Reinforced Concrete Columns with Treated Recycled Concrete Aggregate: An Experimental and Theoretical Study

Hussam N. Badri
Department of Civil Engineering, College of Engineering, University of Tikrit, Tikrit, Iraq
hn230006en@st.tu.edu.iq (corresponding author)

Hasan J. Mohammed
Department of Civil Engineering, College of Engineering, University of Tikrit, Tikrit, Iraq
dr.hassanjassim@tu.edu.iq

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ABSTRACT

Six Reinforced Concrete (RC) columns composed of Treated Recycled Concrete Aggregate (TRCA) and Natural Aggregate (NA) were subjected to experimental and theoretical analyses to ascertain their axial compressive behavior. The method of soaking recyclable aggregate in a NAOH solution was then employed to treat it. The TRCA was subjected to replacement ratios of 20%, 40%, 60%, 80%, and 100% relative to the total weight of NA. The dimensions of the column were 700 mm, 150 mm, and 150 mm, respectively. The column was reinforced with steel of varying diameters. The transverse reinforcement was 6 mm in diameter, whereas the longitudinal reinforcement was 8 mm in diameter. To examine the axial compressive behavior of the columns, the final load values obtained from the static tests were revealed. The measured axial capacity of the columns was then compared with the theoretical values derived from the ACI codes. The incorporation of TRCA contents was observed to enhance the columns' axial capacity, as evidenced by the experimental results. However, the computed theoretical values were found to be more conservative than the experimental observations. This suggests that there is no risk involved in using TRCA and NA-TRCA columns in construction.

Keywords-steel bars; short concrete columns; Treated Recycled Concrete Aggregate (TRCA); NAOH solution; axial capacity

I. INTRODUCTION

The typical ingredients of concrete are cement, aggregates, and water, which serve as binder elements. Given that aggregate constitutes between 60% and 80% of the volume and 70% to 85% of the weight of concrete, it is often regarded as an inert filler, since it does not participate in any significant chemical reactions during the process. Nevertheless, it is an ingredient that determines the thermal, elastic, and dimensional stability of the concrete. Aggregates can be classified into two distinct categories: fine and coarse. Concrete is one of the most popular building materials due to its accessibility, affordability, and flexibility to be molded into desired shapes. It has made a significant contribution to the development of infrastructure across the globe. However, the construction and demolition of buildings inevitably generates a considerable amount of waste. In numerous countries, the recycling of concrete is now feasible through the crushing of Construction and Demolition Waste (CDW) and its subsequent utilization as aggregate in structural concrete [1-4]. The extensive usage of concrete, which inevitably leads to the substantial consumption of NA resources, such as sand and gravel, is bound to give rise to a plethora of environmental concerns. Recycled Concrete Aggregate (RCA) represents a comprehensive solution for the effective management of surplus concrete, potentially alleviating the strain on NA resources [5]. One of the most common failure modes observed in concrete structures is crushing, which is primarily seen in columns [6]. Despite the continued development of new construction materials and recent technical advancements, concrete remains a common building material used in a multitude of construction types [7].

