Experimental Evaluation of Recycled Coarse Aggregate Concrete Incorporating Silica Fume and Steel Fibres: Mechanical, Durability and RC Beam Performance

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Abstract

The present study experimentally investigates the use of recycled coarse aggregate (RCA) recovered from construction and demolition (C&D) concrete waste in M20, M30 and M40 concrete. Natural coarse aggregate was replaced by RCA at 0%, 10%, 20%, 30%, 40%, 50% and 100%. The study further examined the effect of replacing cement with silica fume at 5%, 10% and 15% in mixes containing the selected 30% RCA, followed by the incorporation of crimped steel fibres. Fresh concrete workability, 7-, 28- and 90-day compressive, split tensile and flexural strengths, chemical exposure response, water absorption, microstructural observations and reinforced-concrete beam behaviour were considered. The tabulated results identify 30% RCA as the best-performing replacement level among the investigated RCA-only mixtures. At 28 days, the 30% RCA mixes reached compressive strengths of 26.0, 37.5 and 47.76 MPa for M20, M30 and M40, respectively, compared with 23.80, 34.85 and 43.90 MPa for the corresponding controls. Incorporating 15% silica fume increased these values to 35, 51.5 and 58 MPa. For the M40 beam series, the ultimate load increased from 75 kN for the control to 95 kN for the mix containing 30% RCA, 15% silica fume and 1.5% steel fibre. The results indicate potential benefits from combining processed RCA, silica fume and steel fibres; however, inconsistencies in fibre dosage, beam counts, loading description, durability reporting and some conclusions require verification before design-level interpretation.

Keywords—Construction and demolition waste, recycled coarse aggregate, recycled aggregate concrete, silica fume, steel fibre, durability, reinforced concrete beams.

I. INTRODUCTION

Concrete production depends heavily on natural aggregates, while demolition and construction activities generate substantial quantities of concrete rubble. Recovering coarse aggregate from this waste stream can reduce disposal demand and the extraction of virgin aggregate. Recycled aggregate concrete (RAC), however, is affected by adhered old mortar, higher porosity and water absorption, and the presence of an additional interfacial transition zone. These characteristics may influence workability, strength and durability.

The present experimental programme investigates recycled coarse aggregate (RCA) processed from demolished building concrete, construction waste and laboratory-tested specimens. The material was crushed, screened to a nominal 20 mm size and mechanically treated to remove adhered mortar. Conventional and recycled-aggregate concrete mixtures were evaluated across M20, M30 and M40 grades, followed by investigations of silica fume and crimped steel-fibre incorporation.

The study combines four investigations: (i) the effect of RCA replacement level, (ii) silica fume incorporation in the selected 30% RCA mixtures, (iii) steel-fibre addition, and (iv) the static flexural response of reinforced concrete beams. The discussion is based on the experimental values presented in the results tables; data requiring clarification are identified separately.

II. OBJECTIVES AND SCOPE

• To examine replacement of natural coarse aggregate by RCA at 0%, 10%, 20%, 30%, 40%, 50% and 100% in M20, M30 and M40 concrete.

• To determine the selected RCA replacement level from fresh and hardened concrete test results.

• To investigate 5%, 10% and 15% silica fume replacement of cement in the selected 30% RCA mixes.

• To evaluate the influence of steel fibres on mechanical properties and workability.

• To assess selected durability indicators and the flexural response of reinforced concrete beams, including load, deflection, stiffness, energy absorption and ductility.

III. MATERIALS AND EXPERIMENTAL PROGRAMME

Ordinary Portland cement of 53 grade (UltraTech) was used. Natural river sand was reported as Zone III, with specific gravity 2.65 and water absorption 1.1%. Natural coarse aggregate had a reported specific gravity of 2.70, while the processed RCA had a specific gravity of 2.63. The RCA was obtained from demolished building concrete, construction waste and laboratory-tested cubes/cylinders. It was manually reduced to crusher-feed size, jaw-crushed, screened to a nominal 20 mm size and mechanically processed to remove adhered mortar.

Table 1. Physical properties of natural coarse aggregate and recycled coarse aggregate.

