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Mechanical Performance and Embodied Carbon of M40 Sustainable Concrete Containing Recycled Coarse Aggregate, Carbon Nanotubes, Fly Ash, Silica Fume and Geopolymer Binder

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ABSTRACT.

Recycled coarse aggregate (RCA) lowers the environmental footprint of concrete but weakens it, and few studies show how this loss can be offset by nanomaterials and supplementary binders within one mix series. This paper reports an experimental study of thirteen M40-grade mixes designed to IS 10262:2019, in which RCA replacement (0–60%), multi-walled carbon nanotube (MWCNT) dosage (0–0.15% by weight of cement), fly ash (FA), silica fume (SF) and a fly ash–GGBS geopolymer binder were varied. Workability, compressive strength (3–28 days), split tensile strength, flexural strength and modulus of elasticity were measured, and embodied CO₂ and material cost were estimated for ten mixes. Without CNTs, 28-day strength fell from 44.2 to 31.4 MPa as RCA rose from 0 to 60%. At 40% RCA, 0.10% CNT raised strength from 36.1 to 46.3 MPa (+28.2%), restoring the level of the control, although the difference from the control was not statistically significant (Tukey HSD = 3.7 MPa); 0.15% CNT gave lower strength and workability, consistent with agglomeration. Adding 10% silica fume gave 51.2 MPa, and ambient-cured geopolymer mixes reached 50.4 and 53.8 MPa. Embodied CO₂ was 13% lower for 40% RCA and 73–77% lower for the geopolymer mixes, while the CNT-containing mixes cost 9–26% more than the control. The results indicate that RCA–CNT–SCM combinations can meet M40 strength, but a CNT-free geopolymer reference, durability data and larger specimen numbers are needed before design recommendations can be made.

Keywords: recycled coarse aggregate; carbon nanotubes; fly ash; silica fume; geopolymer concrete; compressive strength; embodied carbon

1. Introduction

Cement production contributes roughly 5–8% of global anthropogenic CO₂ emissions [1], and the extraction of natural aggregates is increasingly restricted. Recycled coarse aggregate (RCA) from demolished concrete addresses both problems, but the porous mortar adhering to RCA grains lowers strength and raises permeability [2]. RCA concrete contains two interfacial transition zones (ITZ), which are thicker, more porous and richer in oriented Ca(OH)₂ than the ITZ of conventional concrete [3, 4]. Strength losses are smaller when RCA is pre-saturated and the water–cement ratio is held constant [2, 5], and treatments such as pozzolanic slurry coating or two-stage mixing can improve RCA concrete further but add process cost [6, 7].

Carbon nanotubes (CNTs) offer a matrix-side route. When well dispersed they bridge nano-scale cracks, fill pores and nucleate C–S–H [8, 9]. Reported optimum dosages are small (about 0.05–0.1% by weight of cement), and performance falls once bundles form [9, 10]. Dispersion by probe ultrasonication with a polycarboxylate superplasticiser is the most common approach [11, 12]. Fly ash and silica fume refine the pore structure through pozzolanic reaction [13, 14, 15], and geopolymer binders made from fly ash and slag can remove Portland cement altogether [16, 17]. CNTs in alkaline geopolymer systems tend to agglomerate unless pre-dispersed [18].

Each of these materials has been studied separately; reports on their combined use in one recycled-aggregate concrete series on a common basis are scarce. This paper therefore compares thirteen M40 mixes in which RCA content, CNT dosage, SCM type and binder system were varied systematically, and reports their fresh and mechanical properties together with embodied CO₂ and material cost.

2. Materials and methods

2.1 Materials

53-grade OPC (IS 12269:2013 [19]; specific gravity 3.15, 28-day mortar strength 53.4 MPa), Class F fly ash (IS 3812 [20]; SiO₂ + Al₂O₃ + Fe₂O₃ = 92.3%), densified silica fume (IS 15388 [21]; SiO₂ 93.5%) and GGBS (IS 12089 [22]) were used. Natural coarse aggregate (NCA) was 20 mm crushed granite (specific gravity 2.71, water absorption 0.82%, Los Angeles abrasion 22.4%). RCA was produced in the laboratory by crushing 28-day-cured M30 concrete cubes and sieving to 4.75–20 mm (specific gravity 2.45, absorption 5.22%, Los Angeles abrasion 31.2%); it was used in saturated-surface-

