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COMPRESSIVE STRENGTH OF CONFINED REINFORCED RECYCLED COARSE AGGREGATE CONCRETE COLUMNS

Thanh-Tung Pham[1], *Khanh-Hung Nguyen[2] and Trung-Tu Nguyen[2]

[1]Faculty of Building and Industrial Construction, Hanoi University of Civil Engineering, Hanoi, Vietnam;
[2]Faculty of Civil Engineering, Lac Hong University, Dong Nai Province, Viet Nam

*Corresponding Author, Received: 05 Sep. 2025, Revised: 04 Nov. 2025, Accepted: 09 Nov. 2025

ABSTRACT: This study examines the compressive behavior of confined concrete incorporating recycled coarse aggregate (RCA) and reinforced with spiral stirrups, aiming to assess its structural viability. Thirty-six cylindrical specimens (150 mm diameter × 300 mm height) were prepared with two RCA replacement levels (0% and 30%) and different spiral stirrup spacings (20, 25, 30, 50, and 100 mm). All specimens were tested under monotonic axial compression at 28 days, and experimental results were compared with theoretical predictions based on Mander's confinement model. The incorporation of 30% RCA led to a moderate reduction in compressive strength, ranging from 2.85% to 9.72% compared to natural aggregate specimens. However, reducing stirrup spacing increased confinement and significantly improved strength and ductility, effectively compensating for the strength loss associated with RCA. Especially, specimens with 30% RCA and a 20 mm stirrup spacing achieved compressive strengths comparable to those of conventional concrete. Mander's model consistently underestimated the compressive strength of confined RCA concrete, indicating that it provides conservative predictions when RCA is used. These results support the structural application of RCA in reinforced concrete, particularly when adequate confinement is provided.

Keywords: Recycled coarse aggregate, Compressive Strength, Confined reinforced concrete, Spiral stirrups

1. INTRODUCTION

Concrete, a manmade material mainly composed of cement and aggregate, plays a crucial role in modern construction. However, rapid urbanization has driven large-scale construction activities, leading to an increasing demand for natural coarse aggregate (NCA). This demand has resulted in the excessive extraction of natural stone, causing significant environmental degradation and resource depletion [1]. At the same time, the demolition of aging structures generates vast amounts of construction waste, placing immense pressure on traditional disposal methods such as landfilling and open dumping. These practices not only contribute to land scarcity but also pose serious environmental risks [2]. To mitigate these challenges, recycling concrete demolition waste into RCA has been recognized as a sustainable and effective alternative [3, 4]. By partially replacing natural aggregates with recycled materials, this approach helps conserve natural resources, reduce construction waste, and minimize environmental impact, promoting a more sustainable and circular construction industry.

RCA can be produced by crushing concrete waste from demolished buildings, roads, and other structures. RCA primarily consists of the NCA from the original concrete, along with adhered cement mortar [5]. The properties of concrete containing RCA are largely influenced by the amount of adhered mortar, which depends on the strength of the original concrete from which the RCA is derived. Exteberria et al. [6] observed that the proportion of adhered mortar is affected by both the crushing process and the water-cement ratio of the parent concrete. A higher water-cement ratio in the original mix typically results in weaker mortar that remains attached to the RCA. The proportion of adhered mortar can be reduced by further crushing RCA to sizes comparable to those of the natural crushed stone aggregates in the original concrete [7].

Concrete made with RCA has several limitations, including lower mechanical properties, higher porosity, lower density, and the presence of microcracks in the interfacial transition zone [4,6, 8-13]. For example, Etxeberria et al. [6] reported that concrete containing 100% RCA typically experiences a 20-25% decrease in compressive strength at 28 days compared to conventional concrete. In terms of porosity and density, studies by Agrela et al. and Nováková et al. [11, 12] indicate that RCA exhibits water absorption rates five to ten times higher than natural aggregates due to the high porosity of residual mortar attached to the particles. Furthermore, RCA has a lower particle density, ranging between 2000–2400 kg/m³, which influences concrete strength, durability, and mix design adjustments [4].

