Behavior of Recycled Aggregate Concrete Slender Column under Concentric Axial Loading

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Abstract. This investigation investigates the structural behavior of slender reinforced concrete RC containing different RCA replacement portions in addition to the slenderness effect. To perform this, eight (8) slender RC columns with two main types of transverse reinforcement (ties and spiral reinforcement) and three recycled coarse aggregate RCA replacement percentages (25, 50, and 100%) were modeled and subjected to axial concentric loading. The gathered experimental results are monitored and analyzed to better estimate the structural characteristics of the RC slender column (The ultimate carrying load, first cracking load, load-displacement curve, and load-strain response). The results showed that replacing NCA with (25, 50, and 100%) of RCA reduced the ultimate capacity of tied RC columns by (13.41, 14.07, and 23.33%), respectively, and reduced their first cracking load values by (19.64, 15.96, 22.50%), respectively. The reduction in ultimate load capacity and the first cracking load were (4.10, 17.33, 22.63%) and (12.26, 23.15, 25.00%) for spirally RC columns, respectively. Spiral transverse reinforcement slightly increases the carrying load capacity compared to tie reinforcement. It delays the fast propagation of the first cracking load, furthers the effect of spiral reinforcement in improving the deformation capacity, reducing the longitudinal and lateral mid-height strains, and developing the flexural stiffness of the load-displacement curve.

Keywords: Concrete; slender columns; recycled aggregate; transverse reinforcement.

1. INTRODUCTION

Due to environmental concerns and the increased demand for sustainable building materials, recycled aggregates are becoming increasingly common in manufacturing concrete. According to recent studies, recycled aggregates can enhance concrete's mechanical characteristics and durability. Recycled aggregates' impacts on the compressive strength, elastic modulus, microstructure, and sustainability of concrete have been studied. These findings provide insight into sustainable concrete structure design and sustainable building techniques. Concrete formed by RCA provides slightly fewer benefits than natural aggregate concrete (NAC), including decreased compressive strength, higher water absorption, and increased porosity. Conversely, it was discovered that RCA concrete had greater ductility than NAC [1-5].

Recycled concrete is produced by combining old concrete blocks with gradation in a certain ratio after processing, partially or completely substituting natural materials like sand and gravel [6]. Utilizing recycled aggregates, especially those derived from demolition waste or prefabricated concrete residuals, is a practical way to create environmentally friendly buildings and preserve sustainable development. Spiral-reinforced restrained concrete columns have been utilized extensively in practical engineering due to their quick and easy construction, ability to mold internally reinforced frames, and good mechanical performance [7]. Numerous aspects of the mechanical characteristics of recycled concrete reinforced using spiral reinforcement have been thoroughly investigated [8-13].

In order to investigate the mechanical characteristics and structural behavior of recycled aggregate slender concrete columns, several experimental investigations have been conducted. For instance, Kumar and Kumar (2020) studied the behavior of slender recycled aggregate columns under axial stress [15], while Park and Han (2012) carried out a laboratory study on the flexural behavior of slender recycled aggregate concrete columns. While Wang et al. [14] examined the structural behavior of slender reinforced recycled aggregate concrete columns under eccentric loading, [17] Tang et al. (2021) researched the structural behavior of slender reinforced recycled aggregate concrete columns under axial load. Analytical modeling methods and numerical simulations have both been used to evaluate the behavior and effectiveness of recycled aggregate slender concrete columns. [16] While Liu et al. (2020) conducted numerical simulations to examine the seismic performance of such columns with various reinforcement ratios, Al-Mahaidi et al. [19] established an analytical model to predict the behavior of slender recycled aggregate concrete columns under axial loading. [19]

Overall, the evaluated research indicates that using recycled aggregates in slender concrete columns may result in lower structural performance than regular concrete. The structural behavior and durability of recycled aggregate slender concrete columns can be enhanced using correct design and construction methods, such as maximizing the reinforcing details and concrete mix proportions. These research results can be used to generate criteria and guidelines for designing and constructing resilient and durable slender concrete columns made of recycled aggregates. This paper examines the influences of replacing NCA with three RCA percentages (25, 50, and 100 %) and the internal transverse reinforcement on RC slender column performance under uniaxial compression loading. The work described is part of a comprehensive research addressing the technical and practical aspects of using RCA in concrete construction.