dry condition after 30 min of soaking. Manufactured sand (Zone II, IS 383:2016 [23]) was the fine aggregate. MWCNTs (outer diameter 8–15 nm, length 10–50 μm , purity above 95%) were dispersed with a PCE superplasticiser (PCE:CNT = 1.5:1) by probe sonication (400 W, 20 kHz, 30 min, below 40 $^{\circ}\text{C}$) in 30% of the mixing water and checked under an optical microscope for bundles larger than about 5 μm . Geopolymer activator was 10 M NaOH blended with sodium silicate (modulus 3.2) at a mass ratio of 2.5, at an activator-to-precursor ratio of 0.45.

2.2 Mix proportions and specimens

OPC-based mixes were designed to IS 10262:2019 [24] for M40 with a target mean strength $f'_{cr} = f_{ck} + 1.65s = 40 + 1.65 \times 5 = 48.25 \text{ MPa}$, $w/c = 0.40$, water 186 kg/m^3 and cement 465 kg/m^3 . In SCM mixes the binder was held at 465 kg/m^3 with FA or SF replacing OPC; geopolymer mixes used 440 kg/m^3 of FA + GGBS. The series (Table 1) comprises RCA variation (M0–M3), CNT variation at 40% RCA (M2, M4–M7), SCM addition to the optimum RCA–CNT mix (M8–M10) and geopolymer mixes (M11, M12). Concrete was mixed in a 100 l pan mixer, compacted in three layers on a vibrating table, covered for 24 h and water-cured at $27 \pm 2 \text{ }^{\circ}\text{C}$ (geopolymer specimens sealed at $27 \text{ }^{\circ}\text{C}$).

2.3 Testing and analysis

Slump and fresh density followed IS 1199 [25]. Compressive strength of 150 mm cubes was determined at 3, 7, 14 and 28 days in a 2000 kN machine calibrated to IS 14858 [26] (IS 516 [27]); split tensile strength of $150 \times 300 \text{ mm}$ cylinders (IS 5816 [28]) and flexural strength of $100 \times 100 \times 500 \text{ mm}$ prisms under third-point loading were determined at 28 days, and the secant modulus E_c was obtained from stress–strain readings on $100 \times 200 \text{ mm}$ cylinders. Three specimens were tested per mix and age. One-way ANOVA with Tukey's HSD test (5% level) was computed from the mean and standard deviation of each mix. Embodied CO_2 was estimated with emission factors from the ICE database [29] (OPC 0.83, FA 0.027, SF 0.014, GGBS 0.052, NCA 0.042, RCA 0.018, NaOH 1.8, Na_2SiO_3 1.5 kgCO_2/kg) and 2.5 kgCO_2/kg for CNT [30]; material cost used Indian market rates of mid-2025.

Table 1. Mix designation, fresh properties and 28-day compressive strength (mean $\pm$ SD of three cubes).

Mix	RCA (%)	CNT (%)	Binder	FA (%)	SF (%)	Slump (mm)	Density (kg/m^3)	f'_c , 28 d (MPa)
M0	0	0	OPC	–	–	85	2420	44.2 ± 1.1
M1	20	0	OPC	–	–	88	2388	40.8 ± 1.3
M2	40	0	OPC	–	–	91	2355	36.1 ± 1.6
M3	60	0	OPC	–	–	95	2322	31.4 ± 1.9
M4	40	0.05	OPC	–	–	84	2353	40.6 ± 1.2
M5	40	0.075	OPC	–	–	78	2350	43.6 ± 1.1
M6	40	0.1	OPC	–	–	72	2348	46.3 ± 1.0
M7	40	0.15	OPC	–	–	63	2345	44.0 ± 1.4
M8	40	0.1	OPC	20	–	76	2320	42.5 ± 1.5
M9	40	0.1	OPC	–	10	69	2310	51.2 ± 0.9
M10	40	0.1	OPC	10	5	73	2315	48.6 ± 1.1
M11	40	0.1	FA70 + GGBS30	–	–	65	2305	50.4 ± 1.0
M12	40	0.1	FA50 + GGBS30	20	5	68	2302	53.8 ± 0.8

