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AN EMPIRICAL STUDY OF THE BEHAVIOR OF RECYCLED AGGREGATE CONCRETE BEAMS FROM CDW IN HANOI, VIETNAM

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ABSTRACT: The employment of recycled materials from construction and demolition waste (CDW) for mixing recycled aggregate concrete (RAC) is widely practiced in developed countries. In Vietnam, however, being a developing country with a rapid rate of urbanization, especially in major cities, the substantial amount of CDW generated is still mainly treated by landfilling. To promote the recycling of CDW, studies of the performance of structural members fabricated with recycled aggregates must be conducted, which are lacking in quantity in Vietnam. Adopting a standard experiment set up of reinforced beams, the study employed local recycled coarse aggregates in Hanoi, Vietnam, produced from crushed concrete and crushed brick (which is mixed with crushed concrete at controlled percentages) to conduct experiments to observe flexural behaviors with reference to equivalent natural aggregate concrete (NAC) such as cracking load, ultimate load, crack pattern, crack width, etc. The results showed that the ultimate loads were only reduced by less than 10% for all percentages of recycled coarse aggregate produced from crushed brick in the concrete mix, compared to the reference beams using NAC. However, the cracking loads of RAC beams were significantly reduced by 17.86% to 50.45% when increasing the content of crushed brick from 0% to 70%. Moreover, together with an increase in the number of flexural cracks, the deflections of RAC beams also increased with increasing content of crushed brick, demonstrating a reduction in the stiffness of the beams. These observations may serve as recommendations to structural engineers in Vietnam when designing flexural RAC members.

Keywords: Construction and demolition waste, Recycled aggregate concrete, Flexural strength, Reinforced concrete beam

1. INTRODUCTION

The studies of recycled aggregate concrete (RAC) employing coarse and/or fine aggregates produced from recycled construction and demolition waste (CDW) in various countries have shown that, given sufficient quality control, this type of concrete is capable of being used in casting structural members. Naturally, RAC has lower values of mechanical properties (compressive strength, modulus of elasticity, or flexural strength) than that of natural aggregate concrete (NAC). Studies of compressive strength, for example, since the 1970s until now generally report an average reduction of 15-20% of this property when 100% natural coarse aggregate (NCA) is replaced by recycled coarse aggregate (RCA) produced from crushed concrete (CC) [1-7]. In all of these studies, RCA is not treated to remove adhered mortar, and no special mixing sequence is adopted. However, even with such a reduction, the strength of RAC in these studies was still adequate for different applications in construction. As a result, further experiments on the behavior of RAC beams have been designed and conducted. For such experiments, the type of recycled aggregates (coarse and/or fine aggregate) and the type of source CDW (CC and/or crushed brick – CB) are considered.

Ajdukiewicz and Kliszczewicz [8] set up a 4-point flexural test apparatus for rectangular beams with cross-sectional dimensions of B×H = 200mm×300mm. The beams were 2,400 mm long and were loaded at equal intervals of 800mm. The values of ultimate load and deflection, together with observations of crack formation, were recorded. It was found that the ultimate load of RAC beams was not reduced by much (only by 3.5%) in comparison with that of reference NAC beams. However, the instantaneous deflection of RAC beams was always larger by 18-100% (i.e., double). In this experiment, the authors employed RCA produced from CC to replace NCA with a replacement rate of 100%, and all other materials remained natural.

With a similar choice of recycled aggregates, in 2015, Arezoumandi et al. [9] conducted experiments on RAC and NAC beams. The test results showed that the reduction of the ultimate load of RAC beams was negligible (less than 1%) compared with equivalent NAC beams. This behavior was also reported by Zhao and Sun [10]. In their experiments employing RCA produced from CC, the ultimate load of RAC beams was lower by 2.6 to 4.1%, with an increasing replacement rate from 30 to 75%.

A number of other publications over the years shared the same conclusion on ultimate load [11,12]. However, in these two studies, it was also observed that the cracking load of RAC beams was much lower that of NAC beams. For instance, two studies in 2013 and 2018 showed a reduction of 20% up to 46.3%. Table 1 summarizes these reduction rates.

Table 1 Reduction rate of flexural strength of RAC beams in previous studies

Authors	Replacement rate of RCA (%)	Reduction rate of flexural strength (%)	
		Cracking load	Ultimate load
[8]	50	14.3	1.5
	100	14.3	3.8
[9]	100	8-18	<1
[11]	20	10.5-10.9	<1
	50	20.3-45.6	<1
	100	26.4-46.3	<5
[12]	50	20	4.8
	100	20	5.5

Note: All studies employed only RCA produced from CC with various replacement rates of NCA.

Ye et al. [13] studied the flexural behavior of reinforced RAC beams in a corrosive environment. The authors employed four mixtures with the replacement rates of 0%, 33%, 66%, and 100% by mass. RAC were mixed with RCA produced from CC collected from demolished structures in China. The authors concluded that a replacement rate of less than 30% is generally recommended so that the flexural behavior of RAC beams is generally comparable to that of equivalent NAC beams.

A comprehensive study by Makul et al. [14] in 2021 summarized the production and promotion of RAC in the past 20 years and highlighted potential developments of this industry in the near future. The authors provided an overview of the current status in Europe, the United States, and a number of countries in Asia. It was found that among the recycled products from CDW, RCA produced from CC is the most useful, and accounts for the majority of the benefit. There are incentive policies in many countries to promote the adoption of RAC, but its utilization rate is still rather limited due to the lack of official regulations and design standards. Intensive studies have been conducted on RAC columns (i.e., structural members under compression) in the US and China. Topics involving other products from CDW (e.g. RCA that contains CB, or recycled fine aggregates), or structural members under other types of loading (e.g. flexure, torsion) are desirable in order to facilitate the wider application of RAC.

