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Review of studies on structural performance of recycled aggregate concrete in China

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This paper presents a review of the studies on the structural performance of recycled aggregate concrete (RAC) elements and structures in the past 10 years in China. The flexural and shear behaviour of RAC beams, the compression performance of RAC columns as well as the flexural performance of RAC slabs are overviewed and summarized. The seismic responses of beam-column joints, shear walls as well as frames made of RAC are also covered. The experimental observations indicate that the structural performance of RAC elements and structures is somewhat similar to that of natural aggregate concrete (NAC) members. A brief introduction to the application of RAC in sustainable buildings in China is also presented.

recycled aggregate concrete (RAC), natural aggregate concrete (NAC), structural performance, elements and structures, seismic behavior, application

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1 Introduction

The recycling and reuse of waste concrete as recycled aggregates for new concrete, i.e., recycled aggregate concrete (RAC), is an important approach for achieving the sustainable concrete structures. Many experimental investigations on the material properties of RAC have been carried out in China [1]. Most of the experiments reveal positive results although RAC exhibits relatively weak behaviour against mechanical actions due to the existence of recycled aggregates.

The use of RAC as structural concrete has been supported by the following facts: 1) the bond between RAC and reinforcement does not differ much from that of conventional concrete [2]; 2) the thermal expansion coefficient for RAC is almost the same as that of conventional concrete [3].

To make RAC as a widely accepted structural material, a comprehensive experimental study has been carried out in recent years in China. The study covered not only the monotonic behaviour of the common reinforced RAC members (including beams, columns and slabs) but also the seismic performance of reinforced RAC elements and structures, such as beam-column joints, shear walls and frame structure. These investigations provide valuable information on the structural performance of RAC. Based on the test results, some recommendations for the design of reinforced RAC members are given in the first specifications for RAC in China-Technical Code for Application of Recycled Aggregate Concrete (DG/TJ08-2018-2007) [4]. This review gives a summary and discussion on the related findings and also a brief introduction of the design provisions in the technical code (DG/TJ08-2018-2007). Hopefully, this work will be helpful for better understanding and

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rational design of elements and structures made of RAC worldwide.

2 Reinforced RAC elements under monotonic loadings

2.1 Flexural behaviour of RAC beams

The flexural behaviour of reinforced concrete beams is the basic and very important property. A large number of experiments on the cracking behaviour, the failure mode, the flexural capacity as well as the deflection of RAC beams have been undertaken in China. Simply-supported RAC beams were incorporated into most of the testes. Figure 1 shows the test setup of Xiao and Lan [5]. The most important mechanical parameters and the corresponding test conditions collected are briefly described and given in Table 1.

The following variables were involved:

1) The influence of recycled coarse aggregates (RCAs) replacement percentage, which is defined as the mass percentage of RCAs within the gross coarse aggregates. (Xiao and Lan [5], Ding et al. [6] and Li et al. [7]).

2) The influence of longitudinal reinforcement ratio (Li et al. [7], Hu et al. [8]).

Based on the experiments noted above, the following conclusions can be drawn:

1) The reinforced RAC beams show very similar crack patterns and failure features, irrespective of the recycled aggregates percentage (Figure 2).

2) The assumption of "plane sections remain plane" in the classic flexure theory, that is, sections perpendicular to the axis of bending which are plane before bending remain plane after bending, is also valid for reinforced RAC beams with various recycled aggregates percentages. That means the procedure developed for reinforced conventional concrete beams could be used for the analysis of RAC beams subjected to flexure.

3) Under same conditions, the cracking and ultimate

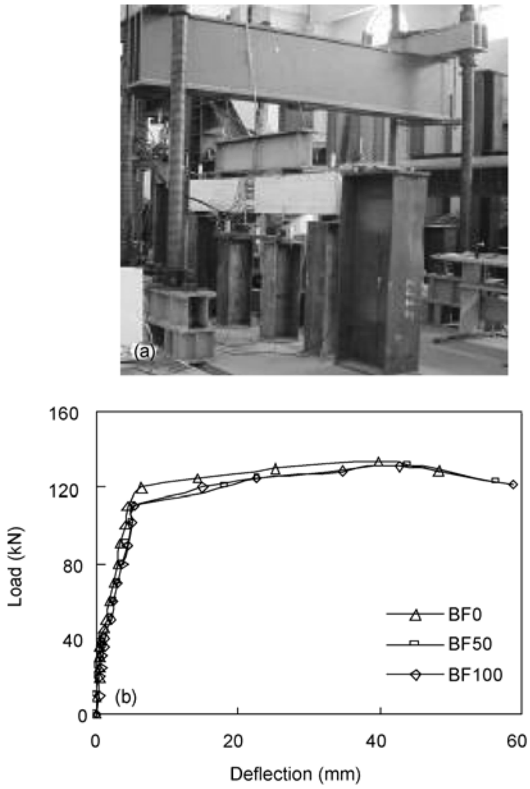


Figure 1 Bend test on RAC beams [5]. (a) Test setup; (b) curves of load versus deflection.

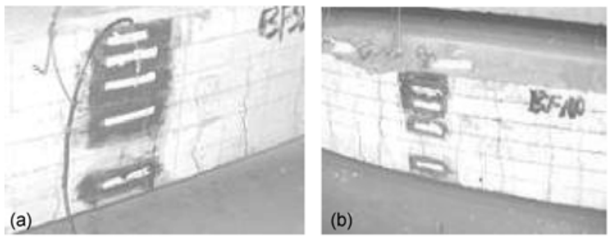


Figure 2 Crack patterns and failure modes of RAC beams [5]. (a) BF50; (b) BF100.

Table 1 Collected test results on the flexural behaviour of RAC beams

Investigator	RCA content (%)	28 Day compressive strength (cube) (MPa)	Size (mm) $L\times B\times H$	Reinforcement ratio	Ultimate load (kN)/ moment(kN m)
Xiao and Lan [5]	0 (BF0)	31	2300×150×300	0.77%	133/33.3
	50 (BF50)	35			131/32.8
	100 (BF100)	34			128/32.0
Li and Song et al. [7]	0	41.9	2000×150×300	0.82%	155/46.5
	30	45.6		0.82%	153/45.9
	70	43.7		0.82%	159/47.6
	100	39.1–50.5		0.55%–2.43%	114–317/47.1–95.1
Hu et al. [8]		38.4	2300×150×300	0%	18/–
		36.4		0.56%	62.5–70/–
		36.8		1.00%	100–125/–
		37.0		1.58%	150–170/–
		38.4		2.49%	320–340/–

moment of the RAC beam are similar to the natural aggregate concrete (NAC) beam, nevertheless the stiffness of the RAC beam reduces to a certain extent.

