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Self-Compacting Concrete with Supplementary Cementitious Materials: A Comprehensive Review of Fresh Properties, Mechanical Performance, Durability, and Sustainability

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Abstract—

Self-compacting concrete (SCC) has emerged as a transformative construction material capable of filling complex formwork and densely reinforced sections under its own weight, eliminating the need for mechanical vibration. This review comprehensively examines recent research on the incorporation of supplementary cementitious materials (SCMs) including fly ash (FA), silica fume (SF), ground-granulated blast-furnace slag (GGBFS), rice husk ash (RHA), and industrial by-products such as lime sludge and sugar factory lime waste into SCC systems. The effects of these materials on fresh-state properties, rheological behavior, compressive and tensile strength, sorptivity, permeability, and overall durability are critically analyzed. Evidence from experimental studies indicates that FA enhances workability through a ball-bearing effect, while SF densifies the microstructure through pozzolanic reactions and pore-filling action, significantly reducing water absorption and sorptivity. The combined use of FA and SF in ternary blends yields superior strength and durability compared to binary systems. Emerging cementless SCC formulations utilizing calcium oxide-activated slag and sugar factory lime waste demonstrate high compressive strength (up to 54.3 MPa) with substantially reduced carbon footprints (as low as 178.6 kg CO_2 eq/m^3). Recycled coarse aggregate has also been shown to be viable in SCC with only marginal strength reductions. This paper identifies critical research gaps and provides recommendations for future work emphasizing multi-objective optimization, long-term durability testing, and circular economy integration in sustainable concrete production.

Keywords—Self-compacting concrete; supplementary cementitious materials; fly ash; silica fume; durability; sustainability; rheology; pozzolanic reaction

I. INTRODUCTION

The global construction industry faces mounting pressure to develop materials that are simultaneously high-performing, durable, and environmentally responsible. Self-compacting concrete (SCC), introduced in Japan during the late 1980s by Okamura [9], represents one of the most significant advances in concrete technology in recent decades. Unlike conventional vibrated concrete, SCC possesses the ability to flow under its own weight, pass through confined spaces with dense reinforcement, and achieve uniform consolidation without mechanical compaction. These attributes translate directly into reduced labor costs, improved construction quality, minimized noise and vibration during placement, and enhanced architectural freedom [6].

Despite these advantages, SCC production traditionally relies on higher cement content and carefully optimized admixture systems, which increase both cost and carbon footprint. Cement manufacturing accounts for approximately 5 to 8 percent of global CO_2 emissions, making it imperative to identify strategies that reduce clinker content while preserving or enhancing concrete performance [7]. Partial replacement of Ordinary Portland Cement (OPC) with SCMs such as fly ash, silica fume, ground-granulated blast-furnace slag, and rice husk ash has therefore attracted intensive research interest over the past two decades.

Each SCM contributes distinct physicochemical characteristics to the cementitious system. Fly ash, a by-product of coal combustion, exhibits spherical morphology that improves flowability and reduces superplasticizer demand [6]. Silica fume, produced during silicon alloy manufacturing, is an ultra-fine highly reactive pozzolan that fills inter-particle pores and accelerates secondary hydration through its reaction with calcium hydroxide [1][2][4]. Slag from iron blast furnaces contributes latent hydraulic activity when activated by alkaline species or chemical activators such as calcium oxide [7]. More recently, industrial waste streams including paper mill lime sludge and sugar factory lime waste have been explored as activators and supplementary materials, contributing to circular economy objectives in construction [5][7].

This review synthesizes findings from experimental investigations and review studies published in high-impact journals including Construction and Building Materials and Cleaner Materials. The primary objective is to provide an integrated understanding of how different SCMs and industrial by-products influence SCC performance across the full spectrum of fresh-state behavior, rheological properties, hardened mechanical properties, durability characteristics, and environmental impact. The paper concludes with identified research gaps and a forward-looking perspective on the optimization of sustainable SCC systems.

II. LITERATURE REVIEW

A. Development and Classification of Self-Compacting Concrete

Self-compacting concrete is characterized by three fundamental fresh-state properties: filling ability, passing ability, and segregation resistance. These properties are assessed through standardized tests including the slump flow test, T50 measurement, V-funnel test, L-box test, J-ring test, and sieve segregation test, as prescribed by EFNARC guidelines [6][7][8]. The slump flow diameter typically falls between 600 and 800 mm for compliant SCC, while the T50 time (time to reach 500 mm diameter) ranges from 2 to 5 seconds for well-proportioned mixes.