Recently, studies on RAC have evolved to incorporate artificial intelligence (AI) and artificial neural network (ANN). Duan et al. [15] were able to predict the 28-day compressive strength of RAC using the ICA-XGBoost model, verifying its accuracy against existing reports. Momeni et al. [16] attempted to adopt ANN to predict the flexural strength of RAC beams. Results of the simulation were compared to experimental results using reinforced NAC and RAC beams in laboratory. The ANN predictive model showed good agreement with a correlation coefficient (R-value) of 0.997, opening up a promising direction for future research.

In most previous studies of RAC beams, the authors opted for RCA produced from CC – which is the best source material in terms of strength and conformity. The quality of RCA is also much easier to control in comparison with recycled fine aggregate. Experimental results of RAC beams employing materials with less conformity (i.e., containing a certain content of CB) are very desirable. This issue is even more relevant in developing countries such as Vietnam, where an effective management system of CDW is still lacking, hence most CDW is mixed CC-CB as described by Nguyen et al. [17].

In Vietnam, currently, studies on RAC have had a number of achievements together with the overall development strategy of construction materials towards a circular economy. For instance, to examine the behavior of RAC in structures, Quang et al. [18] conducted experiments on reinforced RAC columns under centric compression. The authors adopted three mixtures with the replacement rates of 0% (NAC – reference specimen), 50%, and 100% and monitored the long-term performance of the columns, including creep and shrinkage. It was found that the creep coefficient of RAC is 32-45% higher than that of NAC depending on the replacement rate, thus, it is recommended to carefully monitor and maintain RAC structural components in the long-term.

2. RESEARCH SIGNIFICANCE

As presented in the previous section, there is still a general lack of studies on the behavior of RAC in other types of structural components in Vietnam. Moreover, there is also a need to study the behavior of recycled aggregates produced from a mix of CC-CB, because this is the dominant type of CDW in Vietnam currently. To address these issues, the authors adopted an empirical method to study the flexural behavior of RAC beams, in which 100% NCA was replaced by RCA. The RCA in these experiments consisted of CC and CB at controlled percentages. The obtained results would contribute to the understanding of the flexural behavior of RAC beams, including the load-deflection relationship (i.e., cracking load, ultimate load, deflection at midspan), the crack pattern (number, length, and width of cracks), the failure mode, and the strain distribution in concrete and steel reinforcement under loading.

3. PRODUCTION OF RCA FROM CDW

The source material selected in this study was CDW from demolition of the Tan Mai Primary School, Hanoi, Vietnam. CDW was moved to a recycling facility, where it went through a stationary production line to be crushed and sieved. The RCA collected from this production line was then further sieved into the sizes of 10-20mm, and 5-10mm. Fig. 1 presents the final product of RCA from CC. RCA from CB was produced by a similar procedure.

Fig.1 RCA produced from CC of size (a) 10-20mm, and (b) 5-10mm

4. EXPERIMENT DESIGN

4.1 Mix Design of Concrete

Mix proportion details are presented in Table 2.

Table 2 Mix design of concrete

Component	Concrete mix			
	NAC	RAC0B	RAC30B	RAC70B
C	300	300	300	300
S	850	850	850	850
G1	275	–	–	–
G2	825	–	–	–
C1	–	275	192.5	82.5
C2	–	825	577.5	247.5
B1	–	–	82.5	192.5
B2	–	–	247.5	577.5
W	165	165	165	165
A	3	3	3	3

Note: C - cement; S - sand; G1 - NCA size 5-10mm; G2 - NCA size 10-20mm; C1 - RCA from CC size 5-10mm; C2 - RCA from CC size 10-20mm; B1 - RCA from CB size 5-10mm; B2 - RCA from CB size 10-20mm; W - water; A - additives; all units are in kg.

The grain size of the coarse aggregate is controlled by mixing particles of size 5-10mm and 10-20mm at an appropriate percentage to meet the requirements of Vietnamese National Standard TCVN 11969:2018 [19] as shown in Fig. 2.

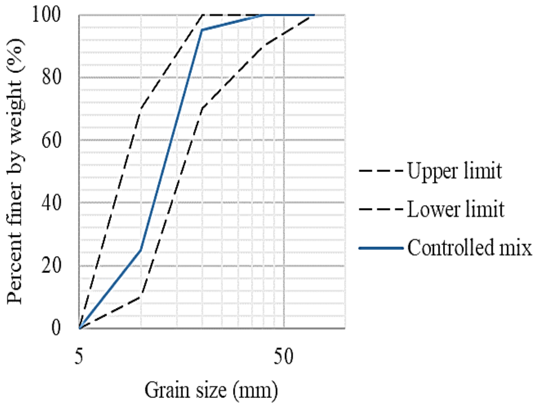


Fig.2 Grain size distribution curve of the controlled mix against the limits in TCVN 11969:2018 [19]

The physical properties of all aggregates employed in the experiment are verified to comply with the requirements of the corresponding Vietnamese National Standards. Tables 3 and 4 present the properties of RCA and NCA against TCVN 11969:2018 and TCVN 7570:2006 [20], respectively. It is seen that RCA from CC can be classified as Class I aggregates (the better type of CA), whereas RCA from CB can be classified as Class II aggregates.