The construction of civil engineering structures frequently employs the use of RC columns. This is due to the growth of buildings and the modifications made to the specifications and design of concrete structures. Consequently, there has been a general increase in the reuse of recycled material in recent years. It became necessary to determine how to use it in construction in order to improve the environmental situation. The usage of RCA in lieu of NA in concrete results in a reduction in the quantity of non-renewable natural resources produced. Such practices confer considerable benefits to the environment. Furthermore, the use of RCA reduces the quantity of land required for landfill disposal, which in turn mitigates the associated air and water pollution. A number of studies have been conducted to examine the impact of incorporating RCA in concrete. The majority of the research indicated that the characteristics of RCA are contingent upon the source of the original concrete, and that RCA is typically of inferior quality to NA. An analysis of the particle form of the recycled aggregate reveals that it is identical to the NA formed from crushed rock. The high-strength concrete exhibited greater mortar adhesion, while the recycled aggregates from the low-strength concrete demonstrated reduced mortar adhesion when processed with the same type of machine and energy input [9]. Despite research indicating that recycled aggregate exhibits reduced strength relative to virgin material, the extent of this decline is contingent upon a multitude of variables, including the specific type of concrete (high, medium, or low strength), the degree of replacement, the water/cement (w/c) ratio, and the moisture content of the pre-used material [10]. The distinction between RCA and virgin aggregate lies solely in the manner by which aged cement and/or mortar adhere to the NA at the core. As the nominal size of the RCA increases, the volume fraction of adhering mortar in the RCA is decreasing [11]. The presence of old mortar adhered to the aggregate results in the formation of numerous micro-cracks, high porosity, a rough surface, high water absorption, and a low apparent density when compared to NA [12-14]. Furthermore, recycled concrete exhibits inferior mechanical properties, limited durability, high shrinkage, and high-water consumption [15, 16]. The practical engineering applications of recycled concrete have been significantly constrained by these shortcomings. To improve the performance of recycled aggregate and recycled concrete, a variety of technologies have been developed. Authors in [16, 17] employed a low concentration of hydrochloric acid to treat the recycled aggregate, subsequently using Scanning Electron Microscopy (SEM) to examine the adherence of mortar on the treated aggregate's surface. The microwave approach was applied by authors in [18] for the treatment of recyclable aggregate. The results demonstrated that this technique is an effective method for removing mortar that has adhered to the surface of recycled aggregate, thereby improving the quality of the aggregate.

The carbonation treatment procedure, which is applied to the surface of the recycled aggregate, involves the use of CO_2 to react with the carbon-bearing materials present in old mortar. The qualities of the recycled aggregate are enhanced, and the pores are filled by the reaction result. Authors in [19] developed a novel carbonation apparatus, examined the impact of carbonation pressure and duration on the properties of recycled aggregates, and demonstrated the effectiveness of employing the carbonation process to enhance the strength of aggregates. As stated in [20], the carbonation process has the potential to enhance the mechanical qualities, resistance to chloride ion penetration, and drying shrinkage of recycled concrete. As observed in [21], carbonation has the potential to reduce the water absorption of recycled concrete while increasing its impermeability. The carbonated aggregate was employed in [22, 23], in the production of recycled concrete and mortar. Moreover, SEM and microhardness testing were employed to examine the microstructure and mechanical properties of the recycled concrete and mortar. The majority of the recycled aggregates used in the aforementioned research were produced in a laboratory setting. The mortar that was attached was recently created and contains a significant quantity of calcium hydroxide (CH). It is reasonable to posit that the linked mortar's capacity to generate supplementary carbonation products upon carbonation will serve to enhance the performance of the recycled aggregate. In contrast, recycled aggregates produced from CDW tend to exhibit reduced alkaline content. Therefore, it can be concluded that the conventional carbonation approach is not an effective method for significantly improving the performance of recycled aggregates derived from CDW.

II. MATERIALS AND METHOD

A. Materials

The following section outlines the materials used in this study and provides a description of their characteristics:

- Cement: The study employed regular Portland cement in the preparation of all the mixtures. The chemical and physical properties of the cement are presented in Tables I and II, respectively.
- Fine aggregate: the concrete mix was prepared using river sand that met the ASTM C778-17 specifications for a maximum size of 4.75 mm and a fineness modulus of 3.28, and the chemical and physical properties of the fine aggregate are presented in Table III.
- Coarse Aggregate: The coarse aggregate used in this experiment was river gravel with a maximum size of 19.5 mm. Two distinct types of coarse aggregates were evaluated, the NA and TRCA. Figure 1 presents images of the RCA that was subjected to cleaning using a NaOH solution. To prepare the RCA utilized in this experiment, the reinforcing concrete and earlier cube specimens from the demolished building were crushed. The RCA sieve analysis findings are illustrated in Table IV.
- Water: The water used to make the concrete has a pH of 7.52, which is in accordance with IQS No. 1703 (1992).