Property	Natural coarse aggregate	RCA
Specific gravity	2.70	2.63
Impact strength (%)	19.04	24.03
Crushing value (%)	22.94	30.26
Bulk density (kg/m³)	1560	1390
Water absorption (%)	0.53	2.88

The higher water absorption, impact value and crushing value reported for RCA indicate that the recycled particles were more porous and less resistant to mechanical action than the natural aggregate. Crimped steel fibres were 50 mm long and 1 mm in diameter, with an aspect ratio of 50, tensile strength of 1100 MPa and elastic modulus of 200 GPa. A liquid superplasticizer (Conplast SP430) was used; the reported specific gravity was 1.20–1.22.

Table 2. Reference mix proportions for M20, M30 and M40 concrete.

Grade	Water (kg/m³)	Cement (kg/m³)	Fine aggregate (kg/m³)	Coarse aggregate (kg/m³)	w/c
M20	158	351	706	1215	0.45
M30	158	394	695	1195	0.40
M40	158	451	674	1160	0.35

Mix design was stated to follow IS 10262:2009 and IS 456:2000. Cube specimens of 150 mm, cylinders of 150 mm diameter × 300 mm height and prisms of 100 mm × 100 mm × 500 mm were tested at 7, 28 and 90 days. Workability was evaluated using slump and compaction factor tests. Durability tests included sulfuric-acid exposure, sodium-sulfate exposure, water absorption and sodium-chloride exposure. Beam specimens were reported as 1100 mm × 150 mm × 100 mm, with a 1000 mm effective span, simply supported, and loaded using a two-point loading arrangement. Longitudinal reinforcement comprised two 10 mm bars at top and bottom, with 8 mm stirrups at 100 mm spacing.

IV. FRESH CONCRETE PROPERTIES

For the RCA-only series, slump increased with RCA replacement. In M20 concrete, slump rose from 68 mm for the control to 100 mm at 100% RCA; corresponding M30 values increased from 63 to 92 mm, and M40 values from 60 to 92 mm. This trend may be associated with the surface characteristics and adhered mortar of the processed RCA; however, the available results do not isolate the contribution of individual aggregate properties. Compaction factor values ranged from 0.80 to 0.95. In the silica-fume series, slump decreased as silica fume content increased: for

example, M20 decreased from 85 mm for A3 to 70 mm for A3S15. Steel-fibre addition also reduced slump, with M40 rich-mix slump falling from 64 mm at 0% fibre to 55 mm at 1.5% fibre.

Table 3. Selected fresh-property values

Mix series	Slump (mm)	Compaction factor
M20: A0 → A6 (0–100% RCA)	68 → 100	0.87 → 0.95
M30: B0 → B6 (0–100% RCA)	63 → 92	0.85 → 0.80
M40: C0 → C6 (0–100% RCA)	60 → 92	0.87 → 0.81
M20: A3 → A3S15	85 → 70	0.90 → 0.86
M40: C3S15F0 → C3S15F1.5	64 → 55	0.92 → 0.82

V. MECHANICAL PROPERTIES OF CONCRETE

The 28-day results show a consistent peak at 30% RCA for all three grades. Beyond 30%, strength generally declined. At 100% RCA, the reported 28-day compressive strengths were 22.25 MPa (M20), 33.0 MPa (M30) and 42.0 MPa (M40), below the corresponding 30% RCA values.

Table 4. 28-day mechanical properties of RCA-only mixtures.

Grade	Mix ID	RCA (%)	Comp. (MPa)	Split tensile (MPa)	Flexural (MPa)
M20	A0	0	23.8	2.8	4.76
M20	A1	10	24.25	3.1	4.85
M20	A2	20	25.2	3.19	5.04
M20	A3	30	26	3.52	5.2
M20	A4	40	23.75	3.04	4.75
M20	A5	50	22.77	2.83	4.55
M20	A6	100	22.25	2.65	4.45
M30	B0	0	34.85	2.99	6.97
M30	B1	10	35.2	3.1	7.04
M30	B2	20	36.1	3.45	7.22
M30	B3	30	37.5	3.72	7.5
M30	B4	40	36.45	3.44	7.29
M30	B5	50	33.4	3.13	6.68
M30	B6	100	33.0	2.75	6.6
M40	C0	0	43.9	3.12	8.78
M40	C1	10	45.8	3.14	9.16
M40	C2	20	46.3	3.46	9.26
M40	C3	30	47.76	3.84	9.55
M40	C4	40	47.0	3.51	9.4
M40	C5	50	44.3	3.42	8.86
M40	C6	100	42.0	3.1	8.4