2. EXPERIMENTAL METHOD

Eight specimens were tested; six were made with different RCA replacement percentages (25%, 50%, and 100%), and two of each selected percentage (tied and spiral reinforced) to get precise results. They were compared with the other two standard specimens with 0% RCA replacement in the column, i.e., 100% natural aggregate RC column. The RCA was obtained through the handling of waste concrete specimens by electric hammer, crusher machine, and then by several sieves to get the precise grade similar to the used NCA. The mixer used was a horizontal rotary mixer with (0.12 m3) capacity.

Four batches of normal strength concrete (NSC) were used to cast all the RC columns with their control specimens based on recycled aggregate replacement percentages to provide the mechanical characteristics of hardened concrete. Three batches were used to cast two columns, and one batch was used to cast eight columns with 100% RA. The remainder from each batch was used to cast three cylinders (100×200 mm) to determine the compressive strength at 28 days of age, three cylinders (100×200 mm) for splitting tensile strength test, and three cylinders (150×300 mm) to determine the Elastic modulus of concrete and three prisms (100×100×400 mm) for flexural strength test. Before the casting process, all the molds were cleaned and oiled. Then, the reinforcement steel cages were placed at the center of the width.

1. All materials were weighted carefully and packed in clean bags.
2. Dry gravel was mixed with sand for a few minutes. Then, cement was added and mixed with the mixture for about five minutes to obtain a homogeneous dry mixture.
3. Clean tap water was added gradually to the mixture and mixed for a few minutes to obtain homogeneous fresh concrete.

After casting, all columns and their control specimens were kept in molds for 24 hours, removed from them, and placed in a curing tank. Finally, a testing program was made to determine the specimens' physical, mechanical, and structural parameters. Standard tests such as compressive and tensile strength, elastic modulus, and the rapture modulus were determined for the control specimens in the hardened phase and after the curing of the concrete. Axial loading capacity investigations were achieved for the concrete column specimens.

The consistency of the fresh concrete was assessed using the slump test, which was conducted following ASTM C143/C143M [20] standards. This test ensured that the chosen mix's water-to-cement ratio was appropriate for achieving the desired workability. The concrete's slump value was around 75 mm with an allowable variation of ±10 mm, indicating that it met the specifications for workability.

3. MATERIALS

The recycled coarse aggregate is prepared by collecting waste concrete samples from laboratory test cubes and cylinders that exhibit a compressive strength of approximately 25-35 MPa, then breaking them with a mechanical hammer and crushing them to the required size using the crusher machine. The next process was grading the RCA with maximum particles of about 10 mm. Table 1 illustrates the physical properties of the used aggregate (RCA and natural sand NS).

Table 1: The physical properties of aggregate.

Aggregate type	Specific gravity	SO_3 Sulfate content, %	Absorption, %	Fineness modulus
NA	2.52	0.05	0.7	6.49
RA	2.42	0.06	3.67	6.65
NS	2.55	0.08	2.78	2.58

Ordinary Portland cement OPC, acceptable and identical to Iraqi specification No.5/1984 [21], was used throughout the present study to cast all specimens, including cylinders, prism, and the RC slender column specimens. Steel bars (deformed type) with 8 mm diameter were used for longitudinal reinforcement, and bar size of 4 mm diameter for transverse reinforcement. According to the American Standard Specification A615/A615M. [22] The mix proportions for the concrete mix that was used in this experiment are shown in Table 2.

Table 2: The mix proportions (kg/m^3).

