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Ultralow Graphene Oxide Dosages in IS-Proportioned M40 Structural Concrete

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Abstract
Graphene oxide (GO) is a potent nano-reinforcement for cementitious systems, yet dosage-level evidence for structural concrete proportioned under Indian Standard (IS) practice is scarce. M40 concrete designed per IS 10262:2019 with OPC 53 cement (IS 12269) was dosed with 0.01, 0.03, 0.05 and 0.08 % GO by mass of cement, dispersed by 40 kHz bath ultrasonication (45 min) with an IS 9103 polycarboxylate ether (PCE) superplasticizer. Testing covered consistency, strength, chloride penetrability, absorption and acid resistance. The response was non-monotonic: at 0.05 % GO, 28-day compressive strength rose 22.9 % (57.9 vs 47.1 MPa), flexural strength 28.8 % and split tensile strength 28.7 %, while charge passed fell 46.0 % and 24-h absorption 45.0 %; at 0.08 %, re-agglomeration degraded workability and erased roughly half the benefit. SEM showed compact interlocking C-S-H with refined portlandite, XRD attenuated the 18.0° portlandite reflection and FTIR shifted Si-O-Si upward from 971 to 989 cm^{-1}. A dosage of 0.05 % GO with PCE-assisted sonication is recommended for durable structural M40 concrete.
Keywords: Graphene oxide; M40 concrete; IS 10262:2019; Bath ultrasonication; Polycarboxylate ether superplasticizer; Rapid chloride permeability; Nucleation; Portlandite refinement

1. Introduction

1.1. Two-dimensional nano-reinforcement of structural concrete

OPC concrete remains the highest-volume engineered material on earth, yet its microstructure — poorly crystalline C-S-H, coarse portlandite plates, capillary porosity and weak interfacial transition zones (ITZ) — caps the strength–durability envelope any binder content can deliver [1,2]. Among nano-carbons, GO — a single-atom-thick sheet bearing basal epoxide, hydroxyl and edge carboxyl groups [3,4] — is uniquely favourable: unlike hydrophobic pristine graphene, which restacks in ionic pore solution, it is hydrophilic, dispersible and reactive towards calcium-bearing hydrates [5,6,30]. Structural M40 — the default strength for columns, girders, bridge substructures and industrial floors in Indian practice — is stricter still: modest paste fraction, angular crushed-rock aggregates and water constrained by IS 456 durability ceilings [10]. Whether GO's effects survive translation into such a system is the question addressed here.

1.2. Mechanisms and the dispersion challenge

Nucleation: the barrier to a critical C-S-H nucleus scales with the cube of the solid–solution interfacial energy [11,12], and Ca^{2+} complexed by deprotonated edge carboxyls creates calcium-rich domains that template silicate condensation [6,13]. **Habit modification:** multiplied nucleation sites fragment portlandite growth [6,14], replacing coarse, weakly bonded CH plates with small, randomly oriented crystallites intergrown with C-S-H. **Reinforcement and pore refinement:** wrinkled surfaces interlock

with nucleating C-S-H and hydrogen-bond to silanol and calcium sites [15], bridging incipient cracks and obstructing capillary continuity — why tensile and transport properties respond more strongly than compression [8,16]. All three are dosage-gated: beyond a critical concentration, ionic strength and π–π stacking re-aggregate sheets into micrometre clusters that revert from reinforcement to defect [9,17].

1.3. Gap, objectives and novelty

Three deficiencies persist: a **standards gap**, since GO-dosage studies under the full Indian Standard chain are essentially absent [1,7]; a **dosage-window gap**, since the ultralow 0.01–0.08 % bwoc band — the only one compatible with structural workability and commercial GO pricing — is far less studied than the 0.1–1 % band dominated by paste work; and a **completeness gap**, since fresh, mechanical, transport, chemical-attack and microstructural responses are seldom reported together. This study accordingly proportions an M40 mix per IS 10262:2019 and tracks 0.01–0.08 % GO bwoc across workability, strength, transport, acid resistance and microstructure — an ultralow-dosage programme with end-to-end IS-code compliance.