4) Comparing the RAC beam to the NAC beam, the research results show that under the action of the same load, the maximum width of cracks of the former, is slightly larger.

To estimate the flexural capacity of reinforced RAC beams, the predictions from the design equations recommended in EC 2 [9] and Chinese Code for Design of Concrete Structures (GB 50010-2002) [10] and the test data are compared.

In the Technical Code for Application of RAC (DG/TJ08-2018-2007), the following formulas are recommended to calculate the flexural bearing capacity of RAC beams.

$$M_u = \alpha_m f_c b\left(h_0 - \frac{x}{2}\right), \tag{1}$$

$$\alpha_m f_c bx = f_y A_s, \tag{2}$$

where M_u is the ultimate moment (kN m); b and h_0 are the width and the effective height of the section (mm), respectively; f_y and A_s are the yield strength (MPa) and the area (mm^2) of the longitudinal reinforcement, respectively; f_c is the cylinder compressive yield strength (MPa) of the RAC; α_m, the modified parameter for f_c, can be taken as 0.95.

In addition, Xiao et al. [11] carried out the reliability analysis of the recycled concrete beams bending capacity by the Monte Carlo method. The main findings of the reliability analysis can be summarized in the following:

1) The reliability index of recycled concrete beams is proved to meet the requirement of the Unified Standard for Reliability Design of Building Structures (GB 50068-2001) [12].

2) The effect of uncertainty coefficient associated with resistance is obvious, while the partial safety factor of recycled concrete compressive strength on the reliability index of ideally reinforced recycled concrete beams bending capacity is neglectable.

2.2 Shear behaviour of reinforced RAC beams

Unlike in reinforced concrete beams under flexure where the longitudinal reinforcement governs the structural response, concrete plays a more significant role in beams subjected to shear loadings. Taking into account the difference between RAC and conventional concrete, the study on the shear performance of reinforced RAC beams is of more importance.

To investigate the influence of the recycled aggregates on the shear behaviour of the reinforced concrete beams, experimental work was carried out both on beams with and without web reinforcements. The details of the experiments are presented in Table 2.

As shown in Figure 3, Xiao and Lan [13], Zhou and Jiang [14] tested the shear behaviour of RAC beams with web stirrups. On the basis of the test results, the characteristics of shear behaviour of RAC beams were discussed. By using a general finite element method, the influence of recycled aggregate replacement percentage, the shear-span to depth ratio and the percentage of stirrups on the shear behaviour of RAC beams were theoretically analyzed [13]. These studies showed that the shear capacity of recycled concrete beam reduces with the increase of recycled coarse aggregates content. The shear failure pattern of RAC beam is typical shear-compression failure when the beam is properly designed. The diagonal section cracking load of RAC beam is slightly lower than that of NAC beam, and average diagonal crack width of RAC beams is slightly larger than that of NAC beams.

It is evident that the influence of RAC can be better reflected using reinforced beams without web reinforcements. To investigate the shearing capacity of RAC beams without stirrups, Zhang et al. [15] conducted an experiment using 13

Table 2 Collected test results on the shear behaviour of RAC beams

Investigator	RCA content (%)	28 Day compressive strength (cube) (MPa)	Size (mm) $L\times B\times H$	The percentages of stirrups	The shear-span to depth ratio	Ultimate load (kN)
Xiao and Lan [13]	0	31 (BS0)	2300×150×300	0.25%	1.5	330
	50	35 (BS50)				298
	100	34 (BS100)				274
Zhou et al. [14]	0	42.2	2250×150×300	0.16%	1.5	190.5
	10	40				188.0
	20	37.8				185.4
	30	34.9				181.4
	40	34.2				174.0
Zhang et al. [15]	0	28.7–38.7	2400 (2000)×150×300	0	1.0–3.0	114–530
	30	32.4			1.5	336
	50	33.3			1.5	350
	70	30.4			1.5	300
	100	29.6–34.1			1.0–3.0	119–509

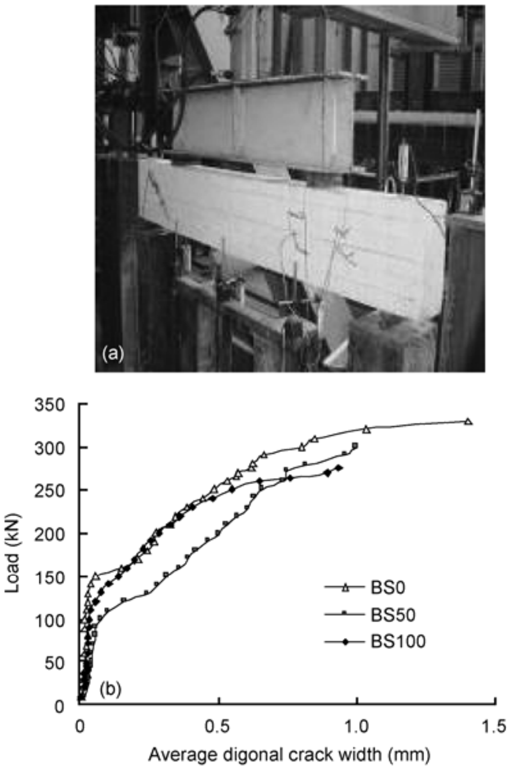


Figure 3 Shear test and results of RAC beams [13]. (a) Test setup; (b) load versus the diagonal crack width.

RAC beams and an NAC beam. The effects of replacement percentages of RCAs and shear-span to depth ratio on the characteristics of shear capacity and deformation of RAC beams were studied. The test result showed the deflection and diagonal crack of RAC concrete beams are bigger than those of NAC beams, and that the shear capacity of RAC beams reduces with the increase of RCAs replacement content while the shear capacity reduces with the increase of shear-span to depth ratio.