TABLE I. CHEMICAL PROPERTIES OF CEMENT

Oxides composition	Content (%)	ASTM C150-97
CaO	57.65	-
Al_2O_3	4.4	8% Max.
SiO_2	18.05	21% Max.
Fe_2O_3	4	5% Max.
MgO	3.8	5% Max.
SO_3	2.1	2.5% Max.
Loss on Ignition (LOI)	1.28	4% Max.
Insoluble Material	0.89	1.5% Max.
Lime Saturation Factor (LSF), Main Compounds	0.91	(0.66-1.02)
C3S	8.28	-
C2S	4.24	< 5 %
C3A	11.16	-
C4AF	75.4	-

- Steel Reinforcement: This study deployed deformed steel bars with diameters of 8 mm and 6 mm as reinforcement.

The 8 mm bars were used for longitudinal reinforcement, while the 6 mm bars were utilized for stirrups. According to Table V, the steel bar stress test results meet ASTM615-150 standards.

TABLE II. PHYSICAL PROPERTIES OF CEMENT

Physical Properties	Test Results	ASTM C150-97
Specific surface area (Blaine Method), m^2/kg	258	230 (Min.)
Setting time (Yicale's method)		
Initial setting, hrs: min	3:15	00:45 (Min.)
Final setting, hrs: min	8:35	10:00 (Max.)
Compressive strength, MPa		
3 days	28.78	15.00 (Min.)
7 days	39.33	23.00 (Min.)

TABLE III. CHEMICAL AND PHYSICAL PROPERTIES OF FINE AGGREGATES

Properties	Test Results	ASTM C778-17
Specific gravity	2.46	-
Moisture content %	6.1	-
Absorption %	1.4	-
Dry Loose Unit Weight, kg/m^3	1480	
Sulfate content (SO_3%)	0.08	0.5% (max)
Material Finer than Sieve 0.075 mm, (%)	4.1	5% (max)

TABLE IV. RESULTS OF SIEVE ANALYSIS OF (RCA)

Sieve size	Cumulative Passing (%)	ASTM C128-07a
19.5 mm	100	100
12.5 mm	100	90-100
9.5 mm	69	50-85
4.75 mm	7	0-15

TABLE V. RESULTS OF A STEEL BAR REINFORCEMENT TEST

Bar diameter (mm)	Yield Strength (MPa)	Ultimate strength (MPa)	Elongation (%)
8	586	673	12.4
6	520	542	4.1

Fig. 1. TRCA.

In accordance with ACI 318-19, the permissible range for steel ratio ρ is 0.01-0.08. First, the steel reinforcement necessary for the minimum ρ must be determined. In this case, $\rho = 0.01$, which represents 4 Ø6 mm longitudinal steel bars. Six 8 mm longitudinal steel bars were used, with a steel ratio of $0.01 < 0.0134 < 0.08$. The dimensions of each specimen's cross-section are 150 mm in length, 150 mm in width, and 700 mm in height, with a 25 mm clear cover thickness. As shown in Figure 2, 6 Ø6 mm steel bars were employed for stirrups, with a spacing of 108 mm.

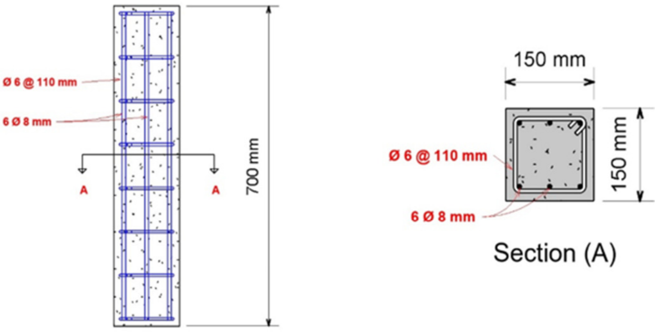

Fig. 2. Details of column samples.

B. Mix Proportion

In this study, six concrete mixtures with an effective w/c ratio of 0.39 were prepared in order to achieve an axial load and a 28-day desired strength of 35 MPa. The NA mix serves as the control mixture and was replaced by TRCA. Table VI provides detailed information regarding the specific mix ratios and replacement ratio.

