The Meso-level Numerical Experiment Research of the Mechanics Properties of Recycled Concrete

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***Abstract*— From a mesoscopic view, recycled concrete (RC) can be taken as a multi-phase composition which is consisted of aggregate, mortar and the interface between them. The three-dimensional grading curve of aggregate is determined by referring to the Fuller curve. And with the Monte Carlo method, the meso-sample of RC can be developed randomly. By the gradually mesh generation method, the randomly distributed aggregates, interfaces and mortar are meshed in turn. Finally, with the meso finite element model just generated, when the recycled aggregate (RA) mixing proportion is 0%,40%,70% and 100%，the numerical uniaxial compression fracture experiments of the RC specimen are carried out respectively. And the damage distribution and evolution processes are simulated and tracked. As the simulation results demonstrate, the damage appearance of cylinder specimen belongs to oblique section damage which gradually grows with the increment of displacement. Meanwhile, the damage region spreads to both sides of the oblique section which corresponds to the CT scanning pictures. Observed from the stress-strain diagram of numerical simulation and servo test, as the RA content increases, the peak strength decreases and so does the slope, which means the compression elastic modulus becomes smaller and agrees with the fact that the mixture of RA leads to the softening of inner structure.**

***Index Terms*— Recycled concrete; Meso-level numerical test; Monte Carlo; Graded mesh generation method**

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I. Introduction

Concrete is one of the most widely utilized structural materials, which can usually be attained by mixing cement, sand, gravel and water. With the fast development of construction industry, an increasing number of building rubble and waste are generated every year. But most of them are directly transported to the outskirts or rural areas where they will be disposed by staking or burying without any treatment at all. Thus they caused huge ecological pollution and great attention has been paid to this phenomenon [1-3]. As a result, the reusing of construction waste has become a worldwide focused subject. Recent studies performed by various researching organizations and specialists are mostly independent individual actions lacking of unified test standards and methods[4-11]. Moreover, the experiment achievement is the analysis and description of single experimental phenomenon or inducement, which is short of further theoretical and numerical analysis.

In this paper, the experiment of the meso damage characteristic of concrete is studied by advanced test equipments such as CT scanner and shows the damage appearance under specific loading when the loading and test are underway simultaneously. It not only should be devised carefully but also calls for great effort and huge amount of manual labor. As the concrete belongs to brittle material and the destruction load has a relatively high discreteness which is difficult to control, however, the results are not so satisfactory. In recent years, as the soaring evolvement of computer technology, the improvement of graphic programs, the mesh dissection software as well as the research basing on numerical simulation to study the material impairment progress have grown into hot topics[12,13].

Concrete can be recognized as a multi-phase composition consisted of aggregate, mortar as well as the interface between aggregate and mortar. In order to acquire the internal impairment process and damage appearance of concrete under external load and other factors, it is necessary to set up the finite element model which can presents the micro structure of concrete. Generally, there are two ways in this area. One is the stochastic mechanics character model, which uses the random distribution function of mechanics character to substitute the actual distribution randomness of aggregate. But the variation in micro structure is still a bit bigger. The other is the random aggregate model, which puts aggregate into the concrete specimen randomly and divide the mesh in the sequence of aggregate, interface and slush to establish meso-level finite element model. It can fine the units on the surface of aggregate and make the units in the aggregate sparse by adopting the graduated way to erect the mesh. Consequently the quantity of units will diminish obviously and the inner structure property of concrete can be reflected more accurately. Basing on the developed finite element model, the damage process can be traced and imitated so that the macro performance of concrete can be examined.

This paper is focused on developing meso-level finite element model of recycled concrete. Based on the existed researching findings and the Fuller curve, the constitution of aggregate can be determined. Using the Monte Carlo method (MC) to place the aggregate, the meso sample of RC can be developed randomly and the graded mesh generation of the sample is based on the sequences of aggregate, interface and mortar. Finally, taking advantage of this micro finite element model, the numerical uniaxial compression fracture experiments are carried out on the RC whose recycled aggregate(RA) mixing proportions are 0%,40%,70% and 100% respectively.