Table 3 Aggregate properties of RCA and verification against TCVN 11969:2018 [19]

Property	Unit	RCA from CC	RCA from CB	Limit	
				Class I	Class II
Density	kg/m^3	2,680	2,550	> 2,300	> 1,800
Water absorption	%	4.8	13.7	< 5	< 20
Crushing value	%	17.7	25.4	< 20	< 30
Los Angeles abrasion	%	33.4	48.7	< 50	< 50
Organic matter	–	Lighter color		Lighter color than the standard color	
Content of particles smaller than 0.075mm	%	0.2	1.2	< 2	< 3
Content of other materials	%	1.2	2.5	< 0.5	< 1
Flakiness index	%	21	27	< 35	

Table 4 Aggregate properties of NCA and verification against TCVN 7570:2006 [20]

Property	Unit	NCA	Limit
Density	kg/m^3	2,760	–
Water absorption	%	0.8	–
Crushing value	%	12.4	11-13
Los Angeles abrasion	%	27.1	< 50
Organic matter	–	Lighter color	Lighter color than the standard color
Content of dust, mud, clay particles	%	0.1	< 1

NAC and RAC in these experiments were mixed at a constant water/cement (W/C) ratio of 0.55. The target cube strength of concrete was f_{cu} = 30MPa for all mix proportions. Four mix proportions were adopted, denoted by numbers as follows:

(i) NAC: 100% natural aggregates;

(ii) RAC0B: 100% RCA from CC, 100% natural sand as fine aggregates;

(iii) RAC30B: 70% RCA from CC, 30% RCA from CB, 100% sand as fine aggregates; and

(iv) RAC70B: 30% RCA from CC, 70% RCA from CB, 100% sand as fine aggregates.

To enhance the final quality of RAC, a two-stage mixing approach (TSMA) was adopted. This concrete mixing process was proposed by Tam et al. [21] and it was reported that the mixing process improved the instantaneous strength and microstructure of RAC as well as its long-term behaviors such as shrinkage or creep [22]. Figure 3 displays the procedure of TSMA employed in this experiment.

Table 5 Properties of concrete mixes

Property	Mix			
	NAC	RAC0B	RAC30B	RAC70B
Dry density (kg/m^3)	2,430	2,380	2,310	2,190
Slump (cm)	15.1	11.5	8.8	12.6

The final four concrete mixes are of good workability, represented by the slump value. They are also classified as heavyweight concrete according to TCVN 3015:1993 [23]. The results of slump and dry density are presented in Table 5.

At 28 days, compression tests were carried out on concrete cylinders of diameter 150mm and height 300mm to determine the compressive strength of NAC and RAC. The results are characterized by the compressive strength (f_c), the mean compressive strength (f_{cm}), the standard deviation (sd), and the coefficient of variation (cv) as presented in Table 6. The mean compressive strength of NAC equals 46.5MPa, with a standard deviation of 3.0MPa. Meanwhile, the mean compressive strengths of RAC range from 34.9MPa to 40.9MPa as the CB aggregate content increases in the concrete mix. They are reduced by 12.1-24.8% compared to NAC. The maximum reduction of the compressive strength is observed in the RAC30B mix, followed by the RAC0B and RAC70B mixes. The result of RAC70B can be explained by the increased content of CB absorbed a significant amount of free water in the first hours after mixing, resulting in a reduction in the W/C ratio, which ultimately contributed to the improvement of the compressive strength during the hardening process. However, further experimental works, such as observations of concrete microstructure and repeatability of tests, are needed to reconfirm the findings in this study.

Table 6 Compressive strengths of NAC and RAC

Mix	Sample	f_c (MPa)	f_{cm} (MPa)	sd (MPa)	cv (%)
NAC	1	42.6	46.5	3.0	6.4
	2	47.0			
	3	49.8			
RAC0B	1	37.5	37.9	1.1	3.0
	2	36.8			
	3	39.5			
RAC30B	1	35.4	34.9	0.7	2.0
	2	35.5			
	3	34.0			
RAC70B	1	43.0	40.9	1.9	4.6
	2	38.4			
	3	41.3			

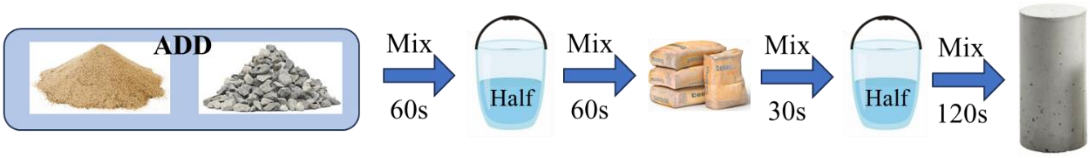


Fig.3 Two-stage mixing approach (TSMA) from Tam et al. (2005) [21]

