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EXPERIMENTAL STUDIES ON BEHAVIORS OF REINFORCED CONCRETE COLUMN STRUCTURES MADE OF RECYCLED AGGREGATES UNDER CONCENTRIC LOADS

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Abstract

The paper presents experimental results and structural analysis of reinforced concrete (RC) columns made of recycled aggregate concrete (RAC) and natural aggregate concrete (NAC) under concentric compressive load. The ratio of recycled aggregates in mixture (i.e, replacement ratio, *r* in %) was 0, 50, and 100% by mass, where *r* = 0% corresponding to NAC. The load and deformation curves including cracking load, ultimate load, crack width, and compressive strain of the tested columns, were analyzed to determine the effects of replacement ratio of recycled aggregate on the behaviors of square column structures. The results show that the increase of *r* reduced the load-carrying capacity of RC columns under the concentric compressive load. Horizontal and vertical cracks also were observed immediately for tested columns with high *r*. The effect of *r* of RAC on the mechanical behaviros, however, became relatively small and did not affect the behaviors of RAC columns, indicating that the RAC tested in this study was feasible for use in recycled concrete structures.

Keywords: recycled aggregate concrete; natural aggregate concrete; construction and demolition waste; square columns; concentric load.

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1. Introduction

Vietnam is undergoing rapid economic development, and the construction sector is among the fastest developing areas. Vietnam's construction growth rates in six consecutive years of 2015–2020 were 10.82%, 10.00%, 8.70%, 9.16%, 9.10%, and 6.76 according to the Report on the Socio-economic Situation in the Fourth Quarter and the year of 2020 by the General Statistics Office of Vietnam [1]. The construction rate slowed to 6.76% only due to the effect of COVID-19 pandemic, while other years increased about a 10% annually. The construction boom has also caused a serious issue for society, which is construction demolition waste (CDW). Giang et al. [2] estimated that about 4,000 tons of CDW were generated in Hanoi in 2020, and the annual increment of building demolition waste from

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2016 to 2020 was 4–5% [3]. This CDW is currently not properly separated and recycled; instead, it is illegally dumped or reused as landfill materials [4]. This causes serious issues for residential areas, especially big cities such as Hanoi, Ho Chi Minh, Da Nang, Hai Phong, and Can Tho. In Directive No. 41/CT-TTg, the five largest cities must reduce final disposal of solid waste to 20% in, and all other provinces to 25% in by 2025 [5]. The Decision No. 491/QD-TTg Approving Adjustments to the National Strategy for Integrated Management of Solid Waste directed that 90% of total construction demolition waste discharged from urban centers be collected and treated by methods that meet the environmental protection requirements, while 60% of discharged CDW be reused or recycled into products or materials by appropriate technologies [6].

Due to the excessive use of sand and natural aggregate used for construction, the Vietnamese government just introduced Decision No. 1266/QD-TTg that sets the development strategy of Vietnam's construction material in the period of 2021–2030, with vision a towards 2050 [7]. This specifies that from 2031 to 2050, the consumption of virgin materials must be limited and requires that 60% of sand, aggregates, and concrete used for construction be produced from recycled materials. Thus, recycling activities are very important in Vietnam and over the world to meet the development requirements of the industry as well as to comply with the Government's legal system.

In recent years, there have been several studies related to recycling CDW in the world as well as in Vietnam. Hoang et al. [8] studied CDW management in Southeast Asia and concluded that this region needed more aggressive methods to achieve sustainable CDW management and development. Nghiem et al. [9] described the CDW generation flow in Vietnam in which the CDW consisted of soil, concrete, bricks, tiles, wood, gypsums, metals, aluminum, glass, etc. Giang et al. [10] reported that the new management in Vietnam required that CDW be collected and recycled as specified in No. 08/TT-BXD Regulating the Management of Construction and Demolition Waste [11].

