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Performance Evaluation of Recycled Coarse Aggregate in Self-Compacting Concrete

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Abstract

This study evaluates the performance of Recycled Coarse Aggregate (RCA) in Self-Compacting Concrete (SCC) as a sustainable alternative to natural coarse aggregate (NCA). SCC mixes of M30 and M50 grades were prepared with RCA replacing NCA at 0%, 20%, 40%, 60%, 80%, and 100%. Basic material properties were examined through standard tests including sieve analysis, specific gravity, and aggregate strength indices. Fresh concrete properties were evaluated using the slump flow and V-funnel tests, while mechanical properties were assessed via compressive and split tensile strength tests. Results showed that up to 40% RCA replacement had negligible effects on workability, with mixes exhibiting excellent flow and no segregation. However, mechanical strength declined with increasing RCA content. Notably, 20% RCA in M50 mixes retained target compressive strength, whereas M30 mixes with the same replacement fell short. SEM analysis at 20% RCA revealed minimal changes in the Interfacial Transition Zone (ITZ), indicating a stable microstructure. Durability evaluation through acid attack tests revealed minimal differences in mass and strength loss between conventional and 20% RCA-replaced SCC.

Keywords Recycled Coarse Aggregate, Self-Compacting Concrete, Fresh Properties, Mechanical Properties, Scanning Electron Microscopy (SEM)

1 Introduction

Sustainable processes are becoming increasingly significant in construction sectors as an approach to address resource depletion and environmental issues. A promising approach is utilizing Recycled Coarse Aggregate (RCA) obtained from construction demolition debris such as crushed concrete and masonry structures. They are widely used in pavement construction and structural concrete with supplementary cementitious materials. RCA encourages resource conservation and waste reduction by providing a sustainable alternative for natural aggregates(Yehia et al., 2015)(Ahmed et al., 2023)(Chakradhara Rao, 2018)(Kumar & Singh, 2024). The circular economy in construction waste management enhances sustainability, reducing resource depletion and landfill waste. This approach lowers environmental impact while promoting cost-effective and efficient resource utilization.

Self-compacting concrete (SCC) has revolutionized the concrete industry with its ability to flow and settle under its weight without the need for mechanical vibrations. SCC gives better surface finishes, provides structural integrity, and improves construction efficiency(Wang et al., 2023)(Kim & Kim, 2023). SCC and RCA together meet the immediate requirement for ecologically friendly construction materials while also being in line with sustainability policies. Despite numerous advantages of RCA in the concrete industry, it has its shortcomings. When compared to natural aggregates, RCA commonly has more porosity, higher water absorption, and more unpredictability in quality. These characteristics might impact SCC's fresh properties and hardened properties. To address this gap, this study is carried out. While previous literatures are focused on independent studies of RCA and SCC, this study examines the replacement of NCA with different proportions of RCA to evaluate the fresh and hardened properties of M30 and M50 SCC. Fresh properties test includes workability test and flowability test whereas the hardened properties test includes compressive strength test and split tensile strength test. Following the mechanical tests, Scanning Electron Microscopy (SEM) analysis was carried out for micro-structural tests. Finally, durability test of concrete was done on selected specimens. All of these tests were conducted in the Concrete Laboratory of REVA University, School of Engineering.

Several researches have been conducted in the past regarding the use of RCA as sustainable material. An extensive review of 163 publications from 1992 to 2018 on Construction and Demolition Waste (CDW) recycling and its applications in construction materials revealed that CDW aggregates offer an effective alternative to natural aggregates, providing an eco-friendly and cost-effective solution for sustainable construction(Reis et al., 2021). Also, it was suggested that the recycled aggregate obtained from CDW can be used in major domains like sand production, pavement construction, ready-mix concrete, concrete blocks, and so on. A comprehensive review of the utilization of recycled aggregate (RA) in concrete production found that replacement levels up to 30% resulted in negligible performance reductions (Marvila et al., 2022). Additionally, the study emphasized the need for improved RA processing techniques and the establishment of international standards for its use. The feasibility of replacing NCA with RCA in M25 grade concrete was experimentally evaluated at replacement levels of 25%, 50%, and 100% (Madhu et al., 2022). Several tests were conducted including compressive strength test, split tensile strength test, flexural strength test, water absorption test, abrasion tests, and rapid chloride penetration test. The results showed that up to 25% RCA replacement maintains comparable strength to conventional concrete, while higher replacement levels lead to reduced strength and durability. Similarly, (Suman & Rajasekaran, 2016) performed a study on evaluating mechanical properties of Recycled Aggregate Concrete (RAC) with Ordinary Portland Cement (OPC) and Portland Pozzolana Cement (PPC) (Suman & Rajasekaran, 2016). In this study, a number of M30 concrete samples were prepared with replacement of NCA with RCA at 0%, 25%, 50%, 75%, and 100%. 7 days and 28 days compressive strength, flexural strength, and split tensile strength were examined revealing up to 25% replacement being acceptable for concrete manufacturing. The 28-days results of full replacement showed 24% loss in compressive strength, 26% loss in flexural strength and 21% in split tensile strength. Additionally, the study suggested that the loss in mechanical strength might be due to adhered mortar in the RCA causing high water absorption. The use of Volcanic Ash (VA) and Recycled Coarse Aggregates (RCA) to develop Self Compacting Concrete (SCC) was studied by (Chakkamalayath et al., 2020). Several mixes with various proportions of OPC and NCA with 30% VA and 30% RCA respectively. From the study, it was revealed that up to 30% RCA in NCA didn't alter the mechanical properties of the concrete. Furthermore, it was suggested that a ternary mix of ground granulated blast-furnaced slag would enhance the durability of RCA mixed concrete. The performance of SCC with RCA at different replacement levels (0%, 25%, 50%, and 100%) via experimental tests and microstructural analyses using SEM indicated that compressive strength decreases by up to 30% at 100% replacement, though supplementary cementitious materials improve the microstructural characteristics (Rizwan et al., 2022).