% of RCA	Cement (kg)	Sand (kg)	Gravel		Water (kg)	W/C
			NCA	RCA		
0	440	575	1096	0	200	0.45
25	440	575	274	822	200	0.45
50	440	575	548	548	200	0.45
100	440	575	0	1096	200	0.45

4. COLUMN SPECIMENS

Eight slender RC columns were modeled and tested throughout this study. The columns were cast with a circular cross-section with a 150 mm diameter and overall unsupported length lu of 1200 mm. Slender columns were designed to consider the slenderness effect with a slenderness ratio klu/r of 32. The dimensions are considered to be within the carrying loading capacity of the laboratory testing machine. Each RC slender specimen had a concrete cover of 15 mm from all column surfaces to avoid the direct effect of the axial loading on the main reinforcing steel bars. The applied loading was concentric axial compression load until the failure occurred. The confinement reinforcements were ties and spiral, and the spacing between ties and spiral reinforcement pitch were 100 and 50 mm, respectively. The spacing of ties was reduced at the ends of the column to reduce the possibility of premature failure outside the test region, which could occur due to the concentrations of stresses and to the purpose of enforcing failure to occur at the middle of the column. Figure 1 shows structural details depending on the way the transverse reinforcement was made (ties and spiral sets). Column specimens were identified with a series of letters and numbers. The first two letters (NA or RA) refer to the type of coarse aggregate (natural or recycled), and the following letter (T or S) indicates the type of transverse reinforcement of the column (tied or spirally reinforced). The numbers (25, 50, or 100) represent the percentage of aggregate replacement, and the last letter (A) means no external confinement.

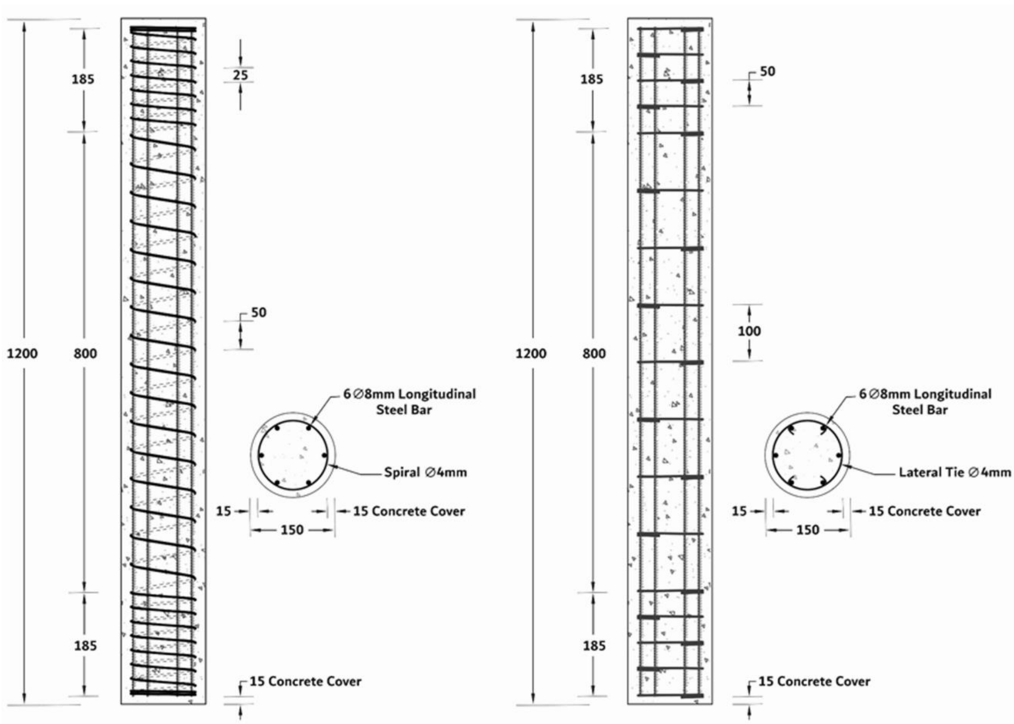


Figure 1: Structural details of slender columns with tied and spiral transverse reinforcement.

