Study on key micromechanics of recycled concrete based on compound random aggregate model

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Abstract. A compound random aggregate program of recycled concrete is developed based on the concrete damage plasticity constitutive mode using computer language. Bifacial mesoscopic models of the recycled concrete are studied with ABAQUS finite element analysis software. The mesoscopic performance of the recycled concrete are studied as follows: uniaxial compression strength, strain change, damage process, stress state, and so on. The influence factors of the mesoscopic mechanical properties of recycled concrete are analyzed. The analysis results show that there are concentration problems of tensile and shear stress in the internal and external interface area of the recycled concrete under the action of uniaxial compression load. The concentration of the tensile stress and shear stress may result in the damage failure of recycled concrete. The initial damage appears the first in weaker interfacial area, after that the damage is developed towards the mortar area. The recycled concrete compressive strength is greatly influenced by the new hardened mortar strength and old hardened mortar strength, and the influence of the interfacial area and the outer surface area is small. The mechanical properties of the recycled concrete are weakened due to the old hardened mortar.

1. Introduction
The recycling of waste concrete has become one of the hot research issues in academia and engineering industry in recent years as the amount of waste concrete generated worldwide is increasing. The development of recycled concrete technology is one of the most important ways to achieve sustainable development of building resources. Many studies at home and abroad show that the mechanical properties of recycled concrete are weakened compared with ordinary concrete, because recycled concrete has a more complicated mesoscopic structure. Most experimental studies of recycled concrete do not consider basically mesoscopic structure problem, so these studies are difficult to reveal the essence of the mechanical properties of recycled concrete. It is necessary to study the microstructure of recycled concrete in order to systematically grasp the mechanical properties of recycled concrete.

In recent years, domestic and foreign scholars have carried out certain research on recycled concrete, and the research results are mainly reflected in the meso-mechanical model of recycled concrete[1-4]. For example, Hrennikoff proposed a lattice model based on theoretical physics. Because this model ignores the smaller particles, there are limitations while simulating the compression of recycled concrete. Mohamed A.R. and Hansen proposed the M-H model, which considers the
randomness of the mesoscopic composition and mechanical properties of concrete, but it has limitations while simulating fracture problems under complex stress conditions. The above analysis shows that the existing recycled concrete calculation model still has certain deficiencies, so how to effectively construct the aggregate model needs further study.

In order to study the damage mechanism of recycled concrete under uniaxial compression and the effect of various phases material properties on macro-mechanical properties of recycled concrete, a random aggregate calculation model of recycled concrete is established by MATLAB and ABAQUS. Damage development and mechanical properties of recycled concrete are analyzed.

2. Mesoscopic aggregate model of recycled concrete
Referring to the relevant processing methods of Dang Nana [5] et al. on the random aggregate model structure, the shape of recycled aggregate is considered as circular and the mortar is evenly attached to the periphery of natural aggregates. The thickness of the inner and outer mortar interface area is 0.5 mm, and the thickness of the hardened mortar is 1 mm. According to the Walraven J.C. formula, the probability that the three-dimensional gradation curve is converted to an aggregate diameter at any point on the specimen cross section can be calculated as

\[ P_k (D < D_0) = P_k \left(1.605n^{1/2} - 0.053n^4 - 0.012n^6 - 0.0045n^8 - 0.0025n^{10}\right) \]  

where \( P_k \) is aggregate volume as a percentage of total volume, \( n = D_0 / D_{\text{max}} \).

In this model, the replacement rate of recycled concrete is taken as 100%, the aggregate size is 5 ~ 20 mm, and the aggregate content is 40%. According to the calculation Walraven J.C. formula, 14 aggregate particles are obtained, ten of these particles is 5 mm to 10 mm in diameter, three of these particles is 10 mm to 15 mm in diameter, and one of these particles is 15 mm to 20 mm in diameter.

The damage plastic constitutive modal (or the CDP modal for short) that comes with ABAQUS software is used. The CDP modal is a continuous medium plastic damage modal, which is based on the Lubliner modal, Lee J and Fenves modal, and it is necessary to define parameters such as damage and plasticity. According to the CDP model, some plastic parameters such as flow rule, yield function and viscosity characteristic are defined. In accordance with the relevant provisions of Code for design of concrete structures (GB 50010-2010), the plastic parameters of RC are reasonably selected. The eccentricity ratio is 0.1, expansion angle is 38º, viscosity coefficient is \(1 \times 10^{0.05}\). When \( x \) is less than or equal to 1, the function expression is shown as

\[ y = \alpha_x x + (3 - 2\alpha_d) x^3 + (\alpha_d - 2) x^3 \]  

When \( x \) is larger than 1, the function expression is shown as

\[ y = \frac{x}{\alpha_d (x-1)^2 + x}, x = \frac{\sigma}{\varepsilon_c}, y = \frac{\sigma_c}{f_c}, \]  

where \( f_c \) is the compressive strength of concrete, \( \alpha_d, \alpha_d \) are respectively the corresponding values of the rise and fall of the stress-strain curve; \( \varepsilon_c \) is the strain peak value.

