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Original Research Paper

Sustainable Utilization of Demolition Waste as Recycled Coarse Aggregate in Concrete: Strength Enhancement Using Silica Fume and Steel Fibres

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Abstract
Construction and demolition waste (CDW) is one of the major solid-waste streams generated by rapid urbanization and infrastructure renewal. Recycled coarse aggregate (RCA) obtained from CDW can reduce the consumption of natural aggregates and support circular construction; however, its higher porosity, adhered mortar, and weaker interfacial transition zone may influence concrete performance. This study experimentally investigates the use of RCA as a partial replacement for natural coarse aggregate in M20, M30, and M40 grade concretes. RCA was incorporated at 0, 10, 20, 30, 40, 50, and 100% replacement levels, and mechanical properties were evaluated at 7, 28, and 90 days. Based on the first-stage results, 30% RCA was identified as the optimum replacement level. At 28 days, the 30% RCA mixes improved compressive strength by 9.24%, 7.60%, and 8.79% for M20, M30, and M40 grades, respectively, compared with corresponding control concretes. Split tensile strength increased by 25.71%, 24.41%, and 23.08%, while flexural strength increased by 9.24%, 7.60%, and 8.77%, respectively. Further modification of the optimized RCA mixes using silica fume at 5, 10, and 15% showed that 15% silica fume produced the highest strength gain, with 28-day compressive strengths of 35.00, 51.50, and 58.00 MPa for M20, M30, and M40 grades. Steel fibres further enhanced post-cracking resistance and flexural performance, with the C3S15F1.5 mix reaching 60.25 MPa compressive strength and 14.50 MPa flexural strength at 28 days. The results confirm that CDW-derived RCA can be used effectively up to 30% replacement, and its performance can be significantly improved by silica fume and steel fibre incorporation.

Keywords: Construction and demolition waste; recycled coarse aggregate; silica fume; steel fibre; sustainable concrete; mechanical properties.

1. Introduction

The construction sector consumes large quantities of natural aggregates, water, energy, and cementitious materials. Natural coarse aggregates generally occupy a major portion of concrete volume, and their extraction from quarries and river systems creates environmental concerns such as land degradation, dust generation, depletion of natural resources, increased transportation impacts, and disturbance to local ecosystems. Simultaneously, the demolition of old buildings and the renewal of infrastructure produce large quantities of construction and demolition waste, much of which is either dumped or underutilized. Converting such waste into recycled coarse aggregate provides a sustainable route for reducing landfill burden and conserving natural aggregate resources.

Recycled coarse aggregate produced from crushed concrete debris has attracted significant attention as an alternative aggregate for concrete. Nevertheless, its use is associated with technical challenges. RCA particles generally contain adhered old mortar and microcracks, leading to higher water absorption, lower density, and a weaker interfacial transition zone compared with natural aggregates. These characteristics can reduce workability and strength, especially at high replacement levels. However, moderate replacement may improve mechanical interlock due to the angular and rough surface texture of RCA, and the use of supplementary cementitious materials and fibres can compensate for the weaknesses of RCA concrete.

Silica fume is a highly reactive pozzolanic material capable of refining pore structure and improving the interfacial transition zone. It reacts with calcium hydroxide to produce additional calcium silicate hydrate gel, thereby enhancing matrix densification and strength. Steel fibres contribute to crack-bridging, stress redistribution, ductility, and post-cracking performance. Combining RCA, silica fume, and steel fibres therefore offers a promising strategy for producing sustainable concrete with improved mechanical performance.

The present study investigates RCA replacement in three concrete grades, M20, M30, and M40. The work first identifies the optimum RCA replacement level based on compressive, split tensile, and flexural strength. The optimized RCA mixes are then modified with silica fume, followed by the incorporation of steel fibres in selected rich mixes. The objective is to develop an experimentally supported framework for the sustainable utilization of demolition waste in structural-grade concrete.

2. Literature Review and Research Gap

Previous studies on RCA concrete have shown that the quality of the parent concrete, attached mortar content, aggregate processing method, particle grading, and water absorption strongly influence concrete performance. RCA

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obtained from good-quality concrete can retain a substantial portion of the strength potential of natural aggregates, whereas mixed demolition debris may reduce consistency and durability. The rough surface texture of RCA may improve mechanical interlock at moderate replacement levels, but the porous adhered mortar and weaker old-new mortar interface often cause strength reduction at higher replacement levels.