TABLE VI. DETAILS OF MIX PROPORTIONS

Col. ID	Mix type	Cement (kg/m^3)	Water (kg/m^3)	Coarse aggregate NA (kg/m^3)	Fine aggregate (kg/m^3)	Coarse TRCA (kg/m^3)	Replacing ratio %
C1	NA	490	191	960	680	0	0
C7	TRCA	490	191	768	680	192	20
C8	TRCA	490	191	576	680	384	40
C9	TRCA	490	191	384	680	576	60
C10	TRCA	490	191	192	680	768	80
C11	TRCA	490	191	0	680	960	100

III. RESULTS

A. Compressive Strength Test

The compressive strength of each mixture was determined by measuring the strength of three cubes with dimensions (150 mm × 150 mm × 150 mm), as depicted in Figure 3. The cubes were subjected to a 28-day testing and curing period. The mean values are presented in Table VII. The 28-day compressive strength data indicate that RCA combinations exhibit higher values than NA mixes.

B. Axial Load of Column Test

To examine the compressive axial behavior of RC columns using NA and NA-RCA, six columns were cast utilizing the mixing ratio portrayed in Table V. All specimens were constructed with identical reinforcement details, employing six bars with a nominal diameter of 8 mm as the reinforcement ratio between the minimum and maximum longitudinal reinforcement in accordance with ACI 318-14 [24]. Furthermore, 108 mm of transverse reinforcement with a 6 mm diameter was included. In accordance with ACI 318M-14, the theoretical values (P_{th}) and experimental maximum axial loads

(P_{exp}) for each column were compared in this study. The following equation is applied in order to ascertain the theoretical axial load for ACI:

$$P_{u(th)} = \emptyset \times P_n$$

$$P_{u(th)} = 0.85\big(0.85f_c'(Ag - Ast) + Ast \times f_y\big) \qquad (1)$$

where, $P_{u(th)}$ is the ultimate load, Ag is gross area (mm^2), fc' is the cylinder concrete compression strength at 28 Days, Ast is the area of tension steel (mm^2), and f_y is the yield strength of steel (MPa). Equation (1) gives the axial capacity at zero eccentricity.

Fig. 3. Compressive test.

TABLE VII. COMPRESSIVE STRENGTH TEST RESULTS

Column designation	Mix type	Compressive strength (MPa)	Change comparing with experimental NC%
CN	NA	37.9	-
C1	TRCA(NAOH)	49.4	30.25
C2	TRCA(NAOH)	43.2	14.02
C3	TRCA(NAOH)	44.2	16.49
C4	TRCA(NAOH)	53.5	41.08
C5	TRCA(NAOH)	45.6	20.18

A total of six TRCA square columns were cast and subsequently subjected to testing. Subsequently, experimental testing was conducted until failure occurred under axial loading, as shown in Figure 4, while the test results are listed in Table VIII.

C. Slump Test

As presented in Table IX, the NA slump measurement was 59 mm, which was conducive to the material's workability. The RCA(NAOH) concrete slump values for RCA20, RCA40, RCA60, RCA80, and RCA100 were 53 mm, 59 mm, 64 mm, 68 mm, and 70 mm, respectively. However, due to the recycled aggregate's porosity, the combined water was absorbed and the workability was reduced, as exhibited in Figure 5.

D. Fresh Density Test

The fresh densities of the RCA and normal concrete are outlined in Table X. The interaction of the concrete ingredients and the porosity of the RCA resulted in the greatest density for NC, with the recycled RCA content increasing steadily. Figure 6 shows the methodology employed to ascertain the wet density of the concrete. Concrete mixtures with densities determined through experimental procedures are classified as semi-normal.

Fig. 4. Axial loading test.