Achieving these fresh properties requires careful balancing of cement content, aggregate volume, water-to-binder ratio, and chemical admixtures. Superplasticizers, particularly polycarboxylate ether-based types, are essential for reducing yield stress and enhancing flowability without increasing water content [4]. Viscosity-modifying agents (VMAs) may be incorporated to improve segregation resistance and ensure stability of the fresh mix, particularly in mixtures prone to bleeding [4]. Grdic et al. [8] demonstrated that SCC incorporating coarse recycled concrete aggregate at 50% and 100% replacement levels could meet all EFNARC fresh-state requirements when water content was adjusted to compensate for the higher absorption of recycled aggregate.

B. Role of Fly Ash in SCC

Fly ash is one of the most extensively studied SCMs in SCC applications. Its spherical particle morphology reduces inter-particle friction, yielding a well-documented ball-bearing effect that improves flowability and reduces superplasticizer demand compared to angular cement particles [6]. Class F fly ash, produced from bituminous coal combustion, exhibits primarily pozzolanic behavior, while Class C fly ash from sub-bituminous coal possesses both cementitious and pozzolanic properties [6].

Leung et al. [1] investigated the sorptivity of SCC with OPC replacement by fly ash at levels of 12.9%, 20%, 30%, 40%, and 50% by weight. Results showed that all fly ash-containing mixes exhibited reduced water absorption compared to the control. The reduction in sorptivity became more pronounced when fly ash content exceeded 20%, attributed to the pore-filling effect of FA particles within the concrete matrix. However, compressive strength generally decreased with increasing fly ash content, with the 50% replacement mix exhibiting a 28-day cube strength of 38.12 MPa compared to 57.68 MPa for the control. This inverse relationship between sorptivity and strength highlights that durability and mechanical performance respond differently to FA incorporation.

Khatib [11] reported a systematic increase in water absorption with increasing FA content in SCC over curing periods of 1, 28, and 56 days, noting a corresponding decrease in compressive strength, consistent with findings by Dinakar et al. [15]. In contrast, Mohamed [16] identified an optimum compressive strength at 30% FA replacement when a water-to-cement ratio of 0.42 was used, demonstrating the sensitivity of the optimum dosage to mix design parameters including curing conditions.

Meko et al. [6] reviewed extensive research on FA in SCC and concluded that the spherical shape of FA particles reduces friction between mortar and coarse aggregate, enabling a higher fine aggregate content in SCC without compromising self-compatibility. The ball-bearing effect was also found to reduce the risk of segregation when combined with appropriate air entrainment. Loss of workability with time was observed to decrease with increasing FA content, indicating improved workability retention in FA-containing SCC.

C. Role of Silica Fume in SCC

Silica fume is a highly reactive pozzolan with an average particle diameter approximately 100 times smaller than that of cement particles, giving it a very high specific surface area (typically 15,000 to 25,000 m^2/kg). This extreme fineness enables SF to fill micro-pores in the cement paste matrix and react rapidly with calcium hydroxide produced during cement hydration, forming additional calcium silicate hydrate (C-S-H) gel. This dual action of pore filling and pozzolanic reaction substantially densifies the interfacial transition zone between paste and aggregate, improving both strength and durability [2][3][4].

Lu et al. [2] investigated the rheological behavior of SCC with silica fume contents ranging from 2% to 16% using a ConTec Viscometer and Bingham model analysis. Yield stress was found to increase monotonically with SF content, while plastic viscosity exhibited a more complex non-monotonic response: decreasing initially from 0% to 4% SF, reaching a minimum around 4 to 6% SF, and then increasing again at higher dosages. Slump flow decreased with increasing SF content and with time after water addition, and at SF dosages of 12% or higher, slump flow declined markedly. These findings demonstrate that SF fundamentally alters the rheological profile of SCC and its effect on workability must be carefully managed through superplasticizer optimization.

Benaicha et al. [4] conducted a systematic comparison of VMA and SF effects on SCC rheology and mechanical performance. Their results showed that 10% SF (SF10) and 0.1% VMA (VMA0.10) produced nearly identical rheological characteristics, including sieve segregation of approximately 7.6% and 7.5%, viscosity of approximately 89 Pa·s for both, and yield stress of approximately 17.6 Pa. This equivalence implies that SF can functionally replace VMA to achieve the required viscosity and stability in SCC formulations, offering the additional benefit of improved hardened properties. SF10 achieved a 28-day compressive strength of 62.1 MPa compared to 65.2 MPa for VMA0.10, with nearly equivalent flexural strength and modulus of elasticity, while providing better long-term strength development due to continued pozzolanic activity.

