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Strength criterion of plain recycled aggregate concrete under biaxial compression

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Abstract. This paper presents results of biaxial compressive tests and strength criterion on two replacement percentages of recycled coarse aggregate (RPRCA) by mass for plain structural recycled aggregate concrete (RAC) at all kinds of stress ratios. The failure mode characteristic of specimens and the direction of the cracks were observed and described. The two principally static strengths in the corresponding stress state were measured. The influence of the stress ratios on the biaxial strengths of RAC was also analyzed. The experimental results showed that the ratios of the biaxial compressive strength σ_{3f} to the corresponding uniaxial compressive strength f_c for the two RAC are higher than that of the conventional concrete (CC), and dependent on the replacement percentages of recycled coarse aggregate, stress states and stress ratios; however, the differences of tensile-compressive ratios for the two RAC and CC are smaller. On this basis, a new failure criterion with the stress ratios is proposed for plain RAC under biaxial compressive stress states. It provides the experimental and theoretical foundations for strength analysis of RAC structures subject to complex loads.

Keywords: recycled aggregate concrete (RAC); replacement percentages of recycled coarse aggregate by mass; stress ratios; biaxial compressive strengths; failure criterion

1. Introduction

Concrete has been the leading construction material for nearly a century. In recent years, recycled aggregate concrete (RAC) is becoming an attractive alternative to the conventional concrete (CC) that contain natural aggregates. The RAC is generally defined as concrete by adding recycled aggregate during the preparation process; but, recycled fine aggregate isn't generally been contained in RAC. So, up to today, many researchers have paid much attention to RAC worldwide. But, most researches (Du *et al*. 2010, Poon *et al*. 2004, Tam *et al*. 2005) have focused on the basic behavior of RAC such as micro-and meso-structure, mixture ratio, durability, shrinkage and

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strengths; however, as for the study of strength of RAC, those under uniaxial stress states were done. Du *et al*. (2010) reported that the micro-hardness of recycled coarse aggregate (RCA) was much higher than that of the interfacial transition zones (ITZs) in the RAC, and the micro-hardness of the interface between the RCA and the new mortar matrix was the lowest. Poon *et al*. (2004) investigated the effect of microstructure of ITZ on the compressive strength of RAC. Their scanning electron microscopy (SEM) observations revealed that the aggregate–cement matrix interfacial zone of RAC consisted mainly of loose and porous hydrates whereas the aggregate–cement matrix interfacial zone of conventional concrete consisted mainly of dense hydrates. Tam *et al*. (2005) found that the microstructure of RAC was much more complicated than that of the conventional concrete. RAC possessed two ITZs, one is between the RCA and new mortar matrix, and the other is between the RCA and the old mortar attached (old ITZ). The old mortar of the RCA formed the weak link in RAC, which was composed of many porosity and cracks. The slump flow decreased for 70% and 100% RCA. In particular, the significant reduction in slump flow occurred for 100% RCA. This is in contrast with the slump flow results obtained for 30% and 50% RCA (Tam *et al*. 2005). The substantial decrease in slump flow at 100% RCA is mostly due to the increased amount of fine aggregate that caused to decrease the free water content in SCC mix (Safiuddin *et al*. 2011). Thomas's *et al*. (2013) experimental results showed that at 28 days, the results show that the use of 20% RA produces no significant changes with respect to the CC. Where the substitution is 100%, there is a significant loss of compressive strength and to ensure similar levels of strength, it is necessary to reduce the w/c ratio by 0.05. After 180 days, it is found that the difference between the compressive strength of the CC and the RAC is higher for stronger concretes (Thomas *et al*. 2013). Hansen and Narud (1983) found that the compressive strength of recycled concrete is strongly correlated with the water-cement ratio of the original concrete if other factors are kept the same. When the water-cement ratio of the original concrete is the same or lower than that of the recycled concrete, the new strength will be as good as or better than the original strength, and vice versa. Compressive strength decreased in both control concrete and concrete with waste concrete aggregates (WCAs) in parallel to w/c ratio. However, compressive strength decreased in proportion to low w/c ratio in concrete with WCAs(Topçu and Sngel 2004). Fathifazl *et al.* (2011) stated that at the age of 224 days, the shrinkage strain in mix EM was 7% and in mix CM 26% higher than in mix CL. Gonzalez-Fonteboa *et al*. (2012) stated that with the strength values for the two loading rates the ratios of strength at low loading rate over strength at standard loading rate were calculated. The results showed that both in compression tests and in tensile test these ratios are very similar in conventional and recycled concretes. This result again confirms that the behaviour of recycled concretes under this type of loading is similar to the behaviour of conventional concretes. Corinaldesi's (2010) tesults obtained showed that structural concrete up to C32/40 strength class can be manufactured by replacing 30% virgin aggregate with recycled-concrete aggregate. Moreover, a correlation between elastic modulus and compressive strength of recycled-aggregate concrete was found showing that 15% lower elastic modulus is achieved by using 30% recycled aggregates. The addition of superplasticizers can compensate for loss of compressive and splitting tensile strength resulting from the introduction of RA, but they are less effective than in NAC. The use of a high-performance superplasticizer is more time-effective in achieving the desired workability and strength when varying the incorporation rate of RA (Matias *et al*. 2013). Density declines approximately linearly with rising replacement rates, by around 7% in concrete made with 100% recycled aggregate (Martínez-Lage *et al*. 2012). The general trends (Limbachiya *et al*. 2012) observed indicate that 30% coarse RCA has no major negative effect on a range of mechanical and durability properties of PC and PC/30%