3. Results and discussion

3.1 Fresh properties

Slump of the control was 85 mm (target $80 \pm 15 \text{ mm}$) and rose slightly to 95 mm at 60% RCA, which is attributed to release of absorbed water from pre-saturated RCA. CNTs reduced slump progressively (91 mm for M2 to 72 mm for M6, -21%) despite higher superplasticiser dosage; M7 (0.15% CNT, 63 mm) fell below the 65 mm lower limit. SF reduced slump (69 mm) because of its large surface area, whereas FA raised it (76 mm). Geopolymer mixes had the lowest slump (65–68 mm). Fresh density fell from 2420 to 2322 kg/m^3 (-4%) at 60% RCA, in line with the lower specific gravity of RCA.

3.2 Effect of RCA and CNT dosage

Without CNTs, 28-day strength decreased from 44.2 MPa (M0) to 40.8, 36.1 and 31.4 MPa at 20, 40 and 60% RCA (−7.7, −18.3 and −29.0%; Fig. 1a), an average of about 9.7% per 20% increment. The 3-day/28-day ratio stayed at 38.5–41.2%, so the loss is attributed to the weaker double ITZ and higher porosity and not to retarded hydration. At 40% RCA, strength rose with CNT dosage to 40.6, 43.6 and 46.3 MPa at 0.05, 0.075 and 0.10% and fell to 44.0 MPa at 0.15% (Fig. 1b). The optimum of 0.10% agrees with reported dosage limits [9, 10]; the decline at 0.15% together with the lower slump is consistent with incomplete de-agglomeration, although agglomeration was assessed only by optical microscopy of the suspension. M6 exceeded M2 by 28.2% and the control by 4.7%, but the latter margin (2.1 MPa) is smaller than the Tukey HSD of 3.7 MPa, so the result should be read as recovery to control strength.

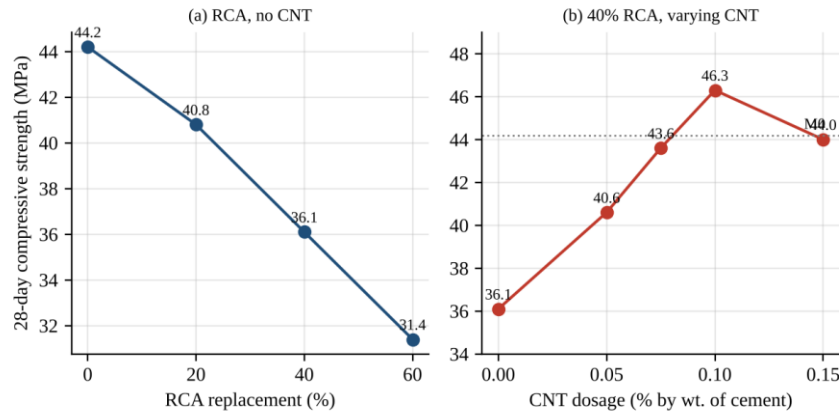


Fig. 1. 28-day compressive strength: (a) effect of RCA replacement without CNT; (b) effect of CNT dosage at 40% RCA (dotted line: control M0).

3.3 Effect of SCMs and geopolymer binder

Replacing 20% of cement by fly ash (M8) gave 42.5 MPa, 8.2% below M6, with the lowest 3- and 7-day strengths of the 40% RCA mixes (Fig. 2); its 14-day/28-day ratio (0.765 against 0.830 for M6) indicates continued gain, but no tests beyond 28 days were made to confirm catch-up. Silica fume (M9) gave 51.2 MPa, 10.6% above M6 and the highest OPC-based strength, with high early strength (20.8 and 31.2 MPa at 3 and 7 days), consistent with filler and pozzolanic action and with consumption of $\text{Ca}(\text{OH})_2$ at the ITZ [14]; the FA + SF mix M10 gave 48.6 MPa. The geopolymer mixes M11 and M12 reached 50.4 and 53.8 MPa under ambient curing, with 3-day strengths of 22.1 and 24.8 MPa, the highest of the series, and reached 85–87% of 28-day strength at 14 days (76–83% for OPC mixes). Calcium from GGBS is the likely reason for ambient-temperature strength development [17]. No CNT-free geopolymer reference was cast, so the contribution of CNTs in M11 and M12 cannot be separated.