Barbhuiya et al. [3] evaluated FA concrete at 30% and 50% OPC replacement levels, with additions of hydrated lime or silica fume. The inclusion of 5% SF by mass of OPC significantly improved both early-age and 28-day compressive strength at both replacement levels. Mercury intrusion porosimetry data confirmed that SF reduced total pore volume through high pozzolanic reactivity and the micro-filler effect of its extremely fine particles, which pack efficiently between cement grains and subdivide pore space. Thermogravimetric analysis demonstrated a reduction in $Ca(OH)_2$ content with SF addition, confirming its consumption in secondary C-S-H formation.

D. Combined Use of Fly Ash and Silica Fume in Ternary SCC Systems

Binary substitution of cement with a single SCM presents trade-offs: FA reduces compressive strength while improving workability, while SF improves strength and durability at the expense of flowability. Ternary systems combining FA and SF in SCC exploit the complementary characteristics of each material to achieve superior overall performance [1][13].

Leung et al. [1] investigated FS-series SCC mixes with a fixed 25% FA content and SF additions of 0%, 5%, 10%, and 15%, giving total OPC replacement levels of 25% to 40%. The combined FA and SF mixes consistently outperformed FA-only mixes in both sorptivity reduction and compressive strength enhancement. At 30% total replacement, the FS2 mix (25% FA + 5% SF) showed a 54.2% reduction in sorptivity coefficient compared to the control, while the F4 mix (30% FA only) achieved only a 31.8% reduction. At 40% total replacement, the FS4 mix (25% FA + 15% SF) achieved a sorptivity coefficient reduction of 63.6% versus 44.9% for F5 (40% FA only). The FS3 mix (25% FA + 10% SF) achieved the highest 28-day cube strength of 74.55 MPa, substantially exceeding the control value of 57.68 MPa, demonstrating the synergistic strength enhancement achievable through ternary blending.

Wongkeo et al. [13] confirmed that water absorption in SCC containing FA alone was higher than control concrete, but addition of SF to the FA-SCC system consistently reduced water absorption, with increasing SF content producing greater reductions. This behavior aligns mechanistically with the role of SF particles in refining the pore structure and blocking capillary pathways that govern water transport. The compressive strength of high-volume FA-SCC was lower than the control but recovered toward and exceeded control values when sufficient SF was incorporated, consistent with findings by Leung et al. [1].

E. Rheological Characterization and Permeability of SCC

Rheological characterization of SCC provides a more fundamental and quantitative description of fresh concrete behavior than empirical workability tests alone. The Bingham model, which expresses shear stress as a linear function of shear rate above a yield stress, is widely used to characterize SCC, though non-linear (shear-thickening) behavior is observed in some cases [2][4].

Lu et al. [2] demonstrated that yield stress grows with SF content and with time after water addition, while plastic viscosity follows a non-monotonic trend with a minimum at approximately 4% SF. At TW = 120 minutes, yield stress ranged from 83 Pa for the control to 369 Pa for the 16% SF mix, highlighting the profound effect of extended mixing time on flow resistance. The relationship between slump flow and rheological parameters was characterized: slump flow correlated strongly with yield stress, while the T500 flow time was more closely associated with plastic viscosity. This distinction is practically important because it allows targeted adjustment of specific rheological parameters through admixture selection and dosage optimization.

Permeability of hardened SCC was also investigated by Lu et al. [2] using a water permeability apparatus at 3.0 MPa pressure over 60 to 110 days. The permeability coefficient of the control group declined sharply during early permeation duration and stabilized at a low long-term value. For SF groups, initial permeability coefficients were lower than the control, but groups with high SF content (12%) showed a slight subsequent increase attributed to the formation of a relatively porous matrix at high SF dosages. Long-term permeability coefficients were lower than the control for SF contents of 8% and 12%, but slightly higher for lower SF contents of 4%, indicating an optimal range for SF dosage from a permeability perspective.

F. Durability of SCC with SCMs

Durability of SCC is governed primarily by the transport properties of the near-surface concrete, which control the ingress of deleterious agents including water, chloride ions, sulfates, and carbon dioxide. Sorptivity, measured by the rate of capillary water absorption per unit area per square root of time, is a widely used indicator of near-surface concrete quality [1][3].

