“BEHAVIOUR OF BEAM-COLUMN JOINTS MADE OF SELF-COMPACTING CONCRETE (SCC) WITH PARTIAL REPLACEMENT OF FINE AGGREGATE BY RUBBER UNDER STATIC LOADING”

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Abstract

Beam-column joints are critical zones in reinforced concrete frames, often governing overall structural ductility and collapse resistance under seismic loads. This study investigates the structural behaviour of exterior beam-column joints constructed with self-compacting concrete (SCC) incorporating crumb rubber as partial replacement of fine aggregate. Four SCC mixes of M35 grade were prepared with 0%, 5%, 10% and 15% volumetric replacement of natural sand by crumb rubber (0.5–2 mm particle size). Fresh properties (slump flow, V-funnel, L-box, J-ring) satisfied EFNARC 2005 criteria. Hardened properties—compressive strength (7, 28, 56, 90 days), split tensile strength, flexural strength, modulus of elasticity and bond strength—were evaluated. Scaled exterior beam-column joint specimens (1:2 scale) detailed as per IS 13920:2016 were tested under monotonic displacement-controlled loading. Rubber inclusion reduced 28-day compressive strength by 8–22% but increased ductility factor by 17–65% and energy absorption by 9–28%. The 10% replacement level provided an optimal balance: 89% of control ultimate load, ductility factor $\mu = 4.96$ (vs. 3.46 for control), 22% higher energy dissipation, and a shift from brittle joint-shear failure to ductile beam-flexural hinging with distributed fine cracks. Durability tests showed higher water absorption and drying shrinkage but improved chloride penetration resistance. The study demonstrates that 10% crumb rubber in SCC is a viable sustainable solution for beam-column joints in seismic zones, enhancing ductility and damage tolerance while recycling waste tyres.

Keywords: Self-compacting concrete; Crumb rubber; Beam-column joint; Ductility; Energy dissipation; Static loading; Waste tyre recycling; IS 13920

1. Introduction

Reinforced concrete moment-resisting frames are widely used in multi-storey buildings, wherein beam-column joints serve as the primary load-transfer hubs. Under seismic loading, inadequate joint confinement often leads to brittle shear failures, as observed in the 2001 Bhuj earthquake (India) and other global events. A major construction challenge in heavily reinforced joints is achieving adequate concrete compaction; self-compacting concrete (SCC) offers a solution because it flows under its own weight, fills congested reinforcement without vibration, and improves bond quality [1,2].

Parallel to constructability concerns, the disposal of end-of-life tyres poses severe environmental problems. India generates approximately 1.6 million metric tonnes of waste tyres annually, much of which is burned or landfilled [3]. Crumb rubber from shredded tyres, when used as a partial aggregate replacement in concrete, can impart enhanced ductility, impact resistance and energy absorption, albeit with some loss of compressive strength due to weak interfacial transition zones and low rubber stiffness [4,5].

Combining SCC with crumb rubber yields rubberized SCC—a material that offers both excellent flowability in congested zones and improved post-peak behaviour. However, research on the structural-scale performance of rubberized SCC beam-column joints, especially under monotonic static loading and using Indian materials, is limited. Most existing studies focus on material characterisation or on plain rubberized concrete elements [6–8], while joint studies predominantly employ cyclic loading [9,10]. Monotonic static testing provides baseline data for gravity-load design and progressive collapse assessment.

The present study aims to: (i) develop M35-grade rubberized SCC mixes (0–15% rubber replacement) conforming to EFNARC guidelines; (ii) characterise fresh, hardened and durability properties; (iii) test 1:2 scale exterior beam-column joints under monotonic loading; (iv) evaluate load-deflection response, ductility, energy absorption and failure modes; and (v) identify the optimum rubber content for balanced strength-ductility performance.

2. Materials and Methods

2.1 Materials

Ordinary Portland Cement (OPC 43 grade) conforming to IS 269:2015 was used. Fine aggregate was natural river sand (Zone II, IS 383:2016, specific gravity 2.65). Coarse aggregate was crushed granite (maximum size 12.5 mm, specific gravity 2.72). Crumb rubber (0.5–2 mm) was obtained from a tyre recycling plant in Haridwar, India, with specific gravity 1.08 and water absorption <0.5%. A polycarboxylate ether-based superplasticizer (PCE) and a viscosity-modifying agent (VMA) were used. Potable tap water conforming to IS 456 was employed for mixing and curing.

2.2 Mix Proportions

Four SCC mixes (R0, R5, R10, R15) were designed for target M35 grade using the modified Okamura method (EFNARC 2005). Fine aggregate was replaced by crumb rubber at 0%, 5%, 10% and 15% by volume. Table 1 summarises the mix proportions per cubic metre. Cement content was fixed at 420 kg/m³, water-cement ratio 0.40. Superplasticizer dosage varied from 0.80% to 1.10% by cement mass to achieve slump flow of 700±50 mm; VMA was added for R10 and R15 mixes (0.05–0.10%).