2 Materials and Methods

The materials used in this study were Ordinary Portland Cement of Grade 53, Fly ash of class 'F', M-Sand and Natural Coarse Aggregate (NCA) with Polycarboxylate Ether (PCE) based admixture for conventional SCC. The RCA used in this study were collected from a demolished RCC building. A representative flowchart of the methodology is shown in Figure 1.

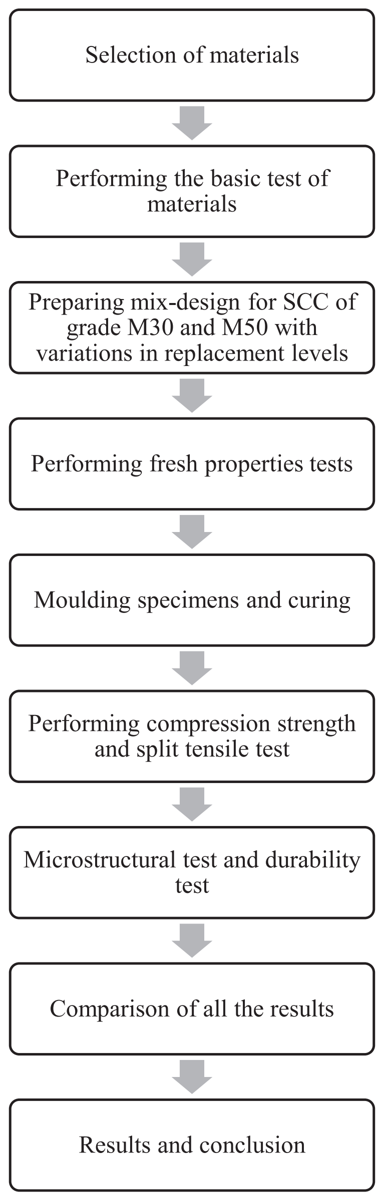

Figure 1: Flow Chart for proposed Methodology

Cement, fine aggregate, coarse aggregate, and recycled coarse aggregate were evaluated for basic properties, including sieve analysis, specific gravity, cement fineness, aggregate crushing value (ACV), and aggregate impact value (AIV)(*IS 383 Coarse and Fine Aggregate for Concrete-Specification*, 2016). Based on these initial tests, mix designs for M30 and M50 grades of concrete were developed according to the (*IS 10262 Concrete Mix Proportioning-Guidelines*, 2019). Replacement of NCA with RCA for 0%, 20%, 40%, 60%, 80%, 100% were done.

Table 1: Mix proportion for M30

Component	Mass (Kg/m^3)	Mix ratio
Cement	320	
Fly Ash (Mineral admixture)	172.31	
Water	186	1 m^3
Fine Aggregate	630.90	
Natural Coarse Aggregate	999.14	
Admixture	4.56	

Table 2 Mix Proportion for M50

Component	Mass (kg/m^3)	Mix ratio
Cement	416.42	
Fly Ash	138.80	
Water	186	1 m^3
Fine Aggregate	614.54	
Natural Coarse Aggregate	973.22	
Admixture	5.14	

The experimental phase of the study involved testing the fresh properties of self-compacting concrete (SCC) using the slump flow test and the V-funnel test. The slump flow test assessed the concrete's ability to flow under its own weight, with recommended slump flow values between 650 mm and 800 mm. The V-funnel test evaluated the concrete's filling capacity, requiring a flow time of eight seconds or less. These are shown in Figure 2a and 2b.

a b

Figure 2: Fresh property test a) Slump test b) V-funnel test

For both M30 and M50, a total of 18 cubes and 18 cylinders were cast, with three samples prepared for each replacement level. Concrete cubes and cylinders of dimensions 150x150x150 mm and 300x150 mm respectively were used in this study. Some photographs of sample are shown in Figures 3a and 3b. After casting, the samples were cured for 28 days, then removed and allowed to dry. Following the curing period, the concrete samples were tested for compressive strength and split tensile strength using a compression testing machine (CTM), during which the weight and failure load of each specimen were recorded as shown in Figures 4a and 4b.

a

b

Figure 3: Concrete samples a) Cubical 150x150x150mm b) Cylindrical 300x150mm

a

b

Figure 4: Hardened tests a) Compressive strength tests b) Split tensile strength test

After these mechanical tests, the results were collected and evaluated thoroughly. The samples with the optimal replacement level of RCA for M30 and M50 were identified. These samples were then collected for Scanning Electron Microscopy (SEM) analysis whose setup is shown in Figure 5. Up to 10,000 times magnification were done in SEM analysis to study the microstructural properties. Properties like density of structures, presence of micropores and voids, surface irregularities, and micro-cracks formations were visually assessed through the obtained images. Finally, the selected samples underwent durability testing, including acid penetration and water absorption assessments as shown in Figure 6.