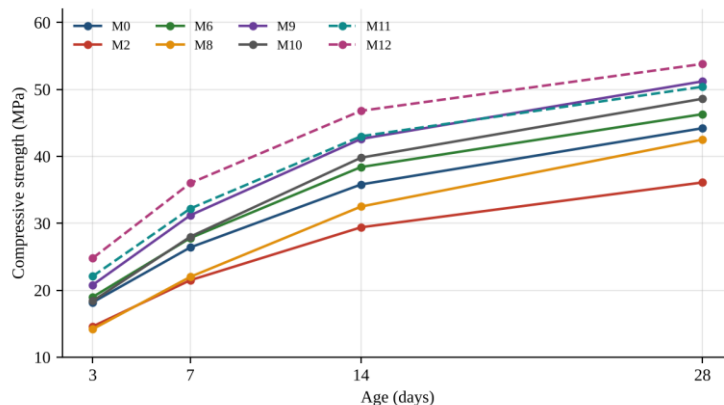


Fig. 2. Compressive strength development of selected mixes (mean of three cubes).

3.4 Tensile strength, flexural strength and modulus

Split tensile and flexural strength followed the compressive trends (Table 2). At 0.10% CNT and 40% RCA, split tensile strength rose 31% (3.12 to 4.10 MPa) and flexural strength 25% (4.82 to 6.05 MPa) above M2, and were 6.5% and 3.4% above the control. The ratios f_{ct}/f_c (0.083–0.092) and f_{lf}/f_c (0.119–0.138) were lowest for the high-strength SF and geopolymer mixes, as tensile strength grows more slowly than compressive strength. The modulus fell from 32.4 GPa (M0) to 24.9 GPa (M3) with RCA, was partly recovered by CNT (30.5 GPa, M6), and was highest for M12 (36.2 GPa). Measured E_c

was 87–97% of the IS 456 value $5000\sqrt{f_c}$ [31] for OPC mixes (falling from 97% for M0 to 89% for M3 as RCA increased) and 98–99% for geopolymer mixes, indicating that the code expression overestimates the stiffness of RCA concrete.

Table 2. 28-day mechanical properties (mean $\pm$ SD of three specimens; E_c single value).

Mix	f'_c (MPa)	f_{ct} (MPa)	f_r (MPa)	E_c (GPa)	f_{ct}/f'_c	f_r/f'_c	$E_c / 5000\sqrt{f'_c}$ (%)
M0	44.2 $\pm$ 1.1	3.85 $\pm$ 0.12	5.85 $\pm$ 0.18	32.4	0.087	0.132	97
M1	40.8 $\pm$ 1.3	3.58 $\pm$ 0.10	5.42 $\pm$ 0.14	30.1	0.088	0.133	94
M2	36.1 $\pm$ 1.6	3.12 $\pm$ 0.14	4.82 $\pm$ 0.20	27.8	0.086	0.134	93
M3	31.4 $\pm$ 1.9	2.88 $\pm$ 0.18	4.24 $\pm$ 0.22	24.9	0.092	0.135	89
M4	40.6 $\pm$ 1.2	3.65 $\pm$ 0.13	5.60 $\pm$ 0.16	29.8	0.090	0.138	94
M5	43.6 $\pm$ 1.1	3.92 $\pm$ 0.11	5.78 $\pm$ 0.15	30.2	0.090	0.133	91
M6	46.3 $\pm$ 1.0	4.10 $\pm$ 0.10	6.05 $\pm$ 0.14	30.5	0.089	0.131	90
M7	44.0 $\pm$ 1.4	3.88 $\pm$ 0.13	5.82 $\pm$ 0.17	28.8	0.088	0.132	87
M8	42.5 $\pm$ 1.5	3.78 $\pm$ 0.14	5.52 $\pm$ 0.19	29.2	0.089	0.130	90
M9	51.2 $\pm$ 0.9	4.35 $\pm$ 0.08	6.18 $\pm$ 0.12	33.2	0.085	0.121	93
M10	48.6 $\pm$ 1.1	4.15 $\pm$ 0.10	5.98 $\pm$ 0.14	31.8	0.085	0.123	91
M11	50.4 $\pm$ 1.0	4.22 $\pm$ 0.09	6.02 $\pm$ 0.13	34.8	0.084	0.119	98
M12	53.8 $\pm$ 0.8	4.48 $\pm$ 0.07	6.40 $\pm$ 0.11	36.2	0.083	0.119	99