FA concrete. However, reduction in resistance to carbonation and chloride ions penetration as well as sulphate attack was observed with increase in RCA proportions beyond 30%. Thus, 30% has been set as the optimum level for the coarse RCA. The experimental results Of Chen *et al*. (2014) showed that the higher the RAC strength, the larger the bond strength between square steel tube and RAC. The above-mentioned test results show that there is a great difference between the properties of RAC and CC. For example, the loose microstructure of RAC leads to low strength so that RAC has a relatively high capability of plastic deformation when compared to CC. It is well known that the conventional analysis and design methods of reinforced concrete, steel-concrete composite structure, are generally still based upon material properties obtained from the basic uniaxial strength test, although we know that the true uniaxial condition in structures is extremely rare. In practice, many concrete structures such as concrete-filled steel tube, shear wall, spiral columns and the node of building, nuclear reactor pressure container, etc are under multiaxial stress states. At the same time, with the wide use of computers, and the finite element method, it has become increasingly evident that it is quite important and urgent for the experimental study on the mechanical property of RAC under multiaxial stress states, and for studies on the design and analysis of nonlinear behavior design of reinforced concrete structure based upon multiaxial mechanical behavior. Hence, one of the main concerns for the usage of RAC in concrete structure applications is its performance under multiaxial stress states. Late in the 1970s, Kupfer (1969) began to perform experimental study of "CC" under multiaxial stress states in order to design for nuclear reactor container. Until now, only a few studies have been carried out to characterize the mechanical behavior of confined recycled aggregate concrete (CRAC) under axial compression. However, literature on the mechanical behavior of RAC under multiaxial stress states hasn't been reported. Based on the related axial tests on conventional concrete and RAC-filled steel tubes, Xiao *et al.* (2012) reported that the compressive strength of confined RAC was slightly lower (within 20%) than that of confined conventional concrete. Furthermore, steel tube confined RAC displayed larger deformation than that of confined conventional concrete. Xiao and Yang (2009) also investigated the property of GFRP (glass fiber reinforced plastics) confined RAC under axial compression. It is found that the strength of GFRP confined RAC is approximately 30% higher compared to that of unconfined RAC. The test data also indicates that with the increase of the RCA content, the strength of confined RAC decreases. Mahgoub *et al*. (2011) reported that RAC can gain significant strength and ductility if it is properly reinforced with lateral reinforcements. The unconfined compressive strength of the six RCA samples did not show the minimum required value which is expected as 0.7 MPa in base layer materials. However it can be improved by adding binders in different quantities for the six samples (Jayakody *et al*. 2011). So, it is necessary for the research of the mechanical behaviors under multiaxial stress states if RAC is widely applied in the practical engineering structure. This paper presents the strength characteristics and failure criterion of structural RAC at all kinds of stress ratios under biaxial compressive stress states, using a large static-dynamic true triaxial machine. The biaxial compressive tests were performed on 100 mm×100 mm×100 mm cubic concrete specimens. It is essential in both theoretical and practical aspect, not only for providing experimental and theoretical basis and mechanical model for the newly revised provisions of Design Code for Concrete Structures by this research, but also for promoting more extensive application of RAC and realizing persistent development strategy of building, resources and environment in all over the world.