2. Materials and experimental methodology

2.1. Materials

OPC 53 conforming to IS 12269:2013 [20] was tested per IS 4031 [24] (Table 1); crushed granite and river sand conformed to IS 383:2016 [21] and were tested per IS 2386 [22] (Table 2), fine aggregate in Grading Zone II and coarse aggregate a 60:40 blend of 20 mm and 10 mm. A chloride-free PCE conforming to IS 9103:1999 [23] (ASTM C494 Type F/G; SG 1.08, 35 % solids) served as water reducer and steric stabilizer. GO was a dry, water-redispersible powder made by the modified Hummers route [4,5] (Table 3).

Table 1. OPC 53 cement (IS 12269:2013).

Property	Result	Requirement
Specific gravity; Blaine (m²/kg)	3.15; 316	—; ≥ 225
Consistency (%); soundness (mm)	29.5; 1.0	—; ≤ 10
Initial / final setting (min)	68 / 285	≥ 30 / ≤ 600
Loss on ignition (%); 28-d mortar strength (MPa)	2.4; 56.5	≤ 4.0; ≥ 53

Table 2. Aggregates (IS 2386 methods).

Property	Fine	CA 20 mm	CA 10 mm
Specific gravity; absorption (%)	2.65; 0.95	2.70; 0.45	2.68; 0.52
Fineness modulus; zone; silt (%)	2.72; II; 2.1	—	—
Impact; crushing value (%)	—	18.2; 22.4	19.6; 23.8
Flakiness; elongation (%)	—	12.8; 9.6	11.4; 10.2

Table 3. As-received graphene oxide.

Attribute	Value
Route	Modified Hummers oxidation of flake graphite [4,5]
Lateral size (SEM); thickness (AFM)	0.5–5 μm; 1–2 layers (~0.9–1.2 nm)
Atomic C/O; oxygen	≈ 2.1; ≈ 32–35 at.%
Groups (FTIR)	–OH ~3420; C=O ~1723; C–O–C ~1220; C–O ~1050 cm^{-1}
Raman I_D/I_G; pH (2 g/L)	≈ 0.94; ≈ 3.0

Fig. 1. As-received GO: (a) SEM; (b) AFM, 1–2 layers; (c) FTIR; (d) Raman.

2.2. GO dispersion: PCE-assisted bath ultrasonication

Stocks (2 g/L) were screened by visual homogeneity, absence of flakes after 30 min standing, and the Tyndall test. *Procedure:* GO (44.5–356 g/m³) was weighed to ±0.1 g, pre-slurried into part of the batch water with 40 % of the PCE dose, hand-stirred 2 min, then sonicated 45 min in a 40 kHz, 300 W bath at 30 ± 5 °C, since heating promotes restacking. Since exfoliation alone is metastable [18], the adsorbed PCE brush supplies the steric barrier [19]; the monolayer requirement (≈ 1.3 g PCE per g GO) is met ~11 times over at 0.08 % — provided admixture is at the sheet surface during exfoliation, hence the 40 % co-sonication.

Fig. 2. Dispersion protocol: (a) GO pre-slurried with 40 % of the PCE; (b) 40 kHz sonication, 45 min; (c) PCE adsorption; (d) transfer to mixer.

2.3. Mix proportioning per IS 10262:2019

The control mix was proportioned strictly per IS 10262:2019 [1], with durability limits cross-checked against IS 456:2000 [10] (Table 4). GO was an addition, not a replacement, and its volume is negligible; the five mixes (C-0.00 to GO-0.08) differ only in GO content — 0, 44.5, 133.5, 222.5 and 356.0 g/m³ — with cement 445, water 178, fine aggregate 595, coarse aggregate 706 : 471 kg and PCE 5.34 kg (1.2 % bwoc) at w/c 0.40 throughout.

Table 4. Stepwise M40 mix design (IS 10262:2019).

Step	Parameter	Value
1–6	Grade; σ; target mean strength (Cl. 4.3); exposure (IS 456 max w/c 0.45)	M40; 5 MPa; 48.25 MPa; moderate
7–11	w/c; water: base 186, slump correction, 12 % PCE reduction; cement = 178/0.40	0.40; 202.7 → 178 kg/m³; 445 kg/m³
12–16	Air 2 %; absolute volumes; CA fraction 0.66 (SG 2.70)	0.339 → 0.661 m³; 1177 kg/m³ (706 : 471)
17–19	FA mass (SG 2.65); PCE 1.2 % bwoc; density	595 kg/m³; 5.34 kg/m³; ≈ 2400 kg/m³