5. TESTING PROGRAM

The RC column specimens were subjected to failure under a compression axial loading test with an AVERY machine with a compression capacity of about 2500 kN. The test was performed in the Construction Laboratory of the Civil Engineering Department at the University of Technology. Each column specimen was located carefully in the testing machine to ensure that the column specimen's axis coincides with the testing machine's axis. The axial loading results were recorded using a Load Cell of about 100 kN capacity. A linear voltage displacement transducer (LVDT) measured the longitudinal and lateral displacement. The longitudinal and lateral strains were recorded using two linear strain gauges located at the middle height of the columns. All LVDT, strain gauges, and the load cell were connected to a data logger machine to save the test readings. Two steel collars (steel rings) with a height of 50 mm and thickness of 10 mm were placed at the top and bottom ends of the column before the loading process to avoid premature failure and to enforce the stresses to concentrate far away from column ends. The average load increment was gradually at a continual rate of 10 kN/sec until failure. The testing results and data were all recorded using the LabVIEW system with a rate of 80 readings per second. Figure 2 shows the procedure for testing RC column specimens.

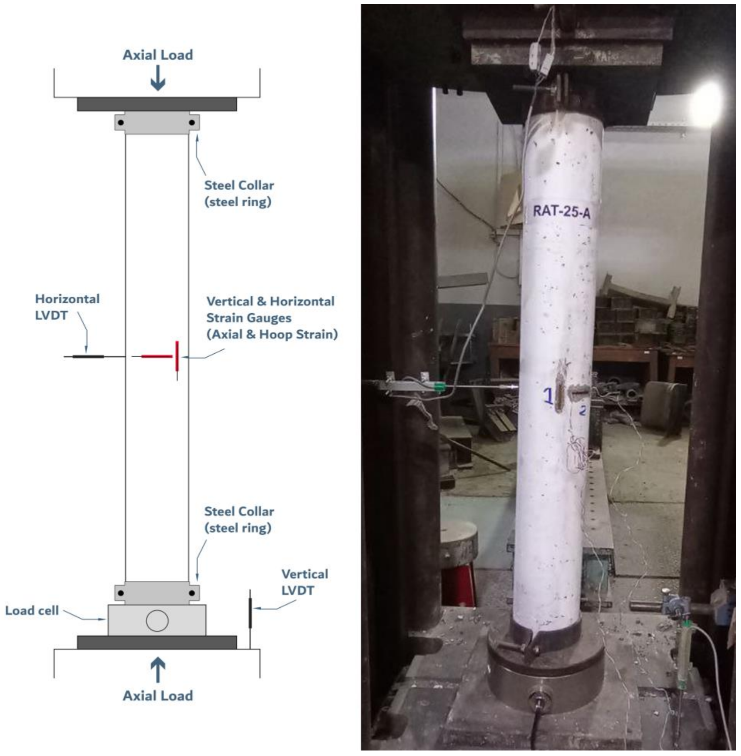


Figure 2: Test instrumentations.

6. RESULTS AND DISCUSSION

6.1 Mechanical Properties

The properties related to the mechanical behavior that were analyzed in this study include the compressive strength ($f'c$), splitting tensile strength (f_t), flexural strength (modulus of rupture f_r), and modulus of elasticity illustrated in Tables 3, 4, 5, and 6, respectively.

Table 3: Compressive strength results for control specimens.

Group	Mix Details	RCA Replacement Ratio (%)	Cylinder Strength in Compression $f'c$ (MPa)	Reduction in $f'c$ (%)
A	NA-100%	-	34.80	-
B	RA-25%	25	32.10	7.8
C	RA-50%	50	29.40	15.5
D	RA-100%	100	24.45	29.7

Table 4: Splitting tensile strength results for control specimens.

Group	Mix Details	Measured $f_{t(Exp)}$ (MPa)	$f'c$ (MPa)	Calculated $f_{t\,(Pre)}$* According to the ACI 318M-19 [23] (MPa)	$f_{t\,(Exp)}$ / $f_{t\,(Pre)}$	Reduction in f_t (%)
A	NA-100%	3.28	34.8	3.3	0.99	-
B	RA-25%	3.08	32.1	3.17	0.97	6.10
C	RA-50%	2.97	29.4	3.03	0.98	9.45
D	RA-100%	2.72	24.45	2.77	0.98	17.07

* ft (predicted) = 0.56√(f'c)

Table 5: Modulus of Rapture results for control specimens.

