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Synergistic Multi-SCM and RCA Approach for Sustainable High-Performance Concrete: A Review

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Abstract

High-performance concrete (HPC) that draws on supplementary cementitious materials (SCMs) and recycled coarse aggregate (RCA) is attracting growing research interest as the construction sector seeks to reduce both its carbon footprint and its dependence on virgin resources. This paper reviews recent experimental investigations into the individual and combined use of rice husk ash (RHA), silica fume (SF), fly ash (FA), ground granulated blast furnace slag (GGBFS), metakaolin (MK), and alccofine as partial cement replacements, together with RCA as a natural aggregate substitute. Optimal replacement levels of RHA (10–20%), SF (10–20%), GGBFS (30–40%), and MK (7.5–12.5%) raise compressive strength by 5–45% while densifying the pore structure and extending service life. RCA can replace up to 50–60% of natural aggregate without unacceptable strength loss when SCMs are incorporated. RHA also acts as an internal curing agent in ultra-high performance concrete, delaying self-desiccation and markedly reducing autogenous shrinkage. Critical research gaps are identified and recommendations for future investigations toward environmentally sustainable HPC are provided.

Keywords Rice Husk Ash; Silica Fume; Fly Ash; GGBFS; Metakaolin; Recycled Coarse Aggregate; High-Performance Concrete; Compressive Strength; Durability; Sustainable Construction.

I. INTRODUCTION

Concrete is the most widely used construction material on earth, with annual global output estimated at approximately 13 billion tons [1]. Ordinary Portland cement (OPC) production alone accounts for roughly 8–10% of anthropogenic CO_2 emissions, while simultaneous natural aggregate extraction and industrial waste accumulation compound the environmental burden [1,2]. Rice husk, an agricultural residue constituting about 22% of paddy weight, yields rice husk ash (RHA) upon controlled combustion, with worldwide annual production reaching approximately 20 million tons [3]. Construction and demolition waste represents a parallel stream that creates both disposal challenges and resource recovery opportunities [4].

Supplementary cementitious materials (SCMs) offer a dual advantage in HPC: they reduce clinker demand and associated CO_2 emissions while improving concrete properties through pozzolanic reactions and micro-filler effects [5]. RHA, with its high amorphous silica content of 85–95%, matches silica fume in pozzolanic reactivity [3]. Recycled coarse aggregate (RCA) carries higher porosity, elevated water absorption of 3.5–6.6% against 0.7–2.8% for natural coarse aggregate (NCA), and lower density compared to virgin material [4,5]. The adhered mortar layer creates weak interfacial transition zones (ITZ) and micro-cracks that reduce mechanical and durability performance. Combining RCA with SCMs mitigates these weaknesses through complementary pozzolanic and filler mechanisms.

This paper reviews findings from multiple investigations examining the individual and combined effects of RHA, SF, FA, GGBFS, MK, alccofine, and RCA on the fresh, mechanical, durability, and microstructural properties of HPC. The aim is to identify optimal replacement levels, clarify governing mechanisms, highlight research gaps, and recommend directions for future work.

II. MATERIALS CHARACTERISATION

2.1 Rice Husk Ash (RHA)

RHA produced through controlled combustion at 500–700°C contains 85–95% amorphous silica with high pozzolanic reactivity [3]. Table 1 presents physical properties reported across several studies. RHA exhibits a macro-mesoporous structure with pore sizes of 2–50 nm and specific pore volume of 0.08–0.12 cm^3/g, enabling water absorption and internal curing [6].

Table 1. Physical properties of RHA [3]

Property	Range
Specific gravity	1.95–2.45
Surface area (m^2/g)	24,000–274,000
Particle size (μm)	3.8–22.3
LOI (%)	2.2–4.4

2.2 Silica Fume and Fly Ash

SF consists of ultrafine spherical particles (0.1–0.35 μm) with 90–96% amorphous SiO_2 and specific surface area of 15,000–27,000 m^2/kg [6]. FA particles are predominantly spherical (1–100 μm) with specific gravity of 2.1–2.7; their ball-bearing effect improves mix workability [6].