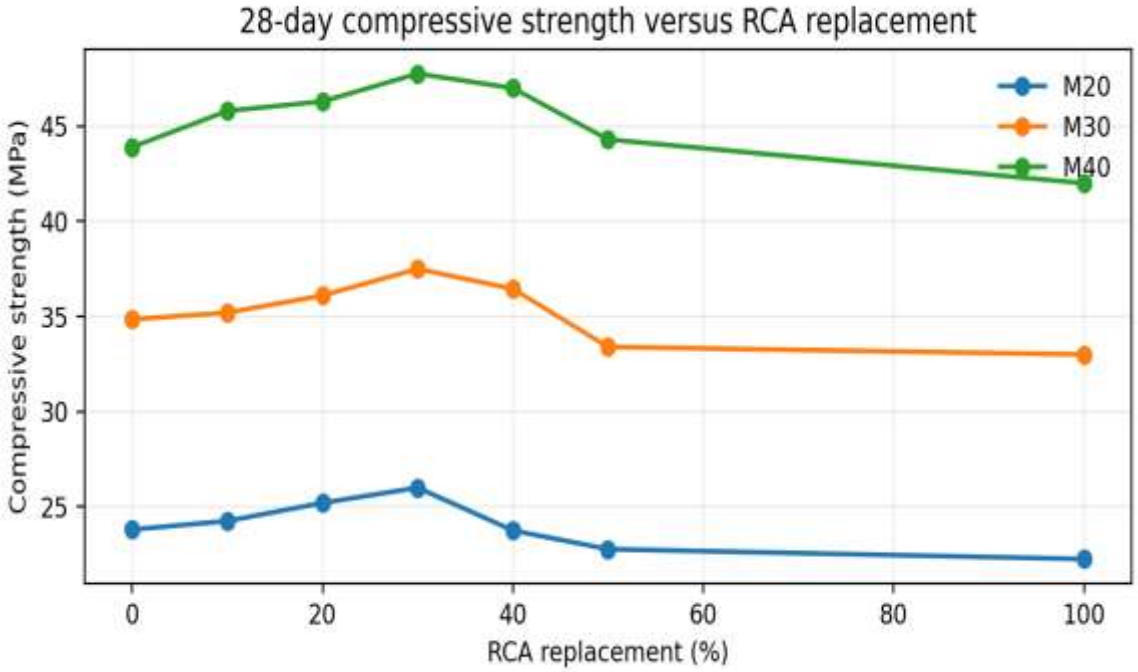


Figure 1. 28-day compressive strength versus RCA replacement; plotted from Table 4.6–4.8.