II. The Random Fomation Of Aggregate

A. The Grading Theory of Concrete Aggregate

Aggregate is the most important ingredient in concrete, which plays a role as skeleton and filler and can be categorized as the fine aggregate and the coarse aggregate. Generally, the aggregate whose diameter is less than 5mm can be viewed as the fine aggregate, while the rest with a diameter bigger than 5mm belongs to the coarse aggregate. Aggregates can also be classified into low-level gravel(5mm~20mm) and intermediate-level gravel(20mm~40mm), namely the first grading and secondary grading, respectively. The proportion between low-level gravel and intermediate-level gravel in the secondary grading aggregate is 5.5:4.5. The size of aggregates can be expressed by the grading curve or the integral curve which is the function of the average aggregates size and confines the given dimension in a specific granule percentage. The ideal Fuller curve can be showed as the parabola below the fine aggregates grading and given by:

$$P = 100\sqrt{\frac{D}{D_{\max}}} \tag{1}$$

where D represents a given particle size, $D_{\max}$ represents the maximum aggregate grain size, and P denotes the percent of aggregate that is finer than D. Using this method, the designed concrete acquires a high strength, good performance against penetration and the economic of cement. For simplicity, the spherical or elliptical aggregate such as the pebble and gravel are assumed to be spherical. Counting on the Fuller curve, the three dimensional grading curve of the aggregates can be determined. Using this three dimensional grading curve, the placed concrete has an excellent compactness and workability as well as a high strength.

B. The Random Aggregate Method

The distribution of the aggregate granule in the specimens of RC in space is a stochastic process which can be simulated by MC. When the computer simulation is carried out, basic random variables of the random number are a group of variables distributing evenly in the domain of [0, 1] and the probabilistic density function (PDF) with the random variable x expressed as:

$$f(x) = \begin{cases} 1 & x \in [0,1] \\ 0 & x \notin [0,1] \end{cases} \tag{2}$$

where x is a variable distributing uniformly in the domain[0,1]. Inside the structure, the random sample serial $\{x_n\}$of x can be derived, which usually can be called as the random number of x evenly distributing in the domain of [0, 1].

In order to imitate the mathematical model which is close to the real aggregate distribution, these variables should satisfy the following criteria:

- The sphere must distribute randomly in the space defined by the contour of the structure, and the coordinate of the sphere center determines the place of the sphere.
- The sphere center coordinate (X,Y,Z)is assigned by the random numbers in a specific range so that the spatial random distribution of the sphere can be guaranteed.
- These coordinates (X,Y,Z)must fulfill the demand that the distance between two centers should be bigger than the sum of two spherical diameters and their interfaces δ so that the spheres will be independent of each other with no overlapping or intersection, as shown in Fig.1.
- The distance between the spherical centers and every surface of the sample should be greater than the sum of the sphere diameter and the thickness δ of interface in order to make sure that all the generated spheres are within the domain of the sample.

Therefore, the centers of all the aggregates distribute uniformly in the specimen with the Coordinate constraint

$$x_c \in [x_{\min}, x_{\max}],\ y_c \in [y_{\min}, y_{\max}],\ z_c \in [z_{\min}, z_{\max}]$$

.

Therefore,

$$\begin{cases} x_c = x_{\min} + (x_{\max} - x_{\min})x \\ y_c = y_{\min} + (y_{\max} - y_{\min})y \\ z_c = z_{\min} + (z_{\max} - z_{\min})z \end{cases} \tag{3}$$

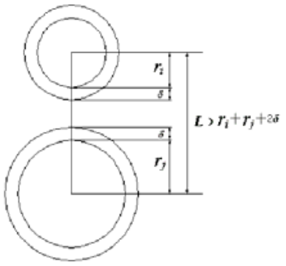


Figure 1. The shortest distance between the aggregates

C. The Calculation of the Aggregate Granule Number

The typical three-dimensional random models of the concrete aggregate consist of sphere aggregate model, ellipsoid aggregate model, rubble aggregate model and so on. And the aggregates can be divided into two kinds, i.e., the natural and recycled aggregates. Here, only sphere aggregate model is investigated. When the sphere aggregate is placed, it should not beyond the placing area. Additionally, it should meet the condition that the aggregates don't cross with each other. The designed mix proportion of water, cement, sand and gravel is 1, 2.50, 3.79 and 7.15, respectively. The aggregate grading is secondary grading with diameters varying from 5mm to 20mm and from 20mm to 40mm. In this paper, the representing particle diameters are 12.5mm and 30mm, respectively. Following the above requirements, the aggregate placement is implemented in the cylinder specimen whose diameter and height is 100mm and 200mm, respectively. The simulation object are the large-sized gravel (20mm~40mm) and intermediate-sized gravel (10mm～20mm). The diameter of aggregate can be determined by the three-dimension Fuller grading function defined as Eq.(1). The corresponding results are listed in Table I.