In the Technical Code for Application of Recycled Aggregate Concrete (DG/TJ08-2018-2007) [4], the following formula is used to calculate the shear capacity of RAC beams,

$$V_u = a_v\left(0.7 f_t b h_0 + 1.25 f_{yv}\frac{A_{sv}}{s}h_0\right), \tag{3}$$

where a_v is the reduction coefficient considering the RCAs content influence; f_t is the tensile strength of RAC (MPa); f_{yv}, A_{sv} and s are the yield strength (MPa), the area (mm^2) and the spacing of the stirrups (mm), respectively. The other symbols share the same meanings as in eqs. (1) and (2).

2.3 Reinforced RAC columns under axial and eccentric compressions

The compressive behaviour of RAC columns under axial loading was studied by Zhou et al. [16]. The compressive behaviour of reinforced RAC columns under axial and eccentric compressions was studied by Xiao et al. [17]. A summary of the specimens tested is presented in Table 3.

Based on the experimental results from Table 3 as well as from Figure 4, it was proved that in comparison with the NAC columns, the failure modes of RAC columns still have compression failure, tensile failure and a balance failure under the compressive loading with different eccentricities. The assumption "plane sections remain plane" is also suitable for RAC columns. The load capacity calculation of RAC columns can be estimated by the equation for NAC columns used in the current Chinese Building Design Code GB50010 (2002) [10]. In the technical code for RAC [4], the following equation is used to predict the compression bearing capacity of RAC column under axial loading.

$$N \leqslant 0.9\alpha_m \phi(f_c A + f_y^{'} A_s^{'}), \tag{4}$$

where α_m is adjustable coefficient of RAC column; ϕ is the stability coefficient. The other symbols have the same meanings as in eqs. (1) and (2).

2.4 Compressive performance of RAC filled steel tube columns

For concrete filled steel tube columns, many experiments have verified the benefits due to the confinement of the steel tube on the core concrete. To investigate the possible confinement on RAC, Yang and Han [18] tested the compressive performance of RAC filled steel tube (RACFST) columns. In their tests, 56 RACFST members under short-term loadings, including 24 stub columns, 8 beams and 24 eccentrically loaded columns, were tested. The corresponding normal CFST members, including 6 stub columns, 2 beams and 6 eccentrically loaded columns, were also tested to evaluate the differences between them. The specimens were designed to investigate the effects of the following parameters: 1) cross-section type, circular and

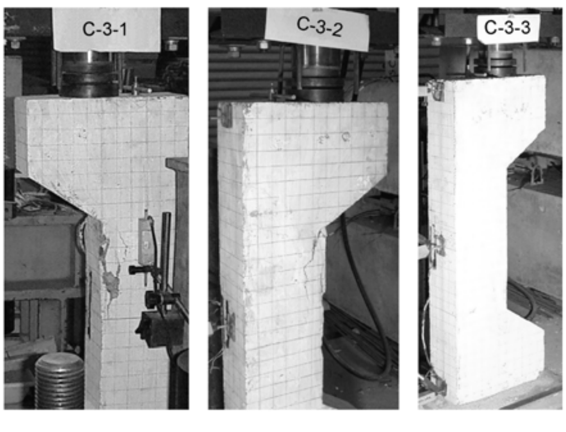


Figure 4 Performance of RAC columns when eccentricity is 100 mm [17].

Table 3 Collected test results on the compressive performance of unconfined RAC column

Investigator	RCA content (%)	28 Day compressive strength (cube) (MPa)	Slenderness ratio	Eccentricity (mm)	Section size (mm)	Ultimate load (kN)
Xiao et al. [17]	0 (C-e-1) 50 (C-e-2) 100 (C-e-3)	31–34	7	0 (C-0) 30 (C-1) 82 (C-2) 100 (C-3)	180×120	393–501 501–523 315–340 280–310
Zhou et al. [16]	0	42	3	0	200×200	908–920
	5	40.76				890–903
	10	40.2				872–884
	15	38.3				825–863

Note: When the eccentricities are 0, 30, 82, and 100 mm, *e* will be 0, 1, 2, and 3, respectively.

square; 2) RCAs replacement percentage, from 0 to 50%; 3) load eccentricity ratio, from 0 to 0.53 [19].

The test results (Table 4) showed that all the columns failed due to overall buckling of steel tube. Comparisons were made with predicted ultimate bearing capacities of RACFST columns using the existing codes, such as ACI Committee 318 [20], AIJ-1997 [21]. Figure 5 shows the effects of RCAs replacement percentage (r) on the bearing capacity of stub columns (Nue, s) and columns under eccentric loading (Nue, e), where D and B are the outside diameter and width of circular and square members, respectively, e is the load eccentricity, and r_0 is $D/2$ or $B/2$ for circular or square specimens, respectively. It can be seen that with increase of RCAs replacement percentage, the bearing capacity of the tested specimens gradually decreases.

A theoretical model for normal concrete filled steel tube (CFST) columns is adopted for RACFST columns. Similar to normal CFST, confinement factor (ξ_r) is suggested to model the interaction between outer steel tube and core RAC of RACFST columns, and it is defined as

$$\xi_r = \frac{A_s \cdot f_y}{A_c \cdot f_c}, \tag{5}$$

where A_s and A_c are the cross-sectional areas of the steel tube and core concrete (mm^2), respectively; f_y and f_c are the yield strength of steel and the compressive strength of RAC, respectively (MPa).

2.5 Flexural performance of RAC slabs

Zhou et al. [22] studied the performance of RAC slab which

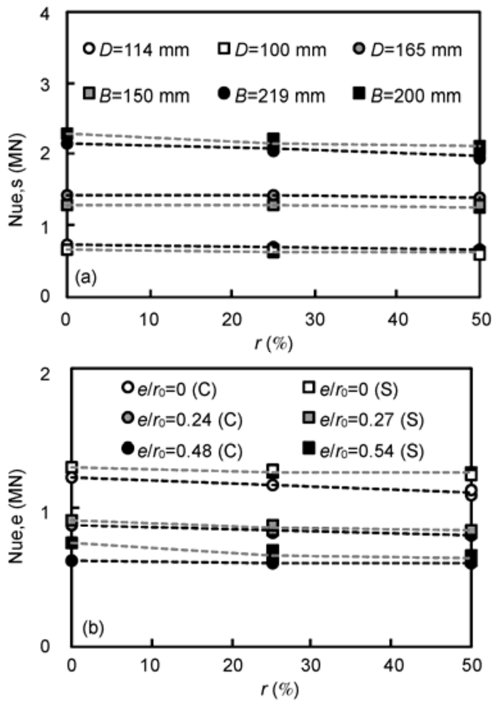


Figure 5 Effects of RCA replacement percentage [19]. (a) Stub columns; (b) eccentrically loaded columns.