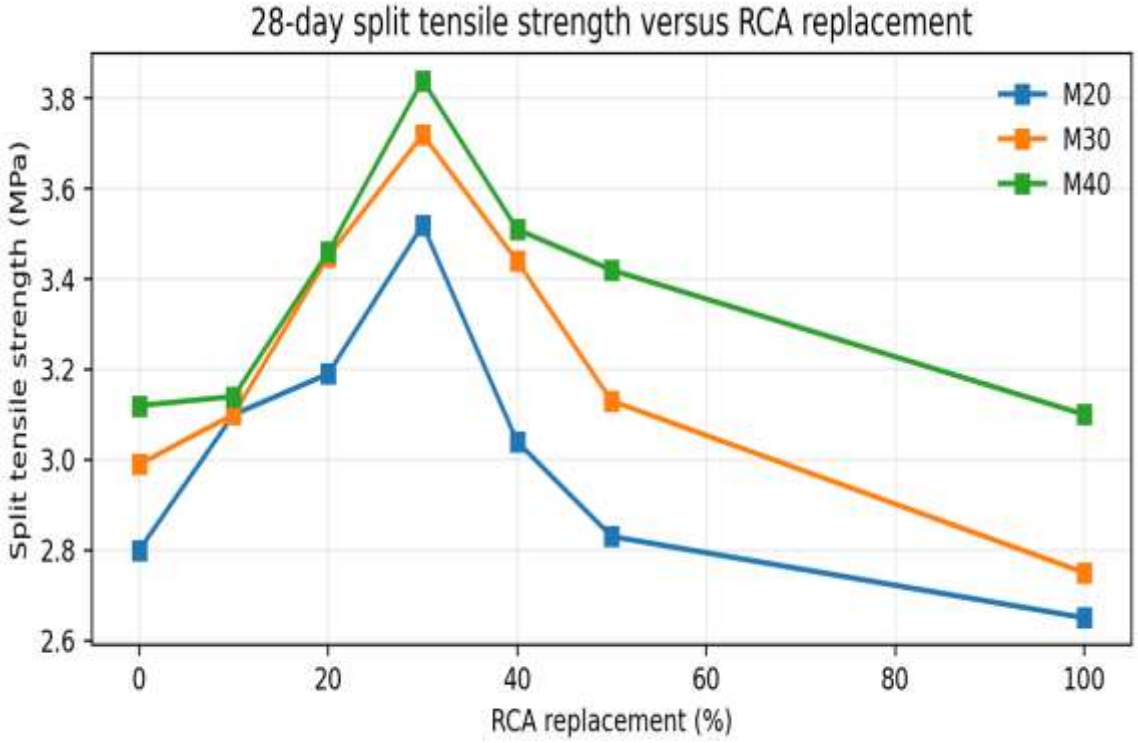


Figure 2. 28-day split tensile strength versus RCA replacement; plotted from Table 4.6–4.8.

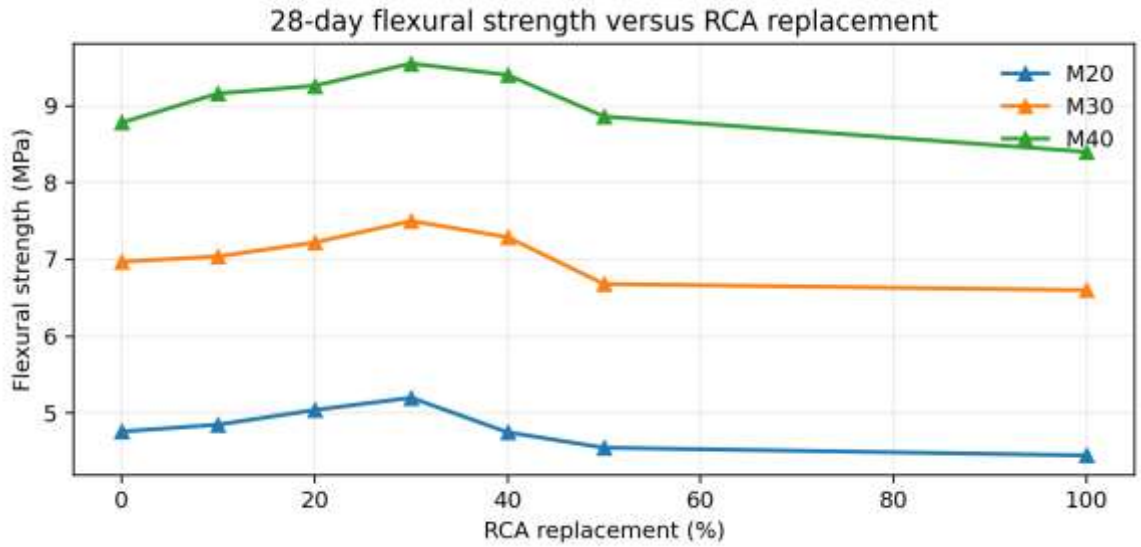


Figure 3. 28-day flexural strength versus RCA replacement; plotted from Table 4.6–4.8.

For M20, 30% RCA increased 28-day compressive strength from 23.80 to 26.0 MPa (9.2%), split tensile strength from 2.80 to 3.52 MPa (25.7%) and flexural strength from 4.76 to 5.20 MPa (9.2%). For M30, the corresponding changes were 34.85 to 37.50 MPa (7.6%), 2.99 to 3.72 MPa (24.4%) and 6.97 to 7.50 MPa (7.6%). For M40, they were 43.90 to 47.76 MPa (8.8%), 3.12 to 3.84 MPa (23.1%) and 8.78 to 9.55 MPa (8.8%). These comparisons are based on the study's tabulated averages.

The selected 30% RCA mixtures were then modified using 5%, 10% and 15% silica fume. The highest 28-day compressive strengths in this series were 35 MPa (M20), 51.5 MPa (M30) and 58 MPa (M40), each at 15% silica fume. Split tensile strengths reached 4.22, 4.88 and 4.95 MPa, while flexural strengths reached 7.00, 10.30 and 11.60 MPa, respectively.