The addition of mineral admixtures has been reported to improve RCA concrete by filling pores, refining the ITZ, and reducing microcracking. Silica fume is especially effective due to its fine particle size and high amorphous silica content. The use of fibres in concrete is another important performance-enhancement approach. Steel fibres help control crack propagation and improve flexural toughness, particularly in concrete mixes containing recycled aggregates where local weakness and microcracking may occur.

Although many studies have examined RCA concrete, fewer studies combine three sequential strategies: RCA replacement optimization, silica-fume modification of the optimized RCA concrete, and steel-fibre improvement of selected mixes across multiple concrete grades. This study addresses this gap by evaluating M20, M30, and M40 grade concretes under a consistent experimental framework and by reporting strength performance at 7, 28, and 90 days.

3. Materials and Experimental Methodology

3.1 Materials

Ordinary Portland Cement of 43 grade conforming to IS 8112:2013 was used as the binder. The cement had a reported specific gravity of 3.15, standard consistency of 30%, and initial setting time of 35 minutes. Natural river sand conforming to Zone II requirements was used as fine aggregate. Crushed granite aggregate of 20 mm nominal maximum size conforming to IS 383:2016 was used as natural coarse aggregate.

Recycled coarse aggregate was obtained from construction and demolition debris consisting mainly of crushed concrete and masonry rubble. The demolition waste was cleaned, crushed, and sieved to obtain 20 mm size aggregate. Potable water satisfying IS 456:2000 requirements was used for mixing and curing. Silica fume was incorporated as a mineral additive to improve matrix densification and strength. Crimped steel fibres of circular cross-section were used to enhance crack-bridging and post-cracking response.

Table 1. Materials, available descriptions and relevant standards

Material / Test	Available description	Relevant standard
Cement	OPC 43 grade	IS 8112:2013
Fine aggregate	Natural river sand, Zone II	IS 383:2016; IS 2386 series
Natural coarse aggregate	20 mm crushed granite	IS 383:2016; IS 2386 series
Recycled coarse aggregate	Cleaned, crushed and sieved CDW aggregate of 20 mm size	IS 2386 series
Water	Potable water for mixing and curing	IS 456:2000
Concrete mix design	M20, M30 and M40 grades	IS 10262:2019
Strength testing	Compressive, split tensile and flexural strength	IS 516:1959 / relevant IS provisions

3.2 Mix Proportions and Experimental Sequence

The investigation was conducted in three sequential stages. In Stage I, RCA replaced natural coarse aggregate at 0, 10, 20, 30, 40, 50, and 100% by weight in M20, M30, and M40 concretes. In Stage II, the optimum RCA mixes identified from Stage I were modified using silica fume at 5, 10, and 15% by weight of cement. In Stage III, selected control and optimized silica-fume-modified mixes were further reinforced with steel fibres at 1.0 and 1.5% volume fractions. This sequence was adopted to first identify the suitable RCA content and then improve the optimized mix through matrix densification and fibre crack control.

Table 2. RCA mix designations used in Stage I

Sl. No.	Mix combination	M20	M30	M40
1	0% RCA	A0	B0	C0
2	10% RCA	A1	B1	C1
3	20% RCA	A2	B2	C2
4	30% RCA	A3	B3	C3
5	40% RCA	A4	B4	C4
6	50% RCA	A5	B5	C5
7	100% RCA	A6	B6	C6

3.3 Specimen Preparation and Testing

Concrete specimens were prepared for compressive, split tensile, and flexural strength tests using standard cube, cylinder, and prism specimens. After casting, specimens were demoulded and cured in water. Mechanical testing was carried out at 7, 28, and 90 days. The manuscript data indicate that 162 cubes and 162 cylinders were used for the three grades in the RCA phase. Flexural strength was determined using prism specimens as per the applicable provisions of IS 516:1959.

Workability was evaluated using slump and compaction-factor observations. The reported workability range for RCA concrete was 60-100 mm slump and 0.80-0.95 compaction factor. Since detailed mix-wise slump records were not available in the submitted data, workability is discussed based on the observed range and the established trend that workability decreases as RCA content increases due to higher surface roughness and porosity.