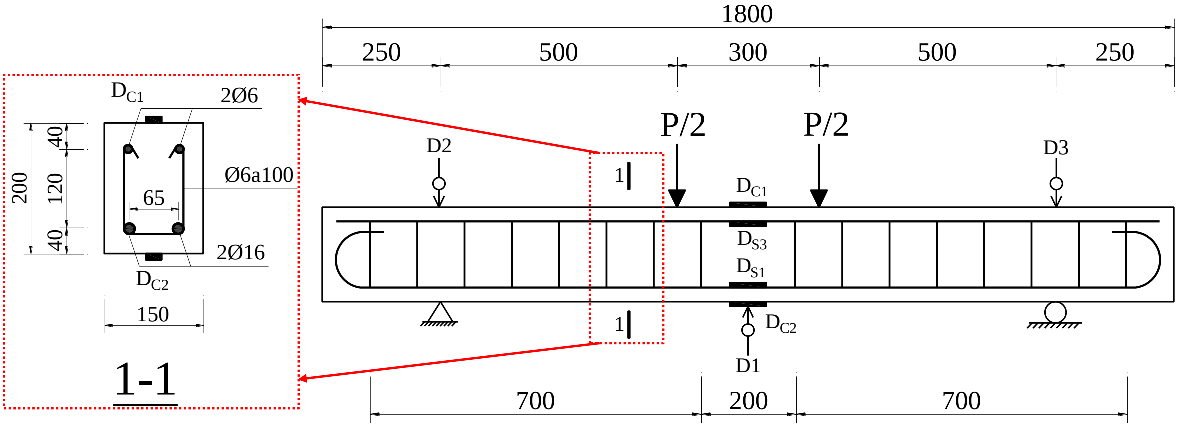


Fig.4 Layout of reinforced concrete beam specimen and four-point bending test

4.2 Beam Specimens and Testing Configuration

4.2.1 Beam details and setup of sensors

Twelve reinforced concrete beams of rectangular cross-section (3 for each concrete mix proportion) were cast to conduct 4-point flexural experiments. The cross-sectional area of all beams was B×H = 150mm×200mm, and the length was 1,800mm. Steel reinforcements (rebars) are arranged as follows (Φ – diameter of rebar):

- Longitudinal reinforcements: 2Φ8 (deformed bar) top reinforcements; 2Φ16 (deformed bar) bottom reinforcements.
- Stirrup: Φ6@100mm (plain bar) throughout, skip at midspan.

Beams were situated on two supports at a distance of 1,300mm. The pure bending length is 300mm. Each beam was arranged with the following sensors (Fig. 4):

- 03 linear variable differential transformer (LVDT) sensors D_1, D_2, and D_3 to measure vertical displacements at designated points (one at the midspan, and two at supports).
- 02 resistance strain gauges D_{C1}, and D_{C2} to measure strains at top and bottom layers of concrete.
- 02 resistance strain gauges D_{S1}, and D_{S2} to measure strains in bottom rebars.
- 01 resistance strain gauge D_{S3} to measure strain in one of the two top rebars.

The LVDT D_1 measured the displacement at the midspan of the beam, denoted as δ_1. Meanwhile, the LVDTs D_2 and D_3 measured the displacements at the two supports, denoted as δ_2, and δ_3, respectively. The deflection of the beam, denoted as δ, is then calculated by formula (1).

$$\delta = \delta_1 - \frac{\delta_2 + \delta_3}{2} \tag{1}$$

It is observed that the displacements at the supports (i.e., δ_2 and δ_3) are slightly different. This is due to the variability of concrete, and the crack occurred first on one side of the beam.

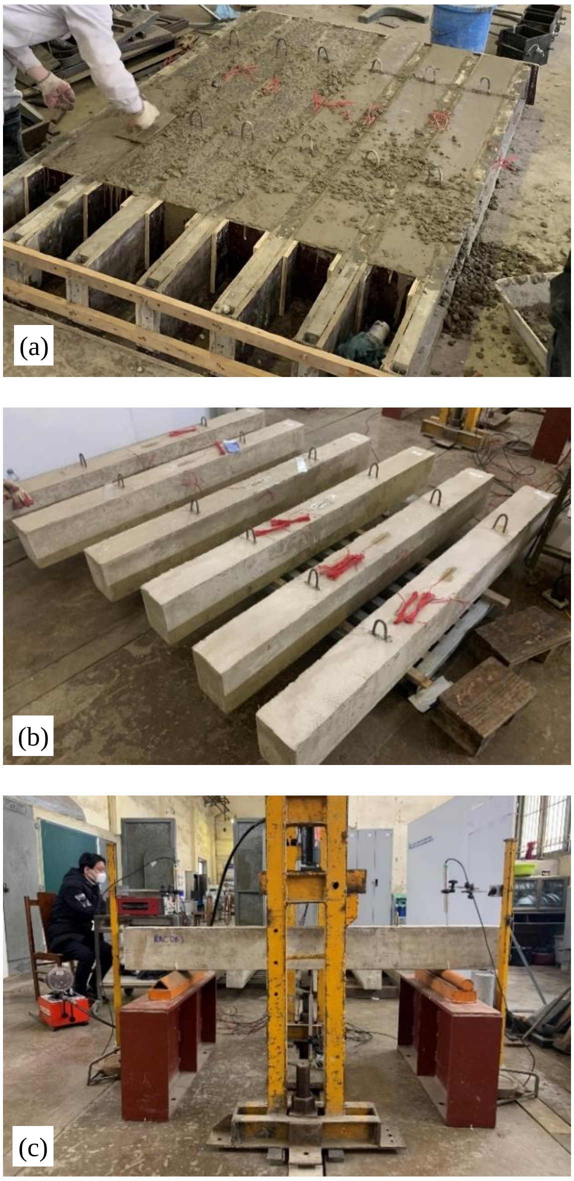


Fig.5 (a) Casting of experimental beams; (b) Beams with installed sensors; (c) Four-point flexural test apparatus

4.2.2 Experiment procedure and apparatus

Experimental beams were cast by the TSMA as shown in Fig. 5a. Each beam group consists of three specimens made of concrete from the same batch. At 3-day old, formworks were removed and the beams were to cure at room temperature. Final products with all strain gauges installed are presented in Fig. 5b.

At 28-day old, each beam was fixed onto the apparatus as shown in Fig. 5c. All measuring instruments, including load-cell, LVDT, and strain gauges, were connected to a TDS-530 data logger to record automatically the testing data. The experiments were carried out using the loading control with a loading rate of 0.25±0.05kN/s. Moreover, the surfaces of the tested beam were carefully observed during the test to detect the first crack due to loading. The formation and propagation of cracks were marked in color on the surface of each tested beam.