Leung et al. [1] reported that all SCC mixes containing FA and/or SF exhibited lower sorptivity than the OPC control. The reduction was attributed to micro-void filling by FA particles and pozzolanic densification of the cement paste matrix by SF. A key finding was the absence of a definitive correlation between sorptivity and 28-day compressive strength across both the F-series (FA-only) and FS-series (FA + SF) mixes, consistent with observations by Dinakar et al. [15]. While FA-SCC showed decreasing compressive strength with increasing replacement, it simultaneously showed decreasing sorptivity, breaking the typical inverse strength-sorptivity relationship. This indicates that durability and strength are controlled by different microstructural mechanisms and that using 28-day strength as a sole durability indicator is inadequate for SCC containing variable SCM combinations.

Barbhuiya et al. [3] evaluated air permeability using the Autoclam permeability system on fly ash concrete with hydrated lime and silica fume additions. Air permeability decreased or remained essentially unchanged with both lime and SF additions compared to plain FA concrete at 30% and 50% replacement levels. Sorptivity indices also improved with both additions, with silica fume showing the most significant benefit at both replacement levels. The underlying mechanism is the formation of additional C-S-H through pozzolanic reactions that reduces effective porosity and refines the pore size distribution toward finer, less connected pores.

Grdic et al. [8] investigated water absorption and waterproofness of SCC with 50% and 100% coarse recycled concrete aggregate. Water absorption increased from 0.55% for control SCC to 0.77% and 0.92% for P50 and P100 mixes respectively, attributed to the higher porosity of the old cement paste adhering to recycled aggregate grains. Notably, all three mixes passed the waterproofness test, with the control concrete showing only 10 mm of water penetration under 7-bar pressure, while the P50 and P100 mixes showed no measurable penetration, attributed to the self-sealing effect of denser SCC microstructure.

G. Industrial By-Products and Sustainable SCC

The integration of industrial waste materials into SCC formulations addresses both the durability enhancement objectives and the environmental imperative to reduce cement consumption. Vashistha et al. [5] reviewed the application of paper mill lime sludge in concrete and mortars, finding that cement replacement levels of up to 30% are generally feasible without significant reduction in compressive strength, with optimal behavior typically achieved at 10 to 20% replacement. Lime sludge, composed primarily of calcium carbonate with minor silica and alumina, can act as a filler or, when calcined, as a pozzolanic material. Combined use of lime sludge with fly ash and silica fume was shown to enhance both strength and durability relative to lime sludge alone.

Bahmani and Mostofinejad [7] developed a fully cementless SCC utilizing GGBFS activated with calcium oxide or sugar factory lime waste. The SCC-CAS-700 mix, containing 630 kg/m^3 slag and 70 kg/m^3 calcium oxide as activator, achieved a slump flow of 718 mm, T50 time of 2 seconds, V-funnel time of 6 seconds, and J-ring height difference of 6 mm, all meeting EFNARC requirements for self-compacting concrete. This mix achieved a 28-day compressive strength of 54.3 MPa, flexural strength of 4.82 MPa, tensile strength of 4.1 MPa, and water absorption of only 4.52%, classifying it as high-strength concrete. Scanning electron microscopy revealed a dense microstructure with well-developed C-S-H phases and minimal pore connectivity, consistent with the superior mechanical and durability performance.

Life cycle assessment using the IMPACT 2002+ methodology demonstrated that lime waste-activated slag SCC (SCC-LAS-550) achieved the lowest carbon footprint of 178.6 kg CO_2 eq/m^3, substantially lower than conventional Portland cement concrete, which typically produces 250 to 400 kg CO_2 eq/m^3. Increasing activator content increased the carbon footprint, indicating the need to balance performance optimization with environmental objectives. This study represents an important advance in cementless sustainable concrete technology and provides a template for circular economy-aligned construction material development.

H. Recycled Aggregate in SCC

The use of coarse recycled concrete aggregate (RCA) in SCC addresses the environmental problem of construction and demolition waste while conserving natural aggregate resources. Grdic et al. [8] produced SCC with 50% and 100% RCA substituting natural coarse aggregate. Equal consistency was maintained by slightly increasing water content to compensate for RCA's higher water absorption (5.08% to 5.88% versus less than 1% for natural river aggregate). Fresh-state testing showed that all three mixes achieved a slump flow of 73 cm (SF2 class), T500 time within the VS2 viscosity class range of 3.5 to 6.0 seconds, L-box ratio above 0.8 (PA2 class), and sieve segregation below 15%.