4. Results and Discussion

4.1 Workability of RCA Concrete

The RCA concrete mixes remained within the reported workable range of 60-100 mm slump, with compaction factor values between 0.80 and 0.95. Workability decreased as RCA content increased. This trend is expected because RCA contains adhered mortar and a rougher particle surface, which increase water demand and internal friction. The decrease becomes more pronounced at higher

RCA contents, particularly beyond 30-40% replacement. Therefore, adequate moisture conditioning, mix adjustment, or the use of water-reducing admixtures may be necessary when RCA content is increased for field applications.

4.2 Mechanical Performance of RCA Concrete

Table 3. Strength properties of M20 concrete with RCA replacement

Mix	RCA (%)	CS 7d	CS 28d	CS 90d	STS 7d	STS 28d	STS 90d	FS 7d	FS 28d	FS 90d
A0	0	15.5	23.8	24.71	1.71	2.8	2.9	2.86	4.76	4.82
A1	10	15.76	24.25	24.9	1.9	3.1	3.2	2.91	4.85	4.91
A2	20	16.38	25.2	26.16	1.95	3.19	3.3	3.02	5.04	5.1
A3	30	16.9	26	26.98	2.16	3.52	3.6	3.12	5.2	5.33
A4	40	15.44	23.75	24.46	1.86	3.04	3.1	2.85	4.75	4.88
A5	50	14.8	22.77	23.55	1.73	2.83	2.9	2.73	4.55	4.65
A6	100	14.46	22.25	22.92	1.62	2.65	2.7	2.67	4.45	4.52

Table 4. Strength properties of M30 concrete with RCA replacement

Mix	RCA (%)	CS 7d	CS 28d	CS 90d	STS 7d	STS 28d	STS 90d	FS 7d	FS 28d	FS 90d
B0	0	22	34.85	35.9	1.83	2.99	3.1	4.32	6.97	7.05
B1	10	22.53	35.2	36.26	1.9	3.1	3.2	4.36	7.04	7.1
B2	20	23.1	36.1	37.28	2.11	3.45	3.6	4.48	7.22	7.3
B3	30	24	37.5	38.8	2.28	3.72	3.8	4.65	7.5	7.62
B4	40	23.33	36.45	37.54	2.11	3.44	3.5	4.52	7.29	7.4
B5	50	21.38	33.4	34.6	1.92	3.13	3.2	4.14	6.68	6.74
B6	100	21.12	33	34	1.68	2.75	2.8	4.09	6.6	6.47

Table 5. Strength properties of M40 concrete with RCA replacement

Mix	RCA (%)	CS 7d	CS 28d	CS 90d	STS 7d	STS 28d	STS 90d	FS 7d	FS 28d	FS 90d
C0	0	33	43.9	45	1.91	3.12	3.2	6.06	8.78	8.9
C1	10	28.99	45.8	47.28	1.92	3.14	3.2	6.32	9.16	9.3
C2	20	29.31	46.3	47.69	2.12	3.46	3.6	6.39	9.26	9.4
C3	30	33.23	47.76	49.19	2.35	3.84	4	6.59	9.55	9.64
C4	40	29.75	47	48.6	2.15	3.51	3.6	6.49	9.4	9.5
C5	50	28.04	44.3	45.63	2.09	3.42	3.5	6.11	8.86	8.9
C6	100	26.59	42	43.46	1.9	3.1	3.2	5.8	8.4	8.54

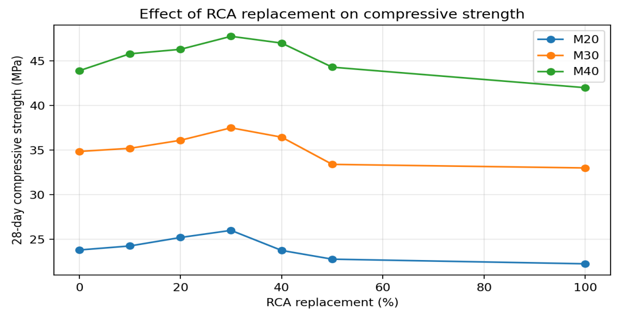

Figure 1. Effect of RCA replacement on 28-day compressive strength.

