The Dynamic Mechanics Behavior on Triaxial Compression of the Recycled Aggregate Concrete

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Abstract. The tests under triaxial compression states were conducted on recycled aggregate concrete (RAC) by different stress ratios (-0.1: -0.1: -1; -0.1: -0.25: -1; -0.1: -0.5: -1; -0.1: -0.75: -1; -0.1: -1: -1) at the strain rates of 10-5/s, 10-4/s, 10-3/s, and 10-2/s. This study was accomplished in the servo-hydraulic multi-axial testing system. The experimental phenomena and failure modes of recycled aggregate concrete under triaxial compression are described, the results of triaxial compressive strength of recycled aggregate concrete are presented, the effects of the strain rate and stress ratio on the triaxial compressive strength of recycled aggregate concrete are studied. This paper built a new dynamic strength criterion. The strength criterion describes the characteristics of structural RAC at different stress ratios and strain rates. The feature of the model is that it can consider the influence of strain rates.

Keywords: recycled aggregate concrete (RAC); triaxial compression; stress ratios; strain rates; failure criterion; octahedral stress space

1. General Instructions
Recycled aggregate concrete refers to the waste concrete that has been crushed, sieved and cleaned, and then replaced aggregate partially or completely with recycled aggregates. It can effectively solve the problem of construction waste and realize the recycling of building materials, which is good for protecting environment and has a good application prospect. In recent years, countries around the world have attached great importance to the research and application of recycled aggregate concrete technology. Domestic and foreign scholars have carried out lots of experiments and theoretical studies on RAC. Padmini et al. (2009) studied the influence of recycled aggregate on the physical properties of the original concrete. Vieira et al. (2011) studied the mechanical properties of RAC after high temperature. Somna et al. (2014) investigated the effect of the water-binder ratio on mechanical properties of RAC, the results show that the influence of water-binder ratio on recycled aggregate concrete and natural concrete is basically same. Abdollahzadeh (2016) put forwards 20 models to predict compressive strength of RAC containing silica fume. Liang (2017) studied the influence of temperature on the strength and stress-strain curve of RAC with different replacement rates. The experimental results show that the compressive strength, tensile strength, elastic modulus of RAC decrease with the temperature improving.

The research of RAC under dynamic triaxial compressive stress states doesn’t appear in recent years. The test date of RAC under complex stress states is still limited, so it is difficult to analyze the dynamic properties of RAC and establish the corresponding dynamic failure criterion. It is necessary...
to carry on an intensive studying on the failure characteristics of recycled aggregate concrete under the dynamic loadings. When the effect of the strain rate is taken into effect, it is more reasonably to capture the mechanical behaviors of RAC structures subjected to earthquake ground motions. Investigation on the properties of RAC under different strain rates can provide the basis for the seismic design of concrete structures.

In this paper, a series of multi-axial dynamic tests on RAC are carried out by the triaxial static and dynamic testing machine at the Dalian University of Technology. The tests include several stress states: uniaxial compression, uniaxial tension, triaxial proportional compression. The stress ratios are -0.1: -0.1: -1; -0.1: -0.25: -1; -0.1: -0.5: -1; -0.1: -0.75: -1; -0.1: -1: -1. The strain rates are $10^{-5}$/s, $10^{-4}$/s, $10^{-3}$/s, and $10^{-2}$/s. In order to fit the test data, a new failure criterion has been built under complex stress states, which is based on the analyze of experimental phenomena and data.

2. Materials and Experimental Procedures

2.1. Materials and Specimens

In this study, there are three cementitious materials, namely, P.I.42.5R Portland cement, one-level fly ash and silica fume. The compressive strength of P.I.42.5R Portland cement with the age of 28 days is higher than 42.5MPa. The coarse aggregates were composed of the natural and recycled aggregate with a maximum size of less than 20 mm. Also, the nature aggregate was the natural crushed stone, the recycled aggregate was from waste concrete. The fine aggregate was from a natural river sand and had a fineness modulus of 2.7. The tap-water was used to make concrete samples. Water reducer is “high-performance polycarboxylate-based superplasticizer”. “Structural RAC” is the theme in this paper and therefore the replacement percentage of RCA in this paper are 50%, as per the Chinese code for the design of RAC structures (LSCGPRC, 2011). The concrete grade is C40 in this test. Table 1 shows the concrete mixture ratio by weight of the mixture and the major parameters of RAC.

| Type of RAC                          | RAC40-50% |
|-------------------------------------|-----------|
| Water (kg/m)                        | 170       |
| Cement (kg/m)                       | 325       |
| Fly ash (kg/m$^3$)                  | 120       |
| Silica fume (kg/m)                  | 25        |
| Fine aggregate (kg/m$^3$)           | 800       |
| Natural coarse aggregate (kg/m$^3$) | 470       |
| Recycled coarse aggregate (kg/m$^3$)| 470       |
| Super-plasticizer (kg/m$^3$)        | 7.8       |
| Compressive strength ($f_{cu}$/MPa) | 52.01     |

*The replacement percentage of recycled coarse aggregate for RAC-50 are 50%. The $f_{cu}$ is the uniaxial compressive strength of 150mm×150mm×150mm cubic RAC specimens.