5. RESULTS AND DISCUSSION

5.1 Load-Deflection Curves

The load-deflection curves obtained from the four-point flexural test are presented in Fig. 6 for all four groups of specimens, including (a) NAC beams, (b) RAC0B beams, (c) RAC30B beams, and (d) RAC70B beams. It can be seen that the flexural behavior is similar among three beams in the same group. The flexural behavior of NAC and RAC beams is characterized by three main stages as follows:

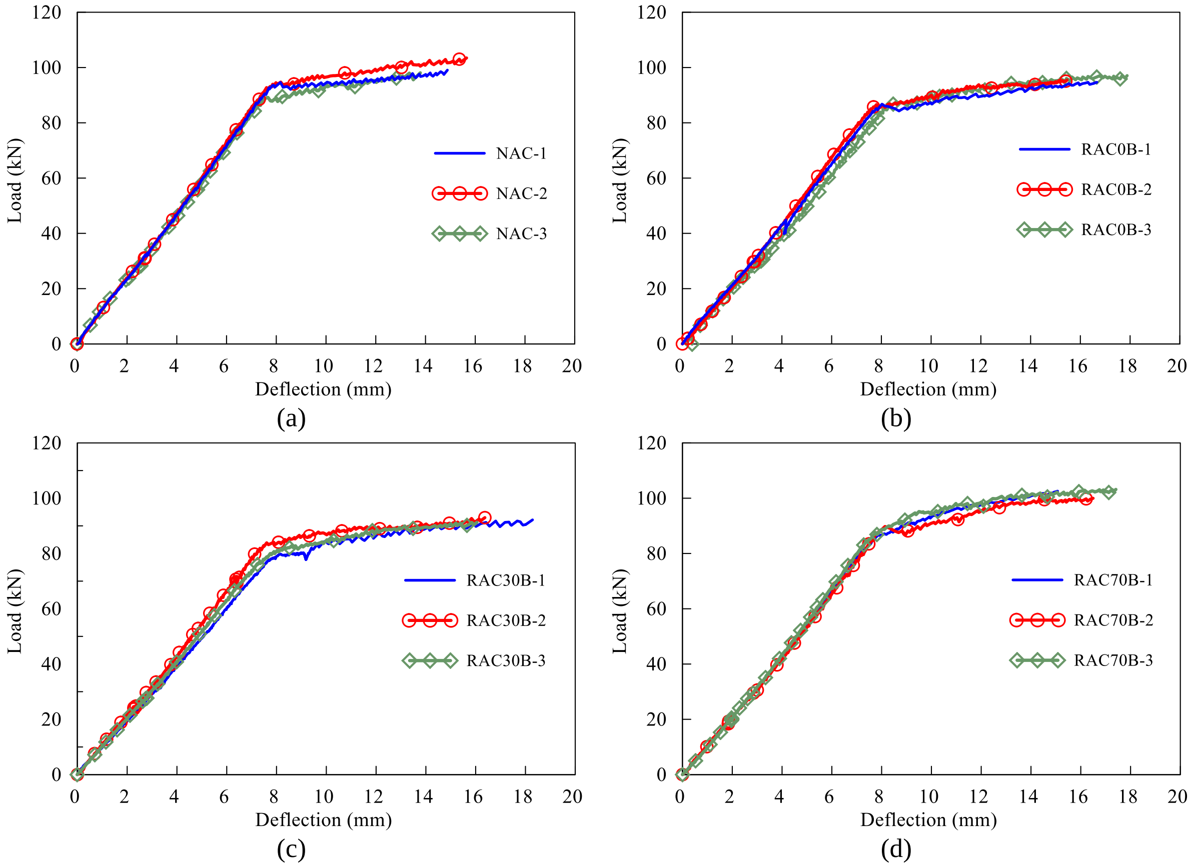
(i) Linear behavior between load and deflection before the cracking of concrete;

(ii) Nonlinear behavior between load and deflection after the cracking of concrete, until before the yielding of steel reinforcement;

(iii) The failure stage is characterized by steel reinforcement yielding, causing the rapid development of beam deflection while the applied load changed at a slight rate, or remained unchanged.

The similarity in the flexural behavior of tested beams in the same group indicates that concrete and beam specimens were fabricated with high quality control. Moreover, the tests were consistently performed for all beam specimens.

Based on the results in Fig. 6, the following parameters were determined for each beam: cracking load (P_{cr}), ultimate load (P_u), and deflection (δ). For each group of specimens, the average values were then calculated for these parameters, denoted as $\overline{P}_{cr}$, $\overline{P}_u$, and $\overline{\delta}$ for average cracking load, average ultimate load, and average deflection, respectively.



(a) (b)

(c) (d)

Fig.6 Load-deflection curves of beam specimens: (a) NAC beams, (b) RAC0B beams, (c) RAC30B beams, and (d) RAC70B beams

Table 7 Summary of main results of experimental beams

Beam designation	Cracking load			Ultimate load			Deflection		
	P_{cr} (kN)	$\overline{P}_{cr}$ (kN)	$\dfrac{\overline{P}_{cr}^{RAC}}{\overline{P}_{cr}^{NAC}}$	P_u (kN)	$\overline{P}_u$ (kN)	$\dfrac{\overline{P}_u^{RAC}}{\overline{P}_u^{NAC}}$	δ (mm)	$\overline{\delta}$ (mm)	$\dfrac{\overline{\delta}^{RAC}}{\overline{\delta}^{NAC}}$
NAC-1	38.26	36.63	–	99.07	100.20	–	14.88	14.77	–
NAC-2	37.28			103.47			15.65		
NAC-3	34.34			98.07			13.79		
RAC0B-1	32.37	30.08	0.821	94.67	95.74	0.955	16.67	16.64	1.127
RAC0B-2	28.45			95.47			15.47		
RAC0B-3	29.43			97.07			17.80		
RAC30B-1	22.56	23.05	0.629	92.17	92.14	0.919	18.29	16.90	1.144
RAC30B-2	23.54			92.97			16.37		
RAC30B-3	23.05			91.27			16.05		
RAC70B-1	17.17	18.15	0.496	102.57	101.90	1.017	15.07	16.33	1.106
RAC70B-2	17.66			99.97			16.50		
RAC70B-3	19.62			103.17			17.41		