TABLE VIII. SUMMARIZED RESULTS OF THE RC COLUMN TEST

Col. Mix	TRCA content (%)	$P_f = P_{exp}$ (kN)	% varying of P_f with NA	$P_n = P_{th}$ (kN)	Δu (mm)	P_f / P_n
C-NA	0	614	Ref.	618.6	2.13	1
C1-TRCA(NAOH)	20	600.5	-2.2	803.1	2.4	0.7
C2-TRCA(NAOH)	40	641.1	+4.4	703.6	2.3	0.9
C3-TRCA(NAOH)	60	657.2	+7	719.6	5.2	0.9
C4-TRCA(NAOH)	80	727.7	+18.5	868.7	5	0.8
C5-TRCA(NAOH)	100	586.7	-4.4	742.1	3	0.8
Average						0.82

Fig. 5. Slump of 100% RCA replacement ratio concrete mixture test.

TABLE IX. SLUMP OF NC AND RCA CONCRETE MIXTURES

Mix Type	Replacing Ratio (%)	Treated Method	Slump (mm)
C-NA	0	0	59
C1-RCA(NAOH)	20	(NAOH)	53
C2-RCA(NAOH)	40	(NAOH)	59
C3-RCA(NAOH)	60	(NAOH)	64
C4-RCA(NAOH)	80	(NAOH)	68
C5-RCA(NAOH)	100	(NAOH)	70

Fig. 6. Fresh density test.

TABLE X. WET DENSITY OF VARIOUS CONCRETE MIXES

Mixture	Fresh density (kg/m^3)
C-NA	2,480
C1-RCA(NAOH)	2,369
C2-RCA(NAOH)	2,349
C3-RCA(NAOH)	2,345
C4-RCA(NAOH)	2,339
C5-RCA(NAOH)	2,330

E. Splitting Tensile Strength Test

The splitting tensile strength (f_t) of the concrete samples is displayed in Table XI. It is evident that both the TRCA percentage of mixture and the TRCA concrete have contributed to the observed increase and decrease in this strength. The TRCA produces voids in the mix, which affects the splitting tensile strength value. As seen in Figure 7, the test method was used to calculate the experimental splitting tensile strength according to the findings. The theoretical splitting tensile strength (ft) for NA is given by:

$$f_t \times ACI = (0.5 - 0.66)\sqrt{f_c} \quad (2)$$

If a mean value of 0.56 is used, it results:

$$f_t \times ACI = 0.56 \times \sqrt{35} = 3.3 \text{ MPa}$$

TABLE XI. SPLITTING TENSILE STRENGTH TEST RESULTS

Mixture	Experimental Splitting Tensile strength (MPa)	(%) change comparing with experimental NA
C-NA	3.89	Ref.
C1-RCA(NAOH)	4.1	+5.46
C2-RCA(NAOH)	3.86	-.87
C3-RCA(NAOH)	3.62	-7.03
C4-RCA(NAOH)	4.26	+9.41
C5-RCA(NAOH)	3.78	-2.73

F. Load-Longitudinal Displacement Relationships of TRCA RC Columns

Figure 8 shows the load-vertical displacement curve of the control specimen with a 0% replacement rate of recycled coarse aggregate. The load-vertical displacement curve diagrams of the treated recycled aggregate columns, as presented in Figures 9 and 10, represent a comparison with the theoretical load value.

Fig. 7. Splitting tensile strength test.

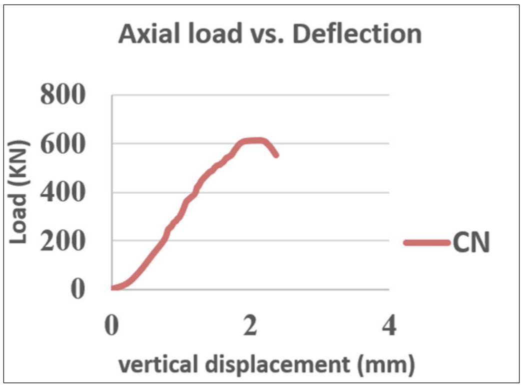

Fig. 8. The load- axial deflection of C-NA (reference) sample.