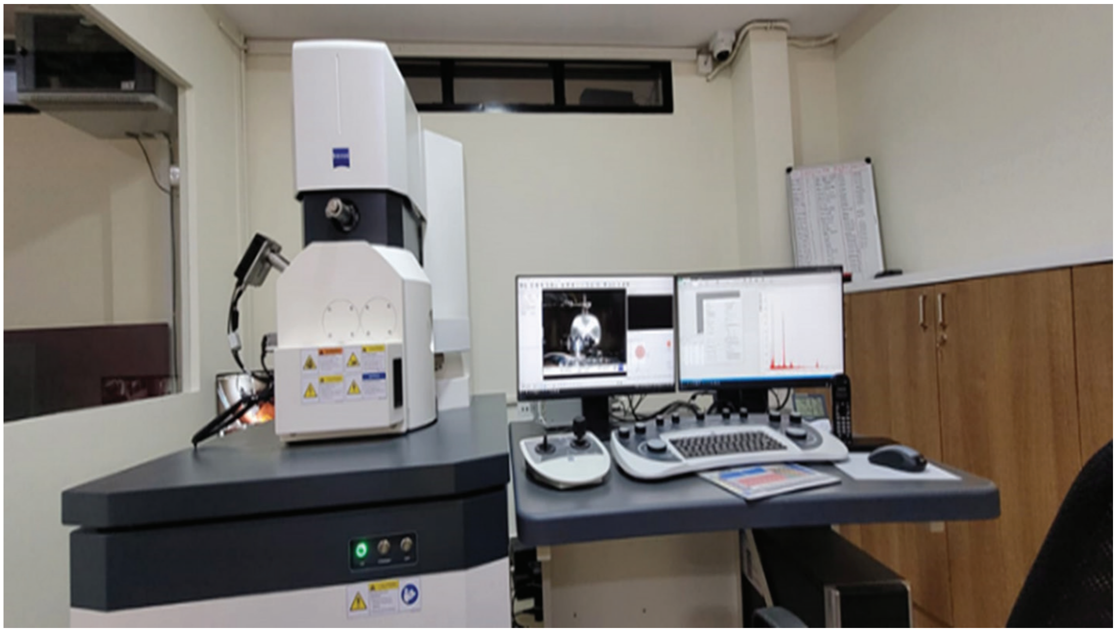

Figure 5: SEM test setup

Figure 6: Durability test acid curing

3 Results and Discussions

3.1 Sieve Analysis

The Sieve Analysis was conducted for Fine Aggregate, NCA and RCA confirming (*IS 383 Coarse and Fine Aggregate for Concrete-Specification*, 2016). The fineness modulus of Sieve Analysis of aggregates is within the permissible limits.

Table 3: Sieve Analysis

S.N.	Materials	Fineness Modulus
1	Fine Aggregate	3.02
2	Natural Coarse Aggregate	8.14
3	Recycled Coarse Aggregate	7.67

3.2 Specific Gravity Test

The specific Gravity of cement is 3.115 which value is within an allowable limit according to IS 12269: 2013 and for the Specific Gravity of Aggregate the value is between 2.5 to 3.0 which indicates that the aggregate being used is allowable for project.

Table 4: Specific Gravity Test

S.N.	Materials	Specific Gravity
1	Cement	3.115
2	Fine Aggregate	2.51
3	Natural Coarse Aggregate	2.65
4	Recycled Coarse Aggregate	2.59

3.3 Aggregate Impact Value (AIV)

The impact value for aggregate was tested for NCA and RCA. The below table indicates that the impact value of aggregate is strong and can be used for construction purposes.

Table 5: Aggregate Impact Value (AIV)

S.N.	Materials	Aggregate Impact Value
1	Natural Coarse Aggregate	21%
2	Recycled Coarse Aggregate	30%

3.4 Aggregate Crushing Value (ACV)

The Aggregate Crushing Value was tested for NCA and RCA. The ACV test resulting in 33% indicates moderate strength level. The aggregate can be considered for general construction applications.

Table 6: Aggregate Crushing Value (ACV)

S.N.	Materials	Aggregate Crushing Value
1	Natural Coarse Aggregate	26%
2	Recycled Coarse Aggregate	33%

3.5 Fresh Properties Test of Concrete

For the fresh properties test of concrete, slump test and V-funnel test was carried out. The results showed that the mixes satisfied acceptance criteria. The results of slump test and V-funnel test are shown in Figure 7 and Figure 8.

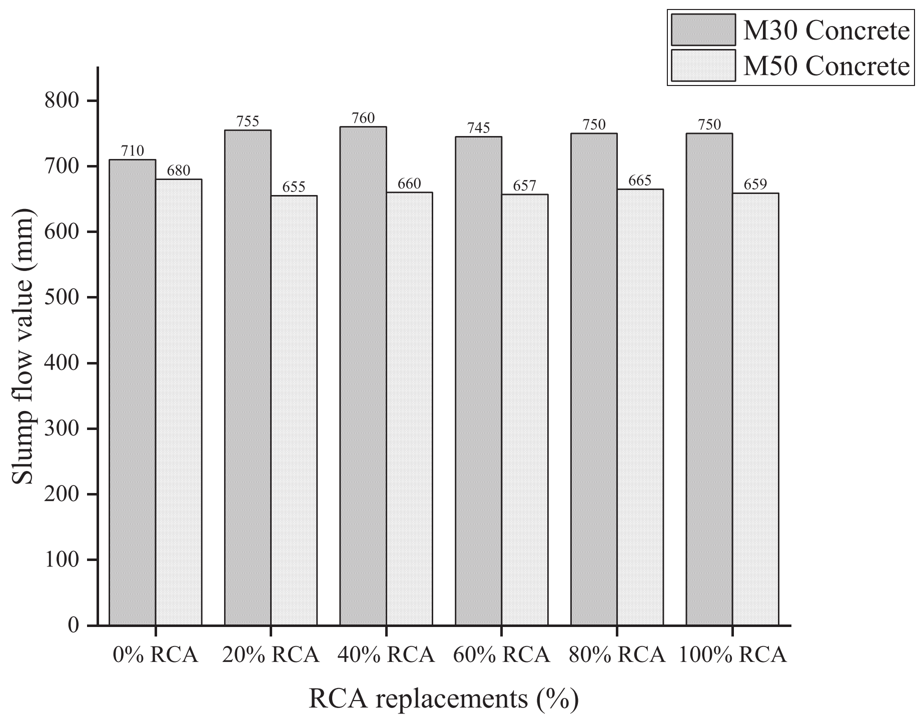

Figure 7: Comparative graph of slump flow value for M30 and M50 grade concrete with partial to full replacement of NCA with RCA