Compared to the average value of the NAC group, the influence of RCA from CC and RCA mixed from CC and CB with various replacement rates can be assessed by the ratios of $\dfrac{\overline{P}_{cr}^{RAC}}{\overline{P}_{cr}^{NAC}}$, $\dfrac{\overline{P}_u^{RAC}}{\overline{P}_u^{NAC}}$, and $\dfrac{\overline{\delta}^{RAC}}{\overline{\delta}^{NAC}}$. The results are summarized in Table 7. In this table, the beams are named with the same designation as the concrete mix, followed by a number (1, 2, or 3) to identify the three beams in the same group.

For the reference group of NAC beams, the cracking loads ranged from 34.34 to 38.26kN, with an average value of 36.63kN and a coefficient of variation of 4.5%. The ultimate loads were recorded by load cell, ranging from 98.07 to 103.47kN, with an average value of 100.2kN and a coefficient of variation of 2.3%. Therefore, the flexural strength of experimental NAC beams is less varied than the cracking strength. At failure, the deflections of NAC beams were measured by LVDT displacements, ranging from 13.79 to 15.65mm, with an average value of 14.77mm and a coefficient of variation of 5.2%. The variation in the deflection can be explained by a slight difference between crack patterns observed on the beams, which will be presented in the subsequent section of this paper. The average deflection of NAC beams corresponds to approximately 1/90 of the clear span.

For the second group of RAC0B beams, the cracking loads ranged from 28.45 to 32.37kN, with an average value of 30.08kN and a coefficient of variation of 5.5%. The reduction in the cracking load was also identified for the two other groups of RAC beams. RAC30B beams had cracking loads ranging from 22.56 to 23.54kN, with an average value of 23.05kN and a coefficient of variation of 1.7%. Meanwhile, the cracking loads of RAC70B beams varied from 17.17 to 19.62 kN, with an average value of 18.15kN and a coefficient of variation of 5.8%. This result indicates that the average cracking load of RAC beams was significantly reduced compared to that of NAC beams as the CB content increases in the RCA composition. The reduction rate ranges from 17.86% to 50.45%. Therefore, flexural cracks would occur earlier on RAC beams, especially when the RCA comprises of a higher CB content. This is because the properties of RCA produced from CB are lower than those of NCA, and RCA produced from CC. This finding agreed well to the conclusion of previous studies [8-12].

The ultimate load is one of the most critical parameters for assessing the flexural behavior of RAC beams. For the group of RAC0B beams, the ultimate loads ranged from 94.67 to 97.07kN, with an average value of 95.74kN and a small coefficient of variation of 1.0%. The average ultimate load of this group of beams was reduced by 4.5% compared to the reference group of NAC beams. Similarly, RAC30B beams had the ultimate loads vary from 91.27 to 92.97kN, with an average value of 92.14kN and a small coefficient of variation of 0.8%. The average ultimate load of these beams decreased by 8.1% in comparison to that of NAC beams. The reduction in the ultimate load was not observed on RAC70B beams in this study. The ultimate loads of this group of beams ranged from 99.97 to 103.17kN, with an average value of 101.9kN and a coefficient of variation of 1.4%. It is observed that the average ultimate load of RAC70B beams is equivalent to that of NAC beams. This surprising result requires more experimental research on RAC70B beams, or additional experiments on RAC with intermediate percentages of RCA from CB in the concrete mix.

Consider the particular group of RAC70B beams, due to the earlier cracking of concrete (expressed by the 50.4% reduction rate in average cracking load), it can be said the contribution of longitudinal reinforcement dominates the load-carrying mechanism. A sufficient longitudinal reinforcement ratio was used for the experimental beams (Fig. 4) to help make the flexural strength of RAC70B beams comparable to that of the reference group of NAC beams. Nevertheless, this remark still needs further confirmation through additional experiments.

The average deflections of three groups of RAC beams ranged in a small interval from 16.33mm to 16.90mm, with a coefficient of variation of approximately 6%. Thus, compared to the reference group of NAC beams, the average deflection of RAC beams increases by 10.6% to 14.4%. This result also indicated that the stiffness of RAC beams after cracking was lower than that of NAC beams.