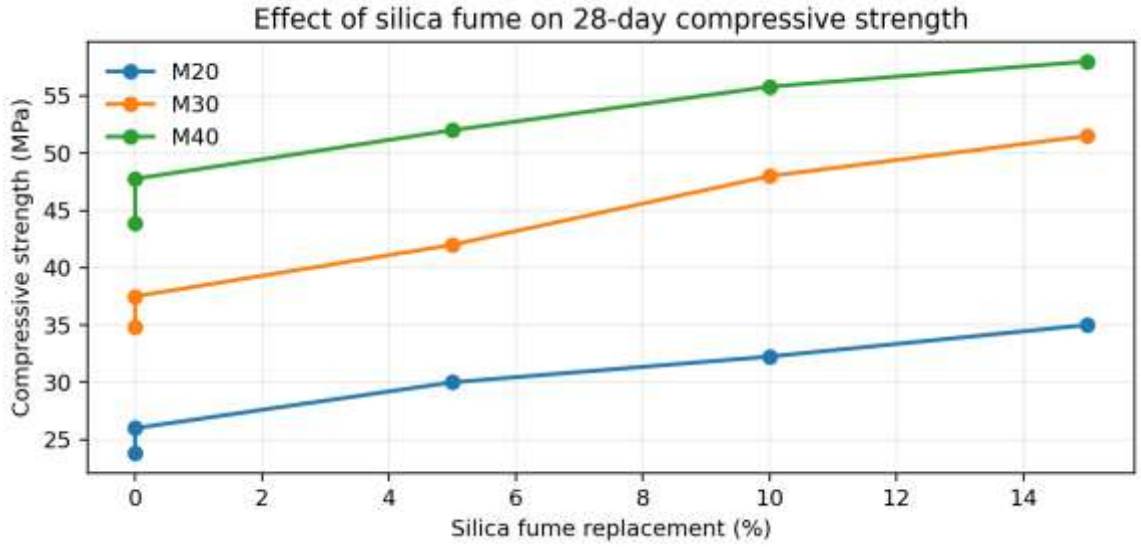


Figure 4. Effect of silica fume replacement on 28-day compressive strength of the 30% RCA mixes.

The steel-fibre series shows further gains in the tabulated strength values. For the M40 rich mix, C3S15F1.5 reached 60.25 MPa at 28 days and 62.06 MPa at 90 days; its 28-day split tensile and flexural strengths were 4.55 and 14.5 MPa. These values should be interpreted cautiously because the mix description and conclusion sections do not consistently identify the fibre dosage.

VI. DURABILITY AND MICROSTRUCTURAL OBSERVATIONS

The durability programme involved 150 mm cubes, initially water-cured for 28 days and then exposed to chemical solutions for 90 days. The acid test used a reported 5% diluted sulfuric-acid solution with pH maintained between 3

and 5. For the M40 series, control C0 recorded 5.29% mass loss and 8.96% compressive-strength loss; C3 (30% RCA) recorded 5.15% and 8.75%; C3S15 recorded 4.55% and 8.07%; and C3S15F1.5 recorded 4.63% and 8.05%.

Table 5. Selected acid-exposure results after 90 days.

Mix ID	Acid mass loss (%)	Acid strength loss (%)
A0	5.12	9.74
A3	5.08	9.36
B0	5.23	9.25
B3	4.93	9.07
C0	5.29	8.96
C3	5.15	8.75
A3S15	4.95	8.83
B3S15	4.82	8.35
C3S15	4.55	8.07
C3S15F1.5	4.63	8.05

In the sodium-sulfate series, C0 showed 7.05% mass loss and 8.06% strength loss, while C3 showed 5.71% and 5.77%, respectively. The C3S15 values were 3.96% and 2.93%. The reported water-absorption table gives increases of 0.36% for C0, 1.49% for C3, 1.42% for C3S15 and 1.32% for C3S15F1.5. In the 5% NaCl test, the reported M40 mass gain was 5.24% for C0, 7.03% for C3, 9.09% for C3S15 and 9.31% for C3S15F1.5; corresponding strength losses were 10.64%, 8.19%, 15.52% and 15.49%. These results do not support a uniformly superior response for every durability indicator.

SEM observations indicate fewer visible pores and voids in the silica-fume-rich specimens and show fibre distribution and apparent bonding within the examined fields. EDX and XRD outputs were also examined; quantitative phase proportions are not inferred because numerical phase-analysis results are not provided.