TABLE I.
THE POSSIBILITY OF AGGREGATE $P(D < D_0)$

D_0(mm)	40	20	5
P(%)	100	70.7	35.4

The aggregates are simplified into two sizes. The average diameter D_1 of aggregates with diameters between 20mm and 40mm is 30mm, while the average diameter D_2 of aggregates whose diameters change from 5mm to 20mm is assumed to be 12.5mm. As shown in Table I, the mass ratio of aggregates with diameters varying from 20mm to 40mm is 29.3% and the mass ratio of aggregates whose diameters range from 5mm to 20mm is 35.4%. The aggregate density is $\gamma_g = 2.8\times10^3$ kg/m^3, the gravel consumption is 1.18×10^3 kg/m^3 and the RA density $\gamma_g = 2.5\times10^3$ kg/m^3. In order to coincide with the actual test method, the aggregate mass varies with the content of RA. The releasing quantities of regenerated coarse aggregate in the RC cylinder are summarized in Table. II.

TABLE II.
THE RELEASING QUANTITY OF REGENERATED COARSE AGGREGATE IN THE RC CYLINDER

Content 0%		Content of RA 40%				Content of RA 70%				Content of RA 100%			
Natural large aggregate	Natural small aggregate	Natural aggregate		RA		Natural aggregate		RA		Natural aggregate		RA	
		Large	Small	Large	Small	Large	Small	Large	Small	Large	Small	Large	Small
13	229	8	137	6	102	4	68	10	179	0	0	15	256

D. The Releasing Rule and Its Validity

The releasing rule is placing larger aggregate first, and then the smaller ones. Meanwhile, all the RA should be placed first, and then the natural aggregate. The process will not be finished until all the previously calculated aggregates are correctly placed.

If the aggregate is sphere, the distance between any of the two sphere centers should larger than their radius summation. In other words, the following constraint must be satisfied:

$$d_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2 + (z_i - z_j)^2} > r_i + r_j \tag{4}$$

where d_{ij} represents the distance between the newly generated aggregate i and all the previously generated aggregate j (j=1, 2, …, i-1). Finally, the randomly generated aggregate distribution graph is shown in Fig.2.

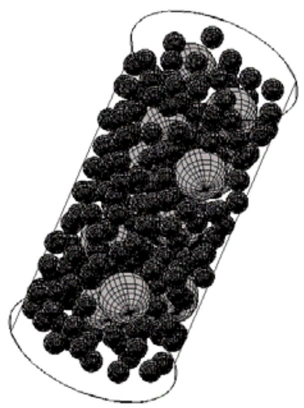
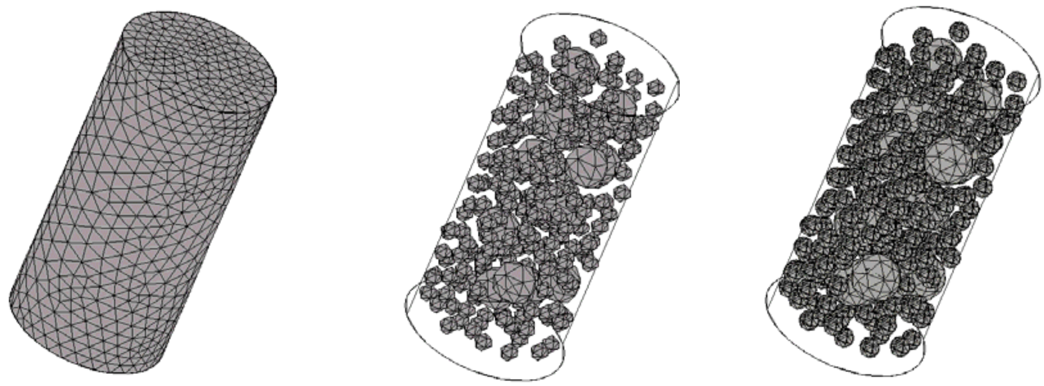


Figure 2. The randomly generated aggregate distribution graph

III. THE MESH DISSECTION OF DIFFERENT MATERIALS OF RC

The contour of RC aggregates is irregular, which may be spherical, ellipse or angular. The best choice is to adopt tetrahedron element using the Delaunay triangular dissection in face with such abnormal contour. When dissecting the spherical or elliptical aggregate whose surface is comparatively smooth, the slicing disposal method is employed, where two longitudes match together as well as miss a circle (360°) are pre generated. With that, the points are dispensed uniformly along the two longitudes. Next, the Delaunay triangular elements can be produced by means of topology from these points to both sides. On this basis, with the graduated mapping technology (commonly graduated value ranging from 1.5 to 2.0), the surface elements are topologied internally to form the Delaunay tetrahedron elements. Finally, the face elements are eliminated and so do those unnecessary nodes.