Group	Mix Details	Measured $f_{r(Exp)}$ (MPa)	$f'c$ (MPa)	Calculated $f_{r\,(Pre)}$* According to the ACI 318M-19 [23] (MPa)	$f_{r\,(Exp)}$ / $f_{r\,(Pre)}$	Reduction in f_r (%)
A	NA-100%	3.78	34.8	3.66	1.03	-
B	RA-25%	3.58	32.1	3.51	1.02	5.29
C	RA-50%	3.43	29.4	3.36	1.02	9.26
D	RA-100%	3.12	24.45	3.07	1.01	17.46

* fr (predicted) = 0.62√(f'c)

Table 6: Modulus of elasticity results for control specimens.

Group	Mix Details	Measured Modulus of Elasticity (MPa)	$f'c$ (MPa)	Calculated Modulus of Elasticity* According to the ACI 318M-19 [23] (MPa)	Reduction in Modulus of Elasticity
A	NA-100%	28092	34.8	27726	-
B	RA-25%	26703	32.1	26629	4.94
C	RA-50%	25460	29.4	25484	9.37
D	RA-100%	23185	24.45	23240	17.47

* Modulus of elasticity = 4700√(f'c)

Three RCA percentages (25, 50, and 100%) were used to replace the NCA in the reference concrete mix (NA-100%); this resulted in reductions in the compressive strength of the concrete by 7.8, 15.5, and 29.7%, respectively, the splitting tensile strength values were reduced by 6.1, 9.45, and 17.07% relative to the concrete mix with 100% NCA, while the flexural strength of the concrete was reduced by 5.29, 9.26, and 17.46%, respectively, and the modulus of elasticity by 4.94, 9.37, and 17. This is because RCA is comparatively weaker and more porous than NCA.

6.2 Ultimate Load and First Cracking Load

All RC column specimens in this investigation were tested under concentric axial loading up to failure. The first cracking load of each column specimen during the testing was registered to document the moment of appearance of the first crack and to record the value of the applied load at this moment. Table 3 and Figure 7 illustrate the first cracking load (P_{cr}) and the ultimate load (P_{ult}) for the tested tied and spirally reinforced columns.

Table 7: First cracking and ultimate loads results.

Col-ID	Ultimate Capacity, P_{ult} (kN)	First Cracking Load, P_{cr} (kN)	P_{cr}/ P_{ult} (%)
NAT-A	620.89	497.98	0.80
RAT25-A	572.30	448.38	0.78
RAT50-A	533.52	418.49	0.78
RAT100-A	476.03	385.95	0.81
NAS-A	660.92	557.98	0.84
RAS25-A	595.46	436.93	0.73
RAS50-A	546.37	428.81	0.78
RAS100-A	511.34	418.49	0.82

It can be observed that varying RCA replacement ratios affect RC slender columns' performance. Based on experimental results gathered through this investigation. It can be seen from Table 8 that increasing the RCA replacement ratio leads to reducing the first cracking load and the ultimate load. In comparison with the reference tied RC column (NAT-A), i.e., 100% NCA, the reduction in the ultimate carrying load and the first cracking load was 92.17 and 87.74%, respectively, for the tied column with 25% RCA replacement ratio (RAT25-A). For the tied column with 50 and RCA content (RAT50-A), the reduction in the ultimate carrying load and the first cracking load were 85.93 and 84.04%, respectively. For the 100% RCA content (RAT100-A), the ultimate carrying load and the first cracking load were reduced by 80.24 and 81.41%, respectively.

Likewise, for the control spirally RC column (NAS-A), i.e., 100% NCA, the ultimate carrying load and the first cracking load were reduced by 90.1 and 80.36%, respectively, for the tied column with 25% RCA replacement ratio (RAS50-A). For the 50% RCA content (RAS50-A), the ultimate carrying load and the first cracking load were reduced by 82.67 and 76.85%, respectively. Finally, for the tied column with 100 and RCA content (RAS100-A), the reduction in the ultimate carrying load and the first cracking load were 77.37 and 75.00%, respectively.