Compressive strength at 28 days was 49.46 MPa for control, 47.54 MPa for P50, and 45.23 MPa for P100, representing reductions of 3.88% and 8.55% respectively. The reduction was attributed to the weaker microstructure of old cement paste adhering to RCA grains and the demand for additional water during hydration of new cement paste reacting with residual paste on RCA surfaces. Tensile strength by bending decreased by 2.49% and 13.95% for P50 and P100 respectively. Despite these modest strength reductions, the RCA-SCC mixes met all EFNARC fresh-state criteria and exhibited excellent waterproofness, demonstrating the technical viability of using recycled aggregate in SCC production. The use of high-quality RCA from demolished structural concrete with compressive strength of 37 to 45 MPa was identified as a key factor in achieving acceptable performance.

III. REVIEW METHODOLOGY

This review was conducted through a systematic literature search of peer-reviewed journals indexed in Scopus, Web of Science, and Google Scholar. Search terms included combinations of 'self-compacting concrete,' 'supplementary cementitious materials,' 'fly ash,' 'silica fume,' 'slag,' 'durability,' 'sorptivity,' 'rheology,' 'recycled aggregate,' 'lime sludge,' and 'sustainable concrete.' The selection criteria prioritized experimental studies and systematic reviews published in journals with impact factors greater than 3.0, focusing primarily on work published between 2000 and 2025. A total of eight primary sources spanning 2009 to 2025 were selected for detailed analysis, supplemented by additional references cited within these works.

Studies were categorized based on their primary focus: fresh-state properties and rheology, mechanical performance, durability (sorptivity, permeability, water absorption), and environmental impact and sustainability. Within each category, findings were cross-referenced to identify convergent evidence, conflicting results, and research gaps. Particular attention was given to the water-to-binder ratio, curing conditions, and replacement levels employed in each study, as these parameters significantly influence the comparability of results across investigations.

IV. RESULTS AND DISCUSSION

A. Fresh-State and Rheological Properties: Synthesis

Table I summarizes the key fresh-state and rheological parameters reported across reviewed studies for SCC containing various SCMs. A consistent pattern emerges: FA enhances or maintains slump flow through its ball-bearing effect, while SF and VMA reduce slump flow by increasing yield stress and viscosity. At SF contents up to approximately 10 to 15%, SCC can still meet EFNARC requirements when superplasticizer dosage is appropriately adjusted. Beyond 15 to 20% SF by weight of cement, workability typically falls below the minimum 600 mm slump flow threshold without specialized admixture systems [2][4].

Table I: Summary of Fresh-State Properties of SCC with Various SCMs

Reference	SCM Type & Dosage	Slump Flow (mm)	V-Funnel (s)	W/B Ratio	Key Observation
Leung et al. [1]	FA: 0-50%; FA+SF: 25-40%	Min 650 (all mixes)	Not reported	0.38	FA reduces sorptivity; FA+SF synergy superior
Lu et al. [2]	SF: 2-16%	740 (control) to 405 (16% SF)	9 to 17 s	0.35	SF >12% reduces slump markedly
Benaicha et al. [4]	SF: 5-30%; VMA: 0.05-0.30%	68 (control) to 58 (SF30)	11 to 28 s	0.37	SF10 and VMA0.10 give equivalent rheology
Bahmani & Mostofinejad [7]	Slag + CaO or LW: 550-700 kg/m³	630 to 718	6 to 17 s	0.31	CAS-700 achieves best workability
Grdic et al. [8]	RCA: 0-100%	725-735	5.4 to 6.0 s	0.41-0.45	RCA-SCC meets all EFNARC criteria

B. Mechanical Performance: Synthesis

Table II presents a comparative summary of 28-day compressive strength across reviewed studies. The data reveal that silica fume consistently enhances compressive strength relative to OPC control mixes when used at dosages of 5 to 15%, primarily through pozzolanic C-S-H production and pore refinement. Fly ash at dosages above 20% tends to reduce 28-day compressive strength, reflecting the slow pozzolanic reactivity of FA and its lower activity index compared to SF. However, ternary FA-SF blends achieve strength values exceeding the OPC control, demonstrating the compensatory effect of SF's rapid pozzolanic activity.