(a) mortar mesh cylinder (b) mesh cylinder aggregate (c) mesh cylinder interface

Figure3. The mesh dissection of three dimensional random aggregate (sphere aggregate)

Introducing the graduated mesh dissection method to divide the element, the element number is cut down in the precondition so that the calculating accuracy is free from its interference. The advantage of this dissection method is that the divided meshes are dense near the surface and interface of the sample while it is sparse in other areas. Usually, the interface thickness is 1/20 of the particle diameter. Taking the RC specimen for example, when the RA proportion is 70%, the mesh dissection is exhibited in Fig.3, making use of the mentioned method. The mortar matrix element is in Fig.3 (a), the aggregate element is shown in Fig. 3(b) and the interface element is described in Fig.3(c). To the end, the micro finite element mesh of the cylinder specimen contains 68318 elements with 12613 nodes.

IV. The Stablishment Of The Three Dimensional Meso-Level Finite Element Modole Of RC

The three-dimensional meso-level finite element model of RC is the key point of numerical simulation, and it is directly related to the accuracy. Hence, the established model should truly reflect the actual condition of the structure as much as possible.

A. The Constitutive Selection of Each Ingredient of RC

On the assumption that each ingredient of the concrete is an isotropic material, the aggregate, interface and mortar are all assumed to be described by the linear Drucker-Prager[8] elastic-plastic model. C and ϕ represent the cohesion and the friction angle, respectively. Their strengthening laws depend on the relation curve that illustrates how α and $\overline{\sigma}$ vary with equivalent plastic strain. And their initial values can be judged from formula:

$$\alpha = \frac{\sin\varphi}{\sqrt{9-3\sin^2\varphi}}, \overline{\sigma} = c\sqrt{3(1-12\alpha^2)} \qquad (5)$$

The relationship curves of $\overline{\sigma}$ of mortar, natural aggregate, RA and interface are all presented in Fig.4, which alter with the change of plastic strain. For α, its relationship curve belongs to the ideal plastic one.

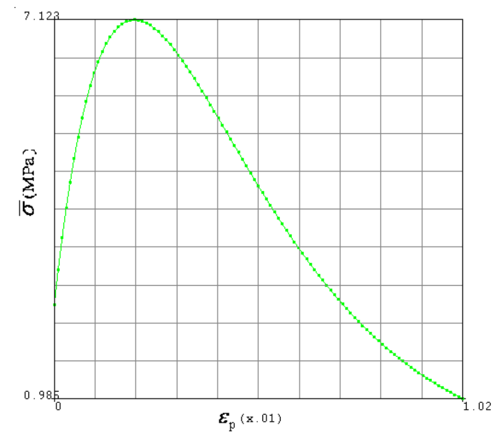


Figure 4. The equivalent stress-equivalent plastic strain relationship of mortar

Moreover, as mortar, RA and interface are all elastic materials prone to be damaged; the smeared crack model is adopted to simulate the after-cracking behavior when the destruction appears. The cracking stresses of mortar, RA, natural aggregate interface and RA interface are 2.5MPa, 2.8MPa, 2.0MPa and 1.2MPa , respectively.

The softening moduli of mortar, RA and aggregate interface are set as 5GPa, 6GPa, 5GPa, respectively. In addition, the residual stresses of mortar, RA, natural aggregate and RA interface are determined as 1.2MPa, 1MPa, 0.6MPa, 0.4MPa, respectively. Finally, the equivalent stress-equivalent plastic strain relationship of natural aggregate, natural aggregate interface, RA as well as RA interface is shown in Fig.5~Fig.8, respectively.

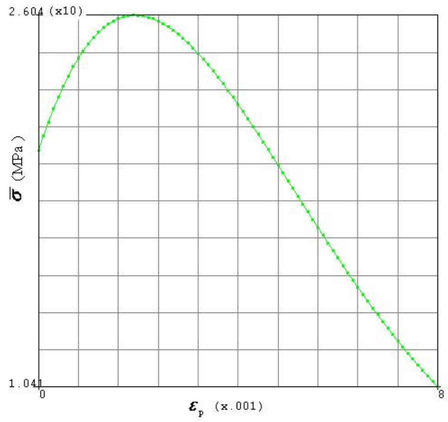


Figure 5. The equivalent stress-equivalent plastic strain relationship of natural aggregate