2. Materials and experimental procedures

2.1 Materials and mix proportions

The cementitious materials used for this investigation are conformed to Chinese standard P·I42.5R Portland cement (standard compressive strength higher than 42.5 MPa at the age of 28 days), class I fly ash and silica fume. The coarse aggregate was the natural and recycled aggregate respectively (diameter ranging from 5 mm to 20 mm); the former is the natural crushed stone, the latter is the recycled limestone aggregate from waste concrete of demolished buildings, and the fine aggregate was natural river sand (fineness modulus of 2.7); water was tap-water. The Content of attached mortar (%) was provided by the manufacturer. This method of measurement was as follows: the recycled coarse aggregate of water saturation 2h by sucking in water heated by the high temperature of 500℃, then was soaked in cold water. The attached mortar was removed by the hot and cold cycle deterioration of adhesive mortar so that the attached mortar content can be obtained. The basic properties of coarse aggregates are given in Table 1. The subject in this paper is “structural RAC” so that the two replacement percentages of recycled coarse aggregate in this paper are 30% and 50%, as per the Chinese code for the design of RAC structures (LSCGPRC, 2011). For achieving a design compressive strength, recycled aggregate concrete requires lower water–cement ratio and higher cement content to be maintained as compared to concrete with fresh granite aggregate (Padmini *et al.* 2009). Table 2 shows the mix proportions by weight of the mixture and the major parameters of RAC. (f_{cu} is the uniaxial compressive strength of 150 mm×150 mm×150 mm cubic RAC specimens.)

2.2 Samples and testing methods

2.2.1 Casting and curing of specimens

The cement, class I fly ash and silica fume were added in turn and mixed for about 1 min, then the fine aggregate were added; the proportional water with high-performance superplasticizer (These also obtain the abilities of increasing slump, durability and retardation besides ordinary water reducing agents.) was added slowly over a period of 1 min; after that, the natural and recycled aggregate were added. Finally these ingredients were mixed for 1 min. All specimens were cast in steel molds and compacted slightly by vibrating table, were demoulded after 24h of the casting and then cured in a condition of 20±3℃ and 95% RH (relative humidity) for 28 days, and then stored in the room with a natural temperature (NSCGPRC 1985). The age of the specimens tested was about three months.

The concrete specimens tested were in 100 mm×100 mm×100 mm, 150 mm×150 mm×150 mm or 150 mm×150 mm×300 mm. The 100 mm concrete cubes were used to measure the strength for biaxial compressive test. For determination of the strength classes for the RAC and the strength of the prism, each batch was cast six 150 mm cubic specimens, and six 150 mm×150 mm×300 mm prismatic specimens.

2.2.2 Apparatus and testing methods

The tests of multiaxial mechanical properties were performed at the State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology. The multifunction triaxial experimental machine is shown in Fig. 1.

Figs. 2 and 3 shows the loading direction and the states of the specimen under biaxial stress states in triaxial experimental machine respectively.

The biaxial compressive tests were conducted in a triaxial testing machine that is capable of developing three independent compressive or tensile forces. The triaxial test process was necessary to insure uniform dimensions for each cubic specimen. The major stress direction was always applied perpendicularly to the surface of specimens. The proportional loading mode was employed. Friction-reducing pads placed between the platens and the specimens were two layers of plastic membrane with mobil lubricants in-between for the compressive loading plane; the tensile loading plane of concrete sample was processed by an attrition machine, then, the samples were glued-up with the loading plate with structural glue. The specimens under biaxial compression were tested at a loading rates of $10^{-5}\,s^{-1}$ in the direction of σ_3; but, those under uniaxial tension were done at $10^{-6}\,s^{-1}$ in the direction of σ_1. Eight different stress ratios under biaxial compression loading were tested. The principal stresses are expressed as $\sigma_1 \geq \sigma_2 \geq \sigma_3$ (compression denoted as negative and tension denoted as positive). For each specific stress ratio, at least two specimens were performed and their average values were used as the presented test results. During this process, results showing obvious deviation have been discarded.