The compression damage index can be calculated as

\[ d_c = 1 - \frac{\sigma_c E_c^{-1}}{\varepsilon_c^{\prime\prime} (1/b_c - 1) + \sigma_c E_c} \]  

Where \( E_c \) is elastic modulus, \( \varepsilon_c^{\prime\prime} \) is plastic strain under uniaxial compression, \( b_c \) is plastic strain ratio.

3. Numerical simulation analysis

3.1. Two-dimensional model
Two-dimensional random modal of recycled concrete is established using the self-editing algorithm based on the computer language MATLAB. The algorithm uses the principle of Monte Carlo method to generate random numbers, which can randomly generate the coordinates of the location of recycled aggregate. In past studies [6], the representative volume element (RVE) had been regarded as the bond between the macroscopic mechanical properties of the concrete and its mesoscopic structure, and its side length should be larger than or equal to triple that of the maximum aggregate particle size. Therefore, when the position coordinates of the aggregate are obtained using the algorithm, two-dimensional plane modal of 60 mm × 60 mm can be generated with ABAQUS.

3.2. Parameters setting and mesh generation
According to the constitutive relationship of plastic damage, the corresponding material parameters of the five-phase materials are given in the recycled aggregate. Based on the relevant test data [7-9], the selected five-phase material parameters are given. When dividing the grids, the global size is 0.5, and the size of the outer four sides is 1. The three circles are filled with three layers of seeds in the thickness direction in order to ensure the calculation accuracy. A transition grid is adopted inside the natural aggregate, and the transition value is taken as 2-2.5. After the grid meshing is completed, displacement loads and constrains are added to the model. The layout of loads and constrains are shown in Figure 1. The upper part of the model has coupling constraints, and 0.05 mm displacement is set at the reference point. The lower part of the model has normal constraints, and the lower midpoint has the horizontal constraints. The two-dimensional random aggregate model is established in this paper which has been generated 19021 units, including 3006 old hardened mortar units, 6957 newly hardened mortar units, 3006 old interface zone units, 3006 new interface zone units and 3046 natural aggregate units. A local grid of a two-dimensional random aggregate model is shown in Figure 2.

3.3. Compressive strength and peak strain analysis
Using rigid displacement loading, the analysis time is one second, the maximum incremental step is set to 1×10⁻⁴, the minimum incremental step is set to 1×10⁻⁸, and the initial incremental step is set to 0.01. After loading, the results are obtained. Because the total number of units is too large, the stress of only some of the units (old hardened mortar unit, old interface unit, new interface unit, natural aggregate unit and 40 new hardened mortar units) can only be extracted in proportion strain value. This paper adopts numerical average method to process and analyze the calculated stress and strain values. The change of the average stress with the average strain is shown in Figure 3. It can be seen from Figure 3 that the peak value of uniaxial compressive strength is about 21.34 MPa, and the corresponding peak strain value is about 0.0017. The data shows that the compressive strength is much smaller than that of natural aggregate. The compressive strength of recycled concrete falls in between the strength of newly hardened mortar and the strength of old hardened mortar. At the same time, through comparison, the calculated results coincide with the experimental values [10], which shows that the model has good calculation accuracy.

3.4. Damage mechanism analysis
The corresponding damage bands under different analysis steps are extracted to study the damage mechanism of recycled concrete under uniaxial compression load. The damage development is shown in Figure 4. The analysis shows that the initial damage occurs first in the inner interface area and then the damage develops in order from the outer interface area, the old hardened mortar area, and the new hardened mortar area. Damage zones appear in all phase materials except the natural aggregates. The damage in the inner and outer interface area appears evenly on the left and right sides. As the load continues to increase, the damage continues to extend until the specimen is destroyed. The limit damage value is 0.89, and eventually an inverted " V " is formed in damage distribution zone.

3.5. Stress distribution

In order to study the cause of the destruction of recycled concrete under uniaxial compression load, the horizontal stress cloud diagram (S11), vertical stress cloud diagram (S22) and shear stress cloud diagram (S12) of the specimen are extracted. The stress cloud diagram of the calculation model (" + " is tensile stress, " − " is compressive stress) is shown in Figure 5. The analysis shows that the maximum stress value of the horizontal stress S11 (Figure 5(a)) appears in the newly hardened mortar area and the natural aggregate area, and the maximum stress value of S11 is between 2.01-2.63 MPa. The maximum stress value of the vertical stress S22 (Figure 5(b)) appears in the old hardened mortar area and the inner and outer interface area, the maximum stress value of S22 is between 2.08-2.34 MPa. The maximum stress value of shear stress S12 (Figure 5(c)) is distributed in the inner and outer interface areas, the maximum stress value of S12 is between 3.03-3.39 MPa, which indicates that there is a concentration of tensile stress and shear stress in the inner and outer interface areas.