The mechanical properties of recycled aggregate concrete have been extensively studied (Guo et al. [12]; Li et al. [13]; Peng et al. [14]; Zhou and Chen [15], Quang et al. [16], Thai et al. [17]). However, research on the use of RAC in structures was limited due to the known low quality of RAC structures [18, 19]. These studies used RAC of mansion demolition waste, which had relatively low quality concrete. Nowadays, the concrete structures being demolished have concrete of a good quality. Many of these are high quality structures, such as bridges, airport runways, high-rise buildings, and even some new constructions that are undergoing restructure [20, 21]. These constructions generate a relatively high quality of demolished concrete suitable for RAC for structures with reasonable quality requirements. Recently, much research has been carried out to study the performance of RAC structures with partially or fully replaced natural aggregate concrete (NAC). The main targets for research were RAC beams and RAC columns, and they were compared to NAC structures to understand the mechanism and applications. For example, the flexural behaviors of RAC beams were extensively discussed by Sato [22], Alnahhal and Aljidda [23], and Seara-Paz et al. [24]. RAC column behaviors were discussed by Choi and Yun [25] with a column size of $400\times400\times2000$ mm and water-to-cement ratio $w/c = 0.436$ and column with size of $400 \times 400 \times 1800$ mm, $w/c = 0.33$ and replacement ratio $r = 0$, 30, 60, and 100%. Hao et al. [26] tested a series of concentrically and eccentrically loaded columns with a size of $150 \times 200 \times 1400$ mm, $w/c = 0.315$, and $r = 0, 50$, and 70%.

Even though the performance of RAC structure had been extensively studied, the utilization of RAC for concrete structures is still limited due to the lack of reliable information on the origin of recycled aggregates and their structural performances. Thus, it is critical to better understand RAC structures and frontier applications. This CDW could add value by high quality recycling. The good practical application of CDW recycling could bring benefits for this industry, therefore encouraging

CDW management and 3R in this country [27]. Thus, this paper presents research on performances of RAC column structures under concentric loading with CDW replacement ratios $r = 0$, 50, and 100% and a water-to-cement ratio $w/c = 0.39$.

2. Material properties

2.1. Origin of concrete

The recycled aggregates (RA) used in this study were taken from a 2-story concrete frame building used for an industry in Hanoi. The building was constructed in 2000, and the concrete cylinder samples were drilled before the demolition work took place. Three samples of concrete with a diameter of 54 mm and maximum length of 150 mm were drilled in 3 column structures on the first floor of the building. The samples were then prepared in the laboratory for compression tests to determine the compressive strength of origin concrete aggregate, as shown in Fig. 1. Table 1 shows the results of the compression tests, including the height (H) and diameter (D) of samples, the calculated coefficients related to drilling direction and reinforcement, and the compressive strength. The results obtained show a strength class C20/25 for the original concrete used (Table 1). This concrete strength was popular for RC structures at that time in Vietnam.

(a) Sampling of concrete

(b) Capping of concrete samples

Figure 1. Origin of concrete samples (C20/25)

Table 1. Compressive strength of drilled concrete cores

Sample	Dimensions (mm)		Maximum load (kN)	H/D	Drilling direction coefficient	Reinforcement coefficient	Compressive strength (MPa)	Mean compressive strength (MPa)
	H	D						
M1	124	54	40.0	2.30	2.3	1.0	20.8	
M2	110	54	41.0	2.04	2.3	1.0	20.7	20.9
M3	98	54	43.5	1.81	2.3	1.0	21.3	

2.2. Mechanical properties of RAC

The demolished concrete was then separated and crushed through a designed system with suitable sieves to produce aggregates 0–5 mm and 5–40 mm in diameter [16]. In this study, only recycled concrete aggregates with 5–20 mm diameter were used as RA. All aggregate tests were taken in accordance with Vietnamese standard TCVN 7572:2006 [28]. The main properties of recycled aggregate were tested and compared to specifications for recycled coarse aggregate of concrete in Vietnamese standard TCVN 11969:2018 [29]. The properties of recycled aggregate were also compared to those specified in JIS A 5022:2018 - Class M; GB/T 25177-2010 (Chinese) type 2 and WBTC No.12/2002 (Hong Kong). Results of comparative studies are shown in Table 2.

Table 2. Properties of RAC

Property	Test results	TCVN 11969:2018 class 1	GB/T 25177-2010 (Chinese) class 2	JIS A 5022:2018 Class M	WBTC No.12/2002 (Hong Kong)
Moisture content (%)	1.87	-	< 2		-
Water absorption (%)	3.53	≤ 5	< 5	≤ 5	≤ 10
Apparent density (g/cm^3)	2.43	≥ 2.3	> 2.35	≥ 2.3	≥ 2.0
Los Angeles abrasion (%)	30	≤ 50	-		
Elongation (%)	12,2	≤ 35	-		

According to the results from Table 2, the used recycled aggregates meet the requirements of TCVN 11969:2018 class 1. The mechanical properties of recycled aggregates were also in the category of class IIIA in a summary by Silva [30], and the mechanical properties of recycled aggregate were as good as those of natural aggregate (NA). This RA also meets the requirement of class M according to JIS A 5022:2018 and Class 2 in GB/T 25177-2010 (Chinese). Compared to multiple international standards, the RA of these experiments could be classified as good as NA used for concrete structures.