Table 1 Physical properties of NA and RA

Type of coarse aggregate	Bulk density (kg/m^3)	Apparent density (kg/m^3)	Water absorption rate(%)	Content of attached mortar (%)	Crushing index (%)
Natural	1470	2720	0.56	0	6.89
recycled	1350	2560	2.91	15.25	11.42

Table 2 Mix proportions and major parameters of the two kinds of RAC

Type of RAC	Water-binder ratio	Water (kg/m^3)	Cement (kg /m^3)	Fly ash (kg/m^3)	Silica fume (kg/m^3)	Fine aggregate (kg /m^3)	Natural coarse aggregate (kg /m^3)	recycled coarse aggregate (kg /m^3)	Super-plasticizer (kg /m^3)	Slump (mm)	28d compressive strength (f_{cu} / MPa)
RAC-30	0.40	170	300	100	20	750	665	285	6.20	240	49.81
RAC-50	0.37	170	320	120	30	800	470	470	7.59	250	51.99

Note: The replacement percentages of recycled coarse aggregate for RAC-30 and RAC-50 are 30% and 50%, respectively

(a) the triaxial testing machine

(b) 12 sets of 1200KW / h electric motor

Fig. 1 The multifunction triaxial experimental machine

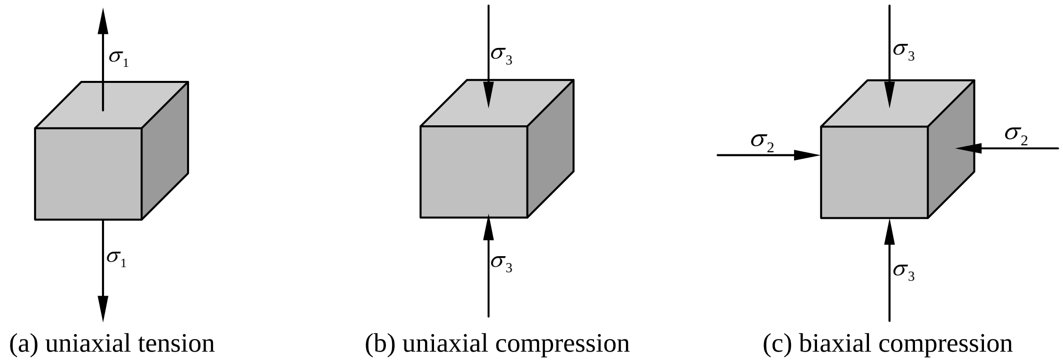

Fig. 2 Uniaxial and biaxial loading directions

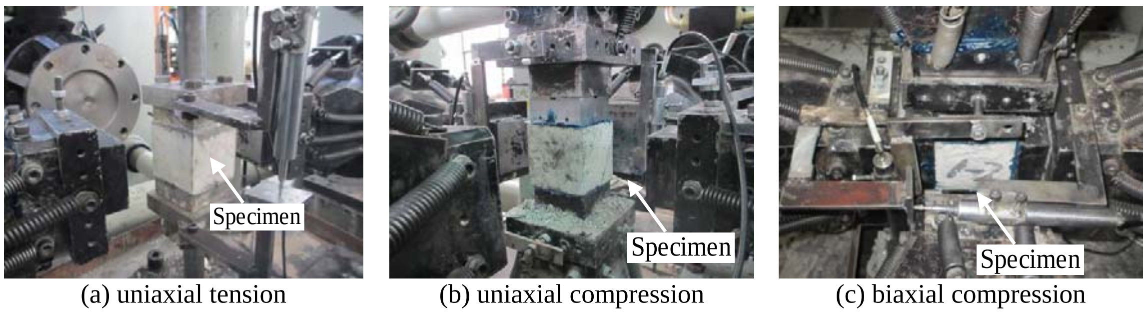

Fig. 3 States of the specimen in triaxial testing machine

3. Test results and discussions

3.1 Experimental results

The experimental results of plain RAC under biaxial stress states are given in Table 3.

3.2 Failure modes

The failure modes, its surface and so on of the RAC specimens under biaxial stress states are shown in Figs. 4(a)-4(x).

From Fig. 4, it is obvious that the adding influence of the recycled coarse aggregate on RAC does not change the failure mode of tensile splitting. In Figs. 4(h)-4(j), the RAC specimen under uniaxial compressive loading is split to multiple minor prisms (prism-type failure). The tensile failures under uniaxial tensile loading are shown in Figs. 4(k) and 4(m), respectively; there was no connection between the direction of the cracking and stress ratios. As shown in Figs. 4(n)-4(w), there are parallel plate-type fragments on the surface of σ_2 and σ_3 under biaxial compressive loading; moreover, the number of cracks becomes greater as the stress ratios increase; but, with the increase of the recycled coarse aggregate, the surface shape of parallel plate-type fragments under biaxial compression is more irregular. It was noticed that the cracks on the loading surface have a random direction because of the influence of recycled coarse aggregates.