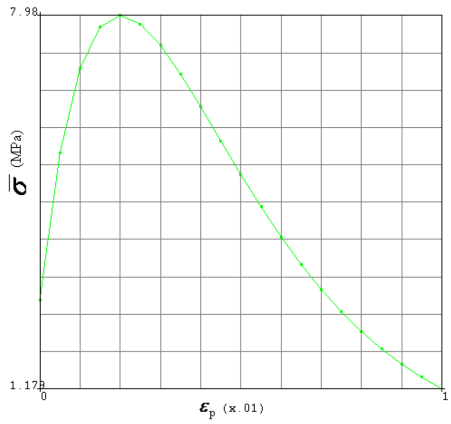


Figure 6. The equivalent stress-equivalent plastic strain relationship of RA

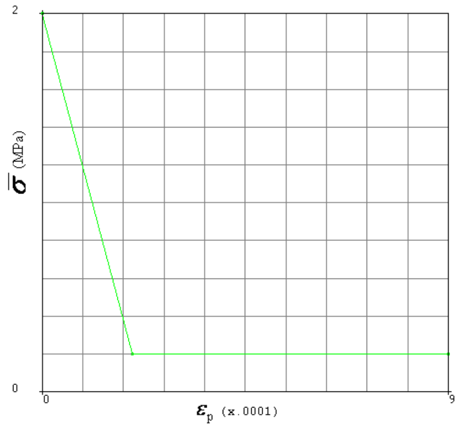


Figure7. The equivalent stress-equivalent plastic strain relationship of natural aggregate interface

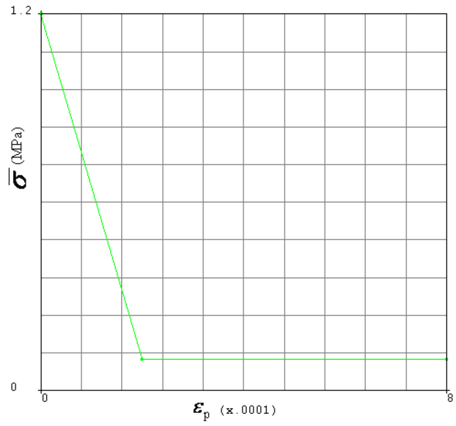
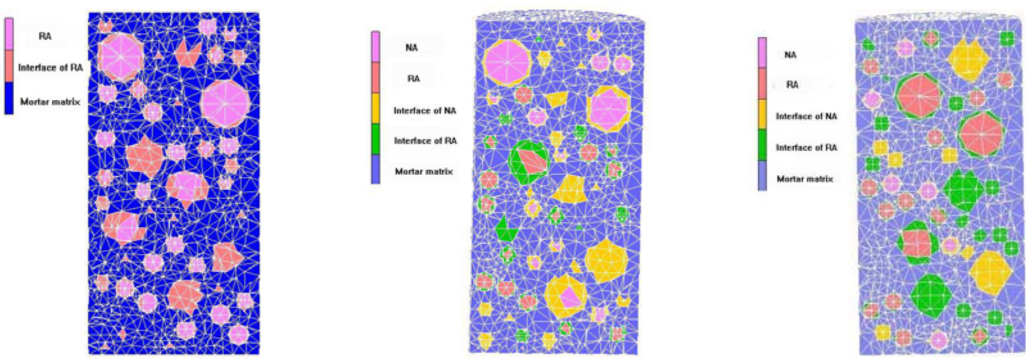


Figure 8. The equivalent stress-equivalent plastic strain relationship of RA interface

B. The Finite Element Information Distribution of RC

To investigate the effect of RA's ratio, the contents of RA are assumed as 0%(100%),40%,70%. According to their constitution information, the structural materials are added to their own elements. When selecting the specimen partly, we can see the element distribution information of each material, which is shown in Fig.9.

From Fig.9, the distribution state of natural aggregate, RA, RA interface, natural aggregate interface and mortar in the structure can be clearly seen. Although the aggregate distribution varies, the same structural face is situated at the same place which manifests the randomness of aggregate distribution.



(a) RA content 100% (b) RA content 40% (c) RA content 70%

Figure 9. The material information of RC cylinder specimen

C. The Solution of Finite Element Model

As the problem concerns with the nonlinear property of material, it should be handled with the incremental method. Taking the stability of the solution into consideration, the incremental iteration format is used, so as to avoid the divergence of the solution. Generally, the methods to solve the nonlinear equation set are Newton—Raphson method and the arc-length method[9-10]. As the latter has a trait of tracing the descent segment (softening segment), it is finally employed in this paper.