2.3. *Material, compressive strength test, and results*

Concrete mix designs used for RCA and NAC are summarized in Table 3. Curing condition, size of cast specimens, and testing standards are summarized in Table 4. In this study, the replacement ratio of RAC for NAC was $r = 0, 50$, and 100%, with water-to-cement $w/c = 0.39$, and the designed compressive strength was C25/30. The compressive strength of RAC and NAC has been studied by

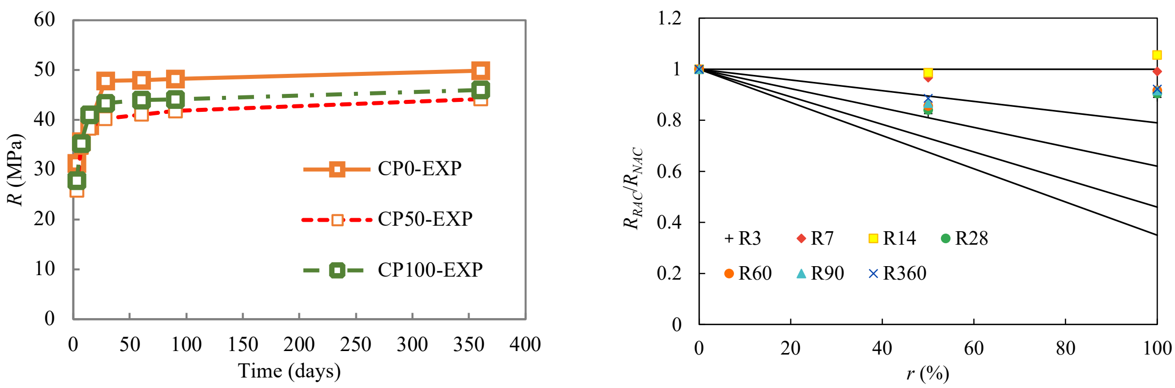
Table 3. Concrete mix designs in this study

Mix	Unit	NAC	RAC	
		CP0	CP50	CP100
Water	kg	190	190	190
Cement	kg	490	490	490
Fine aggregate	kg	700	700	700
Coarse aggregate (5-10 mm) – NA	kg	450	225	–
Coarse aggregate (10-20 mm) – NA	kg	600	300	–
Coarse aggregate (5-10 mm) – RA	kg	–	225	450
Coarse aggregate (10-20 mm) – RA	kg	–	300	600
Admixture	kg	4.9	4.9	4.9

Table 4. Curing conditions and size of tested specimens

Specimen	Curing method	Curing time (day)	Size (mm)
Concrete for compressive strength test	Wet	28	$D = 150, H = 300$
Concrete of RC column (loading test)	Wet	28	$W = 200, H = 200, L = 880$

Choi et al. [31], Katkhuda and Shatarat [32], and other researchers. However, the development of RAC concrete strength is not fully understood. For the RAC used, the compression tests were carried out at 3, 7, 14, 28, 60, 90, and 360 days of age to measure the evolution of the concrete compressive strength (denoted R) with time, as shown in Fig. 2. Compressive strength development of NAC samples ($r = 0\%$) had $R_{28} = 47.9$ MPa. Its R_3, R_7, and R_{14} were 65%, 74%, and 81% of R_{28}, respectively. The compressive strength of r_0 became stable and did not change much after 28 days of curing. Its compressive strength at 360 days reached 49.9 MPa (increased about 4% compared to R_{28}).