One tenth of the compressive strength of concrete is taken as its tensile strength value in this paper, which is 2.13 MPa. According to the Motack’s concrete shear strength formula, the concrete shear strength can be 0.12 times its compressive strength, and the concrete shear strength is 2.56 MPa. It can be seen from Figure 5 that the area where the shear stress (S12) is greater than 2.56 MPa and the area where the vertical stress (S22) is bigger than 2.13 MPa basically overlap, and the overlapping areas are all in an inverted " V " shape distribution, and are basically located in the internal and external interface areas. The main reason is that recycled concrete has tensile stress concentration and shear stress at the internal and external interface areas.

4. Influence factor analysis

4.1. Influence of each phase material strength
The strength of each phase material in recycled concrete materials will affect the macroscopic mechanical properties. Eight working conditions are set up to study the impact of the increase and decrease of the strength of each phase material on the macroscopic properties. The effect of a 20% decrease in each phase material strength on the compressive strength and peak strain of recycled concrete specimens is shown in Table 1. The effect of a 20% increase in each phase material strength on the compressive strength and peak strain of recycled concrete specimens is shown in Table 2. Conditions 1, 2, 3, and 4 correspond to the strength of the new hardened mortar, old hardened mortar, inner interface area, and outer interface area, respectively.

### Table 1. Effect of a 20% decrease in each phase material strength

| Condition | Adjustment coefficient | Peak strain (ε) | Compressive strength (σ/MPa) |
|-----------|------------------------|-----------------|-----------------------------|
| Benchmark | 1                      | 0.0017          | 21.34                       |
| 1         | 0.8                    | 0.00155 (−8.7%) | 18.76 (−12.1%)              |
| 2         | 0.8                    | 0.00159 (−6.5%) | 19.72 (−7.6%)               |
| 3         | 0.8                    | 0.00162 (−4.7%) | 20.34 (−4.6%)               |
| 4         | 0.8                    | 0.00161 (−5.1%) | 20.14 (−5.6%)               |

When the strength of each phase material is reduced by 20% (Table 1), the compressive strength and peak strain of recycled concrete specimens show different degrees of reduction. The material strength of the new and old hardened mortar areas has a bigger influence on the macroscopic compressive properties of recycled concrete, and the material strength of the inner and outer interface areas has a smaller effect on the macroscopic compressive properties of recycled concrete.

### Table 2. Effect of a 20% increase in each phase material strength

| Condition | Adjustment coefficient | Peak strain (ε) | Compressive strength (σ/MPa) |
|-----------|------------------------|-----------------|-----------------------------|
| Benchmark | 1                      | 0.0017          | 21.34                       |
| 1         | 1.2                    | 0.00185 (+9.1%) | 23.77 (+11.4%)              |
| 2         | 1.2                    | 0.00182 (+6.9%) | 23.03 (+7.9%)               |
| 3         | 1.2                    | 0.00178 (+4.9%) | 22.24 (+4.2%)               |
| 4         | 1.2                    | 0.00177 (+4.5%) | 22.24 (+4.2%)               |

When the strength of each phase material is increased by 20% (Table 2), the compressive strength and peak strain of recycled concrete show different degrees of increase. The material strength of the new and old hardened mortar areas has a bigger impact on the macroscopic compressive performance of recycled concrete, and the material strength of the inner and outer interface areas has a smaller impact on the macroscopic compressive performance of recycled concrete.

### 4.2. Influence of old mortar thickness

Compared with natural aggregates, the surface of recycled aggregates has a layer of old hardened mortar, and its microstructure is more complicated. The old hardened mortar thickness of 1.2 mm and 1.4 mm (Conditions 5 and 6 in Table 3) are compared with the original condition (Benchmark in Table 3). The compressive strength and peak strain of the specimen continue to decrease as the thickness of the old hardened mortar increases (Table 3), which indicates that the old hardened mortar weakens the mechanical properties of recycled concrete.

### Table 3. Influence analysis of old mortar thickness

| Conditions | Thickness | Peak strain (ε) | Compressive strength (σ/MPa) |
|------------|-----------|-----------------|-----------------------------|
| Benchmark  | 1         | 0.0017          | 21.34                       |
| 5          | 1.2       | 0.00159 (−6.5%) | 19.99 (−6.3%)               |
| 6          | 1.4       | 0.00156 (−8.2%) | 19.40 (−9.1%)               |

### 5. Conclusions
Through self-made random aggregate program of recycled concrete based on plastic damage constitutive relationship, the large-scale software ABAQUS is used to establish a double interface mesostucture calculation model of recycled concrete. The key performances of the model, such as compression performance, strain peak, stress distribution, damage state, etc., are systematically calculated and analyzed. The conclusions are as follows:

1. Recycled concrete damage occurs in the internal and external interface areas under the uniaxial compression load because there is tensile stress and shear stress concentration in this area.
2. The damage occurred first in the aggregate area of the internal interface. As the load is added, the damage area expands to the old mortar area and the new mortar area until the specimen is destroyed.
3. As the thickness of old hardened mortar increases, the compressive strength and peak strain of recycled concrete specimens continue to decrease. It is recommended that the content of old hardened mortar should be reduced as soon as possible during the processing of recycled aggregates.

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