Intensive research has been conducted to investigate the effects of RCA replacement amount on the properties of RCA concrete. For instance, Verma and Ashish [14] investigated the compressive and flexural strength of concrete incorporating successively RCA. Their study found that at lower replacement levels, the properties of concrete exhibited slight improvements. However, when the replacement of NCA exceeded 50%, the concrete's mechanical properties were significantly compromised. Saha and Rajasekaran [15] conducted experimental studies to evaluate the strength characteristics of concrete made with RCA. Their findings revealed a significant reduction in compressive and flexural strength with the incorporation of RCA. Similarly, Tabsh and Abdelfatah [16] observed that in high-strength concrete, replacing NCA with RCA had minimal impact on strength. However, for conventional concrete, the use of RCA resulted in a considerable reduction in strength.

With respect to the effects of the confined phenomenon on the compressive strength of concrete, Sheikh and Uzumeri [18] studied the effects of stirrup spacing and longitudinal reinforcement arrangement on confined region within the core concrete. Marvel et. al. [19] examined the behavior of high-strength reinforced concrete columns confined with a novel cross-spiral confinement technique. Results revealed that cross-spiral columns with the same volumetric confinement ratio as traditional single-spiral columns (but with double the spacing) achieved similar ultimate strengths and approximately 20% greater ultimate displacements. Concerning stirrup spacing, Yang et al. [20] examined the effects of spacing, configuration, and strength of stirrups on the confinement behavior of multi-spiral composite stirrups in square reinforced concrete columns. The study found that reducing stirrup spacing, which corresponds to an increase in the volumetric ratio of transverse reinforcement, markedly enhances the load-bearing capacity, ductility, and deformation performance of the columns.

With regard to stress-strain models, several have been developed to describe the behavior of confined concrete [16,17-26]. For example, Razvi et al. [17] developed stress-strain models based on tests of 96 columns, accounting for the effects of transverse reinforcement type, volumetric ratio, spacing, yield strength, and arrangement, as well as concrete strength and cross-sectional geometry. Li et al. [25] reported experimental data and recommendations confined to high-strength concrete, where the concrete's compressive strength ranged from 32.5 MPa to 82.5 MPa.

Mander et al. [26] proposed a stress-strain model and introduced the concept of the effectively confined concrete area to determine the confinement effectiveness coefficient, K_e. This coefficient quantifies the degree to which circular spiral reinforcement enhances the confinement of the concrete core, thereby influencing both strength and ductility under axial loading. The mathematical form of the confinement effectiveness coefficient, K_e is expressed by Eq. 1.

$$K_e = \frac{1-\dfrac{s}{2d_s}}{1-\rho_{cc}} \quad (1)$$

where s is the clear spacing between the spiral, d_s is the concrete core dimension to the center line of the perimeter spiral, ρ_{cc} is the ratio of the area of reinforcement to the area of the core of the section.

The effective confinement index $K_e.\rho_h.f_{yh}.f_c^{'}$ is employed to assess the confinement efficiency of reinforcement concrete columns, where ρ_h is the volumetric ratio of the transverse reinforcement, f_{yh} is the tie yield strength, and f_c' is the cylinder strength of plain concrete. The equations from Mander's model will be employed in this study to calculate the compressive strength of the confined concrete.

As discussed above, the use of RAC in the mixture can lead to a reduction in the compressive strength of RCA concrete. However, proper spiral stirrup configurations might enhance compressive strength through confinement effects. This experimental study aims to examine the combination of the impact of the RCA replacement ratio and the confinement effects of spiral stirrup spacing on the compressive strength of RAC columns. To that end, a total of 36 confined reinforced concrete samples with RCA replacement levels up to 30% and various spiral stirrup configurations were fabricated and tested. The experimental compressive strength was compared with theoretical predictions using Mander's formula. The detailed methodology and findings are presented in the following sections.

2. RESEARCH SIGNIFICANCE

This study establishes the efficacy of spiral confinement in mitigating compressive-strength reductions associated with partial replacement of natural coarse aggregate RCA in concrete columns. Tighter pitch produced higher 28-day compressive strength, in several mixes reaching values comparable to natural-aggregate controls. Evaluation against Mander's confinement model showed conservative predictions for RCA concretes. The results define practical detailing ranges for spiral spacing and provide model-validation data. These outcomes support safe structural design with partial RCA substitution and advance sustainable practice for load-bearing members.

3. EXPERIMENTAL SETUP

The experimental program includes the testing of 36 confined reinforced concrete samples subjected to monotonic concentric compression loads. Specimens were prepared, cured, and tested at the Lac Hong University Engineering Lab. Experimental tests were designed and conducted to examine the compressive strength of the concrete at 28 days in the range of 25 - 36 MPa with various RCA replacement ratios and spiral stirrup configurations.