2.4. Batching, casting and curing

Mixes were produced in a 60 L pan mixer at 27 ± 3 °C: aggregates and cement dry-mixed 2 min; ~70 % of water, 1 min; the sonicated GO–PCE dispersion, 1 min; remaining PCE in the final minute (total ≤ 6 min). Specimens (three per mix each) were 150 mm cubes for compression at 7, 14 and 28 days and for the acid intervals, 100 × 100 × 500 mm prisms for flexure, and 150 × 300 mm cylinders for split tension and RCPT coring. Concrete was placed in layers, vibrated, trowel-finished, covered with wet hessian for 24 h and water-cured at 27 ± 2 °C; acid-exposure specimens were cured 28 days first.

2.5. Fresh-state and mechanical tests

Consistency was measured ≈ 12 min after water–cement contact per IS 1199 (Part 2):2018 [25] by slump (300 mm cone) and compacting factor; bleeding, segregation and balling were logged. Compression was tested on cubes in a 2000 kN machine at 0.6 ± 0.2 N/mm²/s per IS 516 (Part 1/Section 1):2018 [26]; flexure under third-point loading, $f_{cr} = Pl/(bd^2)$; split tension diametrally per IS 5816:1999 [27], $f_{ct} = 2P/(\pi LD)$.

2.6. Durability programme

RCPT (adapted ASTM C1202). Slices 50 ± 2 mm thick from mid-height of 28-day water-cured 100 mm cylinders were end-ground, epoxy-sealed, vacuum-saturated and mounted in ASTM C1202-19 cells [28]: 3.0 % NaCl (−), 0.3 N NaOH (+), 60 ± 0.5 V DC for 6 h, charge integrated at 28 and 56 days and classified per the ASTM scale.

Water absorption (IS 2185 Part 1 procedure, adapted). 100 mm cubes were oven-dried at 105 ± 5 °C to constant mass, desiccated and weighed (W_d), immersed 24 h at 27 ± 2 °C, wiped and weighed (W_s); absorption = $[(W_s - W_d)/W_d] \times 100$ %, mean of three [29].

Acid immersion (5 % H_2SO_4, 5 % HCl; 28 and 56 days). After 28 days of curing, cubes were weighed (W_0) and immersed in 5 % acid at 27 ± 2 °C (≈ 10 mL per cm² of surface); pH was monitored

weekly and baths renewed fortnightly. Triplicate cubes retrieved at 28 and 56 days were brushed free of scale, oven-dried at 60 °C for 24 h, and tested for mass change and residual strength against same-age water-cured cubes.

2.7. Microstructural characterization

At 28 days, fragments fractured from cube interiors were quenched in isopropanol and vacuum-dried, then examined by SEM–EDS (gold-sputtered, 10–15 kV, mapping Ca, Si and C), XRD (< 75 µm, Cu-Kα, 5–60° 2θ, the 18.0° portlandite reflection normalized to the 29.4° calcite peak) and FTIR (KBr pellets 1:100, 4000–400 cm^{-1}, 32 scans).

3. Results and discussion

3.1. Fresh-state behaviour

Table 5. Fresh-state properties (IS 1199 (Part 2):2018).

Mix	Slump (mm)	Compaction factor
C-0.00	105	0.92
GO-0.01	92 (−12.4 %)	0.89
GO-0.03	78 (−25.7 %)	0.86
GO-0.05	63 (−40.0 %)	0.82
GO-0.08	41 (−61.0 %)	0.76

Fig. 3. Fresh-state response: (a) slump; (b) compacting factor.

Both indices decay monotonically: the specific surface of exfoliated sheets immobilizes a water film, PCE adsorbed on GO is unavailable to deflocculate cement, and the colloidal solid raises paste viscosity. The loss accelerates in 13, 14, 15 and 22 mm slump steps across successive dosages — a transition from well-separated brush-stabilized sheets to a partly connected network. Yet even at 0.08 % mixes stayed cohesive and segregation-free (CF = 0.76). Practically, at 1.2 % PCE, dosages to 0.05 % retained a workable slump (63 mm); beyond that, admixture dose or w/c must be revisited.

3.2. Mechanical performance and the non-monotonic optimum

Table 6. Compressive strength, 150 mm cubes (IS 516); mean ± SD, n = 3.