2.2. Process of Preparing Specimens

Firstly, the cement, fly ash and silica fume were weighed and mixed for about 1 minute before the fine aggregates were added; secondly, the water and water reducer were slowly added and mixed for approximately 1 minute; thirdly, the coarse aggregates were added in this mixer and mixed for 3 minutes; Lastly, these elements were mixed for additional 1 minute. The concrete mixtures were put in plastic molds and vibrated to be dense and solid by vibrating table. The specimens were removed from molds after 24 hours. Then the specimens were put into a certain humidity condition with the temperature of 20±3°C and the humidity of 95% for 28 days. Finally, the specimens were cured in the
environment with a natural temperature. The natural curing of the specimens tested was about three months.

The shape and size of specimens under uniaxial tensile stress state are shown in Figs. 1-2. The uniaxial compressive specimens were used for RAC40-50% with size 100mm×100mm×100mm. Due to the friction between the loading head and the specimen, the concrete in the middle of the specimen is restrained, so that the value of concrete strength is larger than the actual value. In order to eliminate the deviation, this test used two-layer polyethylene plastic membrane with Mobil-lubricants to achieve this goal. Similarly, Friction-reducing pads are added to the sides of the tensile specimen.

![Figure 1. The size of specimen under tensile state(mm)](image1)

![Figure 2. Compressive loading state](image2)
2.3. Apparatus and Testing Procedures

The uniaxial tension, uniaxial compression and triaxial compression tests under substitution percentage of 50% for RAC at different stress ratios and strain ratios were carried out at Dalian University of Technology. The advantage of this test machine is able to develop forces independently in three directions and ensure uniform dimensions for cubic specimens. This test machine can carry on dynamic tests with all kinds of stress states and control proportional loading. The strain rate that this machine can control is around $10^{-6} \text{/s} \sim 10^{-2} \text{/s}$, which can satisfy the scope of strain rate during the simulated earthquake.

As shown in Fig. 2, by embedded blots at the end of the specimen, tensile stress was transferred to the specimen. In order to reduce stress concentration that the bolts bring about, steel bars with diameter of 8 mm were welded in the bottom of bolts. The connections between compressive specimen and test machine are shown in Fig. 3. The principal stresses are expressed as $\sigma_1 \geq \sigma_2 \geq \sigma_3$. In this paper, compression is defined as negative. For each given stress ratio, a minimum amount of three specimens were tested. During this process, if some results show obvious deviation, these data must be discarded.

3. Test Results and Discussions

Note: The $\sigma_3 / f_c$ is the ratio of dynamic triaxial compressive strength to static uniaxial compressive strength

The dynamic triaxial compressive strengths of RAC40-50% under different strain rates and different stress ratios are given in Tables 2.
The failure patterns of specimens after dynamic tests are shown in Fig. 4. From the Fig. 4, it can be seen that the failure modes of concrete have not been changed because of the increased impact of the
recycled coarse aggregate on RAC. It is the same to the failure patterns of common concrete (Gabet 2007, Fujikake and Mori 2000). It is observed that the failure modes are related to the stress ratios but are irrelevant to the strain rates under triaxial compression states. However, with the increasing of strain rates, the percentages of broken coarse aggregates on the fracture surface were raised, and the cracking sound at the time of failure was much shorter and louder. Also, the number of cracks is less when the strain rate is on the increase. From the Table 2, the $\sigma_{3f}$ have growth trend with the strain-rate varying from $10^{-5}/s$ to $10^{-2}/s$. For example, with the strain rates varying from $10^{-5}/s$ to $10^{-2}/s$, the $\sigma_{3f}$ of RAC40-50% is 3.87, 4.34, 4.67, and 4.83 respectively when $\alpha = -0.1$: -0.5: -1. The failure characteristics of RAC and ordinary concrete is similar. The failure modes are parallel plate-type fragments when $\alpha = -0.1$: -0.1: -1. The failure modes are slant-shear shapes when $\alpha = -0.1$: -0.25: -1, -0.1: -0.5:1, -0.1: -0.75: -1. It can be seen that the angle of cracks with the direction of $\sigma_3$ is about $20^\circ$ -$30^\circ$ when the failure modes are shear-type. The failure modes are extrusion flow when $\alpha = -0.1$: -1: -1. It is observed that the failure modes are greatly affected by stress ratios. It can be seen that with the increasing of stress ratios, the triaxial compressive strength first increases and then decreases. The influence of stress ratios on the relative value of strength changes approximately by a parabolic-like curve. In all strain rates, the triaxial stress ratios corresponding to the maximum of $\sigma_{3f}$ are 0.5-0.75, mostly appearing at 0.5 or 0.75. The change of $\sigma_{3f}$ mainly depends on the stress ratios at the same substitution percentage of RCA and strain rate.