3.5 Statistical analysis

One-way ANOVA showed a highly significant effect of mix on 28-day strength ($F(12, 26) = 72.7$, $p < 0.001$; Tukey HSD = 3.7 MPa). Relative to the control, M2 (−8.1 MPa) and M3 (−12.8 MPa) were significantly lower, M9 (+7.0), M10 (+4.4), M11 (+6.2) and M12 (+9.6 MPa) significantly higher, and M1, M4–M8 not significantly different. The coefficient of variation was 1.5–6.1% for compressive, 1.6–6.2% for split tensile and 1.7–5.2% for flexural strength. With three specimens per mix the power of the test is limited, and the comparisons are based on a single series of batches.

3.6 Embodied CO₂ and material cost

The control emitted about 420 kgCO₂/m³; 40% RCA reduced this to 366 kgCO₂/m³ (−12.9%), CNT at 0.10% added only about 0.47 kg/m³ of nanotube (roughly 1–3 kgCO₂/m³), and the geopolymer mixes emitted 112 and 98 kgCO₂/m³ (−73% and −77%; Table 3). Per MPa of strength, emissions were 9.5 kg for M0, 10.1–10.5 kg for 40–60% RCA without CNT, 8.0 kg for M6, 7.0 kg for M9 and 1.8–2.2 kg for the geopolymer mixes, so RCA alone does not improve carbon efficiency but RCA with CNT and SCMs does. Material cost rose by 16% for M6 relative to M0 and by 9–26% across the CNT-containing mixes; cost per MPa was INR 110 for M0, 121 for M2 and M6, 113 for M9 and 114–118 for the geopolymer mixes (Fig. 3). The cost advantage of RCA is therefore environmental and not economic per unit of strength.

Table 3. Embodied CO₂, CO₂ per MPa and material cost of ten mixes.

Mix	System	CO ₂ (kg/m ³)	CO ₂ /MPa	Cost (INR/m ³)	Cost index	INR/MPa
M0	OPC control	420	9.5	4,850	100	110
M1	20% RCA	395	9.7	4,620	95	113
M2	40% RCA	366	10.1	4,380	90	121
M3	60% RCA	330	10.5	4,180	86	133
M6	40% RCA + 0.10% CNT	369	8.0	5,620	116	121

Mix	System	CO ₂ (kg/m ³)	CO ₂ /MPa	Cost (INR/m ³)	Cost index	INR/MPa
M8	M6 + 20% FA	308	7.2	5,280	109	124
M9	M6 + 10% SF	360	7.0	5,780	119	113
M10	M6 + 10% FA + 5% SF	330	6.8	5,550	114	114
M11	GP + 40% RCA + CNT	112	2.2	5,950	123	118
M12	GP-H + 40% RCA + CNT	98	1.8	6,120	126	114

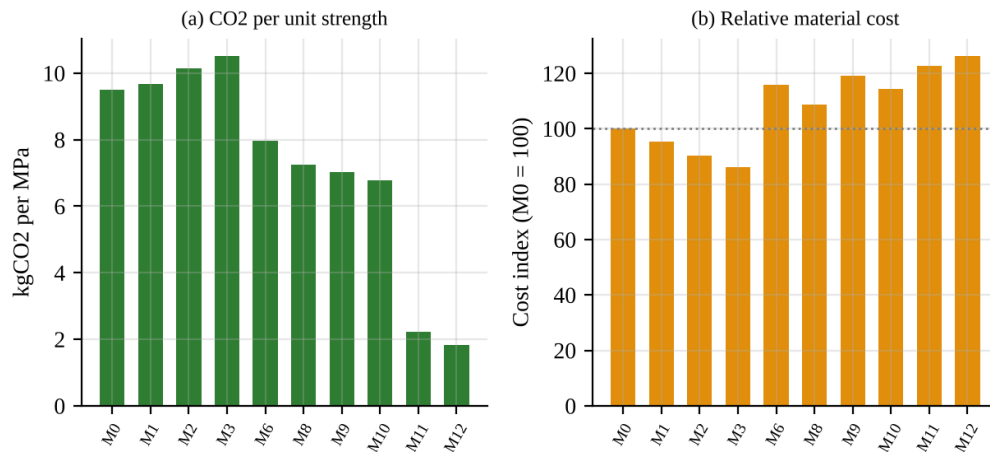


Fig. 3. CO₂ per unit of 28-day strength and relative material cost (M0 = 100) for the mixes in Table 3.