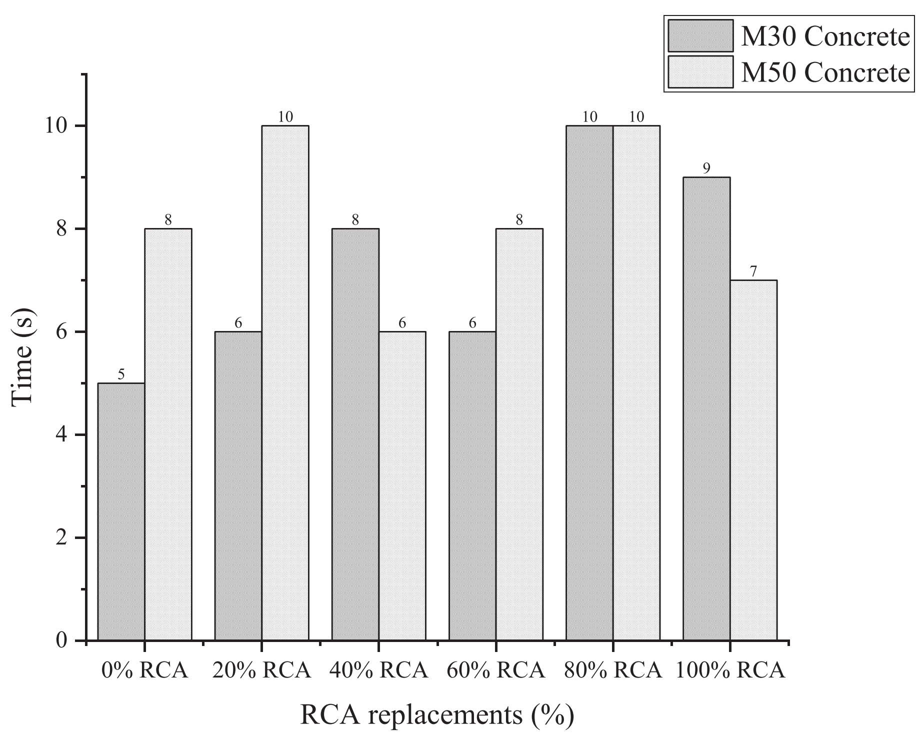

Figure 8: Comparative graph of flowability from V-funnel test for M30 and M50 grade concrete with partial to full replacement of NCA with RCA

3.6 Compressive Strength of Concrete

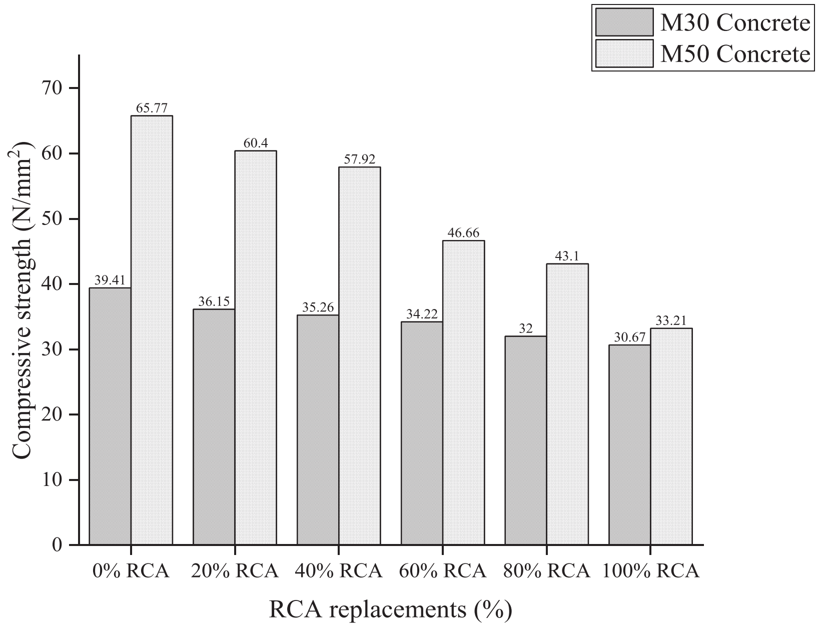

Figure 9: Comparative graph for M30 and M50 grade concrete based on compressive strength with partial to full replacement of NCA with RCA

The bar graph shows M30 and M50 grade concretes with 0%-100% RCA replacement. M50 grade maintains target strength with 20% RCA, while M30 fails to do so. Therefore, M50 with 20% RCA is suitable for non-load bearing or non-wearing structures.

3.7 Split Tensile Strength of Concrete

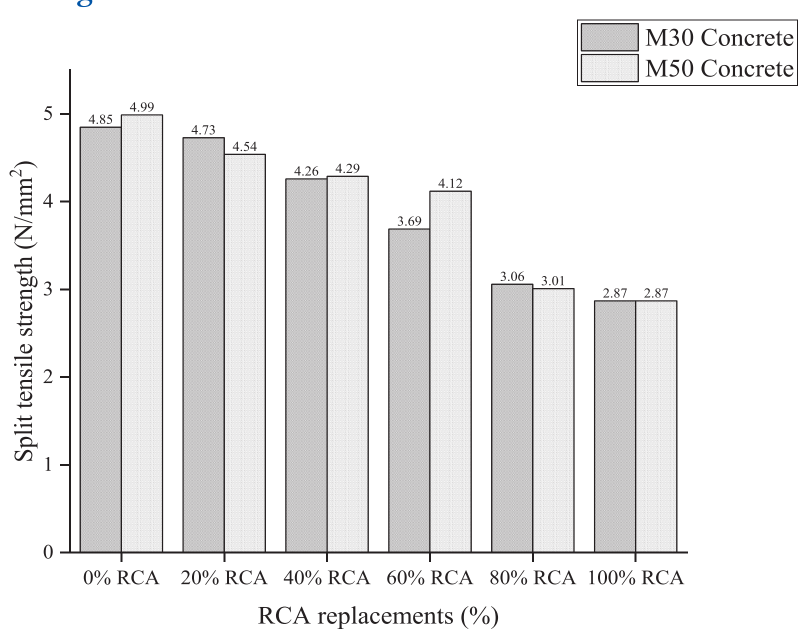

Figure 10: Comparative graph for M30 and M50 grade concrete based on split tensile strength with partial to full replacement of NCA with RCA

The bar graph shows M30 and M50 grade concretes with 0%-100% RCA replacement. For M30, the split strength decreases slightly from 4.85 N/mm^2 to 4.73 N/mm^2 with 20% RCA, while for M50, it decreases from 4.99 N/mm^2 to 4.54 N/mm^2. The conventional mix remains the most appropriate, but RCA can be used with minimal impact on strength.