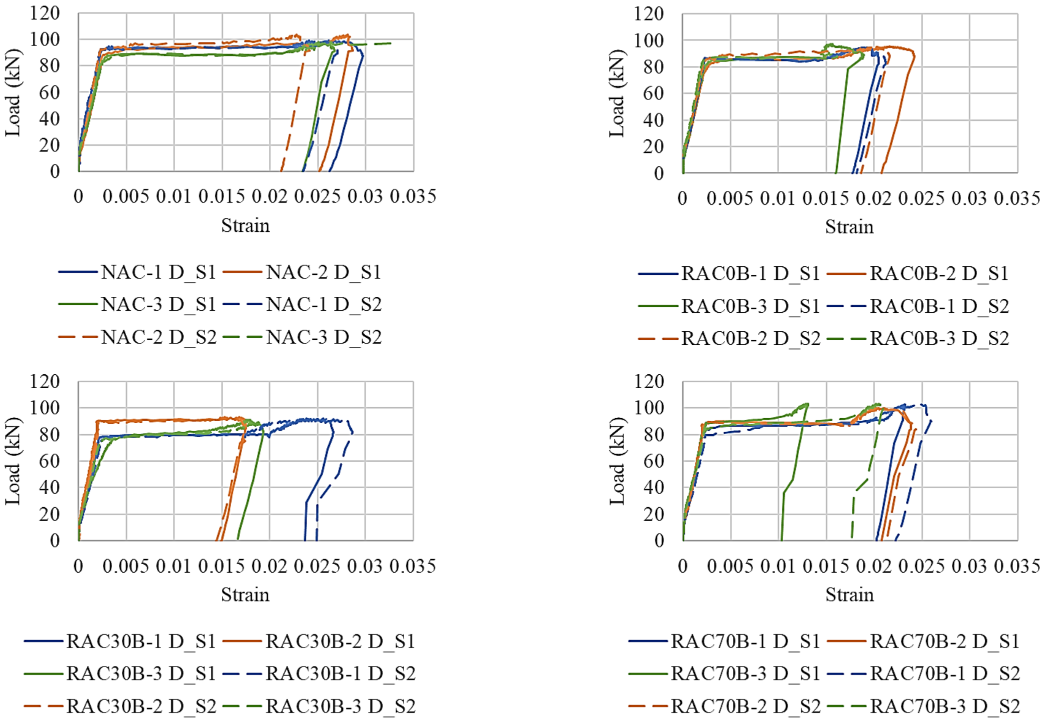


Fig.7 Load-strain curves in tensile steel rebars

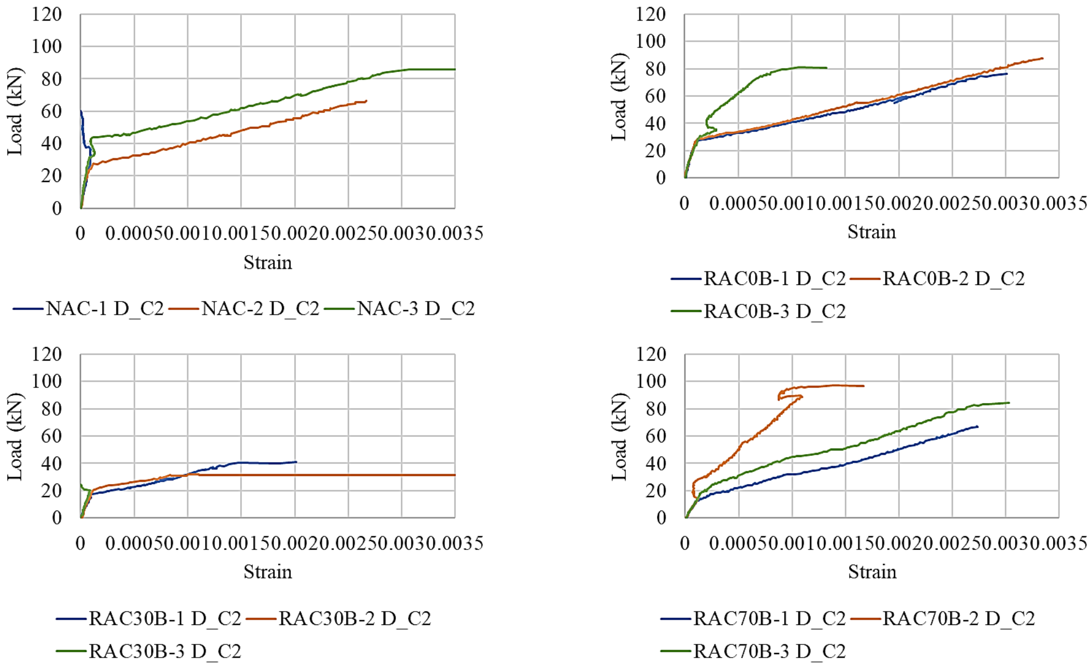


Fig.8 Load-strain curves at the bottom layer of concrete at midspan (in tension)