VII. STRUCTURAL BEHAVIOUR OF REINFORCED CONCRETE BEAMS

The beam study compared conventional concrete (A0/B0/C0), 30% RCA (A3/B3/C3), 30% RCA with 15% silica fume (A3S15/B3S15/C3S15), and the corresponding fibre-reinforced mixes containing 1.5% fibre. The source describes static loading in 5 kN increments and reports a two-point loading arrangement. First-crack load and ultimate load increased progressively across the mix sequence.

Table 6. RC beam response values. *The unit of stiffness is not specified in the reported data.

Grade	Beam ID	First crack (kN)	Ultimate (kN)	Deflection at ultimate (mm)	Stiffness*	Energy (kN·mm)	Ductility
M20	A0	15	50	6.8	7.35	198	2.13
M20	A3	17.5	55	6.77	8.12	205	2.12
M20	A3S15	18	60	7.24	8.29	260	1.77
M20	A3S15F1.5	21	70	6.93	10.1	275	1.73
M30	B0	18	60	7.8	7.69	260	2.29
M30	B3	20	65	8.2	7.93	276	2.1
M30	B3S15	22.5	75	8.8	8.52	345	1.42
M30	B3S15F1.5	25	85	8.11	10.48	360	1.27
M40	C0	22	75	8.42	8.91	335	1.5
M40	C3	24	80	8.31	9.63	372	1.43
M40	C3S15	25	80	7.41	10.8	328	1.2
M40	C3S15F1.5	28.5	95	6.85	13.87	395	1.14

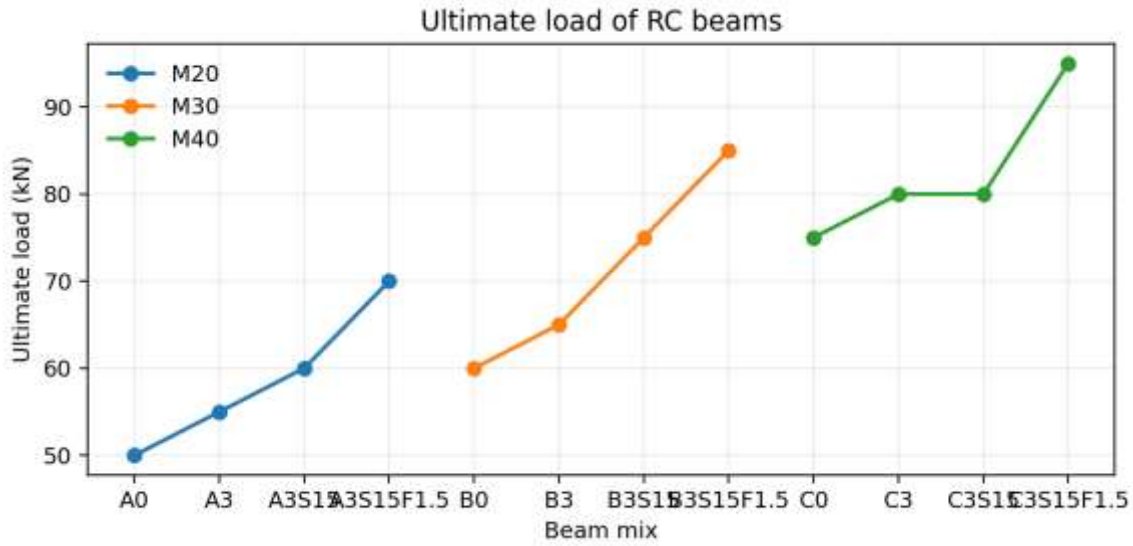


Figure 5. Ultimate load of reinforced concrete beams, plotted from Table 5.1.