3.8 Micro-Structural Test

Following are the images obtained from Scanning Electron Microscopy (SEM) of Concrete.

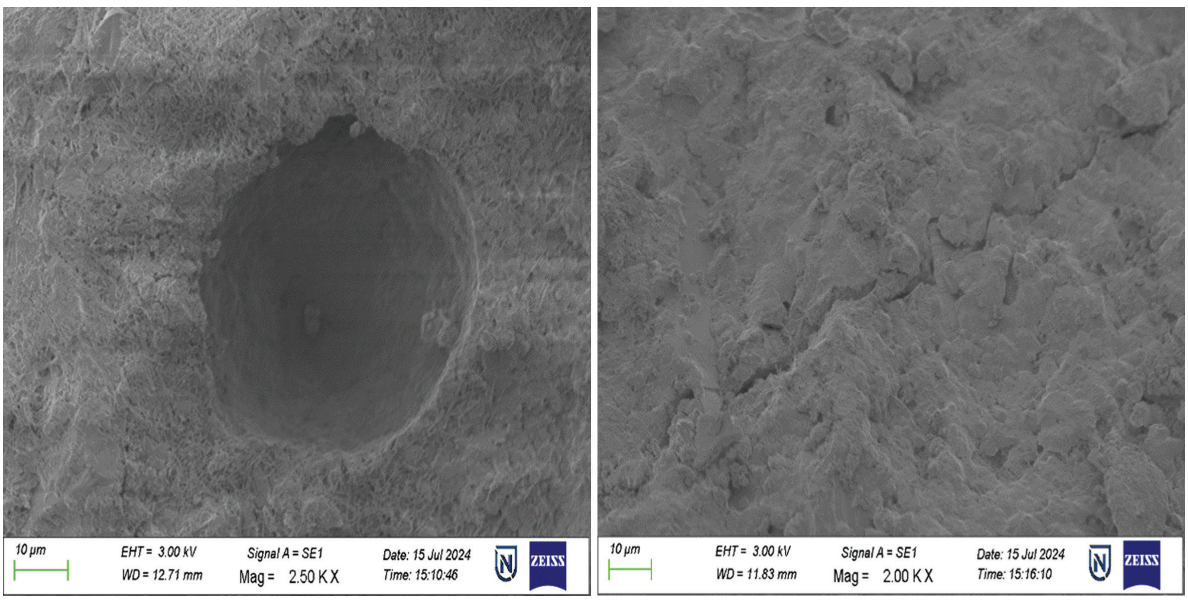

Figure 11: SEM image for M30 grade 0% RCA

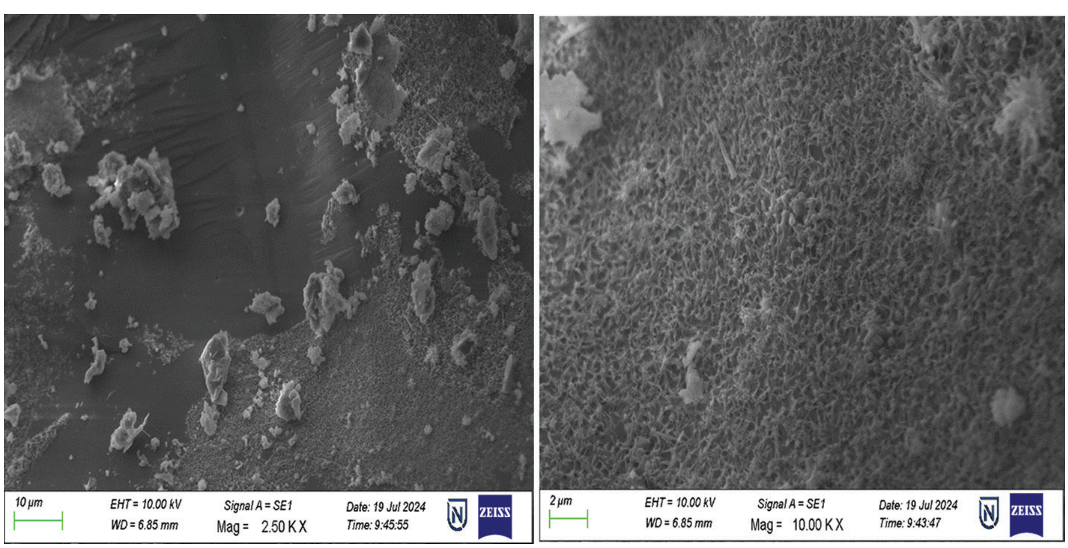

Figure 12: SEM image for M30 grade 20% RCA

The figure shows M30 grade conventional concrete matrix magnified 2000 and 2500 times, revealing a densely packed structure with visible micropores. The surface appears slightly rough, indicating good bonding without voids or micro-cracks from the hydration process. The figure shows M30 grade concrete with 20% RCA at 2500- and 10,000-times magnification. At 2500 times, the surface is partly smooth and rough, while small white patches, likely iron-oxide particles, are visible in the inner strata.