Ⅴ THE NUMERICAL SIMULATION OF THE UNIAXIAL COMPRESSION DAMAGE PROCESS AND RESULT ANALYSIS

Studying the damage of RC from meso-level point, it can be viewed as a composition consisted of natural aggregate, RA, mortar and the interface between mortar and aggregate. Therefore, the damage research of RC is the study of destruction of materials with alien characteristics. As the RA content changes, mortar and interface are able to reveal their own damage traits under the influence of eternal force which is quite important for the study.

A. *Model Parameter*

Lying on the built three-dimensional meso-level finite element model, the uniaxial compression numerical test is carried out. Each material is endowed with its own property and constitutive model. The material parameters of the model are listed in Table. III. The simulation is worked out for cylinder specimen whose diameter is 100mm, height is 200mm. With the meso-level finite element model of RA, the uniaxial compression test is simulated and the RA contents are 0%, 40%, 70% and 100%. The loading is gradually applied by displacement load.

TABLE III.
THE PARAMETERS OF EACH INGREDIENT OF CONCRETE

Material	Elastic modulus(MPa)	Poisson rtion	Cohesive (MPa)	Friction angle (°)
Natural aggregate	52000	0.230	20.0	60
RA	46000	0.167	5.0	55
Slush	26700	0.200	4.0	50
Natural aggregate interface	20000	0.167	2.0	45
RA interface	15000	0.167	1.2	45

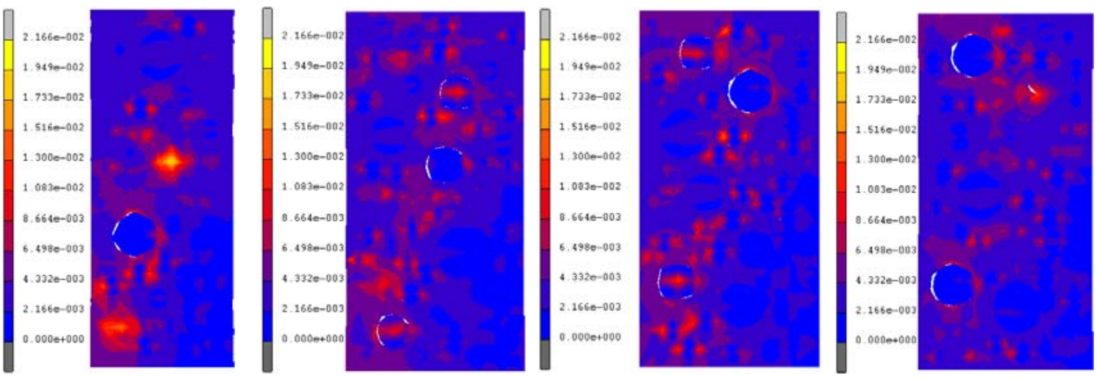
B. Numerical Simulation Result and Analysis

Through the four work cases, in which the aggregate contents are 0%,40%,70%和 100%, the finite element simulation is carried through and the following results are achieved:

(1)The results of uniaxial compression damage process of cylindrical specimen and the corresponding analysis

The central longitudinal sections include four samples, i.e., y=20mm, 40mm, 60mm and 70mm. When the displacement is u_z=4mm, the cracking strain distributions are presented in Fig.10. From 10(a), it can be seen that the strain at the bottom is comparatively large, which on the upper part is relatively small. The result in Fig.10 (d) is against with that in Fig. 10(a). As the whole effects shown from Fig.10 (a) to Fig. 10(d), the failure mode belongs to inclined section failure. And judging from the cracking stress distributions of longitudinal section in the middle two images, the same conclusion can be derived, which verifies the same discipline obtained in the laboratory.

When the central longitudinal section is y=50mm and the displacements are u_z=1.15mm, 1.55mm, 1.95mm, 2.19mm, 3.12mm, 3.67mm, 3.87mm and 4mm, respectively, the variations of cracking strain distribution is in Fig.11. Obviously, this series of pictures demonstrate that with the increasing of displacement, the damage zone expands from the inclined section towards its both sides, which agrees with the real situation.



(a) y=20mm (b) y=40mm (c) y=60mm (d) y=70mm
Figure 10. The cracking distribution picture of longitudinal section when the displacement load is u_z=4mm

The CT scanning is utilized after the cylinder specimen has been destroyed. The scanning spacing is 2mm and the image of every cross-section is taken one after another from bottom to top for only once, as shown in Fig.12. In these pictures, it can be detected that the cracks appear only at the left corner in Fig.12(a), while the rest part is intact. With the sections moving upward, the area where the cracks emerge mobilizes from the top left corner to the low right corner. In Fig.12 (h), the appearance of cracks only exists in the low right corner, while there are no cracks in other region. Apparently, the failure mode coincides with the calculation results.