Table 3 The biaxial strength index of plain RAC under various stress states and stress ratios

Type of concrete	Stress ratios $\alpha=\sigma_1:\sigma_2:\sigma_3$	σ_{1f} / MPa	σ_{2f} / MPa	σ_{3f} / MPa	average value σ_{3f} or σ_{1f} / MPa	average value σ_{3f} or σ_{1f} / f_c
RAC-30	0.00:0.00:-1	0.00	0.00	-26.88	-22.85	1
		0.00	0.00	-22.44		
		0.00	0.00	-22.96		
		0.00	0.00	-19.10		
	1:0.00:0.00	2.82	0.00	0.00	2.59	0.11
		2.53	0.00	0.00		
		2.41	0.00	0.00		
	0.00:-0.10:-1	0.00	-3.27	-31.68	-32.08	1.40
		0.00	-3.51	-32.48		
	0.00:-0.25:-1	0.00	-9.81	-38.93	-38.86	1.70
		0.00	-9.77	-38.78		
	0.00:-0.50:-1	0.00	-17.25	-34.33	-30.03	1.31
		0.00	-13.00	-25.72		
	0.00:-0.75:-1	0.00	-23.01	-30.70	-30.34	1.33
		0.00	-19.36	-25.78		
	0.00:-1.00:-1	0.00	-25.94	-34.55	-32.19	1.41
		0.00	-32.59	-32.67		
		0.00	-28.10	-28.15		
		0.00	-31.04	-31.11		
		0.00	-36.75	-36.84		
RAC-50	0.00:0.00:-1	0.00	0.00	-27.13	-27.74	1
		0.00	0.00	-28.35		
	1:0.00:0.00	3.27	0.00	0.00	3.10	0.11
		2.99	0.00	0.00		
		3.05	0.00	0.00		
	0.00:-0.20:-1	0.00	-7.47	-37.17	-41.24	1.49
		0.00	-8.89	-44.17		
		0.00	-9.53	-47.23		
		0.00	-7.32	-36.40		
	0.00:-0.35:-1	0.00	-15.47	-44.08	-45.90	1.65
		0.00	-15.60	-44.57		
		0.00	-24.51	-49.05		
	0.00:-0.50:-1	0.00	-18.56	-37.09	-42.10	1.52
		0.00	-23.57	-47.10		
	0.00:-0.75:-1	0.00	-36.97	-49.35	-46.32	1.67
		0.00	-32.46	-43.29		
	0.00:-1.00:-1	0.00	-38.06	-38.12	-39.93	1.44
		0.00	-41.65	-41.74		

Note : $\sigma_{1f,}$ σ_{2f} and σ_{3f} are the triaxial failure strengths in the three principal directions respectively; f_c is the uniaxial compressive strength of 100 mm×100 mm×100 mm cubic RAC specimens with two layer of friction-reducing pads, and its strength value is about equal to that of 150 mm×150 mm×300 mm prism.


(a) specimen grinded well


(b) mobil lubricants


(c) plastic membranes


(d) construction structural adhesives


(e) adhesive and loaded steel plates


(f) adhesive fixed setting between steel plates and specimen


(g) adhesive specimen with steel plates


(h) prism-type failure, RP=30%


(i) prism-type failure, RP =50%


(j) prism-type failure, RP =30%


(k) the surfaces of tensile failure, RP =30%


(l) the surfaces of tensile failure, RP =50%


(m) the cracks of tensile failure


(n) α =0.10:1, RP =30%


(o) α =0.25:1, RP =30%


(p) α =0.50:1, RP =30%


(q) α =075:1, RP =30%

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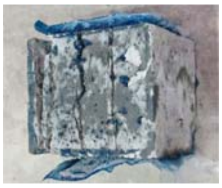