Table 8: First cracking and ultimate loads results.

Col-ID	% of RCA	P_{ult} (kN)	% P_{ult} Reduction	P_{cr} (kN)	% P_{cr} Reduction
NAT-A	0	620.89	-	497.98	-
RAT25-A	25	572.30	13.41%	448.38	19.64%
RAT50-A	50	533.52	14.07%	418.49	15.96%
RAT100-A	100	476.03	23.33%	385.95	22.50%
NAS-A	0	660.92	-	557.98	-
RAS25-A	25	595.46	4.10%	436.93	12.26%
RAS50-A	50	546.37	17.33%	428.81	23.15%
RAS100-A	100	511.34	22.63%	418.49	25.00%

The results collected throughout this investigation confirmed that spiral reinforcement increases the ultimate carrying load and the first cracking load compared to ties reinforcement, as listed in Table 9.

Table 9: Type of transverse reinforcement effect on the first cracking and ultimate loads.

Col-ID	Type of Transverse Reinforcement	P_{ult} (kN)	% P_{ult} Increase	P_{cr} (kN)	% P_{cr} Increase
NAT-A	Tie	620.89	-	497.98	-
NAS-A	Spiral	660.92	6.45%	557.98	12.05%
RAT25-A	Tie	572.30	-	448.38	-
RAS25-A	Spiral	595.46	4.05%	436.93	-2.55%
RAT50-A	Tie	533.52	-	418.49	-
RAS50-A	Spiral	546.37	2.41%	428.81	2.47%
RAT100-A	Tie	476.03	-	385.95	-
RAS100-A	Spiral	511.34	7.42%	418.49	8.43%

Compared with the reference tied RC column (RAT-A), i.e., 100% NCA, the increase in the ultimate carrying load and the first cracking load of the spiral column (NAS-A) were 6.45 and 12.05%, respectively. On the other side, for the spirally RC column with 25% RCA content (RAS25-A), the ultimate carrying load was increased by 4.05 while the first cracking load decreased by 2.55%, as compared to the tied RC column with the same RCA replacement percentage (RAT25-A). In addition, for the spirally RC column with 50% RCA content (RAS50-A), the ultimate carrying load and the first cracking load were increased by 2.41 and 2.47%, respectively. Compared to the tied RC column with the same RCA content (RAS50-A). Finally, for the spirally RC column with 100% RCA content (RAS100-A), the ultimate carrying load and the first cracking load were increased by 7.42 and 8.43%, respectively. Compared to the tied RC column with the same RCA content (RAS100-A).

6.3 Behavior and Failure Pattern

All RC slender columns were subjected to concentric axial loading during the testing program until failure. For the two reference columns (NAT-A) and (RAT-A), at the beginning of the testing process, linear behavior was recorded when the axial load was applied initially; the cracks propagation along the column height (vertical hairline cracks) starts at about 80 and 84% of their ultimate capacity. With increased applied load up to the ultimate range, more cracks were densified, and their width rapidly grew. The RC slender column specimens collapsed suddenly by explosive mode of failure within the test region, accompanied by shreds caused by outward buckling of longitudinal steel bars and the breaking of the transverse ties or spiral reinforcement.

For slender RC columns having 25, 50, 100% of RCA replacement content (RAT25-A), (RAS25-A), (RAT50-A), (RAS50-A), (RAT100-A), (RAS100-A), cracks started approximately at 78, 73, 78, 78, 81, and 82% of their ultimate capacity for tied and spirally reinforced RC columns respectively. With further increments in applied loading, more cracks expanded, and collapse occurred by explosion pattern near the tops of the tested region (except RAS100-A, which exploded in the mid-height) due to longitudinal steel reinforcement buckling in addition to ties and spirals breaking. Modes of failure patterns for both tied and spirally RC columns are presented in Figures 3 and 4, respectively.