Table 1 Mix proportions per m³

Constituent	**R0**	**R5**	**R10**	**R15**
Cement (kg)	420	420	420	420
Water (kg)	168	168	168	168
Fine aggregate (kg)	850	807.5	765	722.5

Constituent	R0	R5	R10	R15
Crumb rubber (kg)	0	42.5	85.0	127.5
Coarse aggregate (kg)	780	780	780	780
SP (%, by cement)	0.80	0.85	0.95	1.10
VMA (%, by cement)	–	–	0.05	0.10

2.3 Fresh and Hardened Concrete Tests

Fresh properties were assessed using slump flow (diameter and T50), V-funnel, L-box, J-ring and sieve segregation tests (EFNARC 2005). Hardened properties: compressive strength on 150 mm cubes at 7, 28, 56 and 90 days (IS 516); split tensile strength on 150×300 mm cylinders; flexural strength on 100×100×500 mm prisms (third-point loading); static modulus of elasticity on cylinders; and bond strength by pull-out tests (IS 2770). Durability indicators (water absorption, sorptivity, rapid chloride permeability RCPT, drying shrinkage) were also measured on companion specimens.

2.4 Beam-Column Joint Specimens

Four exterior joint specimens (one per mix, designated J-R0, J-R5, J-R10, J-R15) were cast at 1:2 scale. Column cross-section 300×300 mm, height 1200 mm; beam cross-section 230×300 mm, length 900 mm from column face. Reinforcement detailing followed IS 13920:2016 for ductile moment-resisting frames (Zone III/IV). Column longitudinal reinforcement: 8 #16 mm (Fe500); ties: 8 mm @ 75 mm in joint core, 100 mm elsewhere. Beam: 4 #16 mm bottom + 3 #12 mm top; stirrups 8 mm @ 75 mm near joint, 100 mm elsewhere. Joint core contained additional 8 mm cross-ties. Cover: 25 mm to stirrups.

SCC was poured without vibration. After 24 h, specimens were demoulded and cured in water at 27±2 °C for 28 days. Strain gauges (120 Ω, 5 mm gauge length) were attached on longitudinal bars at 50 mm from joint face; LVDTs measured beam-end deflection and joint shear distortion.

2.5 Test Setup and Loading Protocol

The specimen was mounted in a 500 kN servo-hydraulic frame. A constant column axial load of 315 kN (≈0.1 fck Ag) was applied and maintained. Monotonic displacement-controlled loading was applied at the beam end (lever arm 300 mm) at 0.5 mm/min until failure (load drop to 80% of peak or deflection >50 mm). Load, deflection, strains and joint distortion were recorded. Crack initiation and propagation were observed using a crack microscope (0.02 mm resolution).

3. Results and Discussion

3.1 Fresh Properties

All mixes met EFNARC acceptance criteria for SCC (Table 2). Slump flow decreased from 720 mm (R0) to 645 mm (R15), while T50 time increased from 3.2 s to 5.2 s, indicating slightly higher viscosity with rubber. V-funnel flow time rose from 7.8 s to 11.2 s, but remained within VF2 class (6–12 s). L-box ratios were ≥0.81, confirming good passing ability. Segregation ratios were below 15% for all mixes. The results agree with Gesoğlu et al. [11], showing that up to 15% crumb rubber can be incorporated into SCC with proper superplasticizer and VMA adjustment.

Table 2 Fresh properties (average of 3 trials ± SD)

Mix	**Slump flow (mm)**	**T50 (s)**	**V-funnel (s)**	**L-box ratio**	**J-ring step (mm)**	**Segregation (%)**
R0	720 ± 12	3.2±0.3	7.8±0.4	0.92±0.02	6.2±0.8	8.5±1.2
R5	695 ± 15	3.8±0.4	8.5±0.5	0.89±0.03	7.1±1.0	9.2±1.5
R10	670 ± 18	4.5±0.5	9.6±0.6	0.85±0.04	8.0±1.2	10.8±1.8
R15	645 ± 20	5.2±0.6	11.2±0.8	0.81±0.05	9.5±1.5	12.5±2.0

3.2 Hardened Mechanical Properties

Compressive strength development is shown in Table 3. At 28 days, strength reductions were 8.1% (R5), 16.8% (R10) and 22.3% (R15) relative to control (38.2 MPa). All mixes continued to gain strength up to 90 days, with f90/f28 ratios of 1.12–1.15, indicating no adverse effect of rubber on long-term hydration. Split tensile strength decreased by 5–17%, flexural strength by 4–15%, while the ft/fck ratio increased from 0.090 to 0.097, showing better relative tensile performance of rubberized mixes. Modulus of elasticity (Ec) dropped from 31.2 GPa (R0) to 26.8 GPa (R15), consistent with the lower stiffness of rubber. Bond strength (pull-out) reduced from 10.2 MPa to 8.5 MPa for 15% rubber, yet remained adequate for code requirements.

