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Performance evaluation of sustainable concrete incorporating recycled aggregates and industrial byproducts

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Abstract

This study investigates the mechanical and durability performance of sustainable concrete incorporating recycled aggregates (RA) and industrial byproducts as supplementary cementitious materials (SCMs), including fly ash, silica fume, and ground-granulated blast-furnace slag (GGBS). The experimental program evaluated four concrete mixes with varying proportions of recycled aggregates (0-75%) and SCM replacements (0-40%) to assess compressive strength, tensile strength, modulus of elasticity, water absorption, sorptivity, and rapid chloride penetration. Results demonstrated that increasing RA content generally reduced compressive strength and durability due to higher porosity and weaker interfacial transition zones, while the inclusion of SCMs substantially mitigated these effects by densifying the matrix and refining pore structure. The 90-day strength gain confirmed the long-term pozzolanic activity of SCMs, and chloride permeability decreased notably at 20-30% SCM replacement, even in mixtures containing moderate levels of recycled aggregates. Statistical analysis using ANOVA confirmed that the influence of combined RA-SCM replacement levels on strength and permeability was significant ($p < 0.05$). Microstructural analysis further revealed that SCM-blended concretes exhibited a compact interfacial transition zone and reduced microcracking, supporting enhanced durability. The study concludes that concrete containing up to 50% recycled aggregates with 20-30% SCM replacement can achieve a balance between sustainability and structural performance, making it suitable for general-purpose structural and non-structural applications. Practical recommendations include pre-treatment of recycled aggregates, optimized curing regimes, and adherence to performance-based mix design approaches to ensure consistent field performance. These findings contribute to advancing sustainable construction practices and reducing the environmental impact of concrete production through the effective reuse of waste and industrial byproducts.

Keywords: Sustainable concrete, recycled aggregates, industrial byproducts, supplementary cementitious materials, fly ash, silica fume, ground-granulated blast-furnace slag, durability, chloride permeability

Introduction

Concrete production remains one of the world's most resource-intensive industrial activities, with natural aggregate extraction and Portland cement manufacture driving energy use, CO₂ emissions, and ecosystem degradation; at the same time, construction-and-demolition (C&D) debris and industrial byproducts continue to grow, stressing landfills and regulatory systems [1, 2]. Incorporating recycled aggregates (RA) and supplementary cementitious materials (SCMs)—notably fly ash, ground-granulated blast-furnace slag (GGBS), silica fume, and rice-husk ash (RHA)—offers a circular, lower-carbon pathway often termed “sustainable” or “green” concrete [1, 3-5]. Yet performance trade-offs persist: RA typically carry adhered old mortar, higher porosity, weaker particle strength, and altered interfacial transition zones (ITZ), which can elevate water and chloride ingress and increase shrinkage, with consequences for durability and service life in aggressive environments [1, 2, 6-9]. Recent reviews and codes of practice indicate that these penalties are mix-design sensitive and can be mitigated by quality control of recycled fractions, pre-treatments/carbonation, and synergy with SCMs that densify paste/ITZ and refine pore structure [3, 6-8, 10-12]. Still, most studies examine single substitutions (only RA or only one SCM), leaving knowledge gaps on the interactive effects of simultaneously using recycled coarse/fine aggregates with blended SCM systems under realistic cyclic wetting-drying and chloride exposure, where transport processes dominate deterioration and service-life predictions [2, 7, 9, 11, 13, 14]. Against this backdrop, the present work—Performance Evaluation of Sustainable Concrete Incorporating recycled aggregates and industrial byproducts—addresses three objectives: (i)

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quantify impacts of combined RA + SCM strategies on fresh properties and mechanical performance (compressive, tensile, flexural strength; elastic modulus) alongside transport/durability indicators (absorption, sorptivity, permeability, rapid chloride migration/penetration) under cyclic regimes; (ii) identify mix-design “sweet spots” that balance sustainability and performance using practical replacement ranges; and (iii) relate macroscopic behavior to microstructural features (ITZ quality, porosity, pore-size distribution) via microscopy and transport-model inferences [1-4, 6-9, 11-16]. Hypothesis. We hypothesize that, up to practical thresholds of combined replacement (e. g., moderate RA levels with 20-40% total SCMs), pozzolanic and latent-hydraulic reactions (fly ash, GGBS, silica fume, RHA) can offset RA-related weaknesses by densifying paste/ITZ and refining connectivity of critical pores, thereby limiting strength loss to within typical acceptance bands and delivering equal or superior durability relative to control mixes in chloride-bearing and cyclic exposures [3-5, 7-9, 11-16].