was simply supported on four sides. In their tests, 12 slabs divided into four groups were tested. All the slabs shared the same cross-section and reinforcement ratio but with different RCA replacement percentages, i.e., 0%, 5%, 10% and 15%, respectively. A summary of the specimens tested is listed in Table 5. The specimens were designed to be subjected to concentrated load. The test results indicated that the recycled aggregates replacement percentage influences

Table 4 Collected test results on the compressive performance of confined RAC columns

Investigator	28 Day compressive strength (cube) (MPa)	Dimension of section $D \times t$ (mm)	L (mm)	e (mm)	e/r_0	N_{ue} (kN)
Yang and Han [18]	42.7 (0% RCA) 41.8 (25% RCA) 36.6 (50% RCA)	○–165×2.57	1650	0	0	1090–1158
				20	0.24	795–855
				40	0.48	600–607
		□–150×2.94	1732	0	0	1245–1273
				20	0.27	825–875
				40	0.53	625–686

Table 5 Summary of specimens for flexural performance of RAC slabs

Investigator	RCA content (%)	Cracking load (kN)	Ultimate load (kN)
Zhou et al. [22]	0 (RC0)	17.4–18	69.8–72.1
	5 (RC5)	15.9–16.9	63.5–67.5
	10 (RC10)	14.5–15.6	58.0–62.4
	15 (RC15)	13.2–14.2	52.6–56.9

the load mid-span deflection behaviour, as shown in Figure 6.

It was also found that with the increase of RCAs replacement percentage, the cracking load and the ultimate load of the slab decrease while the deformation of the slab increase; however, the decreasing tendency of the ultimate load is greater than that of the cracking load.

By studying the deflection of the RAC slabs, the general method (eq. (6)) used for determining the deflection of conventional concrete slab is not suitable for estimating the deflection of the RAC slabs.

$$\Delta = \alpha \frac{Ml_0^2}{B_s}, \tag{6}$$

where Δ is the deflection value of the slab (mm); α is the deflection coefficient; B_s is the stiffness of the slab (N/m); l_0 is the effective length of the slab (mm); M is the ultimate moment (kN m). Nevertheless, the test results showed that the deflection of the RAC slabs can also be obtained by multiplying the value of normal concrete slab by an amplification factor which can be taken as 1.4.

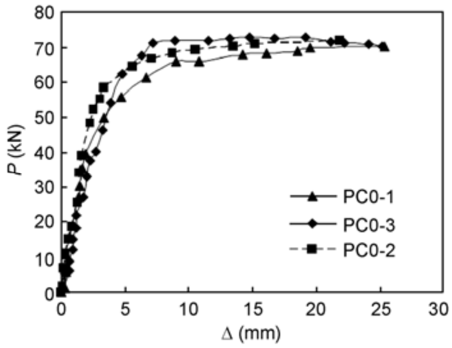


Figure 6 Load mid-span deflection curves of RAC slabs [22].

2.6 Steel deck RAC composite slabs

In order to investigate the promotion of RAC in the steel deck concrete composite slabs, 6 cold formed steel deck-RAC composite slabs without stud were tested under static loading by Xiao et al. [23]. The test specimens and various stage loads of the composite slabs are shown in Table 6, where P_{cr} is the critical value of the slab; P_u is the ultimate load; P_{200} is the load value when the deflection value of the slab is $L/200$.

Based on the test results, the effects of shear-span to depth ratio on the failure model as well as the relationship between the longitudinal slip and load were investigated. The test setup and the main test result are given in Figure 7. It was found that the slip between RAC and steel deck was relatively large. The failure mode was a longitudinal splitting failure. By analyzing the measured load-slip curves, the influence of recycled aggregate content on the bearing capacity of steel deck RAC composite slabs was investigated. With increasing RCAs content, the bearing capacity of the slabs first increased and then decreased. Nevertheless, the RCAs content had nearly no influence on the ultimate shear bearing capacity of the slab. Longitudinal shear capacity became lower as the shear-span to depth ratio increased. A formula related to the shear capacity of the slabs was proposed and recommended as

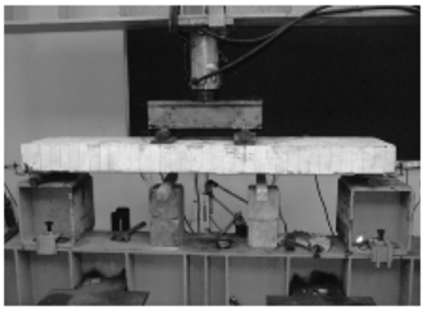


Figure 7 Test setup of composite slabs [23].

$$V_u = \alpha_{lv} \cdot \left(175.406 \rho h_0 / L_v + 0.0391 \sqrt{f_c}\right), \tag{7}$$

Table 6 Various stage loads of the composite slabs

Investigator	RCA content (%)	Shear span L_v(mm)	P_{cr} (kN)	P_{200} (kN)	P_u (kN)	P_{cr}/P_u	P_{200}/P_u
Xiao et al. [23]	0 (B1)	450	24.124	25.284	27.727	0.76	0.91
	30 (B2)	450	31.269	32.491	34.934	0.90	0.93
	30 (B3)	600	27.001	31.858	33.609	0.94	0.95
	100 (B4)	450	16.016	23.011	27.659	0.47	0.83
	100 (B5)	600	11.606	17.531	19.058	0.70	0.92
	100 (B6)	600	11.390	20.352	21.797	0.52	0.93

where α_{lv} is the shear capacity coefficient; ρ is the steel reinforcement ratio; L_v is the shear span (mm); h_0 is the effective height of the section (mm); f_c is the axial compressive strength of the RAC (MPa).

3 Reinforced RAC structures under cyclic loadings

3.1 RAC beam-column joints

Xiao and Zhu [24] investigated the behaviour of reinforced beam-column joints under low frequency reversed lateral loads. In their study, 3 half-scaled specimens were tested. The adopted RCAs replacement percentages were 0%, 50% and 100%, respectively. Figure 8(a) shows the typical test specimens. Based on the test observations, the failure features, the hysteresis loops, the ductility and the degeneration of stiffness under seismic loads were comparatively investigated.