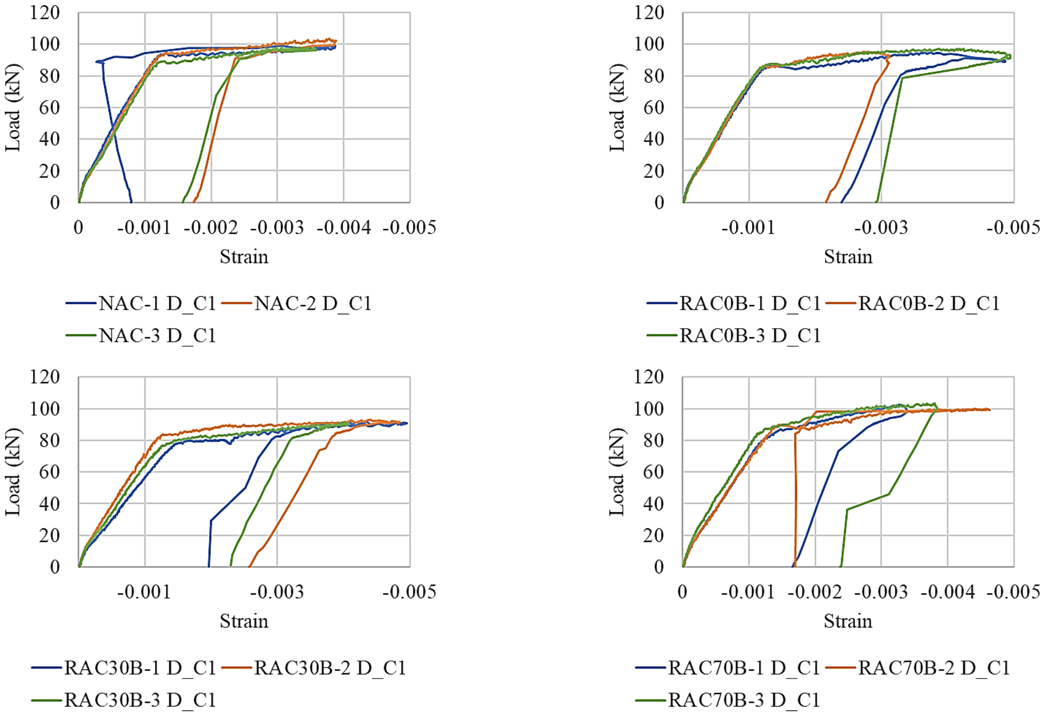


Fig.9 Load-strain curves at the top layer of concrete at midspan (in compression)

Fig.10 Crack patterns of experimental beams (a) NAC beams, (b) RAC0B beams, (c) RAC30B beams, and (d) RAC70B beams

5.2 Load-Strain Curves

The load-strain curves for tensile steel rebars are presented in Fig. 7. As it is observed, the two tensile steel rebars began yielding at the applied load of around 80kN for all experimental beams. This value corresponds to the yielding points in Fig. 6. Therefore, it is possible to conclude that the flexural cracks that opened in the tensile area caused the yielding of tensile longitudinal reinforcement.

Figure 8 displays the strain of concrete at the bottom layer (in tension). The readings are consistent and linear for all three beams of the same group up until a certain point where the readings are disrupted, which might be caused by the separation of the strain gauge from the beam. The loading values at these points were all slightly lower than the recorded cracking load, which may indicate the occurrence of internal cracks within the beams.

At the failure of the beams, concrete in the compressive area was observed to be crushed, corresponding to the ultimate strain in compression as indicated in Fig. 9. Meanwhile, the readings of strain gauges placed on compressive steel rebars were omitted as they do not display a consistent trend.

5.3 Crack Patterns and Failure Mode

Figure 10 shows the crack patterns of all tested beams in this study. The flexural cracks were vertical and concentrated between and neighboring two loading points. These cracks initially appeared at the bottom face in the tensile area of the beams and propagated towards the compressive area with increasing loading. Combined with the results presented in section 5.2, it can be concluded that all tested beams failed by flexural mode. Moreover, it can be seen that compared to NAC beams, the number of flexural cracks increases on RAC beams, particularly on RAC30B and RAC70B beams, as shown in Figs. 10c and 10d.

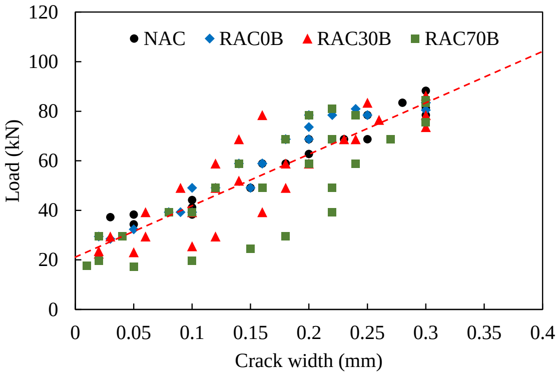


Fig.11 Crack-mounted opening measurements

An optical device was used to measure the crack width during each four-point bending test. After the first crack was observed, the device was placed at the position of this crack to monitor the crack-mounted opening. The result of the measurements aims to determine the applied loads corresponding to the critical crack widths (0.2 and 0.3mm) that are commonly defined in design codes. Figure 11 shows the result of the crack width measurements of 12 beam specimens. A trend line can be drawn for this diagram, which shows that RAC70B beams were cracked at the lowest applied load. For a target crack width of 0.2mm, the applied loads ranged from 60 to 80kN, and for 0.3mm, the applied loads varied from 75 to 90kN. The average applied loads of RAC beams at 0.3mm crack width is lower than that of NAC beams, but the difference between all four groups of beams is less than 4%.

6. CONCLUSIONS

In this study, an experimental program was carried out in the laboratory to assess the flexural behavior of RAC beams made with RCA produced from CC and CB. Results were compared with reference NAC beams. It was found that the cracking load of RAC beams was significantly reduced compared to NAC beams with the increase of CB content in the RCA composition. The reduction rate reached as high as 50.45%. For RAC beams using only RCA produced from CC, the ultimate load was reduced by 4.5% on average, and the deflection increased by 12.7% on average compared to NAC beams. Meanwhile, for RAC beams made with mixed RCA produced from CC and CB, the reduction in ultimate load was not apparent, and several inverse effects were observed due to abnormal behaviors (e.g. water absorption, grain size, microstructure) of CB.

For reaching a critical crack width of 0.3mm, the applied loads of RAC beams were lower than those of NAC beams, but the difference between them was less than 4%. It was also observed that the number of flexural cracks increased on RAC beams, particularly for those with CB in the RCA composition. Hence, it is advisable that when designing structural components made with RAC, the calculation of deformations (e.g. crack width, critical deflection) should be considered carefully. Revisions of design codes may also be needed to facilitate the application of RAC in specific components.

Further experimental work on RAC beams cast with RCA having intermediate percentages of CB (40%, 50%, or 60%) can enrich the results presented in this paper and provide a better view of the variation of flexural strength. The observations of RAC microstructures might also reveal more explanations.

7. ACKNOWLEDGMENTS

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