2.3 Other SCMs

GGBFS exhibits latent hydraulic properties, with 30–40% SiO_2, 30–40% CaO, and glass content exceeding 90% [7]. Metakaolin (MK), calcined at 700–900°C, contains 50–55% SiO_2 and 40–45% Al_2O_3 with specific surface area of 12,000–15,000 m^2/kg [8]. Alccofine-1203 features ultrafine particles (D50: 4–5 μm) with 33–35% SiO_2, 23–25% Al_2O_3, and 31–33% CaO [7].

2.4 Recycled Coarse Aggregate (RCA)

RCA exhibits lower specific gravity, higher water absorption, and lower bulk density than NCA due to adhered mortar [4,9]. Table 2 compares representative physical properties.

Table 2. Physical properties of RCA vs. NCA [4,9]

Property	RCA	NCA
Specific gravity	2.31–2.53	2.62–2.86
Bulk density (kg/m^3)	1240–1430	1430–1650
Water absorption (%)	3.47–6.60	0.68–2.80
Crushing value (%)	21–24	13–15

III. FRESH PROPERTIES

RHA incorporation reduces workability due to its high specific surface area and porous structure, requiring higher superplasticizer (SP) dosages. Safiuddin et al. [5] reported HRWR dosages rising from 0.875% (0% RHA) to 2.45% (30% RHA) at w/b 0.35 to maintain a target slump flow of 600–770 mm. FA improves workability through spherical particle morphology, reducing SP demand by 20–30% versus control mixes [6]. SF reduces workability because of its extreme fineness, with Gupta et al. reporting progressive SP increases as SF content rises from 10% to 20% [6]. RCA reduces workability through rough surface texture, angular shape, and high water absorption; Shah et al. [4] observed slump values declining from 100 mm (control) to 85–93 mm at 25–100% RCA replacement at constant w/c.

Table 3 summarises fresh properties of selected self-compacting HPC (SCHPC) mixtures [5,6].

Table 3. Fresh properties of SCHPC mixtures [5,6]

Mix	w/b	RHA/FA/SF (%)	Slump (mm)	SP (%)
Control	0.35	0	690	0.70
15% RHA	0.35	15 RHA	720	1.40
30% RHA	0.35	30 RHA	750	2.45
25% FA	0.31	25 FA	640	2.00
50%FA-10%SF	0.31	50 FA / 10 SF	630	2.67

IV. MECHANICAL PROPERTIES

4.1 Compressive Strength

4.1.1 Effect of Rice Husk Ash

Rajashekhar Reddy et al. [3] investigated RHA replacement of 5–15% in M40 grade concrete. Table 4 presents 28-day compressive strength results. Optimum 7.5% RHA achieved 43.5 MPa (3% improvement). Strength declined beyond 10% due to dilution of cementitious content and reduced $Ca(OH)_2$ availability for pozzolanic reactions. Zareei et al. reported more substantial gains in M50 concrete: 20% RHA reached 93.3 MPa at 28 days, a 12% improvement over control [3]. The enhanced strength is attributed to pozzolanic reaction between amorphous silica and calcium hydroxide forming additional C-S-H gel that densifies the matrix.

Table 4. Compressive strength of RHA concrete (M40) [3]

RHA (%)	7-day (MPa)	28-day (MPa)	Change (%)
0	28.2	42.2	—
5	27.5	38.4	−9.0
7.5	28.5	43.5	+3.0
10	27.9	40.9	−3.1
12.5	26.0	39.6	−6.2
15	25.6	38.6	−8.5

Optimum at 7.5% RHA; strength declines beyond 10% due to dilution effect.

4.1.2 Effect of Silica Fume

SF improves compressive strength across all replacement levels up to 20%. Gupta et al. [6] reported 20% SF achieved 53.7 MPa at 28 days, a 15.5% improvement over control, as shown in Table 5. Ultrafine SF particles fill interstitial voids, improve packing density, and react rapidly with $Ca(OH)_2$ to form additional C-S-H.