3.7 Practical implications

On the evidence of this series, three routes emerge. For applications needing strength equal to plain M40 concrete with lower carbon, 40% RCA with 0.10% CNT (M6) restored control strength and cut embodied CO₂ by about 12%, at a cost premium and a reduction in workability that must be handled with superplasticiser. Where higher strength is wanted, adding 10% silica fume (M9) gave the highest OPC-based strength at the lowest cost per MPa among the CNT mixes. Where the lowest carbon footprint and high early strength matter, ambient-cured geopolymer mixes (M11, M12) are the most efficient per unit of strength, although their cost and the unseparated role of CNTs call for further work. These observations concern strength and carbon only; suitability for aggressive exposure cannot be judged without durability data.

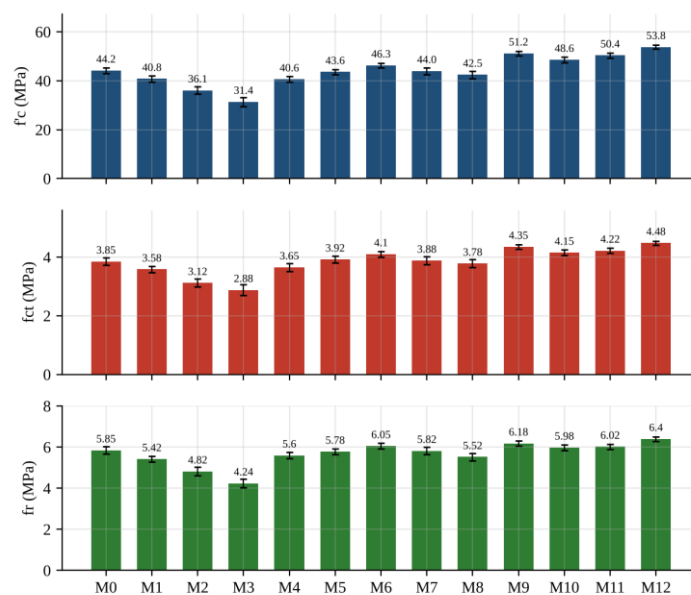


Fig. 4. 28-day compressive, split tensile and flexural strength of all mixes (mean ± SD).

4. Limitations

The study uses one RCA source, one MWCNT type, a single batch series with three specimens per test, and no tests beyond 28 days. No CNT-free geopolymer control was cast. Durability and microstructural characterisation are not addressed here. Cost figures are indicative, and CO₂ values are estimates from literature emission factors and not life-cycle assessments.

5. Conclusions

(1) RCA reduced 28-day strength by about 8–13% per 20% replacement (–18.3% at 40%, –29.0% at 60%). (2) At 40% RCA, 0.10% CNT raised strength by 28.2% to 46.3 MPa, restoring the control strength (difference from control not significant); 0.15% CNT reduced strength and slump, consistent with agglomeration. (3) 10% SF gave the highest OPC-based strength (51.2 MPa) and 20% FA a lower 28-day strength (42.5 MPa) with slower early gain. (4) Ambient-cured FA–GGBS geopolymer mixes with RCA and CNT reached 50.4–53.8 MPa and the highest early strength and modulus. (5) Embodied CO₂ was 13% lower for 40% RCA and 73–77% lower for geopolymer mixes, while CNT and geopolymer mixes carried a material-cost premium; per MPa, geopolymer mixes were the most carbon-efficient and the control the cheapest. (6) The IS 456 modulus expression overestimates the stiffness of RCA concrete. Durability, long-term strength and a CNT-free geopolymer reference are priorities for future work.

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