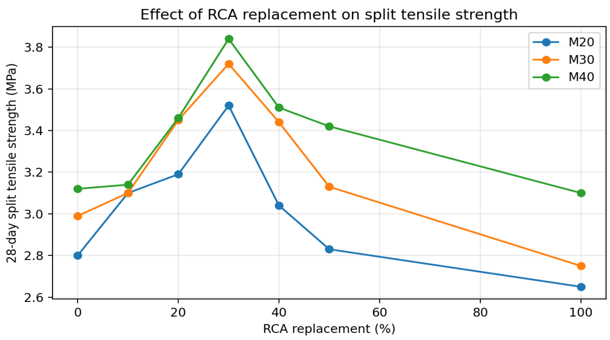

Figure 2. Effect of RCA replacement on 28-day split tensile strength.

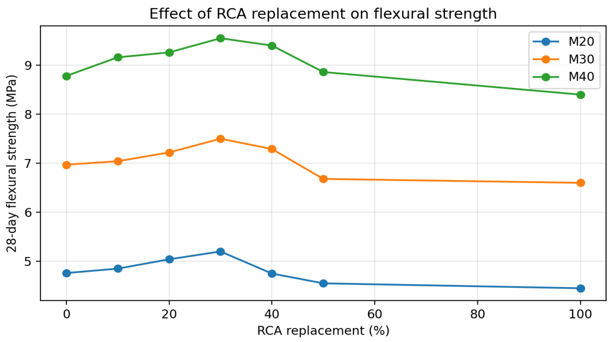

Figure 3. Effect of RCA replacement on 28-day flexural strength.

The results show that 30% RCA replacement produced the highest overall performance for all three concrete grades. At 28 days, the compressive strength of M20 concrete increased from 23.80 MPa for the control mix to 26.00 MPa for A3, corresponding to an improvement of 9.24%. The M30 grade increased from 34.85 MPa to 37.50 MPa, showing an improvement of 7.60%, while M40 increased from 43.90 MPa to 47.76 MPa, showing an improvement of 8.79%.

The tensile and flexural results also confirmed the benefit of moderate RCA replacement. At 30% RCA, split tensile strength increased by 25.71%, 24.41%, and 23.08% for M20, M30, and M40 concretes, respectively. The corresponding flexural strength improvements were 9.24%, 7.60%, and 8.77%.

The strength increase at moderate RCA content can be attributed to the angularity and rough surface texture of RCA, which may improve mechanical interlock within the cement matrix. The presence of residual mortar may also enhance bonding when RCA content is limited and adequate cement paste surrounds the particles. However, strength reduction occurred at higher RCA levels because excessive adhered mortar increases porosity, weakens the interfacial transition zone, increases water absorption, and introduces microcracked particles. This explains why mixes with 50% and 100% RCA generally performed below the optimum 30% RCA mixes.

4.3 Effect of Silica Fume on Optimized RCA Mixes

Table 6. Strength properties of optimized RCA mixes modified with silica fume

Mix ID	CS 7d	CS 28d	CS 90d	STS 7d	STS 28d	STS 90d	FS 7d	FS 28d	FS 90d
A0	15.5	23.8	24.71	1.71	2.8	2.9	2.86	4.76	4.82
A3	16.9	26	26.98	2.16	3.52	3.6	3.12	5.2	5.33
A3 S5	20.1	30	30.9	2.4	3.92	4	4.2	6	6.1
A3 S10	21.61	32.25	33.4	2.54	4.15	4.3	4.52	6.45	6.58
A3 S15	23.45	35	36.33	2.58	4.22	4.3	4.9	7	7.17
B0	22	34.85	35.9	1.83	2.99	3.1	4.32	6.97	7.05
B3	24	37.5	38.8	2.28	3.72	3.8	4.65	7.5	7.62
B3 S5	28.14	42	43.5	2.51	4.1	4.2	5.88	8.4	8.5
B3 S10	32.16	48	50	2.82	4.6	4.7	6.72	9.6	9.75
B3 S15	34.51	51.5	53.5	2.99	4.88	5	7.21	10.3	10.4
C0	33	43.9	45	1.91	3.12	3.2	6.06	8.78	8.9
C3	33.23	47.76	49.19	2.35	3.84	4	6.59	9.55	9.64
C3 S5	34.84	52	53.56	2.83	4.62	4.8	7.28	10.4	10.57
C3 S10	37.39	55.8	57.5	2.97	4.85	5	7.81	11.16	11.33
C3 S15	38.86	58	59.95	3.03	4.95	5.1	8.12	11.6	11.7