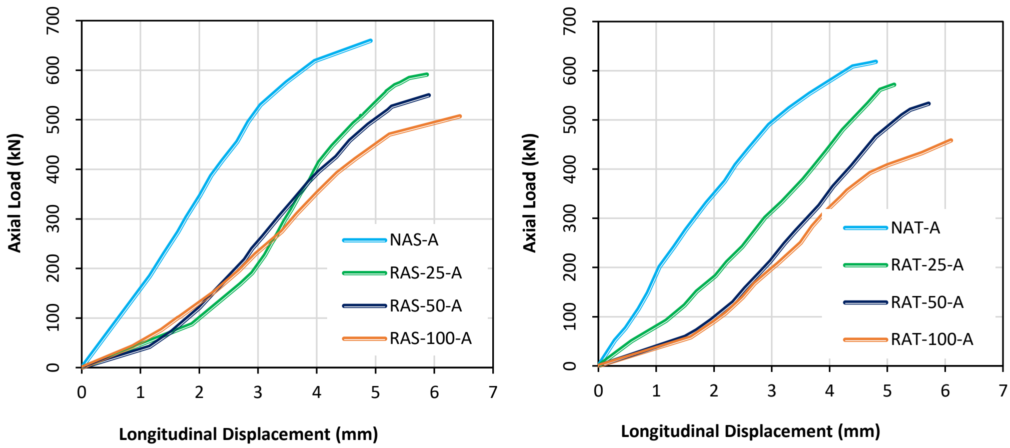
Figure 3: Failure patterns of columns with tied reinforcement.

Figure 4: Failure patterns of columns with a spiral reinforcement.

6.4 Load-Displacement and Load-Strain Relationship

Experimental results indicated that using recycled aggregate reduced the peak load and ductility of the columns compared to those made with conventional concrete. Hence, recycled aggregate concrete (RCA) may demonstrate less response to external loads. This has been attributed to RCA's lower strength and higher porosity compared to natural coarse aggregate (NCA), as indicated by [24]. In the initial stages of loading, the load-displacement curve of RCA concrete with varying contents of RCA (25%, 50%, and 100%) showed a nearly linear correlation between the applied load and displacement, which denotes elastic deformation of the slender columns. As the load increased, the curve showed a nonlinear relationship, indicating the onset of plastic deformation. The peak load of the curve was generally lower than that of the reference NCA columns (NAT-A and NAS-A). Additionally, the post-peak behavior of the curve exhibited a sudden drop in load, which suggests a brittle failure mode.

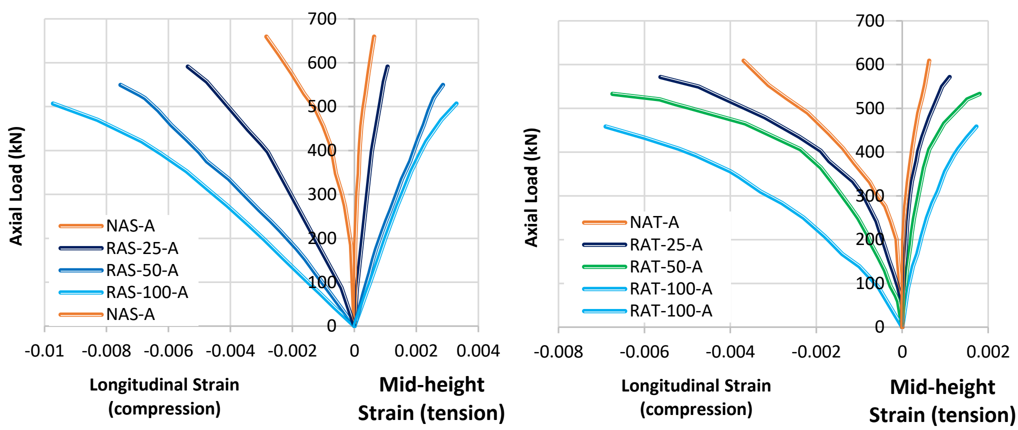
This is due to the lower ductility of recycled concrete as compared to conventional concrete, which can limit its energy absorption capacity. The load-displacement curve of spirally reinforced RCA columns (NAS-A, RAS25-A, RAS50-A, and RAS100-A) showed a steeper slope in the initial loading stages, indicating a stiffer response to external loads. The curve's peak load was relatively higher than tied reinforced columns. However, the post-peak behavior exhibited a sudden load drop, suggesting a more brittle failure mode. Figure 5 demonstrates the load-longitudinal displacement curves for tied and spirally reinforced RC slender columns.