Mix	7 days (MPa)	14 days (MPa)	28 days (MPa)
C-0.00	32.6 ± 0.4	38.8 ± 0.5	47.1 ± 0.6
GO-0.01	34.1 ± 0.4 (+4.6 %)	40.9 ± 0.5 (+5.4 %)	49.3 ± 0.5 (+4.7 %)
GO-0.03	35.8 ± 0.5 (+9.8 %)	42.6 ± 0.6 (+9.8 %)	52.7 ± 0.7 (+11.9 %)
GO-0.05	38.2 ± 0.5 (+17.2 %)	45.7 ± 0.6 (+17.8 %)	57.9 ± 0.7 (+22.9 %)
GO-0.08	35.3 ± 0.6 (+8.3 %)	41.8 ± 0.6 (+7.7 %)	51.4 ± 0.8 (+9.1 %)

Fig. 4. Compressive strength at 7, 14 and 28 days (±1 SD): maximum at 0.05 wt.%, reversal at 0.08 %. Gains grow to 0.05 %, where 57.9 MPa is a 22.9 % enhancement comfortably exceeding the 48.25 MPa design target, then fall by 6.5 MPa at 0.08 %. This upturn-and-reversal is the signature of aggregation-limited colloidal reinforcement: between 0.05 and 0.08 % bwoc, brush coverage and inter-sheet separation cross the threshold at which π–π stacking and van der Waals coagulation become unstoppable, converting nucleation templates into compliant inclusions and stress concentrators.

The gain at 7 days (+17.2 %) barely differs from that at 28 days (+22.9 %): GO-0.05 reaches 38.2 MPa in one week — essentially what the control achieves at 14 days — the time-invariance expected of nucleation control rather than a filler effect.

Table 7. 28-day flexural and split tensile strengths; mean ± SD, n = 3.

Mix	Flexural (MPa)	Split tensile (MPa)	f_cr/f_c	f_ct/f_c
C-0.00	5.20 ± 0.11	3.62 ± 0.09	0.110	0.077
GO-0.01	5.60 ± 0.12 (+7.7 %)	3.90 ± 0.10 (+7.7 %)	0.114	0.079
GO-0.03	6.00 ± 0.13 (+15.4 %)	4.18 ± 0.11 (+15.5 %)	0.114	0.079
GO-0.05	6.70 ± 0.14 (+28.8 %)	4.66 ± 0.12 (+28.7 %)	0.116	0.080
GO-0.08	5.90 ± 0.15 (+13.5 %)	4.06 ± 0.13 (+12.2 %)	0.115	0.079

Fig. 5. 28-day tensile response: (a) flexural; (b) split tensile; (c) normalized ratios.

Tensile-dominated indices out-respond compression at every dosage (+29 % vs +23 % at the optimum), and both normalized ratios climb consistently to 0.05 %. The inversion is informative: compressive failure is governed by matrix density, so gains there track nucleation and pore refinement, whereas flexural and splitting failure propagate through the weakest tensile link — ITZ flaws and incipient microcracks — and respond to anything that bridges or deflects cracks: precisely what hydrogen-bonded, interlocked sheet–C-S-H interfaces provide [15].

3.3. Durability performance

Table 8. RCPT charge passed (C) and ASTM C1202-19 class.

Mix	28 d (C), class	56 d (C), class
C-0.00	2850, Moderate	2280, Moderate
GO-0.01	2310 (−18.9 %), Moderate	1810 (−20.6 %), Low
GO-0.03	1840 (−35.4 %), Low	1395 (−38.8 %), Low
GO-0.05	1540 (−46.0 %), Low	1075 (−52.9 %), Low
GO-0.08	1920 (−32.6 %), Low	1440 (−36.8 %), Low

Fig. 6. RCPT: (a) charge passed at 28 and 56 days with ASTM bands; (b) current–time curves.

The 46.0 % fall in charge passed at 0.05 % — and migration from “moderate” to “low” penetrability already at 0.03 % — is the most consequential durability result. Seeding raises the share of binding C-S-H and segments capillary porosity into discontinuous pockets; sheets plug throats tens to hundreds of nanometres wide, adding tortuosity; and seeded growth densifies the ITZ at aggregate boundaries. The benefit deepens from 28 to 56 days (−46 % → −53 %) as sheets keep nucleating while unhydrated clinker persists; the reversal at 0.08 % tracks agglomeration, since clustered sheets plug nothing and nucleate interconnected interfacial voids.