3.1 Material and Specimen Preparation

For specimen fabrication, typical Ordinary Portland Cement with a 28-day compressive strength of 25 MPa was selected due to its widespread use in local concrete construction. The spiral stirrups were commercially sourced, while the RCA material was obtained from demolished local structures. Although the exact compressive strength and other mechanical properties of the parent concrete were not determined, the source material originated from structural members designed for conventional load-bearing applications, and similar concrete typically exhibits compressive strengths in the range of 25–35 MPa. The RCA was produced using a crusher and sieved to achieve the desired particle sizes. The aggregates were then thoroughly washed with water to eliminate surface impurities, including dust and clay, ensuring they met the quality standards for reuse in concrete. The NCA used in this study was natural crushed rock with a maximum size of 40 mm, and the fine aggregate was natural river sand with a particle size of less than 5 mm. Sieve analysis details, conducted following TCVN 7572-2 [27], are presented in Table 1.

Two sets of mixtures, detailed in Table 2, were prepared for casting the specimens. For each mixture type with a different stirrup configuration, three standard cylindrical specimens (150 × 300 mm, D × H) were fabricated. Spiral reinforcement, with a diameter of 6 mm, was spaced at 20, 25, 30, 50, and 100 mm. Additionally, for each mixture type, a set of three test samples was fabricated without spiral reinforcement for comparison. It should be noted that, although the mix proportions were adjusted to ensure workable concrete, the water-to-cement ratio and workability data, as well as slump tests, were not performed in this study. The specimens were cast into molds and kept for 24 hours before being released and cured under normal conditions until testing. The entire process of mixing, casting, and curing was carried out in accordance with TCVN 3105:1993 [28].

Table 1. Sieve analysis for coarse and fine aggregate

Type	Sieve size (mm)	Cumulative retained (%)
Coarse aggregate	40	0
	20	8.2
	10	50.3
	5	95.5
	< 5	100
Fine aggregate	5	0
	2.5	8
	1.25	27.6
	0.63	52.3
	0.315	78.4
	0.14	93.6

Table 2. Mixture proportions

RCA_R (%)	C (kg/m³)	F (kg/m³)	NCA (kg/m³)	RCA (kg/m³)	W (l)
0	22.16	43.71	87.15	0	12.35
30	22.16	43.71	60.85	26.15	12.35

Note: RCA_R-RCA replacement. C-Cement. F-Fine aggregate. W-Water

To facilitate the quick identification of test samples during experimental work, the specimen naming convention consisted of three components: the letter "G" followed by a number representing the group, the letter "S" followed by a three-digit number indicating stirrup spacing (in millimeters), and the letter "R" followed by the percentage of RCA replacement. For example, the specimen G2S050R30 refers to a sample from group 2 with a stirrup spacing of 50 mm and 30% RCA replacement. During testing, an additional specimen code was assigned using the letter M followed by a digit (1 to 3) to denote the specimen number, while different stirrup configurations were labeled C1 to C12. For instance, the code M2-C7 represents specimen 2 of G2S020R30. Further details are provided in Table 3.

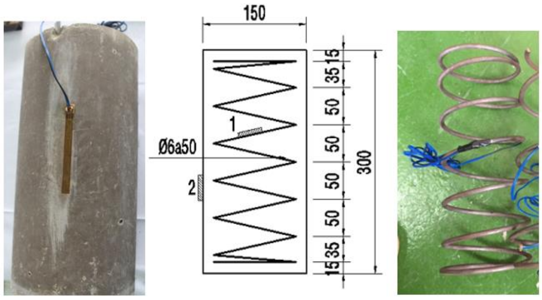
Table 3. Details of specimens

Specimen name	Code name	No specimens	RCA replacement	Stirrup spacing
G1S020R00	M(1-3)-C1	3	0%	20
G1S025R00	M(1-3)-C2	3	0%	25
G1S030R00	M(1-3)-C3	3	0%	30
G1S050R00	M(1-3)-C4	3	0%	50
G1S100R00	M(1-3)-C5	3	0%	100
G1S000R00	M(1-3)-C6	3	0%	No stirrup
G2S020R30	M(1-3)-C7	3	30%	20
G2S025R30	M(1-3)-C8	3	30%	25
G2S030R30	M(1-3)-C9	3	30%	30
G2S050R30	M(1-3)-C10	3	30%	50
G2S100R30	M(1-3)-C11	3	30%	100
G2S000R30	M(1-3)-C12	3	30%	No stirrup