The mentioned-above failure modes indicate that the reason for change of failure modes is providing confinement stress along the directions of $\sigma_1$ and $\sigma_2$. Although the modes of triaxial failure are not same, the reason of the failure for RAC is that the ultimate tensile strain is smaller than the splitting tensile strain along the unloading or less stress planes (He and Zhang 2014).

![Fig. 4 Failure modes](image1)

![Fig. 5. Effect of stress ratios on triaxial compressive strength of RAC under different strain-rates](image2)
4. Failure Criterion

According to the strength characteristics of test results in Table 2 and theory analysis for RAC, the present paper proposes a new failure criterion. The tensile meridian and compressive meridian are proposed respectively as follow:

\[
\sigma_0^R = a_1 (\tau_{01}^R)^2 + \lambda_1 \tau_{01}^R + c_1 \quad (\theta = 0^\circ)
\]
\[
\sigma_0^R = a_2 (\tau_{0c}^R)^2 + \lambda_2 \tau_{0c}^R + c_2 \quad (\theta = 60^\circ)
\]

(a1, \(\lambda_1\), c1, a2, \(\lambda_2\), c2 are parameters, these parameters can be determined through the test data in Table 2. The geometry and physical features of the concrete failure enveloped surface that has now been agreed. \(R_{oct}\) is octahedral normal stress; \(R_{0t}\) and \(R_{0c}\) are octahedral shear stress. \(f_c^R\) is the uniaxial compressive strength. These parameters of tensile meridian and compressive meridian are gained from the features of the failure enveloped surface as follows:

\[
\sigma_{oct}^R = \frac{\sigma_{III}^R + \sigma_{2I}^R + \sigma_{3I}^R}{3}
\]
\[
\tau_{oct}^R = \frac{\sqrt{(\sigma_{III}^R - \sigma_{2I}^R)^2 + (\sigma_{2I}^R - \sigma_{3I}^R)^2 + (\sigma_{3I}^R - \sigma_{III}^R)^2}}{3}
\]
\[
\sigma_0^R = \frac{\sigma_{oct}^R}{f_c^R} \tau_0^R = \frac{\tau_{oct}^R}{f_c^R}
\]

Where \(\sigma_{oct}^R\) is octahedral normal stress; \(\tau_{01}^R\) and \(\tau_{0c}^R\) are octahedral shear stress. \(f_c^R\) is the uniaxial compressive strength. These parameters of tensile meridian and compressive meridian are gained from the features of the failure enveloped surface as follows:

\[
c_1 = c_2 = \frac{\sigma_{III}^R}{f_c^R} = \frac{\sigma_{II}^R \times \eta^R}{f_c^R}
\]

The tensile–compressive meridians and hydrostatic stress axis gather at a point under triaxial equal tensile force, the value of c is the ratios of the triaxial equal tensile strength to uniaxial compressive strength at the same strain rate; in other words, the values of crossing point coordinates between failure enveloped surface or tensile–compressive meridians and hydrostatic-pressure axis; \(\sigma_{II}^R\) and \(\sigma_{III}^R\) are the strength under uniaxial and triaxial tension respectively; \(\eta^R\) is proportional coefficient of \(\sigma_{II}^R\) and \(\sigma_{III}^R\).

\[
\lim_{\xi^R \to 0} \frac{\gamma_{R}^I}{\gamma_{c}^R} \Rightarrow \frac{\lambda_2}{\lambda_1}
\]

When the hydrostatic stress tends to zero, the deviatoric plane is approximately triangle.

\[
\lim_{\xi^R \to -\infty} \frac{\gamma_{R}^I}{\gamma_{c}^R} = 1 \Rightarrow a_1 = a_2
\]

On the deviatoric plane, the closed curve has characteristic of three-fold symmetry. When the hydrostatic stress or the octahedral normal stress keeps reducing, its shape transforms from an approximate triangle to a circle (\(\gamma_{c}^R / \gamma_{c}^R = 1\)).