Table 9. 24-hour water absorption, 100 mm cubes (mean of three).

Mix	C-0.00	GO-0.01	GO-0.03	GO-0.05	GO-0.08
Absorption (%), Δ vs control	5.35	4.61 (−13.8 %)	3.72 (−30.5 %)	2.94 (−45.0 %)	3.58 (−33.1 %)

Fig. 7. Water absorption versus dosage: 45 % reduction at 0.05 wt.%.

Absorption indexes interconnected, gravity-drainable capillary porosity, and its 45 % reduction at 0.05 % mirrors RCPT in relative terms — two independent transport indices peaking at the same

dosage, confirming genuine pore refinement rather than an admixture artifact.

Table 10. Mass change (Δm) and strength loss (Δf), %.

Mix	H_2SO_4 28 d	H_2SO_4 56 d	HCl 28 d	HCl 56 d
C-0.00	−4.6 / −21.4	−8.9 / −33.7	−3.1 / −16.2	−5.4 / −26.5
GO-0.01	−3.9 / −18.2	−7.4 / −29.5	−2.7 / −14.0	−4.6 / −23.0
GO-0.03	−3.3 / −15.3	−6.0 / −25.0	−2.2 / −11.5	−3.9 / −19.3
GO-0.05	−2.8 / −12.6	−4.7 / −19.8	−1.9 / −8.9	−3.2 / −14.7
GO-0.08	−3.4 / −16.1	−6.2 / −26.2	−2.4 / −12.3	−4.1 / −20.9

Fig. 8. Acid attack: (a, b) mass and strength loss in 5 % H_2SO_4; (c, d) in 5 % HCl.

H_2SO_4 is consistently the more aggressive medium — roughly 1.3–1.4 times the strength loss of HCl at every age — because HCl degrades by dissolution (soluble $CaCl_2$ leaches out) whereas H_2SO_4 adds an expansive route whose gypsum/ettringite crystallization pressures crack and spall the surface zone. GO slows both mechanisms: at 0.05 %, 56-day strength loss falls from 33.7 % to 19.8 % (H_2SO_4) and 26.5 % to 14.7 % (HCl) — a 41–45 % relative improvement — with comparable mass-loss reductions. The mechanism is primarily transport-gating: acid attack of immersed concrete is diffusion-limited, so the refined, tortuous, ITZ-densified network of GO-0.05 slows inward $H^+/SO_4^{2-}/Cl^-$ and outward Ca^{2+} flux alike, keeping the reaction front and degraded skin thin. Residual 56-day H_2SO_4 strength of GO-0.05 is ≈ 46.4 MPa, effectively at the unexposed control (47.1 MPa): for infrastructure facing sulphate-bearing soils, effluents or acid rain, 222.5 g GO per m^3 yields acid-aged strength that still meets grade.

3.4. Microstructural evidence

Fig. 9. SEM of 28-day fracture surfaces: (a) C-0.00; (b) GO-0.05; (c) GO-0.05 ×20,000; (d) GO-0.08.

The control displays the textbook weaknesses of hydrated cement: stacks of euhedral portlandite plates, needle ettringite spanning open pores, friable flocculated gel. GO-0.05 is transformed: portlandite survives only as small, randomly oriented crystallites locked within continuous gel, and C-S-H packs into an interlocking fabric wrapping crumpled GO templates — carbon-rich lamellae welded into the hydrate, EDS-confirmed by C-enrichment co-located with Si/Ca gel. GO-0.08 closes the loop: clusters of restacked sheets tens of micrometres across within shells of porous, poorly bonded hydrate — the defect signature predicted when restacking outpaces stabilization, and the correlate of the 6.5 MPa deficit and the transport rebound.

Fig. 10. XRD of 28-day pastes (Cu-Kα, 5–60° 2θ); inset: normalized CH intensity versus dosage.

The 18.0° portlandite reflection — the (001) basal series of coarse CH — attenuates 38 % at 0.05 % GO while broadening, its normalized intensity falling 1.00 → 0.91 → 0.78 → 0.62 → 0.81 across the series: the fingerprint of crystal-size reduction predicted in Section 1.2. The rebound at 0.08 % tracks loss of seeding surface, and dovetails with the acid results: less free portlandite means less feedstock for gypsum, and a denser matrix means slower ingress.

Fig. 11. FTIR of 28-day pastes, 4000–400 cm^{-1}.