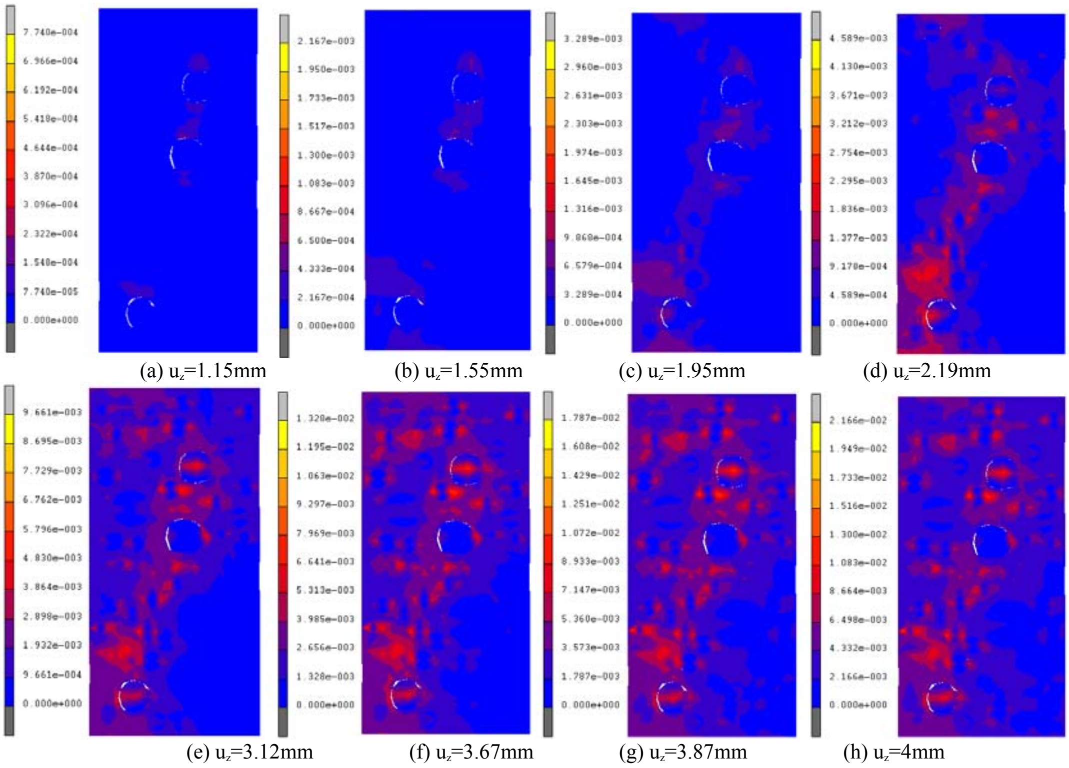


Figure 11. The variation picture of the cracking strain distribution of the middle longitudinal section