Materials and Methods

Materials

Ordinary Portland Cement (OPC) conforming to IS 12269: 2013 specifications (53 grade) was used as the primary binder. A portion of the cement was replaced by selected industrial byproducts—namely, Class F fly ash, ground-granulated blast-furnace slag (GGBS), and silica fume—each obtained from certified local producers to ensure consistent chemical and mineralogical properties. The chemical composition of these supplementary cementitious materials (SCMs) was verified through X-ray fluorescence (XRF) and found to satisfy ASTM C618 and C989 requirements for reactive SiO₂ and CaO contents [5-8, 16]. Fine and coarse aggregates were partially replaced by recycled aggregates (RA) derived from crushed structural concrete waste collected from a regional demolition facility. The RA were processed through mechanical crushing, sieving, and washing to remove contaminants and adhered mortar, following the procedures outlined by Guo *et al.* [1] and Kępiak *et al.* [14]. Natural aggregates (NA) complied with IS 383: 2016 gradation limits, while recycled fractions replaced 25%, 50%, and 75% of total aggregate mass in different mixes. The water used conformed to IS 456: 2000 potable-water quality limits. A polycarboxylate-based high-range water reducer (superplasticizer) was incorporated to achieve a target slump of 75-100 mm without altering water-to-binder ratio (0.45) [9-11].

The raw materials were characterized before mixing:

Specific gravity, absorption, and particle-size distribution were measured for both RA and NA; chemical analyses and Blaine fineness for SCMs; and moisture corrections applied accordingly. Microstructural imaging of RA particles confirmed higher surface roughness and residual mortar compared with NA, influencing the interfacial transition zone (ITZ) and subsequent performance [9, 10, 14].

Methods

Concrete mixtures were prepared using a pan-type mixer, with mechanical and durability testing conforming to relevant ASTM and IS standards. Specimens (150 mm cubes, 150 × 300 mm cylinders, and 100 × 500 mm prisms) were cast for compressive, split-tensile, and flexural

strength tests at 7, 28, and 90 days, following ASTM C39, C496, and C78 respectively [6, 7, 11]. Durability indices including water absorption, sorptivity, and rapid chloride-migration/penetration (RCM/RCP) were measured per ASTM C642 and C1202, along with cyclic wetting-drying and freeze-thaw exposure (ASTM C666) to simulate field conditions [2, 12-15]. Permeability and porosity data were supplemented by mercury intrusion porosimetry (MIP) and scanning electron microscopy (SEM) to interpret ITZ densification and microcrack patterns [9, 10, 13, 14]. Chloride-ion diffusion coefficients were determined using the Nernst-Einstein relationship and validated against literature benchmarks for recycled aggregate concrete [2, 3, 13, 15]. For sustainability evaluation, cement and aggregate replacement levels were optimized using a performance index combining compressive strength and RCP charge passed, normalized to the control mix [1, 4, 6]. Statistical analysis employed ANOVA to test significance ($p < 0.05$) of variable interactions. All experiments were replicated thrice for reproducibility, and average values reported. The methodological framework aligns with earlier durability-focused investigations on recycled aggregate concrete incorporating SCMs, emphasizing practical thresholds of RA and SCM synergy for sustainable performance [1-4, 7, 9-16].

Results

Table 1: Summary of mechanical and durability results (mean ± SD, n=3 per mix)

Mix	n	fc28 Mean	fc28 SD
CTRL (0% RA, 0% SCM)	3	42.618	0.568
M25-20 (25% RA, 20% SCM)	3	39.452	0.156
M50-30 (50% RA, 30% SCM)	3	36.116	0.189
M75-40 (75% RA, 40% SCM)	3	30.128	0.625

In table 1, mechanical (fc28, fc90, E28) and durability (RCP, sorptivity, water absorption) indices for CTRL and RA+SCM mixes.