(r) α =1:1, RP =30%

(s) α =0.20:1, RP =50%

(t) α =0.35:1, RP =50%

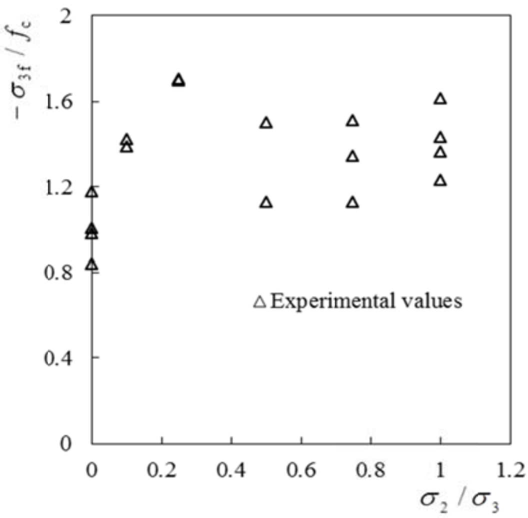
(u) α =0.50:1, RP =50%

(v) α =0.75:1, RP =50%

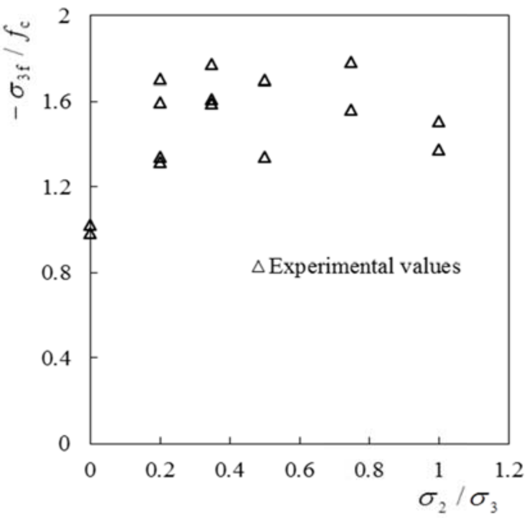
(w) α =1:1, RP =50%

(x) the batch failure specimen after experiment

Fig. 4 Failure modes of plain RAC under multiaxial stress states



(a) RAC-30



(b) RAC-50

Fig. 5 The influence of the stress ratios on the principal stress $-\sigma_{3f}/f_c$ under biaxial compression

The mentioned-above failure modes demonstrate that providing confinement stress along σ_2 directions will change the failure modes. Although the failure modes under uniaxial and biaxial stress states are different, the failure cause is that the splitting tensile strain along the unloading or less stress planes is greater than the ultimate tensile strain of RAC.

3.3 Strength characteristics

Note: The f_{cu} is the uniaxial compressive strength of the 150 mm×150 mm×150 mm cubes without friction-reducing pads at 28 days. The f_t is the uniaxial tensile strength of the 100 mm×100 mm×100 mm cubes without friction-reducing pads at 3 months. The f_c is the uniaxial compressive strength of the 100 mm×100 mm×100 mm cubes with friction-reducing pads at 3 months. As shown in Table 3, it is apparent that the uniaxial tensile strengths f_t (2.59, 3.10 MPa) for 30%, 50% of the replacement percentages on the recycled coarse aggregate, are both 0.11 times that of the uniaxial compressive strength f_c (22.85, 27.74 MPa). However, the ratio of the tensile strength to compressive strength in the two references (Qin 2003, Song *et al.* 1991) are 0.70-0.75 and 0.092, respectively. The above-mentioned discussion indicates that the tensile-compressive ratios for the two replacement percentages of RCA-30 and RCA-50 are the same. Sagoe-Crentsil *et al.* (2001) also found that the ratio of splitting tensile strength to compressive strength was found to be in good agreement with established values derived for equivalent grade concretes made with normal-weight natural aggregates.

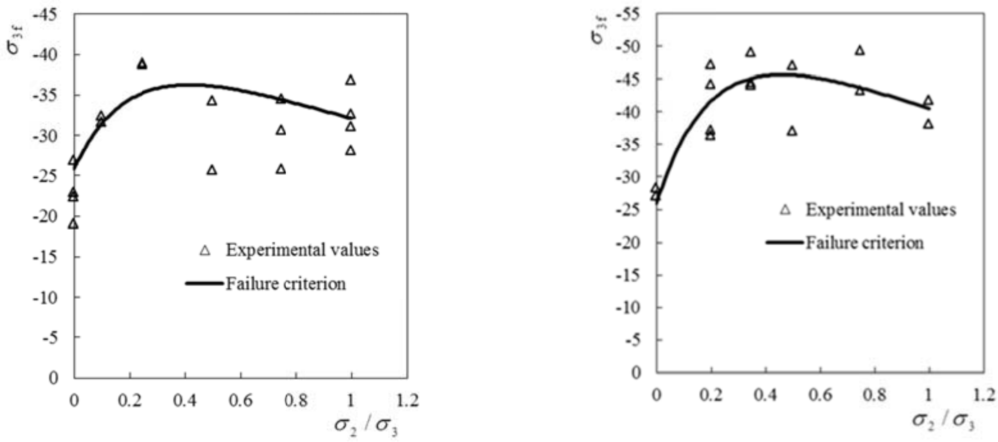
Figs. 5(a) and 5(b) shows the influencing regularity of the stress ratio on the principal strength σ_{3f} for the two replacement percentages of RCA-30 and RCA-50, respectively.