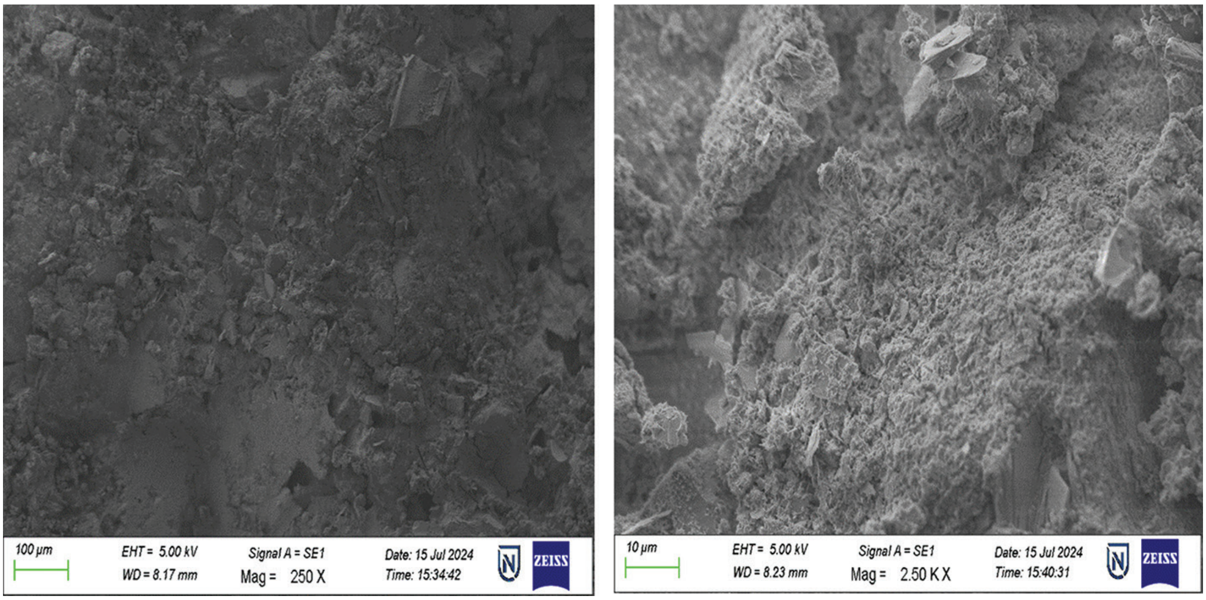

Figure 13: SEM image for M50 grade 0% RCA

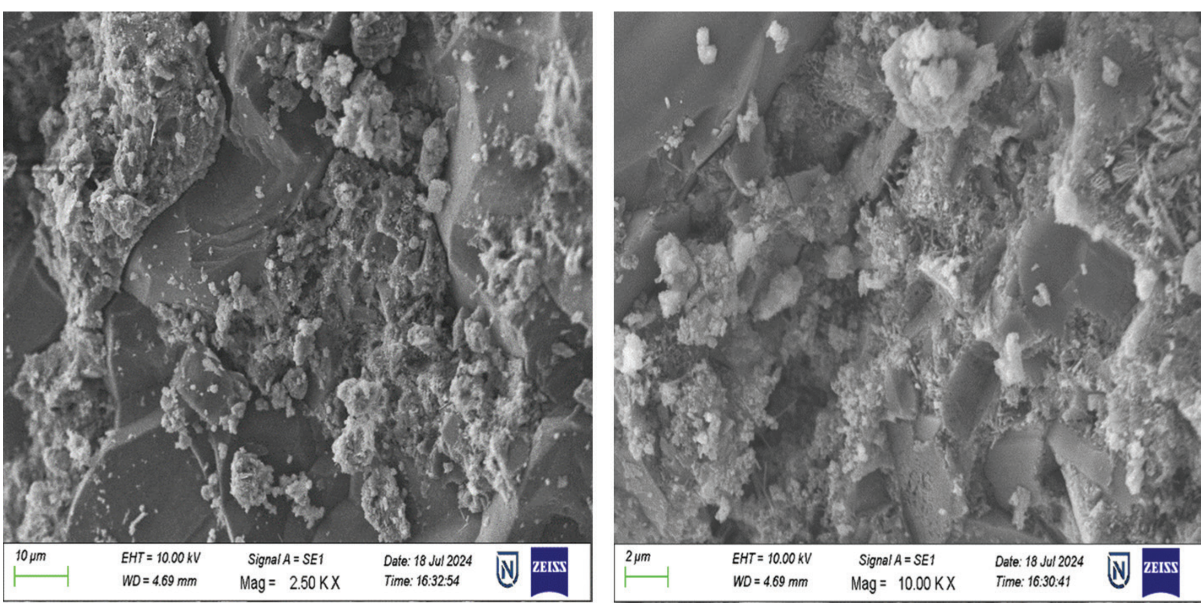

Figure 14: SEM image for M50 grade 20% RCA

The figure shows the surface structure of M50 grade concrete with 20% RCA at 2500- and 10,000-times magnification. At 2500 times, the surface appears smooth. At 10,000 times, white crystal-like spike particles called ettringite are visible, which are detrimental to the concrete matrix. The higher magnification reveals an even smoother surface with more pronounced ettringite, confirming their negative impact when present in large amounts.

3.9 Durability test of Concrete

3.9.1 Acid attack test

The Acid attack test evaluates concrete durability in acidic conditions by submerging cured specimens in sulfuric or hydrochloric acid for a set time. Observations focus on weight loss, surface erosion, and changes in compressive strength. Results indicate degradation extent and resilience against acid attacks. Minimal weight loss, surface damage, and strength decline suggest a durable concrete mix suitable for acid-exposure environments. In this study, 5% H_2SO_4 solution was used and cured for 28 days.

a) Acid Mass Loss Factor (AMLF)

By immersing the cubes in an acidic solution and measuring the mass at a predetermined time, the percentage loss is calculated. Acid Mass Loss Factor (AMLF) is the definition of the change in mass with age relative to each specimen's original mass. By

$$\text{AMLF} = \frac{\text{Specimen mass change after acid immersion}}{\text{Initial mass}} \times 100$$

Table 7: Acid Mass Loss Factor (AMLF)

Grade	Specimen	Mass (kg) Before	After	Difference	AMLF
M30	0% RCA	8.11	7.59	0.52	6.41%
	20% RCA	8.08	7.55	0.53	6.56%
M50	0% RCA	8.02	7.57	0.45	5.61%
	20% RCA	8.31	7.84	0.47	5.66%