(a) (b)

Figure 5: Load-longitudinal displacement curves for a: tied and b: spirally RC slender columns.

Using RCA as a replacement material in varying percentages of (25, 50, and 100%) resulted in an increase in mid-height strain values in both longitudinal and horizontal directions. Initially, the load-strain curve for RCA columns has a linear relationship between stress and strain, similar to NCA columns (NAT-A and NAS-A). However, as the stress level increases, the curve experiences a sudden drop in stress or a sharp decline in the slope, suggesting a more brittle behavior. In general, spirally reinforced RCA columns (NAS-A, RAS25-A, RAS50-A, and RAS100-A) have a more gradual and smooth increase in strain with increasing load, indicating a more ductile behavior compared to tied reinforced concrete. Conversely, the load-strain curve of tied reinforced RCA columns (NAT-A, RAT25-A, RAT50-A, and RAT100-A) demonstrates a steeper slope in the initial stages of loading, suggesting a stiffer response to external loads but a more abrupt drop in load after the peak load is reached, indicating a more brittle failure mode. Figure 6 illustrates the load-longitudinal displacement curves for tied and spirally reinforced RC slender columns.



(a) (b)

Figure 6: Load-Strain curves for a: tied and b: spirally RC slender columns.

7. CONCLUSIONS

Based on the experimental results collected throughout this investigation, there are several conclusions were gathered as the following:

- RCA percentages (25, 50, and 100%) were used to replace the NCA in the reference concrete mix (NA-100%); this resulted in reductions in the compressive strength of the concrete by 7.8, 15.5, and

29.7%, respectively, the splitting tensile strength by 6.1, 9.45, and 17.07%, the flexural strength of the concrete by 5.29, 9.26, and 17.46%, and the modulus of elasticity by 4.94, 9.37, and 17.

- Increasing the RCA replacement ratio reduced both the first and ultimate cracking loads. When compared to the reference tied RC column (NAT-A) containing 100% NCA, the tied column with 25% RCA replacement ratio (RAT25-A) experienced a reduction of 92.17% and 87.74% in the ultimate carrying load and the first cracking load, respectively. The tied column with 50% RCA content (RAT50-A) reduced by 85.93% and 84.04% in the ultimate carrying and the first cracking loads, respectively. Similarly, the ultimate carrying load and the first cracking load were reduced by 80.24% and 81.41% for the tied column with 100% RCA content (RAT100-A).
- The increase in ultimate carrying load and first cracking load for spirally reinforced columns compared to tied RC columns was 6.45% and 12.05%, respectively. For spirally reinforced columns with 25% RCA content, the ultimate carrying load increased by 4.05%, while the first cracking load decreased by 2.55%. For spirally reinforced columns with 50% RCA content, the ultimate carrying load and first cracking load increased by 2.41% and 2.47%, respectively. Finally, for spirally reinforced columns with 100% RCA content, the ultimate carrying load and first cracking load increased by 7.42% and 8.43%, respectively, compared to tied RC columns with the same RCA content.
- Using RCA as a replacement material in concrete columns decreases peak load compared to NCA columns. However, using spiral reinforcement in RCA columns leads to a stiffer response to external loads and a higher peak load compared to the tied RC columns. The post-peak behavior of the curve in both tied and spiral-reinforced RCA columns exhibits a sudden drop in load, indicating a brittle failure mode. Overall, the study highlights the importance of using spiral reinforcement in recycled concrete columns to improve their performance under external loads.
- The addition of RCA results in higher mid-height strain values and a more brittle behavior as the stress level increases. However, using spiral reinforcement in RCA columns leads to a more gradual and smooth growth in strain with increasing load, indicating a more ductile behavior compared to tied reinforced concrete columns. The findings suggest that spiral reinforcement could be a promising alternative to tied reinforcement in RCA concrete columns to improve structural performance.

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