(a) Concrete compressive strength over time

(b) Concrete strength ratio as a function of r

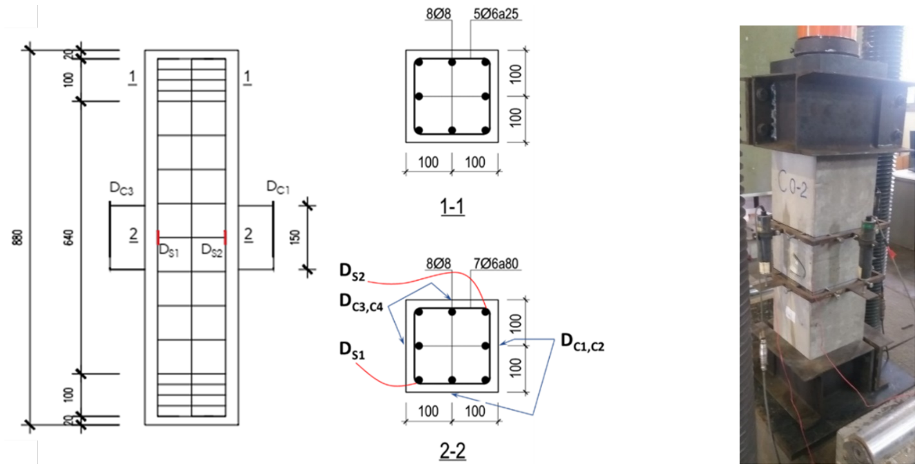
Figure 2. Effect of RA replacement ratio (r) on concrete compressive strength

For RAC with $r = 50\%$ and 100%, the compressive strength at 28 days was 40.2 MPa and 43.3 MPa, respectively. Test results showed that at 7 days, the compressive strength reached about 85%, while at 14 days, it reached about 95% of that at 28 days. The reason for earlier compressive strength development in RAC could be explained by the existence of cement mortar around the recycle aggregates. This mortar absorbed water in the mixture, thus affecting w/c of the mixture. After 28 days, RAC samples showed similar behaviors as NAC in that the concrete strength became stable, and the concrete strength reached 44.2 MPa and 46.0 MPa for $r = 50\%$ and 100%, respectively. These are 5–10% increases in compressive strength at 360 days. RA replacement reduces the compressive strength of concrete. However, $r = 100\%$ showed higher strength than $r = 50\%$. This could also be explained by the effects of internal curing water initially in RA on the new cement paste and the unhydrated cement particles contained in the old, adhering mortar, resulting in a new calcium-silicate-hydrate (C-S-H). This C-S-H can gradually fill the region around RAC and improve the bonding between RAC and the new cement paste, thus resulting slight improvement of mechanical performance of RAC (Poon et al. [33], Sakata and Ayano [34], Li et al. [35] and Xiao et al. [36]), indicating that the RA tested in this study was suitable to use in concrete as aggregates.

3. Mechanical behaviors of reinforced recycle aggregate column

3.1. Experiment setup

The tested columns had the dimensions of 200 × 200 × 880 mm, which is a typical section for low buildings in Vietnam, as shown in Fig. 3. Longitudinal reinforcing steel bars were 8 mm in nominal diameter, while stirrups used 6 mm nominal diameter steel wire with a regular spacing of 80 mm in the middle and 25 mm at two ends of the columns. The specifications of these steel bars are shown in Table 5.



(a) Layout of column samples (b) Experiment setup

Figure 3. Detailed layout and set-up of tested columns

Table 5. Specifications of steel bars

No	Steel types: Nominal diameter (mm)	Tensile strength: Yield load P_c (daN)	Yield strength R_c (MPa)	Ultimate load P_b (daN)	Ultimate strength R_b (MPa)	Elongation ε (%)
1	∅6	800	283.1	1280	452.9	27.9
		840	297.2	1200	424.6	29.1
		840	297.2	1260	445.9	29.1
2	∅8	1650	328.0	2490	495.0	28.0
		1720	341.9	2500	497.0	29.7
		1700	338.0	2460	489.1	29.3

In this study, eight specimens were divided into three groups with different RA replacement ratio $r = 0\%$, 50%, and 100%; with water-to-cement $w/c = 0.39$ and named C0, C50, and C100, respectively. Of these, two NCA samples named C0-1 and C0-2 were considered the control columns. Each group of RCA samples had three column samples to determine the average value of the parameter studied.