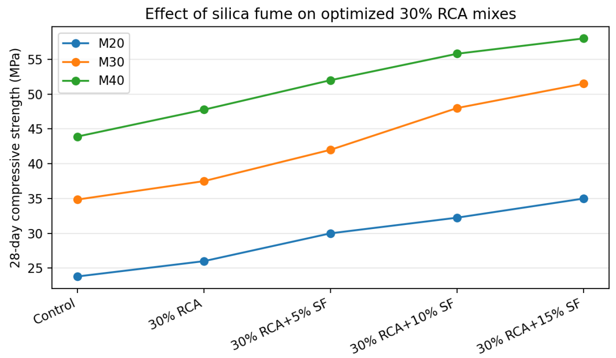

Figure 4. Effect of silica fume on 28-day compressive strength of optimized 30% RCA mixes.

Silica fume significantly improved the performance of the optimized 30% RCA mixes. At 15% silica fume, the 28-day compressive strength increased to 35.00 MPa for M20, 51.50 MPa for M30, and 58.00 MPa for M40. Relative to the corresponding 30% RCA mixes without silica fume, these values represent improvements of 34.62%, 37.33%, and 21.44%, respectively. The improvement is mainly due to the pozzolanic reaction of silica fume with calcium hydroxide, which produces additional C-S-H gel. Its very fine particle size also contributes to pore filling and ITZ refinement.

The split tensile and flexural strengths also improved with silica fume addition. The effect was more evident in M30 and M40 concretes because the denser matrix and lower porosity allowed better stress transfer. The best performance was consistently observed at 15% silica fume among the available test levels. This indicates that silica fume is effective in compensating for RCA-related porosity and ITZ weakness.

4.4 Effect of Steel Fibres on Selected Mixes

Table 7. Strength properties of steel-fibre-reinforced selected mixes

Mix ID	CS 7d	CS 28d	CS 90d	STS 7d	STS 28d	STS 90d	FS 7d	FS 28d	FS 90d
A0F0	15.5	23.8	24.71	1.71	2.8	2.9	2.86	4.76	4.82
A0F1	18.76	28	28.84	2.16	3.52	3.6	4.1	5.85	5.95
A0F1.5	20.27	30.26	31.17	2.31	3.78	3.9	4.38	6.25	6.3
B0F0	22	34.85	35.9	1.83	2.99	3.1	4.32	6.97	7.05
B0F1	26.8	40	41.2	2.23	3.65	3.8	5.36	7.65	7.7
B0F1.5	28.14	42	43.26	2.58	4.21	4.3	6.25	8.93	9.15
C0F0	33	43.9	45	1.91	3.12	3.2	6.06	8.78	8.9
C0F1	33.17	49.5	50.99	2.38	3.88	4	6.54	9.34	9.41
C0F1.5	34.84	52	53.56	2.6	4.25	4.4	7.49	10.7	10.18
A3S15F0	23.45	35	36.33	2.58	4.22	4.3	4.9	7	7.17
A3S15F1	24.88	37.29	38	2.59	4.23	4.3	5.46	7.55	7.66
A3S15F1.5	26.4	39.41	40.59	2.6	4.25	4.4	5.88	8.4	8.5
B3S15F0	34.51	51.5	53.5	2.99	4.88	5	7.21	10.3	10.4
B3S15F1	34.8	52	54.13	3.01	4.9	5.1	7.88	10.95	11.12
B3S15F1.5	36.18	54	55.62	3.03	4.92	5.25	8.12	11.6	11.55
C3S15F0	38.86	58	59.95	3.03	4.95	5.1	8.12	11.6	11.7
C3S15F1	38.12	60	61.89	3.08	4.51	5.3	9.67	12.5	13.53
C3S15F1.5	40.37	60.25	62.08	3.12	4.55	5.5	10.15	14.5	14.45

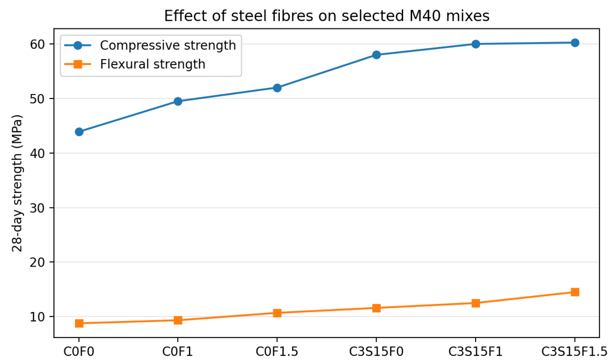

Figure 5. Effect of steel fibres on selected 28-day strengths of M40 concrete mixes.