Table 5. Compressive strength of SF concrete (M40) [6]

SF (%)	7-day (MPa)	28-day (MPa)	Change (%)
0	32.2	46.5	—
10	35.9	51.8	+11.4
15	35.8	52.5	+12.9
20	36.2	53.7	+15.5

4.1.3 Effect of Fly Ash and GGBFS

FA reduces early-age strength but supports long-term strength gain. Mustapha et al. [6] reported 25% FA reduced 28-day strength by ~35% versus control; however, a ternary blend of 40%PC–50%FA–10%SF achieved 87.1 MPa at 28 days, exceeding control (82.4 MPa) by 5.6%. GGBFS improves strength at optimal replacement: 40% GGBFS achieved 49.9 MPa at 28 days, a 7.3% gain, as shown in Table 6 [6].

Table 6. Compressive strength of GGBFS concrete (M40) [6]

GGBFS (%)	7-day (MPa)	28-day (MPa)	Change (%)
0	32.2	46.5	—
10	31.8	47.3	+1.7
20	33.4	48.9	+5.2
40	34.8	49.9	+7.3

4.1.4 Effect of Metakaolin and Alccofine

Swaminathan et al. [8] investigated MK (5–10%) combined with RHA (10–15%) in HPC. Table 7 shows that 7.5% MK + 12.5% RHA achieved 71.4 MPa at 28 days (36.5% improvement) and 78.9 MPa at 56 days, attributed to combined pozzolanic reactions forming additional C-S-H and C-A-S-H phases. Durai et al. [7]

reported a ternary blend of 30% GGBFS, 15% alccofine, and 10% MK in M40 concrete attained 54.1 MPa at 28 days (9.7% improvement) and 70.2 MPa at 90 days.

Table 7. Compressive strength of MK-RHA HPC [8]

MK (%)	RHA (%)	7-day (MPa)	28-day (MPa)	56-day (MPa)
0	0	41.0	52.3	57.1
5	12.5	49.4	69.9	75.8
7.5	12.5	56.4	71.4	78.9
10	12.5	51.3	66.5	76.3

Optimum: 7.5% MK + 12.5% RHA — 36.5% gain at 28 days.

4.1.5 Effect of Recycled Coarse Aggregate

RCA incorporation generally reduces compressive strength due to porous adhered mortar and weak ITZ. Shah et al. [4] reported 28-day strengths of 25.5, 27.8, 27.1, and 29.3 MPa for 25%, 50%, 75%, and 100% RCA respectively, versus 40.9 MPa for control. Combining SCMs with RCA mitigates this loss; Table 8 shows that 100% RCA with 15% RHA achieved 22.8 MPa — a 41% improvement over 100% RCA without RHA [4].

Table 8. Compressive strength of RCA-RHA concrete [4]

RCA (%)	RHA (%)	7-day (MPa)	28-day (MPa)
0	0	25.8	32.6
100	0	12.6	16.2
100	10	14.8	19.8
100	15	15.9	22.8
100	20	14.2	20.4

4.2 Split Tensile Strength

Split tensile strength follows trends broadly similar to compressive strength. Table 9 compiles results from multiple studies [6,8]. Qureshi et al. [6] reported 10% SF improved tensile strength by 21.5% and 15% RHA by 6.2%. The MK–RHA combination (7.5% MK + 12.5% RHA) achieved 45.8% improvement [8], attributed to enhanced ITZ density and reduced micro-cracking.

Table 9. Split tensile strength of SCM-modified concrete [6,8]

Mix	7-day (MPa)	28-day (MPa)	Change (%)
Control (RAC)	2.15	3.25	—
10% SF	2.85	3.95	+21.5
15% RHA	2.30	3.45	+6.2
30% GGBS	2.00	3.10	−4.6
20% FA	1.95	2.70	−16.9
Control (HPC)	—	4.32	—
7.5% MK + 12.5% RHA	—	6.30	+45.8

4.3 Flexural Strength

Table 10 summarises flexural strength data. Rajashekhar Reddy et al. [3] reported 7.5% RHA achieved 5.5 MPa at 28 days, a 12.2% improvement. Salas et al. [6] showed chemically treated RHA (ChRHA) reached 5.4 MPa at 56 days, exceeding both control (3.7 MPa) and SF mix (5.1 MPa).