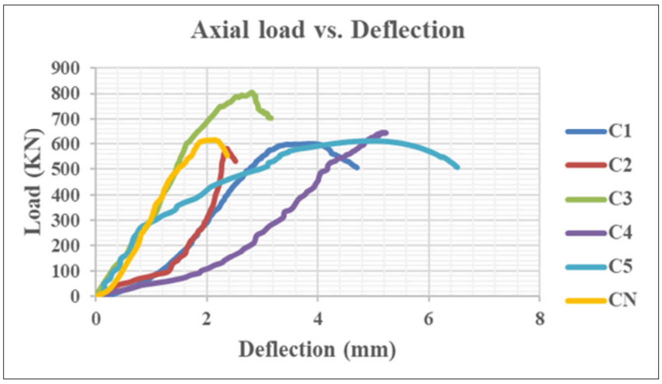

Fig. 9. The load- axial deflection of TRCA column (by NAOH) samples.

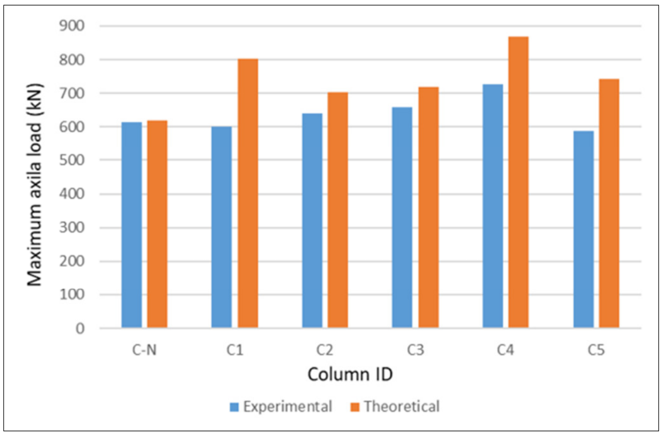

Fig. 10. Experimental and theoretical max. axial load.

G. Failure Pattern of Columns

The testing phase demonstrated that the failure mechanism in all reinforced columns exhibited a gradual progression, commencing with the separation of a substantial quantity of concrete. Subsequently, the steel reinforcing bars became visible, which ultimately resulted in localized failure. Figure 11 depicts the occurrence of cover spalling and longitudinal reinforcement buckling in the case of reinforced columns.

IV. CONCLUSIONS

A lack of research was identified in the area of axial compressive behavior of concrete columns with Treated Recycled Concrete Aggregate (TRCA) using the method of soaking recyclable aggregate in an aqueous sodium hydroxide solution. The axial compressive behavior of six Reinforced Concrete (RC) columns with varying replacement levels was examined both theoretically and experimentally. From the presented data, this study leads to the following conclusions:

- The compressive strength of all mixtures incorporating TRCA was found to be higher than that of the control mixture. The percentage increase in compressive strength was 30.25, 14.02, and 16.49, respectively. The compressive strength of the mixture with replaced TRCA aggregate was found to be 41.08% and 40.18% higher than that of the reference normal mixture for replacement levels of 20%, 40%, 60%, 80%, and 100% of the TRCA aggregate, respectively.

(a) (b) (c) (d) (e)

Fig. 11. Failure mode of columns: (a) C1-TRCA(NAOH), (b) C2-TRCA(NAOH), (c) C3-TRCA(NAOH), (d) C4-TRCA(NAOH), (e) C5-TRCA(NAOH).

- The fresh density of all mixes containing TRCA was slightly lower than that of the regular mix.
- The predicted theoretical maximum loads were found to align with the experimental results for the tested columns. In comparison to the experimentally tested columns, the average of the experimental maximum loads related to the theoretical results was 0.82.
- It was observed that the axial load increased in proportion to the TRCA contents in the columns. A comparison of the experimental axial load to the control column specimen, Natural Aggregate (NA) revealed increases of 4.4%, 7%, and 18.5% for 40%, 60%, and 80% replacement, respectively. Although the axial compressive loads of the two column specimens were found to be lower than that of the control column specimen NA, the actual values obtained in this study did not align with the theoretical axial load values provided by the ACI code. It is therefore evident that the experimental axial load value is pertinent when using TRCA.
- The failure mechanism observed in all reinforced columns exhibited a gradual progression, commencing with the separation of a substantial quantity of concrete. Subsequently, the steel reinforcing bars became visible, which ultimately resulted in localized failure.

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