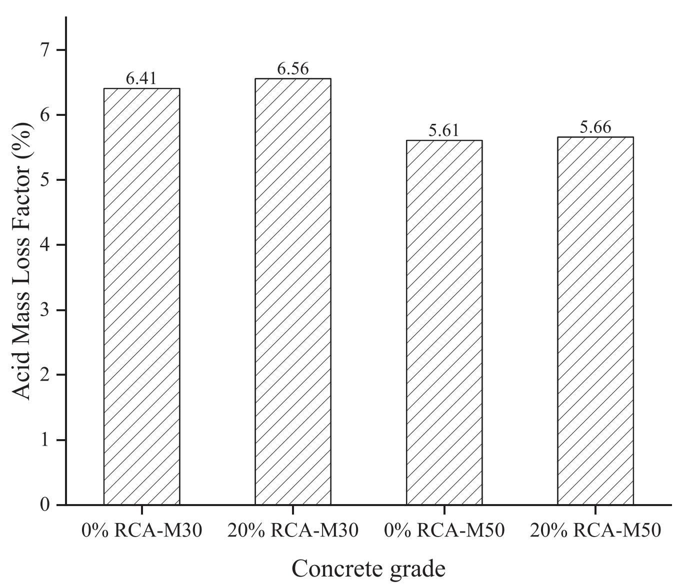

Figure 15: Acid Mass Loss Factor M30 & M50

b) Figure 15 shows the AMLF for conventional M30, 20% RCA M30, conventional M50, 20% RCA M50. The AMLF for conventional M30 & M50 are 6.41% and 6.56% respectively. Similarly, at 20% RCA replacement in the M30 & M50 the AMLF is 6.56% and 5.66%. These results indicate that there is minimum difference in the AMLF when 20% RCA replacement is done in the conventional M30 and M50 SCC. This also signifies that at 20% RCA replacement, sufficient resistance to acid exposure can be expected. **Acid Strength Loss Factor (ASLF)**

ASLF shows the change in mechanical strength (compressive strength, tensile strength) of concrete after being immersed or exposed to acid for a certain time. Table 10 shows the calculation of ASLF of M30 and M50 SCCs.

Table 8: Acid Strength Loss Factor

Grade	Specimen	Compressive strength (N/mm²)		Difference	ASLF
		Before	After		
M30	0% RCA	39.41	29.34	10.07	25.55%
	20% RCA	36.15	29.33	6.82	18.87%
M50	0% RCA	65.77	41.20	23.1	35.93%
	20% RCA	60.40	38.23	21.03	35.49%

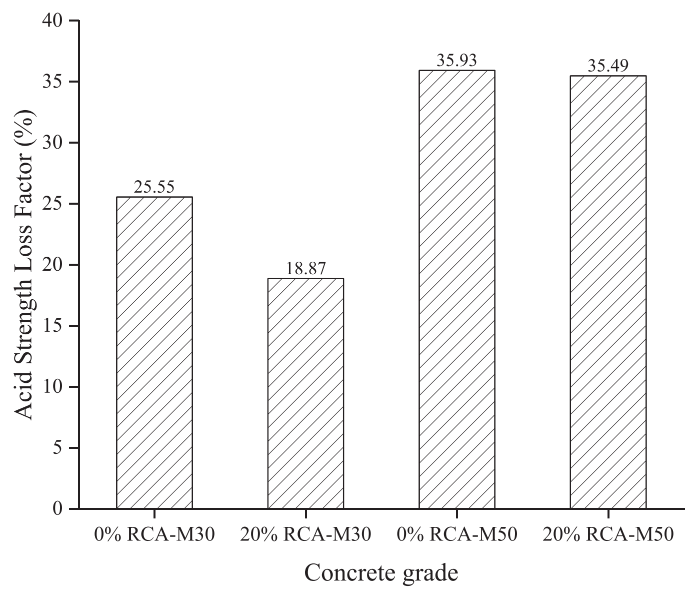

Figure 16: Acid Strength Loss Factor M30 & M50

Figure 16 illustrates the ASLF in concrete specimens submerged in a 5% H_2SO_4 solution and cured for 28 days. M30 grade conventional SCC shows a strength decline of 25.55% whereas M30 SCC with 20% RCA replacement shows strength decline of 18.87%. This shows that loss in compressive strength was much lower at 20% RCA-M30 than the conventional M30. Similarly, the ASLF of conventional M50 and 20% RCA-M50 were found to be 35.93% and 35.49% respectively. In M50 SCC, only a slight variation in the ASLF was seen.

4 Conclusion

This study examines the performance of RCA in the production of SCC as a sustainable alternative to natural aggregates. Initially, basic material tests were done complying with various national and international standards. SCC mixes were prepared with varying RCA replacements 0%, 20%, 40%, 60%, 80%, & 100% for both M30 and M50 concrete. Fresh concrete properties were evaluated using slump test and flowability test. Similarly, mechanical properties were evaluated using compression strength test and split tensile strength test. Based on these tests, optimal replacement of RCA was found and thus the selected specimens were later analysed using SEM for microstructural test. Finally, the specimens were subjected to durability test (acid attack test).

In conclusion, SCC with RCA demonstrates good workability with no segregation and excellent flowability, as confirmed by the V-funnel test. Substituting 20-40% of natural aggregate with RCA does not significantly impact fresh properties, but compressive and tensile strength decrease with higher RCA concentration. In this study, up to 20% RCA replacement in the M50 concrete maintains target strength. However, 20% RCA in M30 failed to maintain target strength in compressive test. RCA with more defects or cracks results in greater strength loss, while its porosity may accelerate early cement hydration, leading to quicker strength development compared to SCC with natural aggregates.

Microstructure analysis via SEM shows minimal variation in the Interfacial Transition Zone (ITZ) at a 20% RCA replacement level. Class-F fly ash contributes to a denser pore structure with reduced capillary porosity and no observed CH crystals. Durability tests in this study included AMLF and ASLF. Slight variations in the mass loss were seen in the conventional and 20% RCA replacement SCCs. This indicates that 20% RCA replacement in M30 and M50 SCC show sufficient resistance to acid attacks. Similarly, minimal changes in the compressive strength was seen in the 20% RCA replacement of M50 SCC when compared to conventional M50 SCC. However, at 20% RCA replacement of M30 SCC, the difference in ASLF lowers distinctly.

Disclaimer

The authors declare no conflict of interest.