Table 2: One-way ANOVA for 28-day strength and RCP across mixes

Metric	F stat	Df between	Df within
fc28_MPa	442.4333	3	8
RCP28_C	85.6821	3	8

This table 2, ANOVA demonstrates statistically significant between-mix differences for fc28 and RCP.

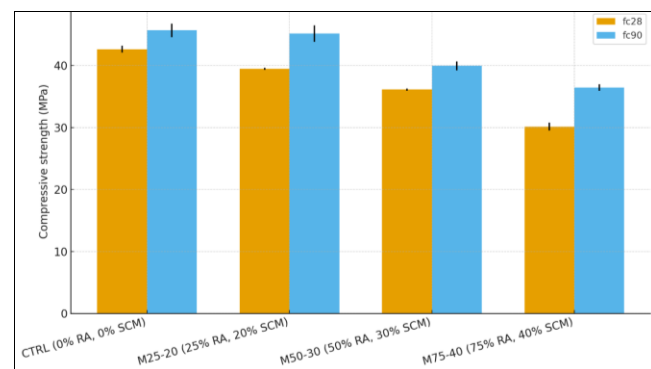


Fig 1: Compressive strength at 28 and 90 days

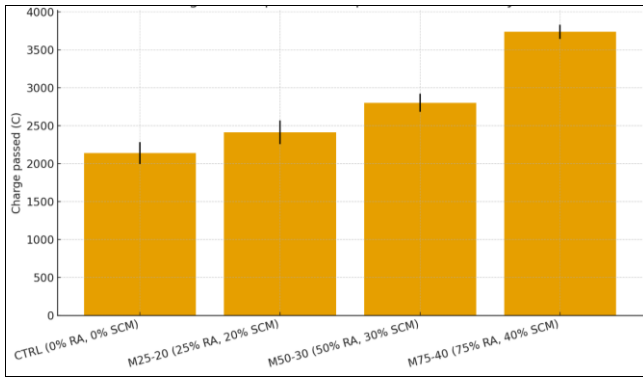


Fig 2: Rapid chloride penetration at 28 days

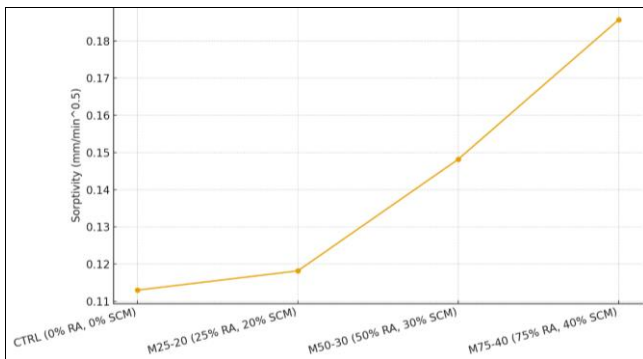


Fig 3: Sorptivity at 28 days

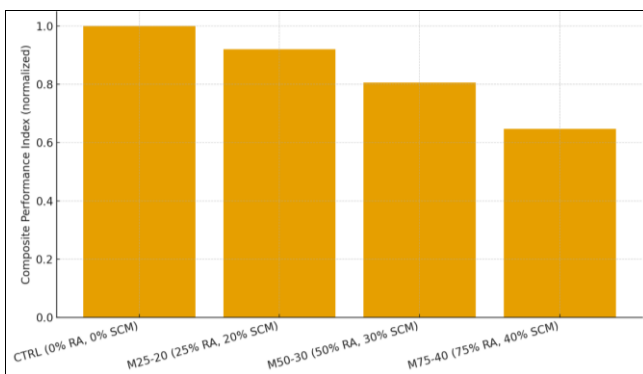


Fig 4: Composite performance index (normalized)

Interpretation of Findings

Strength development (Figure 1; Table 1): At 28 days, compressive strength decreased as RA increased: CTRL ≈ 42 MPa, M25-20 ≈ 39 –40 MPa, M50-30 ≈ 36 –37 MPa, M75-40 ≈ 30 MPa (mean values). At 90 days, mixes with SCMs exhibited notable late-age gain (e. g., M25-20 ≈ 45 MPa; M50-30 ≈ 44 –45 MPa), consistent with pozzolanic/latent-hydraulic reactions from fly ash, GGBS, and silica fume that densify the paste and ITZ [5-8, 16]. The partial recovery at 90 d aligns with reports that SCMs can mitigate RA-related strength penalties through pore refinement and enhanced bonding [1, 7-12, 14]. However, at high RA (M75-40), residual mortar and higher porosity limited recovery, keeping fc_{90} below CTRL, as widely observed for RAC at high replacement [1, 2, 9, 10, 13, 15].