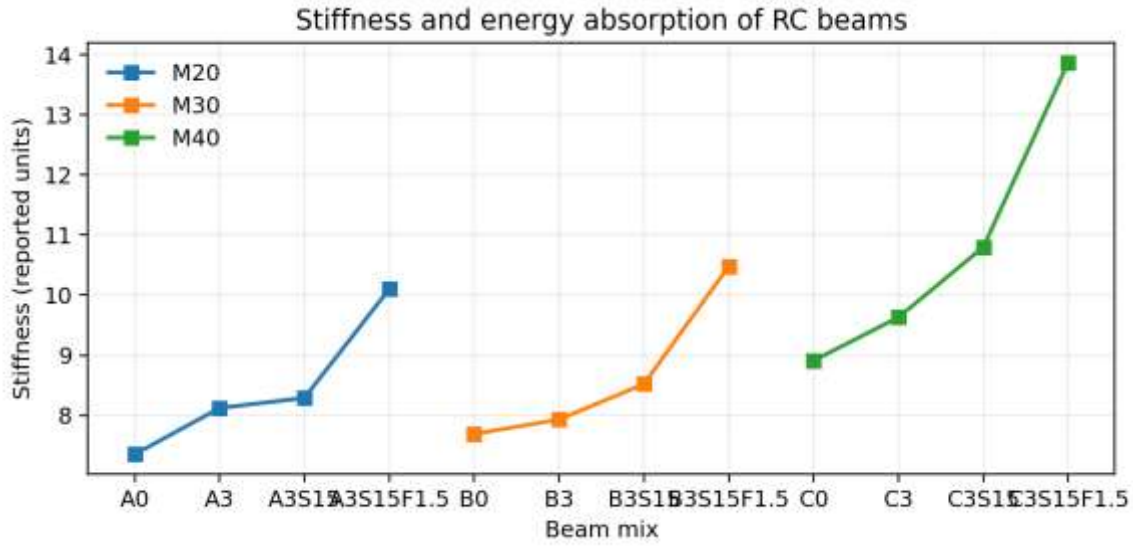


Figure 6. Reported beam stiffness values, plotted from Table 5.2.

For M20, ultimate load increased from 50 kN (control) to 70 kN (A3S15F1.5), a 40% increase. For M30, it increased from 60 to 85 kN (41.7%). For M40, it increased from 75 to 95 kN (26.7%). The M40 rich fibre mix also recorded the highest reported stiffness (13.87) and energy absorption (395 kN·mm), compared with 8.91 and 335 kN·mm for the M40 control. Ductility ratios decreased from 1.50 to 1.14 in the M40 sequence, indicating that higher load and stiffness were accompanied by a lower reported ductility index.

All beam specimens were reported to exhibit flexural failure, with cracks extending towards the compression zone as loading increased. The ANSYS comparison for M40 lists experimental and numerical maximum deflections of 8.42/9.23 mm (control), 8.31/9.04 mm (C3), 7.41/8.34 mm (C3S15) and 6.85/5.23 mm (C3S15F1.5). The final fibre-mix numerical value is lower than its experimental value, contrary to the study's general statement that numerical deflections were slightly higher.

VIII. DISCUSSION

The results indicate that a moderate RCA replacement was more favourable than very high replacement in the investigated mixtures. The 30% RCA level produced the highest tabulated compressive, split tensile and flexural strengths among the RCA-only series. This outcome is consistent with a balance between the contribution of the original aggregate skeleton and the additional porosity and adhered mortar associated with RCA. At 100%

replacement, the 28-day compressive strength was lower than the 30% RCA mixture by approximately 14.4% for M20, 12.0% for M30 and 12.1% for M40.

Silica fume addition improved the strength results in the selected 30% RCA mixes, with the 15% level giving the highest tabulated values. The likely contribution of fine-particle packing and pozzolanic reaction is discussed in the study; however, the study does not provide a controlled microstructural quantification or uncertainty analysis to isolate these mechanisms. Steel fibres improved the measured tensile/flexural response and the reported beam load, stiffness and energy absorption, while the reduction in slump indicates a workability trade-off.

IX. CONCLUSIONS

• Among the tested RCA-only mixtures, 30% replacement of natural coarse aggregate gave the highest reported 28-day compressive, split tensile and flexural strengths for M20, M30 and M40 concrete.

• At 30% RCA, 28-day compressive strengths were 26.0, 37.5 and 47.76 MPa for M20, M30 and M40, respectively, compared with 23.80, 34.85 and 43.90 MPa for the control mixtures.

• Replacing cement with 15% silica fume in the selected 30% RCA mixes produced the highest reported 28-day compressive strengths of 35, 51.5 and 58 MPa for M20, M30 and M40.

• Steel-fibre addition improved several reported strength and beam-response indicators, although slump decreased as fibre content increased.

• For M40 beams, the ultimate load increased from 75 kN for the control to 95 kN for the 30% RCA–15% silica fume–1.5% fibre mix. The corresponding reported stiffness and energy absorption were also the highest within the M40 series.

• The observed gains must be balanced against reduced reported ductility and the inconsistencies identified in the study. Further testing with verified fibre dosage, documented loading geometry, replicate statistics and corrected durability procedures is necessary before structural design adoption.

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