3.2 Test apparatus and procedure

This experimental study aimed at determining the compressive strength of concrete specimens with and without RCA replacement, as well as the effects of stirrup spacing on the compressive strength. Figure 1 demonstrates the experimental setup. Axial concrete strain was measured using a surface-mounted strain gauge bonded directly to the concrete. The strain in the stirrup was monitored through a strain gauge fixed along the stirrup and embedded within the specimen before casting. The approximate placement of both gauges is illustrated in Figure 1b. A 2000 kN capacity compressive testing machine with a piston stroke of 50 mm, and a hydraulic pump rated pressure of 40MPa was employed. To perform the compression test, the specimen was placed into the testing machine, and the testing load was increased at a specimen at a rate of 1.0 ± 0.05 kN/s. Continue loading the specimen until the load indicator drops off steadily and the cylinder is visibly fractured. The applied load and the corresponding strain in both the concrete and the stirrup were continuously recorded throughout the entire loading cycle until failure. The experimental compressive strength of specimens was calculated following TCVN 3118: 2022 [29]. The procedure was applied to all the specimens within this study.

(a) Compression testing machine



(b) Strain gauges installation

Fig.1 Experimental Setup

4. RESULTS AND DISCUSSION

As mentioned earlier, a total of 36 confined reinforced concrete specimens were tested to investigate the influence of RCA replacement and spiral stirrup spacing on 28-day compressive strength. The experimental results were compared against theoretical values derived from Mander’s equation. In addition, the cracking behavior and failure modes of the specimens were thoroughly analyzed, with detailed results presented in the subsequent sections.

4.1 Cracking and Failure Modes

The majority of specimens in this experimental study exhibited a typical failure pattern, as shown in Fig. 2. Initially, under small applied loads, the specimens displayed linear elastic behavior, maintaining a linear load-deformation relationship up to 50% of the maximum load. As the load approached 75% of the maximum, the specimens transitioned into the elastic-plastic phase, where the load-deformation response became non-linear. During this phase, microcracks formed along the edges of the specimen’s top surface, accompanied by irregular concrete spalling. As the axial load neared its peak, additional cracks developed, and fracture-splitting sounds became audible. At maximum load, numerous cracks propagated, the concrete cover spalled, and the axial load began to decrease. Specimens with small stirrup spacing demonstrated ductile behavior and uniform cracking, indicating effective confinement and higher ultimate strain. In contrast, wider spacing led to localized spalling and reduced energy absorption. Higher RCA replacement ratios caused earlier cracking and larger spalled zones, reflecting RCA's higher porosity and weaker interfacial transition zones.

(a) G2S025R30

(b) G2S020R30

Fig.2 Compressive failure of different specimens

4.2 Experimental Compressive Strength

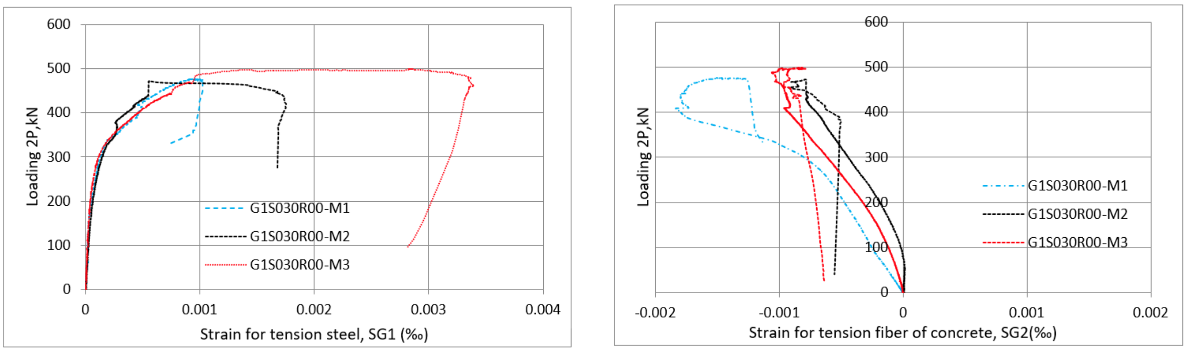
Table 4 presents the experimental results of the compressive strength and strain relationship of all tested specimen groups at 28 days. It is noted that the results reported in this study represent the mean values of the tested specimens. Because of the limited number of samples per test configuration, statistical significance testing was not performed. As can be seen, the presence of spiral stirrups notably increases the compressive strength in both types of reinforced specimens, those made with and without RCA, due to the enhanced confinement provided by the stirrups. Additionally, the reduction in stirrup spacing further contributes to compressive strength improvement. For example, the compressive strength for conventional concrete specimens increases from approximately 32.04 MPa to about 35.64 MPa when the spiral stirrup spacing reduces from 100 mm to 20 mm. The identical trend holds for the compressive strength of concrete specimens with 30% RCA. When comparing specimens with identical stirrup configurations, concrete without RCA replacement exhibits compressive strength approximately 0.5% to 4% higher than that incorporating 30% RCA. This finding confirms that compressive strength decreases as the replacement percentage of the recycled aggregate increases.