The Si-O-Si asymmetric stretch, the most structure-sensitive mid-IR feature of hydrated cement, shifts upward from 971 cm^{-1} (control) through 974, 979 and 989 cm^{-1} at 0.01, 0.03 and 0.05 %, easing back to 977 cm^{-1} at 0.08 %. A higher wavenumber denotes stronger, shorter Si–O bonds and increased chain connectivity: more polymerized, more mature C-S-H at the same age — the vibrational echo of nucleation.

3.5. Synthesis: why 0.05 % is the optimum

Fig. 12. Integrated mechanism: (a) exfoliation and steric stabilization; (b) seeded nucleation; (c) pore plugging and ITZ densification; (d) restacking beyond ~0.05–0.08 %.

At ultralow dosage, well-dispersed GO acts as hydration catalyst and pore architect: seeding C-S-H, refining portlandite, toughening the matrix at crack tips, disconnecting the capillary network — so that 0.05 % bwoc, roughly one ten-thousandth of the cement mass, lifts every measured property by 23–46 %. But the same ultrahigh surface area that makes each sheet valuable makes the population fragile:

as dosage rises, a fixed PCE dose must stabilize ever-larger sheet area while competing with cement for adsorption, and restacking kinetics win. Beyond ~0.05 %, each additional gram contributes more agglomerate defect than nucleation template, so performance decays — never below control within the tested range.

4. Conclusions and field recommendations

4.1. Core findings

- An IS-proportioned M40 concrete tolerated 0.01–0.08 % GO bwoc with no segregation or balling, but workability fell progressively: slump 105 → 41 mm, compaction factor 0.92 → 0.76.
- Mechanical response was non-monotonic: at 0.05 %, 28-day compressive strength rose 22.9 % (57.9 vs 47.1 MPa), flexural 28.8 % and split tensile 28.7 %; at 0.08 %, re-agglomeration removed roughly half the benefit (compressive +9.1 %) — a practical ceiling for this stabilization system.
- Durability improved more than strength: RCPT charge fell 46.0 % (2850 → 1540 C, "moderate" → "low"), absorption 45.0 % (5.35 → 2.94 %), and 56-day acid strength loss from 33.7 % / 26.5 % to 19.8 % / 14.7 % (H_2SO_4 / HCl).
- Microstructure corroborated the optimum: interlocking C-S-H, refined portlandite (38 % attenuation of the 18.0° reflection) and a Si-O-Si shift from 971 to 989 cm^{-1} at 0.05 %, versus clusters with interfacial voids at 0.08 %.

4.2. Recommended field mix

Table 11. Recommended structural M40 mix with GO, per m^3.

Parameter	Recommendation
Grade / mix	M40, target mean 48.25 MPa (IS 10262:2019); OPC 53 445 kg, water 178 kg, w/c 0.40, FA 595 kg, CA 1177 kg (20 : 10 mm = 60 : 40)
PCE (IS 9103); GO	1.2 % bwoc (5.34 kg), 40 % co-sonicated; 0.05 % bwoc (222.5 g)
Dispersion	40 kHz bath, 45 min, ≤ 35 °C, dosed within 10 min
Expected performance	28-d f_ck ≈ 58 MPa; RCPT ≈ 1500 C; absorption < 3 %; improved acid/sulphate resistance
Plant checks	Tyndall clarity of stock; slump 55–75 mm; 7-d cube strength ≥ 36 MPa

On cost-effectiveness grounds the mix suits durability-critical elements — bridge decks and substructures, marine and sulphate-exposed foundations, industrial floors, chemical plants, and precast work where batching is controlled.

4.3. Limitations and future work

The 0.05 % optimum is an operating point of the dispersion system, not a universal constant, and should not be extrapolated by plants lacking reliable shear or sonication. GO cost dominates (~₹10–20 per gram ⇒ ₹2,200–4,500 per m^3), so the premium must be justified by life-cycle costing per exposure class. Evidence is batch-scale (≤ 60 L), and ASTM C1202 is a comparative conductivity index, not a diffusion coefficient. Priority follow-ups: creep and shrinkage; chloride diffusion and rebar corrosion to substantiate the service-life gains; fire behaviour; better stabilizers and probe/bath dispersion to push the agglomeration ceiling beyond 0.08 %; SCM synergy; and field-scale pours with plant QC and life-cycle assessment.

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