Table 3 Compressive strength development (MPa)

Mix	**7 d**	**28 d**	**56 d**	**90 d**	**f90/f28**
R0	24.8±0.8	38.2±1.1	41.5±1.2	42.8±1.3	1.12
R5	22.9±1.0	35.1±1.4	38.4±1.5	39.8±1.6	1.13
R10	20.5±1.2	31.8±1.6	35.2±1.8	36.6±1.9	1.15

Mix	7 d	28 d	56 d	90 d	f90/f28
R15	18.8±1.3	29.7±1.8	33.0±2.0	34.2±2.1	1.15

3.3 Durability Indicators

Water absorption (24 h) increased from 3.8% (R0) to 5.2% (R15) due to higher porosity at rubber-paste interface. Sorptivity followed a similar trend. However, RCPT charge passed decreased from 1850 C (R0) to 1420 C (R15), a 23% improvement, attributed to rubber particles acting as physical barriers to ion migration [12]. Drying shrinkage at 90 days increased from 520 με to 680 με (+31%) because compressible rubber reduces internal restraint. Carbonation depth after accelerated exposure (5% CO_2, 60% RH, 90 days) was 4.2 mm (R0) vs 5.8 mm (R15), still within acceptable limits for 25–30 mm cover.

3.4 Structural Behaviour of Beam-Column Joints

Table 4 summarises the monotonic test results for the four joint specimens (average of two replicates). Control joint J-R0 failed in brittle joint shear: ultimate load 118.5 kN at deflection 28.4 mm, ductility factor μ = 3.46, energy absorption 2.85 kN·m. With increasing rubber content, ultimate load decreased modestly (by 4.8%, 11.2% and 16.7% for 5%, 10% and 15% rubber, respectively), but ultimate deflection increased significantly (+11%, +24%, +37%). Consequently, ductility factor increased to 4.05, 4.96 and 5.72, i.e., gains of 17%, 43% and 65%. Energy absorption rose by 9%, 22% and 28%.

Table 4 Structural test results (mean of two replicates)

Specimen	Pu (kN)	Δu (mm)	Py (kN)	Δy (mm)	μ = Δu/Δy	Energy (kN·m)	Failure mode
J-R0	118.5	28.4	92.0	8.2	3.46	2.85	Joint shear (brittle)
J-R5	112.8	31.6	85.5	7.8	4.05	3.12	Joint shear + beam flexure
J-R10	105.2	35.2	78.0	7.1	4.96	3.48	Beam flexure (ductile)
J-R15	98.7	38.9	70.5	6.8	5.72	3.65	Beam flexure (highly ductile)

Failure mode transitioned from brittle joint-shear (J-R0) to beam flexural hinging with distributed fine cracks (J-R10, J-R15). Crack widths at failure were 2.3 mm (J-R0) vs. 1.0 mm (J-R15). Joint shear distortion at peak load was higher for rubberized joints (0.012 rad for J-R10 vs. 0.008 rad for J-R0), but the load drop after peak was gradual, allowing large plastic rotations. Strain gauge data confirmed that in J-R10, beam bottom bars yielded before joint stirrups, whereas in J-R0 joint stirrups yielded first—evidence of the desired “strong column-weak beam” mechanism.

3.5 Optimum Rubber Content and Code Compliance

The 10% rubber replacement (J-R10) retained 89% of the control load capacity while achieving a ductility factor μ = 4.96. According to IS 13920:2016, special moment-resisting frames for seismic zones III-V require a ductility factor of at least 4–5. Thus, J-R10 satisfies the code’s implicit ductility demand. Joint shear stress at failure for J-R10 was $0.92\sqrt{f_{ck}}$, which is within the IS 456 limit of $1.2\sqrt{f_{ck}}$ for M35 concrete. Therefore, the 10% rubberized SCC joint is both safe and code-compliant. The increased water absorption and drying shrinkage at 10% rubber are moderate (+28% water absorption, +23% shrinkage) and can be managed by appropriate cover (30–40 mm) and curing. The improved chloride resistance is an added benefit for coastal or deicing-salt environments.

4. Conclusions

1. **Workability:** Rubberized SCC mixes with up to 15% crumb rubber (0.5–2 mm) satisfy EFNARC 2005 fresh property criteria when superplasticizer and VMA dosages are optimised.

2. **Strength:** 28-day compressive strength decreases linearly with rubber content (8–22% for 5–15% replacement), but 90-day strength gain is unaffected. Split tensile and flexural strengths are less affected (5–17% reduction).

3. **Ductility and energy absorption:** Beam-column joints with 10% rubber exhibit 43% higher ductility factor (4.96 vs. 3.46) and 22% higher energy absorption compared to control, with failure mode shifting from brittle joint shear to ductile beam flexural hinging.

4. **Optimum replacement:** 10% volumetric replacement of fine aggregate by crumb rubber offers the best balance: 89% of control ultimate load, μ = 4.96, and enhanced crack distribution (max width reduced from 2.3 mm to 1.0 mm).

5. **Durability:** Rubber increases water absorption and drying shrinkage but improves chloride ion penetration resistance. The 10% mix is suitable for moderate exposure environments with proper cover.

6. **Sustainability:** Using 10% rubber recycles ~85 kg of waste tyre rubber per m^3 of concrete, reduces natural sand consumption by 10%, and provides a sustainable alternative for earthquake-resistant construction.

Future work should include cyclic (seismic) loading tests, long-term durability under natural exposure, hybrid fibre-rubber mixes, and full-scale validation.

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