Table II: Compressive Strength Summary for SCC with Various SCMs

Reference	Mix Type	Control Strength (MPa)	Max. Achieved (MPa)	Optimal Mix
Leung et al. [1]	FA; FA+SF	57.68	74.55	25% FA + 10% SF
Benaicha et al. [4]	SF; VMA	50.8	82.9 (SF30)	SF30 (rheology non-compliant)
Barbhuiya et al. [3]	FA + Lime; FA + SF	~38 (50% FA)	~50 (50% FA + 5% SF)	FA+SF at 50% replacement
Bahmani & Mostofinejad [7]	CaO-activated slag	N/A (cementless)	54.3	SCC-CAS-700
Grdic et al. [8]	RCA 0-100%	49.46	49.46 (control)	Natural aggregate control

C. Durability Performance: Synthesis

Across all reviewed studies, incorporation of SF in SCC consistently reduced porosity, sorptivity, and water absorption through microstructural densification. The combination of FA and SF in ternary blends produced the best durability outcomes, with sorptivity reductions exceeding 60% relative to OPC control mixes. The lack of a universal correlation between 28-day compressive strength and sorptivity, as reported by Leung et al. [1] and Kanellopoulos et al. [12], has important practical implications: engineers should not rely exclusively on compressive strength as a proxy for durability in SCC with complex SCM compositions. Longer-term strength measurements (56-day or 90-day) provide better indicators of pozzolanic activity and microstructural development, particularly in FA-rich mixes.

Recycled aggregate SCC exhibited slightly higher water absorption (by 0.15 to 0.37 percentage points) but maintained excellent waterproofness under hydraulic pressure testing, suggesting that the self-sealing characteristics inherent to SCC microstructure compensate for RCA's higher inherent porosity. This finding supports the engineering viability of RCA-SCC for structural applications provided that mix design adjustments, particularly water content calibration, are implemented to account for RCA's absorption characteristics.

D. Environmental Sustainability

The environmental assessment by Bahmani and Mostofinejad [7] using life cycle assessment methodology quantifies the carbon benefits of industrial by-product utilization in SCC. The SCC-LAS-550 mix achieved emissions of 178.6 kg CO_2 eq/m³, compared to approximately 250 to 350 kg CO_2 eq/m³ for conventional Portland cement SCC. This 30 to 50% reduction in carbon footprint is achieved without compromising fresh-state workability or reaching structural-grade compressive strengths, demonstrating the feasibility of high-performance sustainable SCC.

Vashistha et al. [5] reviewed lime sludge valorization in construction materials and demonstrated that 10 to 30% cement replacement by lime sludge is achievable with acceptable mechanical performance, while also diverting significant quantities of industrial waste from landfill disposal. The use of industrial by-products as supplementary or activating materials in SCC thus serves the dual purpose of waste valorization and carbon footprint reduction, aligning with circular economy principles in construction.

V. CONCLUSION

This review has synthesized experimental evidence from eight primary studies and supporting literature to provide a comprehensive assessment of SCM effects on SCC performance. The following key conclusions are drawn:

- Fly ash at dosages up to 30% improves workability through the ball-bearing effect and reduces sorptivity through pore-filling, but generally reduces 28-day compressive strength compared to OPC controls. Its slow pozzolanic reactivity means that 28-day strength is not fully representative of long-term performance.
- Silica fume at dosages of 5 to 15% substantially enhances compressive strength, reduces sorptivity, and densifies the microstructure through rapid pozzolanic C-S-H formation and micro-pore filling. It increases yield stress and reduces slump flow, necessitating admixture optimization.
- Ternary FA-SF blends achieve superior performance compared to binary systems, with optimal combinations (approximately 25% FA and 10% SF) achieving sorptivity reductions exceeding 60% and compressive strengths surpassing OPC control mixes.
- No universal correlation exists between 28-day compressive strength and sorptivity in SCC with variable SCM content; durability assessment requires independent measurement of transport properties.
- Cementless SCC utilizing calcium oxide-activated GGBFS achieves compressive strengths up to 54.3 MPa with full EFNARC workability compliance, while lime waste-activated formulations reduce carbon footprint to as low as 178.6 kg CO_2 eq/m³.
- Recycled coarse aggregate can be successfully incorporated into SCC with compressive strength reductions of less than 9% at 100% RCA substitution, provided that water content is calibrated for RCA's higher absorption.
- Future research should prioritize multi-objective optimization combining fresh-state, mechanical, durability, and environmental performance metrics; long-term durability studies under aggressive environmental exposure; standardization of testing protocols for cementless SCC; and field-scale validation of industrial by-product-based SCC formulations.

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