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5 APPENDICES

5.1 Design Mix for M30 Grade as per IS Code 10262-2019

5.1.1 Stipulation for proportioning

Grade: M30
Type of cement: OPC 53
Nominal size of aggregate: 20mm
Type of aggregate: Crushed angular
Exposure: Severe
Slump flow class: SF3 (760mm – 850mm)
V-Funnel: Class VI (flow time ≤ 8sec)
Admixture: Superplasticizer (Polycarboxylate ether PCE)
Mineral Admixture: Fly ash
Specific Gravity of Cement: 3.115
Fine aggregate: 2.51
Fly ash: 2.20
Coarse aggregate: 2.65
Chemical admixture: 1.08

5.1.2 Target Strength

f'_{ck} =Target average compressive strength at 28 Days
S = Standard deviation
f_{ck} = characteristic compressive strength at 28 Days for M30
Standard deviation (S) = 5.0 N/mm² (Table 2)(*IS 10262 Concrete Mix Proportioning-Guidelines*, 2019)
For a tolerance factor of 1.65 So, Target mean strength can be given by,
Characteristic strength = 30 + (5 * 1.65) = 38.25 N/mm².

5.1.3 Air Content

From 10262-2019 (Table 3) air to be expected is 1.0% for 20mm nominal max size aggregate.

5.1.4 Selection of water-cement ratio (w/c ratio)

From (*IS 456 Plain and Reinforced Concrete-Code of Practice*, 2000)(Table 5),
Maximum water-cement ratio prescribed for severe condition = 0.45
According to the target strength of 38.25 w/c ratio is 0.5, which is exceeding the limit provided by IS code. So, the taken w/c ratio is 0.45.

5.1.5 Cementitious content calculation

Water content recommended by IS 10262-2019 (table 4) for 20mm aggregate is 186 kg/m3
Cementitious content (cement & fly ash) = 186/0.45=413 kg/m3
For the SCC, here 35% fly ash is considered
Fly ash = 413 * 35% = 144.55 kg/m3
OPC cement content = 413-124 = 268.45 kg/m3

From IS 456-2000 (Table 5)(*IS 456 Plain and Reinforced Concrete-Code of Practice*, 2000), the minimum cement content for severe condition should be 320 kg/m3. Thus make OPC cement content=320 kg/m3 and maintain 30% Fly ash content=172.31 kg/m3. Thus, new total cementitious material=492.31 kg/m3.

Volume of cementitious material: 320/3.115+172.31/2.2 =181.05 liters

Volume of water: 186/1=186 liters

Volume of admixture, 1% by mass of cementitious materials = (0.01 * 492.31)/1.08 = 4.56 liters

5.1.6 Aggregate proportioning

Assume 40% fine aggregate and 60% coarse aggregate,

Total volume of aggregate=1000-(181.05+186+4.56) =628.39 liters

FA=251.356 liters = 251.356*2.51=630.90 kg/m3

CA=377.034 liters = 999.14 kg/m3

5.1.7 Mix Proportion for 1m3

Cement: 320 kg/m3
Fly ash: 172.31 kg/m3
Water: 186 kg/m3
Fine aggregate: 630.90 kg/m3
Coarse aggregate: 999.14 kg/m3
Admixture: 4.56 kg/m3

5.2 Design Mix for M50 Grade as per IS Code 10262-2019

5.2.1 Stipulation for proportioning

Grade: M50
Type of cement: OPC 53
Nominal size of aggregate: 20mm
Type of aggregate: Crushed angular
Exposure: Severe
Slump flow class: SF2 (660mm – 750mm)
V-Funnel: Class VI (flow time ≤ 8sec)
Admixture: Superplasticizer (Polycarboxylate ether PCE)
Mineral Admixture: Fly ash
Specific Gravity of Cement: 3.115
Fine aggregate: 2.51
Fly ash: 2.20
Coarse aggregate: 2.65
Chemical admixture: 1.08

5.2.2 Target Strength

f'_{ck} =Target average compressive strength at 28 Days

S = Standard deviation

f_{ck} = characteristic compressive strength at 28 Days for M50

Standard deviation (S) = 5.0 N/mm² from IS 10262-2019 (Table 2)

For a tolerance factor of 1.65 So, Target mean strength can be given by,

Characteristic strength = 50 + (5 * 1.65) = 58.25 N/mm².

5.2.3 Air Content

From 10262-2019 (Table 3) air to be expected is 1.0% for 20mm nominal max size aggregate.

5.2.4 Selection of water-cement ratio (w/c ratio)

From IS 456-2000 (Table 5),

Maximum water-cement ratio prescribed for severe condition = 0.45

According to the target strength of 38.25 w/c ratio is 0.335, which is okay. So, the taken w/c ratio is 0.335.

5.2.5 Cementitious content calculation

Water content recommended by IS 10262-2019 (Table 4) for 20mm aggregate is 186 kg/m3

Cementitious content (cement & fly ash) = 186/0.335=555.22 kg/m3

For the SCC, here 25% fly ash is considered

Fly ash = 555.22 * 25% = 138.80 kg/m3

OPC cement content = 555.22-138.80 = 416.42 kg/m3

From IS 456-2000 (Table 5),

The minimum cement content for severe condition should be 320 kg/m3 which is okay.

Volume of cementitious material: 416.42/3.115+138.80/2.2 = 196.77 liters

Volume of water: 186/1 =186 liters

Volume of admixture, 1% by mass of cementitious materials = (0.01*555.22)/1.08 = 5.14 liters

5.2.6 Aggregate proportioning

Assume 40% fine aggregate and 60% coarse aggregate,

Total volume of aggregate=1000-(196.77+186+5.14) = 612.09 liters

FA=244.836 liters = 244.836*2.51=614.54 kg/m3

CA=367.25 liters = 973.22 kg/m3

5.2.7 Mix Proportion for 1m3

Cement: 416.42 kg/m3

Fly ash: 138.80 kg/m3

Water: 186 kg/m3

Fine aggregate: 614.54 kg/m3

Coarse aggregate: 973.22 kg/m3

Admixture: 5.14 kg/m3