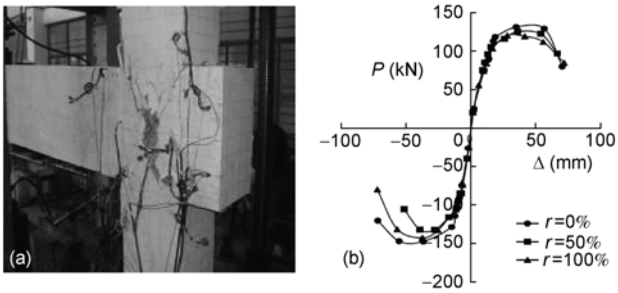


Figure 8 Failure mode and results of RAC column-beam joints [24]. (a) Failure mode; (b) skeleton curves.

The test results in Table 7 indicated that the seismic behaviour of the reinforced beam-column joints made of RAC is slightly weaker than that with conventional concrete, as can be seen from the skeleton curves of the specimens illustrated in Figure 8 (b). However, it was found that the ductility coefficient and the stiffness of the RAC joints are able to meet the related requirements for the current earthquake-resistance design provisions.

On the basis of the test data, Xiao and Zhu [24] concluded the following equation to calculate the shear capacity of joints made of RAC, which is in the Chinese Code for the Design of Concrete Structures (GB50010-2002) [10].

$$V_u = 0.1\left(1+\frac{N}{f_c b_c h_c}\right) f_c b_j h_j + f_{yv}\frac{A_{sv}}{s}(h_o - a_s), \qquad (8)$$

where f_c is the axial compressive strength (MPa); b_c and h_c are the width and the effective height of the column section (mm), respectively; b_j and h_j are the effective width and the effective height of the joint core section (mm), respectively; N is the axial compression of the column (kN); a_s is the cover thickness (mm). The other symbols share the same meanings as in eq. (3).

3.2 Pre-cast RAC beam-column joint

To explore the potential of RAC in precast concrete structures, Xiao et al. [25] investigated the behaviour of RAC frame joints with precast beams and columns. The testing variables were the types of steel reinforcement connections, i.e., welded reinforcement, beam reinforcement connector and column reinforcement connector. Four specimens were tested under lateral reverse loadings with simulated practical boundary conditions. The test setup and steel reinforcement connection are displayed in Figure 9.

The test results (Table 8) indicated that the behaviour of the precast RAC joints is similar to that of joints with conventional concrete. The failure process can be divided into five stages: crack primarily, crack entirely, beam yielding, and limit state and ultimate failure. The type of the steel reinforcement connection has a significant effect on the bearing capacity, ductility and energy consumption of the joints. However, the ductility and energy consumption of the RAC joints were found to be able to meet the design requirements for precast concrete structures. This study gives a positive result towards the use of RAC in precast concrete structures.

3.3 RAC high rise shear walls

Cao et al. [26, 27] evaluated the cyclic behaviour of high rise shear walls made of RAC (Table 9). 6 high-rise shear wall specimens with shear-span to depth ratio 2.0 were

Figure 9 Test setup and steel reinforcement connection of pre-cast joint [25]. (a) Test setup; (b) connection.

Table 7 Summary of specimens for seismic behaviour of RAC column-beam joints

Investigator	RCA content (%)	28 Day compressive strength (cube) (MPa)	Ductility coefficient	Ring stiffness
	0	42.0	4.85	3.95
Xiao and Zhu. [24]	50	42.5	4.28	3.94
	100	40.0	4.34	4.11

Table 8 Collected test results on the seismic behaviour of pre-cast RAC joints

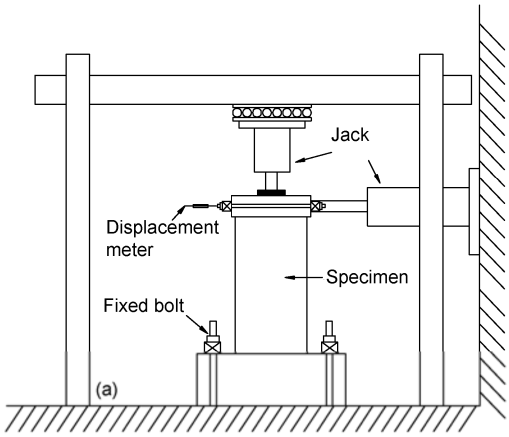
Investigator	Name of specimens	Types of steel reinforcement connections	28 Day compressive strength (cube) (MPa)	Ductility coefficient	Stiffness deterioration coefficient
Xiao et al. [25]	PJ-0	Welding	42.0	7.54	0.77
	PJ-1		36.8	9.34	0.65
	PJ-3	Beam connector	38.1	2.13	1.89
	PJ-4	Column connector	37.3	8.59	0.88

Table 9 The properties of the shear wall specimens [25]

Specimens		Percentage of recycled aggregate replacement (%)		Reinforcement ratio in the walls (%)	Axial-force ratio
		Fine	Coarse		
Low-rise shear wall	RCSW1.0-1	0	0	0.25	0.2
	RCSW1.0-2	100	33	0.25	0.2
	RCSW1.0-3	100	67	0.25	0.2
	RCSW1.0-4	100	100	0.25	0.2
	RCSW1.0-5	100	100	0.25	0.4
	RCSW1.0-6	0	100	0.25	0.2
	RCSW1.0-7	100	100	0.25	0.2
High-rise shear wall	RCSW2.0-1	0	0	0.25 (0.25)	0.2
	RCSW2.0-2	0	0	0.25 (0.15)	0.2
	RCSW2.0-3	50	50	0.25 (0.15)	0.2
	RCSW2.0-4	100	100	0.25 (0.15)	0.2
	RCSW2.0-5	100	100	0.25 (0.15)	0.4
	RCSW2.0-6	100	100	0.25 (0.15)	0.2

designed. The recycled coarse and fine aggregates replacement percentage of the specimens were changed from 0% to 100%. The reinforcement ratio in the lower half part of the walls was 0.25 while that in the upper half part was 0.25 or 0.15. The axial-force ratio was 0.2 or 0.4. Specimen RCSW2.0-6 was designed the same as RCSW2.0-4 except that the extra inclined steel bracings were embedded in the walls. The size of the specimen was 160 mm×1000 mm×2000 mm. The properties of all the specimens are listed in Table 9.