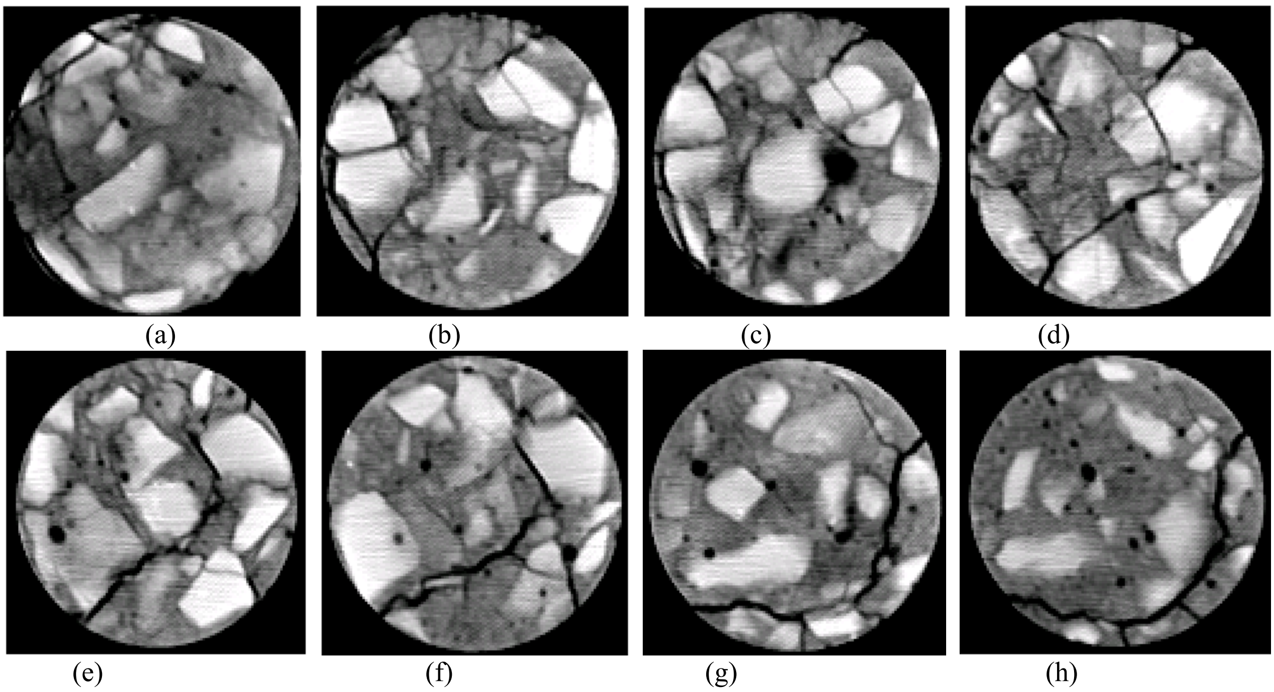


Figure 12. The cross-section damage pictures of cylinder specimen

(2)The stress-strain relationship abstraction and analysis of uniaxial compression damage process

The compressive stresses are collected from the nodes in the middle of the specimen for each simulated load application. Then their average is treated as the compression load in each loading step. The corresponding compression strain is the quotient of the displacement load with the specimen height. Relying on these data, the stress-strain curve can be drawn. The stress-strain curve of specimen of C30 RC for both numerical simulation and servo test is shown in Fig.13. It can be seen that the peak strength of the experiment is a little larger than the calculated one by 5%, which roughly meets with the numerical experiment. As the content of RA increases, the uniaxial compression strength drops as well as the elastic modulus. This can be attributed to the relatively more internal flaws in RC. There is a certain distance between the specimen and the ball, which leads to there is an initial displacement load stage that the specimen is not compressed at the beginning of test, It can also be used to explain why there is a slow slop in the initial part of the stress-strain curve.

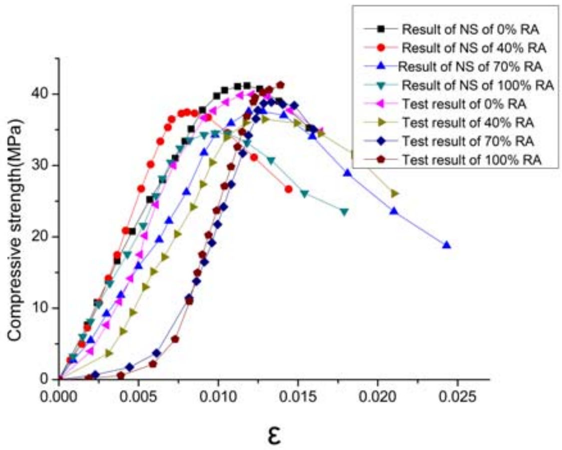


Figure 13. The compress stress-strain relationship curve for recycle concrete cylinder specimen

Ⅵ. Conclusions

The paper establishes on the mesostruture of RC and simplifies the RC into a composition that is consisted of slush, natural aggregate, RA and the interfaces between them. Considering the mix percentage of RA, the test concrete grading and the dimension of specimen, the natural aggregate and RA are generated randomly. The graduated mesh dissection method is adopted to divide the aggregate, so as to reduce the mummers of element and achieve the goal that the meso-level three -dimensional finite element simulation can be done with by one computer without any expense of accuracy.

The uniaixal compressive numerical test is carried out relying on the established three dimensional meso finite element model. And the distribution and evolvement of the impairment are tracked and simulated. Through the comparison between the numerical simulation and test results of cylindrical specimen with RA contents 0%, 40%, 70% and 100%, the following conclusions can be drawn:

- The failure mode of the cylinder specimen belongs to the inclined section damage which increases as the displacement load grows. The damage zone develops from inclined section to its both sides, which meets with the actual cases.
- The peak strength is smaller than the cube strength, which represents the size effect and well corresponds to the experiment.
- With increasing content of RA, the peak strength declines and so does the slope of the ascending part in the stress-strain curve, which verifies a diminished elastic modulus.
- The numerical stress-strain curve is not able to reflect the slowly ascending initial segment in real situation.

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