It is noteworthy that an appropriate spiral stirrup configuration in RCA concrete can enhance the compressive strength of specimens through confinement effects. These effects may help compensate for the reduction in strength typically associated with RCA replacement. As shown in Table 4, the peak compressive strength sustained by a conventional concrete specimen with a stirrup spacing of 50 mm is approximately equivalent to that of an RCA concrete specimen with a stirrup spacing of 30 mm. With respect to the applied load and strain relationship, Fig. 3 depicts the changes in the applied load and the strain in the stirrup steel and concrete fiber for different specimens in the C3 (G1S030R00) group during the test. The C3 group was chosen as a representative case because it best illustrates the transition in stress–strain behavior during the compression tests among all specimens

Table 4. The average strain in concrete and stirrup with different stirrup configurations

Stirrup spacing (mm)	Without RCA			With 30% RCA		
	f'_c (MPa)	Concrete strain (‰)	Stirrup strain (‰)	f'_c (MPa)	Concrete strain (‰)	Stirrup strain (‰)
No stirrup	30.43	0.00357	-	27.47	0.00439	-
100	32.04	0.00308	0.00348	31.89	0.00433	0.00408
50	32.76	0.00283	0.00295	32.40	0.00430	0.00400
30	33.22	0.00244	0.00292	32.72	0.00384	0.00344
25	34.46	0.00211	0.00270	33.48	0.00363	0.00296

20	35.64	0.00160	0.00232	34.24	0.00327	0.00276

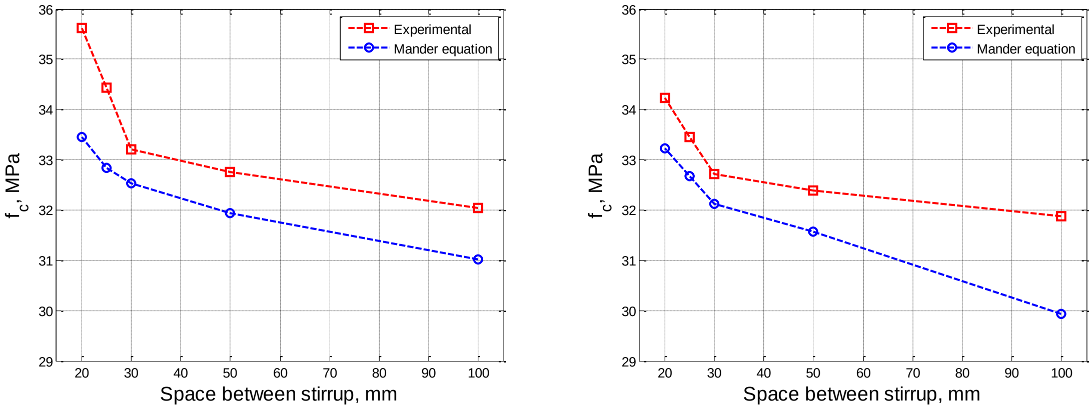


(a) Strain in steel b) Strain in concrete

Fig.3 Load versus strain relationship in specimens:

4.3 Experimental compressive strength versus values from using Mander's equation

In order to compare the experimental 28-day compressive strength with theoretical estimation, Mander's equation was employed to compute the compressive strength of all concrete specimens in this study. Figure 4 shows the comparison between the experimental compressive strength of concrete specimens and the calculated results using Mander's equation. As can be seen clearly, the application of Mander's equation conservatively estimated the compressive strength for both types of concrete (with and without RCA replacement). The average difference is approximately 3.22% for the concrete with 30% RCA replacement and 3.88% for the no RCA replacement. It can be explained that Mander's model captures general confinement behavior but does not fully account for the distinct material characteristics of RCA concrete. Mander's model was originally calibrated for normal-weight concrete made with natural aggregates, assuming a relatively homogeneous and dense matrix with uniform lateral strain distribution.