Based on the test findings (see Figure 10), the load-carrying capacity, the stiffness and its degradation, ductility, hysteretic behaviour, energy dissipation and failure phenomenon of each shear wall were analyzed. The results indicated that compared to the high-rise NAC wall, RAC shear wall show poorer performance, and that the higher the coarse aggregates replacement, the poorer the performance of the recycled aggregate concrete shear wall, but it is still able to satisfy seismic requirements through rational design.



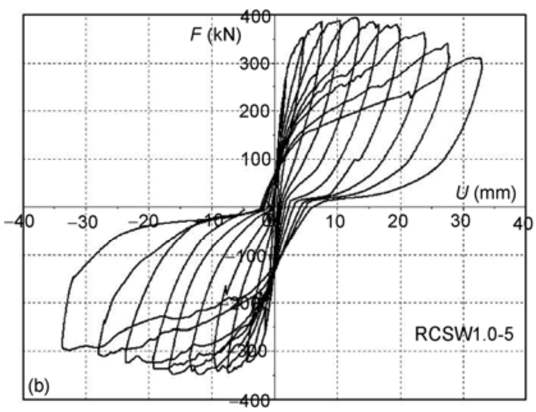


Figure 10 Test on RAC high rise shear wall [27]. (a) Test set-up; (b) hysteretic loops.

3.4 RAC low rise shear walls

Cao et al. [27, 28] further examined the cyclic behaviour of low rise shear walls made of RAC with a size of 160 mm× 1000 mm×1000 mm. 7 specimens (Table 9) were tested altogether. The influence of the recycled aggregates' replacement percentage, the axial load ratio, as well as the presence of the concealed bracing were investigated. The failure modes of some specimens are shown in Figure 11.

The main findings of the tests (Table 10) are:

Table 10 Corresponding conditions for shear wall tests

Investigator	Specimens	Research parameters	Ductility coefficient	Stiffness deterioration coefficient
Cao et al. [26]	High-rise RAC shear walls	RA content, replacement percentage, concealed bracing	7.359–8.789	0.188–0.197
Cao et al. [27]	Low-rise RAC shear walls	The axial compression ratio, RA content, replacement percentage, concealed bracing	5.108–7.817	0.088–0.153

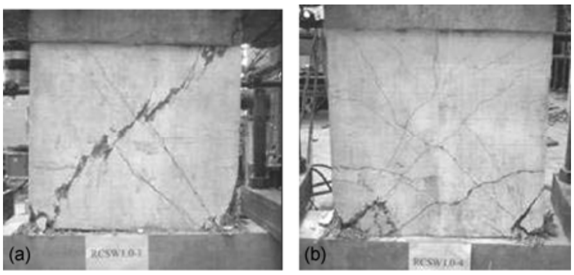


Figure 11 Failure modes of some RAC low rise shear walls [27]. (a) RCSW1.0-1; (b) RCSW1.0-4.

1) Compared to the low-rise NAC wall, the RAC shear walls show almost the same performance of load-carrying capacity, stiffness, ductility and energy dissipation. It is feasible to use recycled coarse aggregates in the shear wall.

2) Compared to the low-rise NAC wall, the seismic performance of RAC shear walls with recycled fine aggregates shows a little decline. Compared to the recycled coarse aggregates, the recycled fine aggregates have slightly larger influence on the seismic performance of the shear wall. The replacement percentage of recycled fine aggregates should be strictly limited.

3) The recycled concrete shear wall with concealed bracing shows good performance on load-carrying capacity, stiffness, ductility, and energy dissipation. With setting of concealed bracing in the low-rise shear wall with recycled concrete, seismic performance was improved greatly.

3.5 RAC block walls

Xiao et al. [29] reported the seismic behaviour of small-sized RAC hollow block walls. The test, included four specimens confined by tie column-beam systems, was carried out under low cyclic horizontal loadings, as shown in Figure 12. The testing variables were axial-load ratio and the different ratios of reinforcement in tie column. The corresponding test results are listed in Table 11, where P_{cr}, $P_{\max}$ and P_u are the cracking value, maximum value, and ultimate value of the load, respectively; Δ_{cr}, $\Delta_{\max}$ and Δ_u are the corresponding displacements.

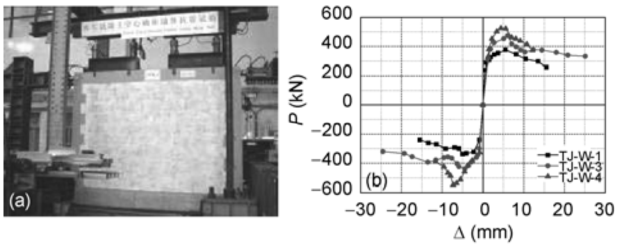


Figure 12 Seismic test and results of recycled concrete block walls [29]. (a) Test setup; (b) skeleton curves.

Based on the experiment observations, the damage process, the failure mode, the ultimate load and the deformation capacity as well as the energy dissipation of each specimen were studied. In addition, the interaction mechanism between the RAC block masonry wall and the tie column- beam confined system was investigated.

It can be seen that generally, the small-sized RAC block wall has good seismic behaviour, and that the increase of the reinforcement ratio in the columns does not improve the seismic performance of the walls. The inflection point was found to occur in the descending stage of skeleton curves, which means the tie column-beam confined system affects the resistance mechanism of the small-sized RAC block wall specimens.