Eq. (1) can be expressed by another form:

\[
\sigma_0^R = a (\tau_{0}^R)^2 + \lambda \tau_{0}^R + c \quad (0^\circ \leq \theta \leq 60^\circ)
\]
By repeated trial calculation of strength values under all kinds of stress ratios, the equation of the deviatoric plane can be expressed as the following form:

\[ \lambda = \lambda_1 (\cos 1.5\theta)^{\alpha} + \lambda_2 (\sin 1.5\theta)^{\beta} \quad (0^\circ \leq \theta \leq 60^\circ) \]  

(9)

Where \( a_1, \lambda_1, c_1, a_2, \lambda_2, c_2 \) are parameters in the failure criterion, calculated by the least square method of experimental results in Table 2 to Eq. (1), and four different stress states are required to determine these four parameters. This paper provided the data related to four different stress states: uniaxial tension (\( \theta = 0^\circ \), \( f_t \)); uniaxial compression (\( \theta = 60^\circ \), \( f_c \)); biaxial equal compression (\( \sigma_1 = \sigma_2 \), \( \theta = 0^\circ \), \( f_{cc} \)); and triaxial (\( \sigma_1 > \sigma_2 > \sigma_3 \), \( \theta = 0^\circ \), or \( \sigma_1 > \sigma_3 = \sigma_2 , \theta = 0^\circ \)). The calculated results in terms of the six parameters \( a, \lambda_1, c, \lambda_2, \alpha \) and \( \beta \) are given in Table 3.

Fig. 6 offers the contrast of Eqs. (8) - (9) with test data, the results show that the dynamic strength criterion accords with test data, which provide references for engineering applications. It can be concluded from Fig. 6 that the model for RAC under triaxial compression, has good accuracy and applicability.

The relationship between parameters and strain rates was analyzed by regression analysis.

\[ X = m + n \log\left( \frac{\xi}{\xi_s} \right) \]  

(10)

Where X represents parameters in Eq. (8-9), \( \xi \) is the strain rate of RAC; \( \xi_s \) is the quasi static strain rate of RAC.

The value of m and n are shown in table 4.

### Table 3. Failure criterion parameters of RAC under different strain rates

| Kinds of RAC | Strain rates | a    | \( \lambda_1 \) | \( \lambda_2 \) | c    | \( \alpha \) | \( \beta \) |
|--------------|--------------|------|-----------------|----------------|------|---------------|------------|
| RAC40-50%    | 10\(^3\)/s   | 0.1623 | -1.4743        | -0.8740        | -0.1154 | 1.1680        | 2          |
|              | 10\(^4\)/s   | 0.2806 | -1.3052        | -0.6650        | -0.1061 | 1.1310        | 2          |
|              | 10\(^3\)/s   | 0.1716 | -1.4795        | -0.8180        | -0.1363 | 1.0700        | 2          |
|              | 10\(^2\)/s   | 0.2946 | -1.3711        | -0.6090        | -0.1167 | 1.0220        | 2          |

### Table 4. Relationship between strain-rate and value of parameters in failure criterion

| Parameters | m     | n     |
|------------|-------|-------|
| \( \lambda_1 \) | 0.1841 | 0.02879 |
| \( \lambda_2 \) | -0.8378 | 0.0642 |
| c          | -0.1135 | -0.00341 |
| a          | 0.1841  | 0.02879 |
| \( \alpha \) | 1.173  | -0.0499 |
5. Conclusions

- The corresponding $f_c$ is lower than the triaxial $\sigma_3$ at all kinds of the stress ratios and strain rates for RAC40-50%. The compressive strength depends on the strain rates and the stress ratios. Although recycled coarse aggregate was added on RAC, the failure mode of concrete does not been changed. The failure modes of RAC under triaxial compression are parallel plate-type, slant-shear shapes and extrusion-flow.

- The change of the triaxial compressive strength increases at first and then decreases with the increasing of stress ratios. The influence of stress ratios on the relative value of strength changes approximately by a parabolic-like curve. When the value of $\sigma_2/\sigma_3$ is between 0.5~0.75, $\sigma_3/f_c$ obtains the maximum value.

- A dynamic failure criterion of RAC under triaxial stress states is established, which introduces strain ratio as a variable.

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