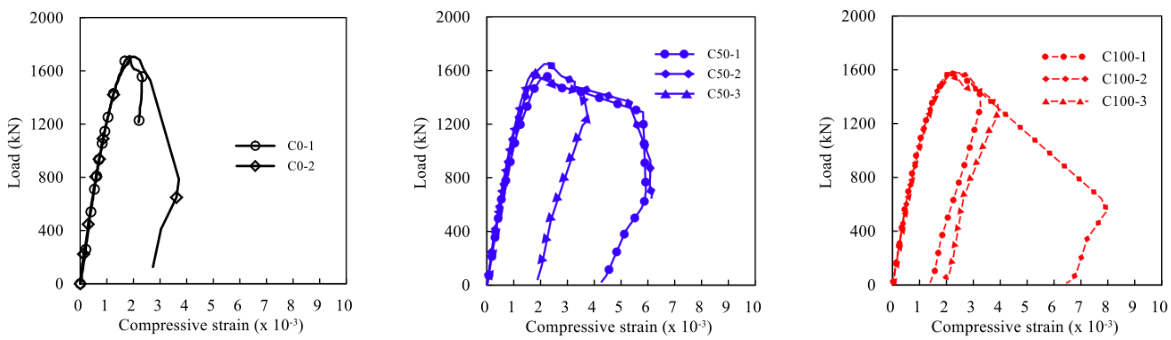
Four linear variable differential transformers (LVDT) with a 50-mm stroke were attached on four of the column faces. The LVDT was used to measure the relative displacement at two sections separated by 150 mm, as shown in Fig. 3. The compressive strain was calculated by Eq. (1):

$$\varepsilon_{comp.} = \frac{1}{4}\left(\frac{f_1}{150} + \frac{f_2}{150} + \frac{f_3}{150} + \frac{f_4}{150}\right) \tag{1}$$

where, $\varepsilon_{comp.}$ is the average compressive strain of the tested columns, with f_1, f_2, f_3, and f_4 being the relative displacements measured at the four outer faces of the column. Two strain gauges (D_{s1}, D_{s2}) were attracted to two opposite corner longitudinal steel bars, as illustrated in Fig. 3. All of the data in tests were recorded by the 30-channel datalogger TDS-530. During the tests, both ends of the columns were capped with a couple of 5-mm thick steel cages to ensure the force was transmitted uniformly.

3.2. Experiment results and analysis

The relationship between axial load and compressive strain of tested columns is shown in Fig. 4. The failure mode of tested columns was quite similar for different replacement ratios $r = 0, 50$, and 100%. For NAC columns, the elastic modulus showed higher values [16], and the ultimate loads were



(a) r = 0% (NAC) (b) r = 50% (RCA) (c) r = 100% (RCA)

Figure 4. Axial load - strain curves of column samples with different r values

Table 6. Results of columns tested under concentric load

Column name	Dimensions (mm)	r (%)	Ultimate load, $P_{u,r}$ (kN)	Mean ultimate load (kN)	Strain at peak ($\times 10^{-3}$)	Mean strain ($\times 10^{-3}$)	$P_{u,r}/P_{u,r=0}$
C0-1 C0-2	200×200×880	0	1711 1706	1708	1.87 1.96	1.91	1.00
C50-1 C50-2 C50-3	200×200×880	50	1561 1653 1586	1600	2.23 2.21 1.83	2.09	0.94
C100-1 C100-2 C100-3	200×200×880	100	1583 1589 1561	1577	2.40 2.21 2.20	2.27	0.92

achieved at higher values and small column strains compared to RAC columns. With increasing RA replacement ratios, the ultimate concentric load was achieved with a larger strain, as shown in Table 6.

The ultimate concentric load of NAC was slightly higher than that of $r = 50$ and $r = 100$. The effect of replacement ratio on ultimate axial load is shown in Fig. 5, where $P_{u,r}/P_{u,r=0}$ of $r = 50\%$ and 100% are 0.94 and 0.92, respectively. This indicates that the ultimate loads were reduced by 6.33% and 7.67% for $r = 50\%$ and $r = 100\%$. Fig. 5 shows a comparative result between this study and recent studies carried out on RAC column samples. Choi and Yun [25] investigated columns of 400 × 400 × 2000 mm having $w/c = 0.43$, while column samples with size of 400×400×1800 mm having $w/c = 0.33$, and with different $r = 0\%, 30\%, 60\%$, and 100% and the longitudinal steel reinforcement ratio of 1.4% for all tested samples. The results of $P_{u,r}/P_{u,r=0}$ versus r were varied in which for $r = 30\%$ of $w/c = 0.43$, the $P_{u,r}/P_{u,r=0}$ was greater than 1.0, while this value of $w/c = 0.33$ was smaller than 1.0. These values were in opposite when $r = 60\%$ for those mixtures. The $P_{u,r}/P_{u,r=0}$ was both smaller than 1.0 for all of these tests. Ajdukiewicz and Kliszczewicz [20] also conducted tests for concentric column with $w/c = 0.36$. Their results were unchanged in values of $P_{u,r}/P_{u,r=0}$ with all values $r = 0\%$, 50%, and 100%. Fig. 5 shows that the w/c ratio affects the ultimate load and water absorbed in adhering mortar affects w/c ratio resulting in the ultimate load of column.