3.6 RAC plane frame

Xiao, Sun and Falkner [30] investigated the seismic behaviour of RAC plane frames. The important parameters and objective of the test are presented in Table 12. Based on the tests of 4 large scaled frame specimens under low frequency cyclic lateral load with constant vertical actions, as shown in Figure 13, the failure pattern, the hysteresis curves, the skeleton curves, the energy dissipation capacity, and the stiffness degradation law of the frame structures made with recycled coarse aggregates were investigated. The effects of different RCAs replacement percentages (i.e., 0%, 30%, 50% and 100%) on the performance of the reinforced RAC

Table 11 Measured bearing capacity and displacement of wall specimens

Investigator	Specimen size (mm)	The vertical stress (MPa)	P_{cr} (kN)	$P_{\max}$ (kN)	P_u (kN)	Δ_{cr} (mm)	$\Delta_{\max}$ (mm)	Δ_u (mm)	Ductility coefficient
Xiao et al. [29]	3200×2200×220	0.3	239.29	357.09	303.16	0.666	5.263	10.113	μ_1=7.9
		0.3	305.44	456.22	387.64	1.056	5.266	15.064	μ_1=4.99
		0.6	328.64	536.23	455.68	1.056	5.874	8.593	μ_1=5.56

Table 12 Collected test results on the seismic behaviour of RAC plane frame

Investigator	Specimens	RCA content (%)	Objective	Axial load on column (kN)
	F0	0	To contrast	150
	F30	30		150
Xiao et al. [30, 32]	F50-1	50	To investigate the influence of RA content	150
	F100-1	100		150
	F50-2	50	To investigate the influence of the recycled lightweight masonry blocks	150
	F100-2	100	To investigate the influence of axial load	300

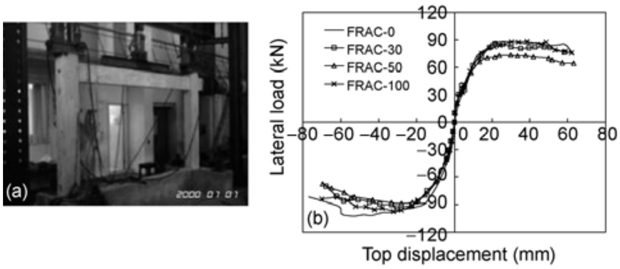


Figure 13 Test setup and skeleton curves of specimens [30]. (a) Test setup; (b) skeleton curves.

Figure 14 Test specimen filled with recycled concrete blocks [32].

frames were examined. It is concluded that the general seismic performance of the frame structure made of RAC declines with an increase of the RCAs replacement percentage. Nevertheless, a frame structure with a higher content of recycled aggregates still behaves well enough to resist an earthquake attack.

The interesting test results indicated the following:

1) All the investigated frames behaved similarly in the aspects of the failure pattern under low frequency lateral loading regardless of the RCA replacement percentage.

2) The presence of recycled aggregates reduced the yield, the maximum and the ultimate loads of the frames; however, this reduction was less than that of the mechanical properties of the concrete material.

3) The characteristic displacements among the test specimens proved that there are no obvious differences between the frames with RAC and conventional concrete, particularly in the aspects of the ductility coefficients and lateral drifts.

4) From the hysteresis loops, the energy dissipation and the rigidity degradation points of view, the seismic performance of the frames made with RAC is comparable to that with conventional concrete. And the frames with a properly designed RAC according to Chinese Code GB50011 (2001) [31] is able to resist an earthquake.

In addition, Sun and Xiao et al. [32] further examined the influence of the filling of RAC blocks on the performance of the RAC frames subjected to the cyclic lateral loading (Figure 14). The main finding can be summarized in the following: The infilled wall could work well together with the frame. The stiffness and capacity of resistive horizontal loads of the frame were improved greatly, but the deformation and energy dissipation performance were weaker than frames which were not filled with RAC blocks. The influences of infilled wall of frame on the main frame structure should arouse attentions of designers.

4 Shaking table tests on RAC structures

To check the seismic behaviour of RAC realistically, much expensive and complex shaking table test was also carried out in China on RAC structures. This work was performed in view of the reconstruction of the damaged areas by the Wenchuan Earthquake, which occurred in May 2008.

4.1 Small-sized RAC hollow block structure

Xiao et al. [33] investigated the behaviour of a RAC masonry structure with a shaking table test. In the study, the Wenchuan Wolong seismic wave was used to study the behaviour of RAC masonry structure of “tie column + ring beam + cast-in-place slab” under seismic conditions. The test, as shown in Figure 15, included not only the dynamic characteristics of structure but also the damping ratio, the frequency changes and the top floor displacement of the structure under different levels of seismic activity.

On the basis of the test results, it was found that maximum drift of the model structure is less than the allowable value of earthquake resistant structure in the Code for Seismic Design of Buildings [31]. Although tiny cracks were found on the walls, the test results proved that RAC masonry structure confined by a “tie column + ring beam” system exhibits fairly good seismic behaviour.

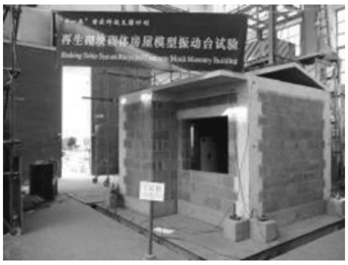


Figure 15 RAC block masonry model [33].

4.2 RAC frame structure

Xiao et al. [34] also investigated the seismic performance of RAC frame structures using the shaking table test; see Figure 16. The structure had six stories and a non-symmetrical layout. The seismic fortification intensity was 8 degrees, the design group was the second group of earthquake according to the related Chinese Code [31]. After the shaking table test, the failure mechanism of the model structure was analyzed. The natural frequency and damping ratio of the model structure were calculated. In addition, the acceleration response and displacement response of the model for each loading case were also obtained. The maximum inter-storey displacements obtained from WCW with PGA of 0.130, 0.185, 0.370, 0.415, 0.550 and 0.750 g were demonstrated in Figure 17.

Based on the intensive analysis of the test results, the following conclusions and corresponding suggestions are derived:

1) In the shaking table model tests, in the case of the RAC frame structure with 100% RCAs replacement percentage, the failure first occurred at the ends of the beams, then at the bottom of columns, which is characterized in a manner of "strongest joints, stronger columns and weaker beams".

2) The structural displacement response was considerably influenced by the lower order vibration modes, and the

Figure 16 General view of the RAC frame model [34].

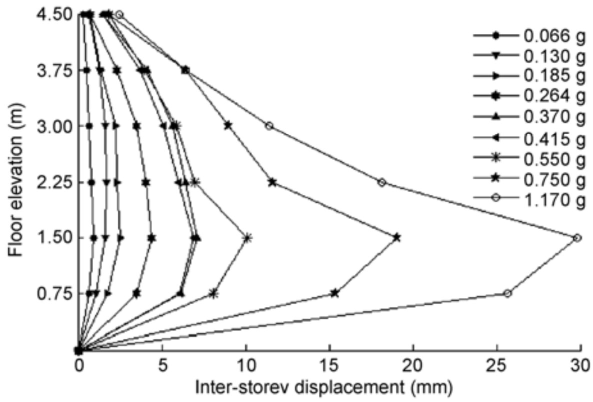


Figure 17 Maximum inter-storey drifts under WCW [34].

distribution of the maximum storey displacement assumed the inverted triangular form basically along the height of the RAC frame model structure throughout the shaking table model tests.