Table 10. Flexural strength of SCM-modified concrete [3,6]

Mix	7-day (MPa)	28-day (MPa)	Change (%)
Control	3.9	4.9	—
5% RHA	4.2	5.5	+12.2
7.5% RHA	3.7	5.5	+12.2
10% RHA	3.5	4.7	−4.1

4.4 Modulus of Elasticity

Salas et al. [6] reported 56-day elastic modulus values of 29.1 GPa (control), 30.2 GPa (conventional RHA), 31.8 GPa (SF), and 32.1 GPa (chemically treated RHA). The improved elastic modulus reflects a denser microstructure and enhanced ITZ from pozzolanic and micro-filler effects.

V. DURABILITY PROPERTIES

5.1 Water Absorption

Water absorption reflects accessible pore volume and pathways for aggressive agents. Table 11 presents water absorption data from multiple investigations [4,5]. Safiuddin et al. [5] reported 15% RHA reduced water absorption by 38.5% at 28 days. Alharthai et al. [4] showed 100% RCA with 15% RHA cut absorption from 7.6% to 4.9% (35.5% reduction). The improvement is attributed to pore refinement from pozzolanic reactions and micro-filler effects reducing capillary porosity and pore connectivity.

Table 11. Water absorption of SCM-modified concrete [4,5]

Mix	28-day WA (%)	56/90-day WA (%)	Reduction (%)
Control (w/b 0.35)	5.2	4.4	—
5% RHA	4.3	—	−17.3
10% RHA	3.9	—	−25.0
15% RHA	3.2	2.7	−38.5
30% RHA	3.5	3.3	−32.7
Control (RAC)	7.5	6.7	—
100% RCA + 15% RHA	4.9	4.0	−34.7
100% RCA + 20% RHA	5.3	4.6	−29.3

5.2 Chloride Ion Penetration Resistance

Chloride penetration resistance is critical for reinforced concrete in marine and de-icing salt environments. Table 12 presents RCPT (Rapid Chloride Permeability Test) results [6,8]. ChRHA achieved a "Very Low" rating (960 Coulombs), comparable to SF (970 Coulombs) [6]. The optimum MK–RHA combination passed only 438 Coulombs [8]. Qureshi et al. [6] reported SCMs improved chloride resistance by 20–46%, with GGBS providing the maximum improvement (44–46%) due to high alumina content and chloride-binding capacity.

Table 12. RCPT results for SCM-modified concrete [6,8]

Mix	Charge Passed (C)	Classification
Control	3529	Moderate
10% Conventional RHA	1413	Low
10% ChRHA	960	Very Low
10% SF	970	Very Low
Control (HPC)	937	Very Low
7.5% MK + 12.5% RHA	438	Very Low

ChRHA = Chemically treated RHA. Classification per ASTM C1202.

5.3 Acid and Sulfate Resistance

Alharthai et al. [4] reported 100% RCA exposed to 5% HCl suffered 17.3% and 39.7% strength loss after 1 and 3 months respectively. Adding 15% RHA reduced losses to 12.8% and 31.1%; 20% RHA gave 12.3% and 31.2% losses. Qureshi et al. [6] reported 1% steel fiber combined with 10% SF improved acid resistance by 74–83%. Enhanced resistance arises from reduced $Ca(OH)_2$ content and a refined pore structure that limits aggressive ion ingress.

5.4 Electrical Resistivity

Table 13 presents electrical resistivity data from Safiuddin et al. [5]. RHA dramatically increases resistivity through pore refinement, reduced connectivity, and lowered alkali ion concentration from pozzolanic reactions.

Table 13. Electrical resistivity of RHA-SCHPC [5]

Mix	28-day (kΩ·cm)	56-day (kΩ·cm)
Control (w/b 0.35)	6.1	8.9
15% RHA	34.5	52.8
30% RHA	85.4	121.2

30% RHA at 56 days: 121.2 kΩ·cm — 13.6× increase over control.

5.5 Autogenous Shrinkage in UHPC

Van et al. [10] demonstrated that RHA markedly mitigates autogenous shrinkage relative to SF in ultra-high performance concrete (UHPC) across all curing temperatures (20°C, 65°C, 90°C). RHA's mesoporous structure (2–50 nm pores) absorbs water during mixing and releases it progressively during hydration, maintaining internal relative humidity (RH) and reducing self-desiccation. Internal RH measurements confirmed that RHA delays the drop below 98% from 2 days (SF) to 10 days (RHA), while the RHA–GGBS combination extends this to 4 weeks.