It can be seen from Figs. 5(a) and 5(b), that the biaxial σ_{3f} is greater than the corresponding uniaxial compressive strength f_c for the same replacement percentages of RCA-30 and RCA-50 at all stress ratios. For example, the increase times of RCA-30 and RCA-50 is 1.13~1.70 and 1.31~1.80 respectively. In addition, the influencing extent of the stress ratio on $-\sigma_{3f}/f_c$ is different with the two different replacement percentages. The biaxial stress ratios corresponding to the maximum σ_{3f} are 0.25 or 0.75. At the same replacement percentages of recycled coarse aggregate and stress states, the change of σ_{3f} is dependent on the stress ratio. The influence of stress ratio on the σ_{3f} changes approximately by a parabolic-like curve for every replacement percentages. For example, when σ_2/σ_3 is equal to 0.5, the values of σ_{3f} (-34.33, -39.93 MPa) for the two replacement percentages of RCA-30 and RCA-50 are 1.50, 1.70 times that of the corresponding uniaxial compressive strength (22.85, 27.74 MPa) respectively, which is in disagreement with the conclusion on CC in the references (Qin 2003, Song *et al.* 1991). That is, the ratios of $-\sigma_{3f}/f_c$ in this paper are higher than that of “CC” in the above reference under biaxial compressive stress states. The significance of this is that the increase times of strength for recycled aggregate concrete are great than that of CC under biaxial compressive stress states. So, the design of strength for recycled aggregate concrete under biaxial compressive stress states has bigger safety reserves. Tests (Kupfer and Gerstle 1973, Koya 1973, Mills and Zimmerman 1970) were performed biaxial concrete-strength on CC. The results of the biaxial compressive strength tests of Kupfer and Gerstle were about 1.18 to 1.27 times uniaxial compressive strength, when 200 mm×200 mm×50 mm plate specimens with brush-bearing platens as friction-reducing pads were used. The test results of Koya were about 1.25 to 1.40 times the uniaxial compressive strength when the maximum loading force was parallel with the direction of the cast, when testing 100 mm cubes with two resin sheets and silicon grease; the results of Mills and Zimmerman, using 57.4 mm cubes with two resin sheets and axle grease, were about 1.275 to 1.568 times the uniaxial compressive strength.

So, through the above-mentioned discussion, it is indicated that the increasing ratios of the biaxial to uniaxial compressive strength are dependent on the stress ratios, stress states, and replacement percentages of recycled coarse aggregate.

Table 4 The parameters values of failure criterion for plain RAC on the two replacement percentages

Type of concrete	*a*	*b*	*c*
RAC-30	-3.4218	-6.6870	-1.1331
RAC-50	-3.0792	-7.6899	-0.9355



(a) RAC-30 (b) RAC-50

Fig. 6 The comparison of Eq. (1) and test values under biaxial compression

3.4 Failure criterion

Based on the strength characteristic of experimental results in Table 3 and theoretical analysis of the failure enveloping plane for RAC, the present paper proposes a new failure criterion.

$$\frac{\sigma_{3\mathrm{f}}}{f_{\mathrm{c}}}=\frac{a\cdot\alpha^2+b\cdot\alpha+c}{(1+\alpha)^3} \tag{1}$$

Where α = σ_2/σ_3 (for 0≤ α ≤1) is the stress ratios; f_{c} is the uniaxial compressive strength of plain RCA-30 and RCA-50, respectively. Using regression analysis of the test results (see Table 3) of the two replacement percentages of plain RCA-30 and RCA-50 calculated by Eq. (1) respectively, the corresponding values of *a, b* and *c* are obtained. The calculated results in terms of the three parameters *a*, *b* and *c* are given in Table 4 on the two replacement percentages of recycled coarse aggregate for RCA.