3) The structural system in the RAC frame model demonstrated good performance in resisting earthquakes. The test result indicated that the RAC frame model structure has good ultimate deformation capacity and ductility.

4) The RAC frame structure with proper design and construction had good load-bearing capacity, deformation capacity and other seismic performances. It is feasible to apply and popularize the recycled concrete frame buildings in aseismic regions.

5 Milestone in the application of RAC in China

5.1 Beijing (2007)

Under the technical support of Prof. Chen, Beijing Architectural College constructed a three storey building "Civil Engineering and Transportation Laboratory" using recycled concrete in 2007 (Figure 18). The recycled aggregates were produced from demolished concrete pavements and building waste.

Figure 18 Three-story pilot building with RAC in Beijing, China.

5.2 Sichuan, the Wenchuan earthquake-hit area (2008)

On 12 May, 2008 a devastating earthquake struck the Sichuan Province of the People’s Republic of China. It had a magnitude of 8.0 on the Richter scale. The damage intensity reported in many of the most severely affected areas reached the level of X and XI, including Dujiangyan City. Most of the buildings and constructions were damaged and destroyed seriously during the earthquake and its aftershocks. Massive construction and demolition (C&D) waste was generated from removing these collapsed and dilapidated buildings for reconstruction in the earthquake-hit area.

The demonstrative project presented in this paper involves two kinds of structures. The buildings are located in Dujiangyan City, Sichuan Province of the People’ Republic of China. Figures 19 (a) and (b) show the waste concrete in disaster area and the RCAs. After concrete production process, RCAs became building materials in Figures 19 (c) and (d). Similarly, Figure 20 shows how to use RAC block masonry as building materials in an engineering building project. Figures 20 (a) and (b) present two typical RAC blocks in construction. The application effects can be seen in Figures 20 (c) and (d).

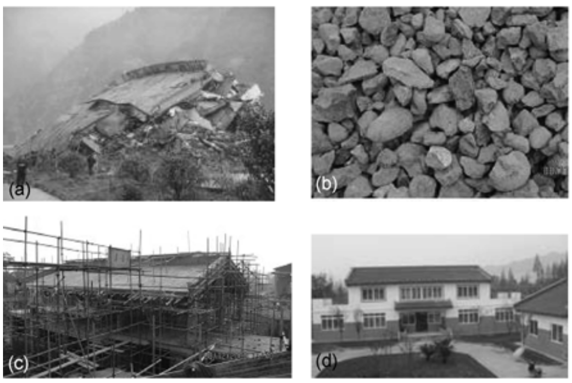


Figure 19 Demonstrative project with RAC frame structure in Dujiangyan, China. (a) Waste concrete; (b) recycled aggregate; (c) construction site; (d) finished appearance.

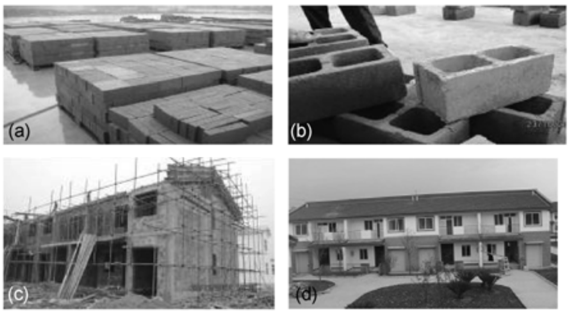


Figure 20 Demonstrative project with RAC masonry structure in Dujiangyan, China. (a) Recycled bricks; (b) recycled hollow units; (c) construction site; (d) finished appearance.

5.3 Shanghai, Expo Park (2010)

The Shanghai Ecological House in the 2010 Shanghai World Expo Park was constructed using recycled aggregate concrete. It occupies 1300 m^2 of land, with an overall area of 3001.17 m^2, whereby it has 4 floors above the ground with a total area of 2222.03 m^2, and one floor underground with an area of 779.14 m^2. Figure 21 displays the waste concrete, the recycled aggregates, the recycled concrete and construction site, respectively.

6 Conclusions and remarks

This paper gives a comprehensive report on the relevant researches and findings on the structural performance of recycled aggregate concrete (RAC) in mainland China. The main conclusions can be summarized as follows:

1) A large number of experimental work has been carried out in China to investigate the structural performance of RAC elements and structures, both under monotonic and cyclic loadings.

2) The structural behaviours of RAC elements/members are generally weaker in comparison to those of structures made of natural aggregate concrete (NAC).

3) Through proper design, RAC can be used as a structural material from the view point of the loading capacity behaviour.

4) More tests on the serviceability properties of RAC elements and structures need to be carried out in the future.

5) The bending reliability index of recycled concrete beams is proved to meet the requirements of the Unified Standard for Reliability Design of Building Structures (GB 50068-2001).

6) To realize a safe and economic design of RAC structures, more efforts are still required in this filed, both in the aspects of test and nonlinear analytical work.

7) The recycled coarse aggregates (RCAs) are being adopted in building engineering projects as load bearing

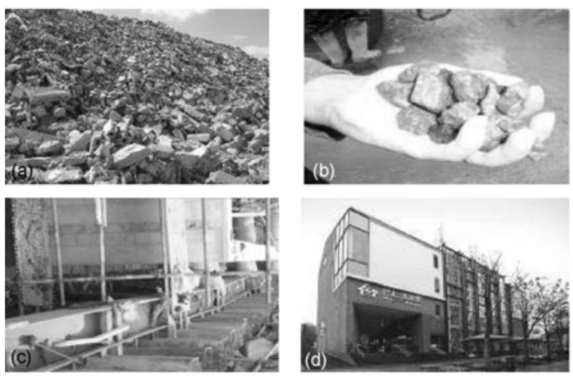


Figure 21 Shanghai ecological home located in the 2010 Shanghai World Expo Park. (a) Waste concrete; (b) recycled aggregate; (c) construction site; (d) finished appearance.

members of structures such as the Shanghai World Expo buildings, and demonstration projects such as illustrated above which were carried out in Beijing and Sichuan earthquake hit-areas.

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