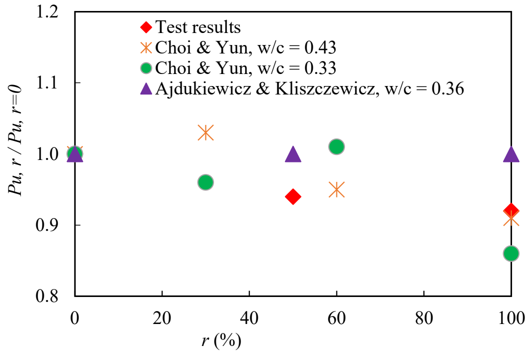
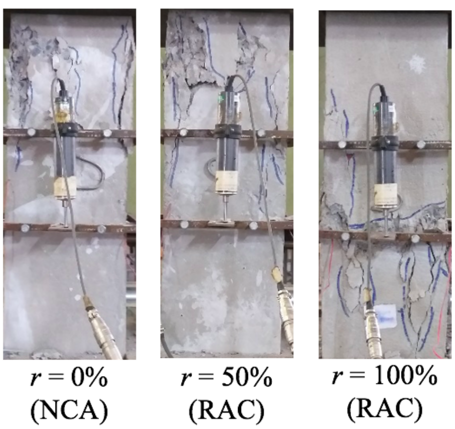
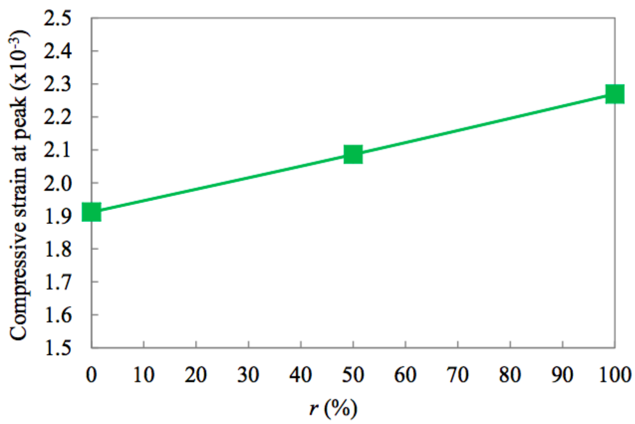


Figure 5. Effect of RA replacement ratio (r) on ultimate load of column samples

The failure modes of RAC and NAC columns are shown in Fig. 6. The inspection of failed columns showed that the cracks appearing on RAC columns were quite similar to cracks on NAC columns. After testing, both ends of RAC and NAC columns remained unbroken while cracks were mostly concentrated in the middle zone. The experimental results indicate that the RA from old buildings was good enough to meet Vietnamese and international standards for recycled aggregates. Moreover,



(a) Failure mode



(b) Column strain at peak as a function of r

Figure 6. Failure modes of columns under ultimate concentric load

using this material in column structures showed an acceptable performance in terms of ultimate load and deformation under compression, which could be applied in practical works.

4. Conclusions

Construction demolition waste from a 20-year-old building was taken and separated properly for recycling research activities. Mechanical properties of RA were tested and compared with Vietnamese standard 11969:2018 for recycled coarse aggregate for concrete and JIS A 5022:2018 - Class M; GB/T 25177-2010 (Chinese) type 2 and WBTC No.12/2002 (Hong Kong). This RA was then used for RAC columns and compared to NAC columns in terms of ultimate load and deformation under compression. A series of loading tests were carried out, and the experimental results were analyzed. The main conclusions are as follows:

- Conventional recycled aggregates from old RC buildings could meet mechanical requirements for recycling as specified in the Vietnamese and international standards for the normal type of concrete.

- The ultimate loads of RAC columns were reduced by 6.33% and 7.67% with $r = 50\%$ and 100%, respectively compared to NAC columns.

- The ultimate load peak of NAC columns was achieved at the higher value at smaller compressive strain compared to RAC's ultimate loads. As the replacement ratio increased, the compressive strain to obtain the peak load also increased.

- The failure mode of RAC columns was similar to that of NAC columns.

- Recycled concrete aggregates are potential materials for use in column structures with an acceptable performance for ultimate load and deformation under compression, which could be applied in practical work.

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