(a) Without RCA (b) With 30% RCA

Fig.4 Experimental compressive strength versus calculated values using Mander's equation.

With respect to the application of Mander's equation for the two types of concrete, Fig. 5 illustrates the impact of spiral stirrup spacing on the compressive strength predictions obtained using Mander's equation for both conventional and RCA concrete. When the stirrup spacing is small (e.g., 20 mm), the predicted values align closely with the experimental results for both concrete types. However, as the spacing increases, the discrepancy between predicted and measured strengths becomes more significant, reaching approximately 3.64% at a spacing of 100 mm. This trend can be attributed to the diminished confinement effect at larger spacings, which reduces the enhancement in compressive strength and causes the concrete behavior to resemble that of unconfined specimens.

Although Mander's model provides a robust analytical framework for predicting the behavior of confined concrete, its underlying assumptions were developed for mixes incorporating natural aggregates. The recycled coarse aggregate used in this study presents higher porosity, a weaker interfacial transition zone, and more heterogeneous stiffness compared with natural aggregate concrete. These characteristics can reduce confinement effectiveness and alter the stress–strain response. Consequently, Mander's model may slightly overpredict the confined strength of RCA concrete. Future work should consider modifying the model parameters, such as the effective lateral stress or confinement efficiency factor, to better capture the influence of RCA microstructure on confined behavior.

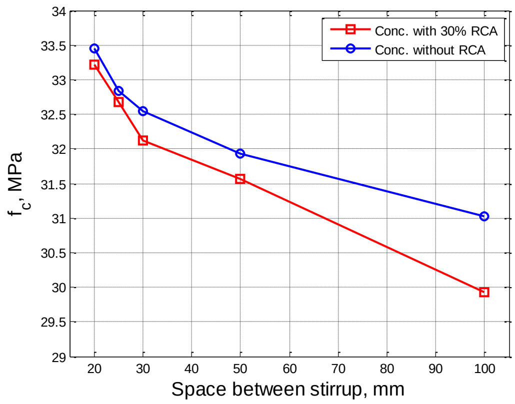


Fig.5 Calculated f'_c using Mander's equation

5. CONCLUSIONS

This paper examines the compressive behavior of confined reinforced concrete columns incorporating up to 30% RCA replacement and spiral stirrup spacings of 20, 25, 30, 50, and 100 mm. A total of 36 cylindrical specimens were fabricated and tested. The key conclusions from the experimental study are as follows:

(i) All specimens exhibited similar cracking patterns from initiation to failure. Compressive strength generally decreased as RCA content increased when using the same mix proportions.

(ii) As the RCA replacement percentage increased, the maximum compressive strength at 28 days decreased by approximately 2.85% to 9.72% compared to specimens without using RCA.

(iii) Although RCA incorporation reduced the 28-day compressive strength of specimens, confinement provided by spiral stirrups helped compensate for this reduction. With appropriate spiral stirrup configurations, the compressive strength of RCA columns approached that of conventional reinforced concrete specimens. The findings suggest that reinforced concrete with up to 30% RCA replacement and proper spiral stirrup spacing can serve as load-bearing structural elements in compression.

(iv) Mander's equation provided a conservative estimate of the 28-day compressive strength for confined concrete with 30% RCA replacement.

For future studies, factors such as spiral yield strength, concrete cover thickness, and loading rate should be investigated to establish comprehensive performance-based design criteria for RCA in load-bearing applications. Long-term durability aspects, including creep, shrinkage, and permeability, also promise evaluation to assess the practical use of RCA in structural elements. Moreover, advanced techniques like digital image correlation, acoustic emission monitoring, and microstructural analysis could be employed to quantify crack propagation and link failure mechanisms to internal damage development.

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