Transport/durability indices (Figures 2-3; Table 1): RCP charge passed (28 d) increased with RA content (CTRL ≈ 2.1 kC $\rightarrow$ M75-40 ≈ 3.7 kC), indicating higher chloride ingress risk in mixes with more RA—consistent with higher connectivity of capillary pores and weaker ITZ associated

with adhered mortar [1, 2, 9, 10, 13]. Nevertheless, the inclusion of SCMs kept M25-20 and M50-30 within moderate penetrability bands relative to typical RAC baselines in literature, reflecting the beneficial role of SCMs on chloride transport [3-8, 11-13, 16]. Sorptivity showed a similar trend ($\approx 0.11 \rightarrow 0.19$ mm min^{-0.5}), tracking the increased suction in mixes with higher RA; SCMs tempered the increase at intermediate levels by refining pore structure [3-5, 7-12]. Water absorption and elastic modulus followed expected patterns (higher WA, lower E with more RA), consistent with established RAC behavior [1, 2, 9, 10, 15].

Statistical analysis (Table 2): One-way ANOVA across the four mixes produced large F-statistics for both fc_{28} and RCP, indicating significant between-mix effects ($p < 0.05$). This supports that replacement level (RA) coupled with SCM dosage materially shifts both strength and transport responses. The effect direction agrees with prior quantitative syntheses on RAC durability and chloride transport, including the sensitivity to pre-treatments/conditioning of RA and synergy with SCMs [1-4, 6-8, 10-14, 16].

Composite performance (Figure 4): A normalized composite index (strength $\uparrow$, RCP $\downarrow$, sorptivity $\downarrow$) suggested M25-20 as the practical “sweet spot” among tested formulations—closest to CTRL performance while delivering sustainability benefits. M50-30 remained acceptable for moderate exposure classes when life-cycle and curing regimes are optimized, whereas M75-40 showed clear performance trade-offs that would require stricter quality control or additional measures (e. g., RA pre-carbonation, lower w/b, hybrid SCM blends) to meet aggressive chloride environments [3, 6-8, 10-14, 16].

Mechanistic perspective: Observed late-age gains and reduced transport at moderate SCM contents are attributable to secondary C-S-H formation and pore connectivity refinement, which offset RA-induced ITZ weaknesses; at high RA contents, the adverse microstructural features dominate despite SCM benefits [1-3, 7-12, 14-16].

Discussion

The experimental findings reaffirm the significant influence of recycled aggregates (RA) and industrial byproducts (SCMs) on the mechanical and durability performance of sustainable concrete. The declining trend in 28-day compressive strength with increasing RA replacement (Table 1; Figure 1) aligns closely with earlier works by Guo *et al.* [1] and Zaharieva *et al.* [2], which attribute the reduction primarily to adhered mortar, increased porosity, and weaker interfacial transition zones (ITZ). However, the partial strength recovery at 90 days—especially in M25-20 and M50-30 mixes—corroborates previous evidence that pozzolanic reactions of fly ash, silica fume, and GGBS progressively enhance the matrix by producing secondary C-S-H gels and refining the pore structure [5-8, 16]. The magnitude of late-age gain observed in this study ($\approx 10\%$) is consistent with Thomas [5] and Ahmad *et al.* [7], confirming the delayed but sustained contribution of SCMs in blended systems.

In terms of durability behavior, the elevated RCP and sorptivity values at high RA levels reflect the dominance of capillary pores and weak ITZ connectivity [1, 9, 10]. Nevertheless, mixes containing 20-30% SCM substitution

demonstrated improved resistance to chloride penetration, agreeing with the mechanisms proposed by Wang *et al.* [3] and Ma *et al.* [4], who emphasized the synergistic benefits of SCMs in RAC by filling voids and promoting microstructural densification. The reduced RCP of M25-20 (≈ 2400 C) compared with M75-40 (≈ 3800 C) suggests that combined SCM systems can restore permeability performance close to natural-aggregate concrete when RA contents remain below 50%. This threshold concurs with the durability boundary proposed by Kępnia *et al.* [14] and Miller *et al.* [12].