The addition of steel fibres improved strength, particularly flexural performance, by bridging cracks and increasing the energy absorption capacity of concrete. In the control-series mixes, the addition of 1.5% steel fibre increased 28-day compressive strength from 23.80 to 30.26 MPa for M20, from 34.85 to 42.00 MPa for M30, and from 43.90 to 52.00 MPa for M40. For the optimized RCA-silica fume mixes, the highest 28-day compressive strength was obtained for C3S15F1.5 at 60.25 MPa, while the highest 90-day compressive strength was 62.08 MPa.

Flexural strength showed the most pronounced improvement. For C3S15F1.5, the 28-day flexural strength reached 14.50 MPa, compared with 8.78 MPa for the M40 control mix. This demonstrates the effectiveness of combining matrix densification through silica fume with fibre crack control. While compressive strength improvement due to steel fibres is moderate, fibre reinforcement is highly beneficial for tensile cracking, flexural response, and post-cracking ductility.

4.5 Sustainability Implications

The use of 30% RCA directly reduces the demand for natural coarse aggregate and diverts a portion of demolition waste from landfills. This supports circular-economy principles by converting waste into a value-added construction material. The addition of silica fume, an industrial by-product, further supports sustainable construction by improving material performance and reducing dependence on conventional cementitious systems. The incorporation of steel fibres improves serviceability and crack resistance, which may extend structural life and reduce repair frequency.

A full life-cycle assessment was not available in the submitted experimental data; therefore, the sustainability assessment in this paper is limited to material substitution, resource conservation, and performance-based benefits. Future studies should include embodied carbon, transportation distance, cost analysis, and durability-based service-life modelling to quantify the environmental benefits more completely.

5. Limitations and Future Scope

The present study is based on the available experimental strength data. Detailed RCA material characterization values such as water absorption, crushing value, Los Angeles abrasion value, adhered mortar percentage, and gradation curves were not available in the submitted dataset and should be measured in future work. Mix-wise slump values and standard deviation/error-bar data were also not available, limiting statistical interpretation. Microstructural tests such as SEM, XRD, MIP, and ITZ imaging were not conducted; therefore, the microstructural discussion is based on accepted mechanisms of RCA, silica fume, and fibre-reinforced concrete.

Future research should include complete RCA characterization, water absorption correction, durability tests such as RCPT, sorptivity, water permeability, carbonation, acid/sulphate resistance, and long-term shrinkage/creep studies. Field-scale trials and life-cycle cost/carbon analysis are also recommended to establish practical adoption guidelines for RCA-based sustainable concrete.

6. Conclusions

1. RCA derived from CDW can be used as a partial replacement for natural coarse aggregate in M20, M30, and M40 concretes. Among the tested replacement levels, 30% RCA produced the optimum mechanical performance.
2. At 30% RCA replacement, 28-day compressive strength increased by 9.24% for M20, 7.60% for M30, and 8.79% for M40 compared with their respective control mixes.
3. Split tensile strength at 30% RCA improved by 25.71%, 24.41%, and 23.08% for M20, M30, and M40 concretes, respectively. Flexural strength improved by 9.24%, 7.60%, and 8.77%, respectively.
4. Higher RCA contents reduced strength because of increased adhered mortar, higher porosity, greater water absorption, and weaker ITZ. Therefore, RCA replacement beyond 30-40% should be adopted only after mix modification or aggregate treatment.
5. Silica fume significantly enhanced the optimized 30% RCA mixes. At 15% silica fume, 28-day compressive strengths reached 35.00 MPa, 51.50 MPa, and 58.00 MPa for M20, M30, and M40 concretes, respectively.
6. Steel fibres improved crack resistance and flexural performance. The C3S15F1.5 mix achieved the highest 28-day compressive strength of 60.25 MPa and 28-day flexural strength of 14.50 MPa among the available mixes.
7. The combined use of 30% RCA, silica fume, and steel fibres provides a technically feasible route for producing sustainable concrete with improved strength, resource efficiency, and reduced dependence on natural aggregates.

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