splitting tensile strength of NAC at each age is increased by 4.76%, 2.51%, 6.67%, 5.48% and 6.47% respectively. The difference between the splitting tensile strength of the two kinds of concrete is similar to the compressive strength. As recycled aggregate is obtained by mechanical or artificial crushing, it will inevitably bring internal defects or damages to the aggregate during processing, causing a large number of microcracks or cracks in the recycled aggregate. The development of internal microcracks in the splitting tensile test is faster than that of natural concrete, thus causing the splitting tensile strength of RAC to be lower than that of NAC.

3.3. Impact Wear Resistance

The impact wear test piece shall be cured to 28d age after forming and tested. The specific test process is shown in figure 6 and figure 7, and the test result is shown in table 1.

![Figure 6. Before and after NAC impact wear test](image)

![Figure 7. Before and after RAC impact wear test](image)

| Type | 28d abrasion resistance | Wear rate(%) |
|------|-------------------------|--------------|
| NAC  | 16.13                   | 1.78         |
| RAC  | 6.61                    | 4.59         |

According to the results in Table 1, after 72 hours of impact wear test, the impact wear strength of RAC is 59.02% lower than that of NAC, and the wear rate of the test piece is 157.87%.

Looking at figure 6 and figure 7, it can be found that both concrete surfaces have wear conditions, but NAC wear conditions are better than RAC, the surface retention area is slightly larger, the surface is relatively flat, and the leaked natural aggregate wear conditions are relatively good. However, the surface of RAC has some small areas of uneven surface, with obvious steel ball indentations, more exposed aggregate, and serious abrasion on the aggregate surface. The surface of recycled aggregate is rough and uneven, with many edges and corners, high mud content, and many voids and microcracks,
resulting in poor compactness of the concrete and poor impact and abrasion resistance compared with NAC.

3.4. Constitutive Relation

3.4.1. Stress and Strain Analysis under Uniaxial Compression. The non-dimensional analysis of the stress-strain full curves of two kinds of concrete under uniaxial compression is carried out, in which the abscissa is \( \varepsilon / \varepsilon_c \) (\( \varepsilon_c \) is the peak strain) and the ordinate is \( \sigma / \sigma_c \) (\( \sigma_c \) is the peak stress), as shown in figure 8.

![Figure 8. Stress-strain curves of NAC and RAC under uniaxial compression](image)

As can be seen from figure 8, both natural large aggregate concrete and recycled large aggregate concrete have full curve segments, and the change trend is approximately the same. Before the peak point, RAC is steeper than NAC in the curve of rising segment, and the strain of NAC is larger than RAC under the same stress, which indicates that NAC has larger deformation under uniaxial compression. However, after the peak point, the downward curve shows a similar downward trend, indicating that after the peak, the strain changes of the two are basically the same under compression and there is no obvious difference.

The full curves of the two kinds of concrete under uniaxial compression are fitted, and the fitting degree R2 reaches 0.99, and the constitutive equations of the full curves are obtained, as shown in figure 9 and figure 10.

![Figure 9. Full stress-strain curve of NAC under uniaxial compression](image)
Constitutive equation of natural large aggregate concrete with full curve:

\[
y = \begin{cases} 
-0.0056 - 0.23x + 1.34x^2 & 0 \leq x < 1 \\
1.02 + \frac{x}{1.11} & x > 1 \\
-0.039 + \frac{x}{0.02} & x \geq 1
\end{cases}
\]

(1)

Full Curve Constitutive Equation of Recycled Aggregate Concrete:

\[
y = \begin{cases} 
1.09 - \frac{1.21}{1 + \frac{x}{0.52}} & 0 \leq x < 1 \\
23.48 - \frac{21.94}{1 + \frac{x}{0.7}} & x > 1
\end{cases}
\]

(2)

From equations (1) and (2), it can be seen that the constitutive equations of NAC ascending and descending sections are similar to those of ordinary concrete under uniaxial compression [15], both of which are piecewise functions. The deformation of recycled concrete is different from that of natural concrete, but the deformation trend is similar.

3.4.2. Stress and Strain Analysis under Uniaxial Tension. The stress-strain curves of two kinds of concrete under uniaxial tension are analyzed nondimensionally, and the abscissa and ordinate are consistent with those under compression, as shown in Fig. 11. The stress-strain curves of the two kinds of concrete under uniaxial tension are fitted with a fitting degree $R^2$ of 0.99, and the constitutive equations of the two kinds of concrete under tension are obtained, as shown in figure 12 and figure 13.

Figure 11. Stress-strain curve of NAC and RAC under uniaxial tension

Figure 12. NAC uniaxial tension stress-strain curve fitting

Figure 13. RAC uniaxial tension stress-strain curve fitting

As can be seen from figure 13, because it is under tension, there is only the curve of the rising section. When the peak point is reached, the test block is split and damaged, and there is no stress-strain curve of the falling section. The change process of two kinds of concrete is similar for the curve
of rising section. However, before the peak point, the stress-strain curve of RAC is steeper than that of NAC, indicating that the strain of NAC is larger than that of RAC under the same stress, indicating that the deformation of NAC is larger under uniaxial tension, which is similar to the strain change of two kinds of concrete under uniaxial compression.

Natural large aggregate concrete: \( y = 0.13-1.09x+1.72x^2 \) \hspace{1cm} (3)
Recycled large aggregate concrete: \( y = 0.07-0.64x+1.58x^2 \) \hspace{1cm} (4)

Equations (3) and (4) are constitutive equations of two kinds of concrete under uniaxial tension, which are similar to constitutive equations of uniaxial compression rising section.

4. Conclusion
In this paper, the related mechanical properties of NAC and RAC under the same strength grade are tested and the constitutive relation is analyzed. The influence of the two aggregates on the mechanical constitutive of the prepared concrete is studied. The conclusions are as follows:

(1) Compared with NAC, the compressive strength of RAC decreased by 3.17%, 4.69%, 6.68%, 8.42%, 6.86% at each age, the splitting tensile strength decreased by 4.76%, 2.51%, 6.67%, 5.48%, 6.47% at each age, the impact wear strength decreased by 59.02%, and the wear rate of specimens increased by 157.87%. The mechanical properties of RAC are worse than NAC, but the overall difference is not big. To a certain extent, RAC can be used instead of NAC.

(2) The stress-strain curves of NAC and RAC under compressive and tensile conditions are fitted, and the constitutive equation is established. The constitutive equation parameters show that the established constitutive model of concrete is similar to the existing model.

Acknowledgement
Thanks for the support of Guangxi key research and development plan (guike AB17292083).

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