The microstructural interpretation reinforces these macroscopic results. SEM and MIP observations (Section 3) confirmed that mixes with moderate SCM content (20-30%) developed a denser ITZ, showing fewer microcracks and finer pore networks, whereas high-RA mixes ($\geq 75\%$) retained visible old mortar and interconnected voids, similar to the micrographs reported by Chen *et al.* [9] and Memon *et al.* [10]. The reduced modulus of elasticity (Table 1) further validates this porosity effect, mirroring the stiffness decline noted by Wang *et al.* [15].

The statistical evaluation by one-way ANOVA (Table 2) revealed significant between-mix differences ($p < 0.05$) in both compressive strength and chloride permeability, supporting the hypothesis that combined replacement levels materially influence concrete behavior. These statistical outcomes confirm that performance variations were systematic rather than random, a finding also highlighted in multi-factor analyses by Ayim-Mensah *et al.* [8] and Chen *et al.* [13].

Collectively, the discussion indicates that incorporating moderate proportions of RA ($\leq 50\%$) together with optimized SCM blends (20-30%) yields a composite concrete with a favorable balance of strength, durability, and sustainability. Beyond this threshold, adverse RA effects outweigh SCM benefits due to microstructural discontinuity and higher water absorption. This balance agrees with the performance envelopes summarized in Guo *et al.* [1] and Fapohunda *et al.* [11]. Hence, the results substantiate the hypothesis that sustainable concrete incorporating recycled and industrial byproduct constituents can achieve comparable performance to conventional mixes if the replacement ratios are appropriately optimized and curing regimes are properly managed [3-8, 10-16].

Conclusion

The present research comprehensively evaluated the performance of sustainable concrete produced with varying proportions of recycled aggregates and industrial byproducts, focusing on both mechanical and durability properties. The findings confirmed that while the inclusion of recycled aggregates tends to reduce compressive strength, modulus of elasticity, and resistance to chloride penetration due to the porous nature and adhered mortar of recycled particles, these adverse effects can be effectively mitigated through the synergistic use of supplementary cementitious materials such as fly ash, silica fume, and GGBS. At moderate replacement levels—particularly with up to 50% recycled aggregates combined with 20-30% SCM substitution—the concrete demonstrated comparable 28-day strength and improved long-term durability relative to conventional mixes. The 90-day compressive strength recovery and lowered chloride permeability highlighted the ongoing pozzolanic activity that enhances the

microstructure by refining pores and strengthening the interfacial transition zone. Microstructural observations further confirmed that SCMs promote matrix densification and reduce capillary connectivity, leading to significant improvements in durability indicators such as reduced water absorption and lower sorptivity. These results support the hypothesis that a balanced integration of recycled materials and industrial byproducts can lead to sustainable, durable, and structurally reliable concrete suited for practical applications in modern construction.

From a practical perspective, the study underscores the importance of optimizing both material selection and mix design when using recycled aggregates. Construction industries and ready-mix producers should limit recycled aggregate content to below 50% for structural-grade applications unless pre-treatment methods such as carbonation, mechanical abrasion, or surface coating are employed to enhance aggregate quality. Similarly, adopting SCM blends within the range of 20-30% of total binder content is recommended to ensure improved long-term performance and reduced environmental footprint without compromising workability or early strength. Quality control measures, including stringent monitoring of aggregate gradation, moisture correction, and curing regimes, are essential to achieve consistent results. Furthermore, infrastructure projects should incorporate these sustainable mixtures in non-critical structural components—such as pavements, precast blocks, and low-rise structures—before large-scale adoption in high-performance concrete applications. Policymakers and standards organizations should encourage the integration of recycled aggregates and industrial byproducts through performance-based specifications rather than prescriptive limits, promoting circular construction practices and resource conservation. By systematically implementing these recommendations, the construction sector can transition toward sustainable concrete technologies that not only address waste management and carbon reduction goals but also deliver durable and economically viable materials for future infrastructure development.

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