For the other replacement percentages between RAC-30 and RAC-50, the above-mentioned *a*, *b* and *c* are computed by linear interpolation. Fig. 6 gives the comparison of Eq. (1) and test values. It can be seen from Fig. 6 that the model of failure envelopes in principal stress space for RAC under biaxial compression, is of better precision and applicability.

4. Discussion

During the crash of demolished concrete, recycled aggregates with plate-shaped particles and cracks are generally made by the jaw crusher. In comparison with the natural aggregates, recycled aggregates have a rough surface with more sharp corners and porosity and its surface is slightly flattened. The particle size of recycled aggregates is between boulder concrete and crushed stone concrete. Cement mortar all more or less adhere to the surface of recycled aggregates. So, recycled aggregate has the less apparent density and bulk density, the larger water absorption rate and crush index. In addition, as the replacement level increases, the shrinkage of RAC also increases (Limbachiya *et al*. 2012). For the conventional concrete, it is a three-phase composite material at microscopic scale: a cementitious part, aggregate and the interfacial transition zones (ITZs) between the two. But, with regard to the RAC, it possess two ITZs, one is between the RCA and new mortar matrix (new ITZ), and the other is between the RCA and the old mortar attached (old ITZ). The old mortar of the RCA formed the weak link in RAC, which was composed of many porosity and cracks. Poon *et al*. (2004) scanning electron microscopy (SEM) observations revealed that the aggregate-cement matrix interfacial zone of RAC consisted mainly of loose and porous hydrates whereas the aggregate-cement matrix interfacial zone of the CC consisted mainly of dense hydrates. Then, the adding of recycled coarse aggregate can lead to the difference among the microstructures: these pores and cracks increase the consumption of water, which leading to less water for hydration at the ITZ regions of RAC; so that the compressive, tensile and shear strengths of RAC are generally less than those of the CC. Therefore, under uniaxial stress states, the compressive strength is less than that of the conventional concrete. Saravanakumar and Dhinakaran (2013) concluded that concrete with 50% recycled aggregate gives reasonable compressive strength. Concrete designed for a characteristic compressive strength of 50 MPa after replacing 50% of NA with RA gives a compressive strength of 35 MPa and it can be tried in the field. But, Suzuki *et al*. (2009) found that the incorporation of 40% of the recycled waste porous ceramic coarse aggregates (PCCA) leads to a non-shrinking HPC that results in an insignificant internal stress accompanied by a significant increase of the compressive strength. In this paper, the tensile-compressive ratios for the two replacement percentages of RCA-30 and RCA-50 are the same. It indicates that the decreasing ratios of the tensile and compressive strength for two replacement percentages of recycled coarse aggregate is alike. In addition, the tensile stress exceeds the tensile strength of concrete, more micro-cracks occur. The larger the plastic deformation is under multiaxial compression, the higher the increasing ratios are. Furthermore, the deformation from the initiation and growth of every new crack of the concrete specimen under biaxial compressive stress states is confined in varying degrees so that the values of $-\sigma_{3f}/f_c$ are higher than 1 for all stress ratios.

5. Conclusions

Based on the experimental work and the analysis of the test results, the following conclusions can be drawn

• The ratios between the uniaxial compressive strength f_c (the prismatic compressive strength) and its corresponding cubic strengths f_{cu} for RAC are less than that of the CC. The tensile-compressive ratios for the two replacement percentages of RCA-30 and RCA-50 are the same; moreover, the differences of tensile-compressive ratios for RAC and CC are also smaller.

• The adding effect of recycled coarse aggregate on plain RAC does not change the macroscopical failure modes of concrete. The failure modes of RAC under uniaxial and biaxial compression are that of prism-type and parallel plate-type respectively; moreover, the number of cracks becomes greater as the stress ratios increase; with the increase of the recycled coarse aggregate adding, the surface shape of parallel plate-type fragments under biaxial compression is more irregular. But, the failure modes under uniaxial tension are tension failure. The effect of confinement stress can change the failure modes.

- The ultimate strength σ_{3f} of RAC under biaxial compression for all stress ratios is higher than the corresponding uniaxial compressive strength f_c for the same replacement percentages of recycled coarse aggregate. The increasing extent of the biaxial to uniaxial compressive strength depends on the stress states, the stress ratios, and the replacement percentages of recycled coarse aggregate for RAC. The ratios of $-\sigma_{3f}/f_c$ in this paper are higher than that of "CC" under biaxial compressive stress states.
- A new failure criterion with the stress ratios under biaxial compressive stress states is proposed for plain RAC.

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