VI. MICROSTRUCTURAL PROPERTIES

SCM incorporation refines pore structure, reducing total porosity and shifting the distribution toward smaller pores. Safiuddin et al. [5] reported total porosity decreased from 13.71% (control, w/b 0.50) to 6.77% (30% RHA, w/b 0.35) at 28 days. MIP analysis revealed increased harmless pores (<20 nm) and reduced harmful pores (>200 nm) with SCM addition [5].

XRD analysis confirms reduced $Ca(OH)_2$ content and enhanced C-S-H formation from pozzolanic reactions. Van et al. [10] reported RHA-containing UHPC exhibited lower CH content than SF-containing UHPC at extended hydration. TGA-DTG analysis confirmed FA–RHA ternary blends achieved the lowest CH relative weight (1.32%) and highest C-S-H content (6.53%), correlating with superior mechanical performance.

SEM observations reveal denser microstructure, improved ITZ, and tight embedding of RHA particles within the cement matrix. Zhao et al. reported RHA-modified mixtures exhibited 3.1–17.2% higher elastic modulus and hardness in the ITZ region. EDS analysis confirmed a reduced Ca/Si ratio from 1.65 (control) to 1.37 (20% RHA), indicating enhanced C-S-H formation at the interface.

VII. RESEARCH GAPS AND FUTURE SCOPE

7.1 Research Gaps

Despite progress in individual SCM studies, several gaps remain. First, studies on the combined synergistic effects of RHA and RCA in HPC are limited, and the optimum binary SCM–RCA combination has not been systematically mapped [9]. Second, long-term durability data under realistic exposure conditions spanning 10–50 years are scarce; most studies extend only to 90 days [4]. Third, standardised production protocols for consistent RHA and RCA quality across sources and regions are absent [3]. Fourth, structural performance data from full-scale elements incorporating these materials are limited. Fifth, high-temperature performance and post-fire residual properties of SCM–RCA concrete have received insufficient attention.

7.2 Future Scope

Priority areas for future research include: advanced processing technologies (controlled combustion, surface treatment) for consistent SCM and RCA quality; nano-material integration for multi-scale strength enhancement; machine learning and optimisation algorithms for mix design; geopolymer and alkali-activated binder systems exploiting these materials; performance-based specifications for sustainable concrete; and comprehensive life cycle assessment accounting for regional production conditions and transport distances.

VIII. CONCLUSIONS

This review of experimental investigations into SCM–RCA high-performance concrete yields five principal conclusions.

Regarding fresh properties, RHA and SF reduce workability and require elevated SP dosages (up to 2.45% for 30% RHA), while FA enhances flowability and cuts SP demand by 20–30%. Optimal SCM combinations provide a workable balance between these competing effects.

Regarding mechanical properties, optimal replacement levels are RHA 10–20%, SF 10–20%, GGBFS 30–40%, and MK 7.5–12.5%. SF delivers the largest single-material strength gain (15.5% at 20% replacement). The MK–RHA combination (7.5% + 12.5%) achieves 36.5% improvement at 28 days. RCA replacement up to 50–60% remains acceptable when 15% RHA is incorporated.

Regarding durability, SCM incorporation cuts water absorption by 25–45%, upgrades chloride permeability rating from Moderate to Very Low, and raises electrical resistivity by up to 13.6 times. RHA provides exceptional internal curing in UHPC, extending internal RH maintenance from 2 to 10 days and substantially reducing autogenous shrinkage [10].

Regarding microstructure, SCMs reduce total porosity from 13.7% to 6.8%, refine pore size distribution, diminish $Ca(OH)_2$ content, increase C-S-H formation, and densify the ITZ — all of which contribute to the improved mechanical and durability performance documented in the literature [5,10].

Regarding sustainability, combined RHA–RCA use is projected to deliver a 20–25% reduction in carbon footprint relative to conventional OPC–NCA concrete, while simultaneously conserving natural resources and valorising agricultural and demolition waste streams [1,3,4].

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