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A Comprehensive Review on Sustainable Self-Compacting Concrete Utilizing Industrial and Agricultural Wastes

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Abstract-

The increasing global concern over natural resource depletion and industrial waste accumulation has driven extensive research into sustainable concrete production. Self-compacting concrete (SCC), owing to its superior flowability, workability, and durability, offers significant potential for integrating industrial and agricultural by-products as supplementary cementitious materials (SCMs) and aggregate substitutes. This review synthesizes findings from five key studies examining the performance of SCC incorporating ferrochrome slag (FS) as a fine aggregate replacement, rice husk ash (RHA) as a cement substitute, limestone powder (LP), unground rice husk ash (URHA), metakaolin (MK), and nano silica (NS) as supplementary materials. The review covers fresh-stage properties, mechanical strength, durability characteristics, microstructural behavior, environmental implications, and statistical validation methods. Results consistently indicate that FS can replace natural fine aggregate up to 40% without significant compromise in structural performance, while RHA incorporated at 10-15% enhances compressive and tensile strength. Combined use of LP and URHA in slag-cement SCC further improved strength efficiency and reduced shrinkage. Functional ANOVA analysis confirmed no statistically significant difference in compressive and split tensile strength when sand is partially replaced with FS. Environmental assessments reveal reduced carbon footprint, embodied energy, and cost savings when waste materials are incorporated.

Keywords: Self-compacting concrete; Ferrochrome slag; Rice husk ash; Supplementary cementitious materials; Limestone powder; Durability; Sustainability; Functional ANOVA; Microstructure

I.INTRODUCTION

The global construction industry is a major consumer of natural resources, with concrete being the second most used material after water. The production of ordinary Portland cement (OPC) contributes about 7–8% of global CO_2 emissions, releasing nearly one tonne of CO_2 per tonne of cement [Sandhu & Siddique, 2021]. Rapid urbanization is increasing demand for materials, depleting natural resources like river sand and limestone, while generating large volumes of industrial and agricultural waste.

Self-compacting concrete (SCC), developed in Japan in the late 1980s, flows and consolidates under its own weight without vibration, making it suitable for complex and densely reinforced structures [George et al., 2024]. Its enhanced workability is achieved through optimized mix design using supplementary cementitious materials, superplasticizers, and viscosity modifiers, though it is generally more expensive than conventional concrete.

Industrial by-products like ferrochrome slag (FS) and agricultural waste such as rice husk ash (RHA) offer sustainable alternatives. FS, generated during ferrochrome production (14.4 million tonnes globally in 2020), produces about 1.2 tonnes of waste per tonne of alloy and poses environmental risks due to chromium content. Its use in concrete reduces landfill burden and natural aggregate demand. RHA, obtained from controlled burning of rice husk, contains over 87–88% silica and acts as a pozzolanic material, improving strength and durability by forming additional CSH gel [Das et al., 2021; Sandhu & Siddique, 2021].

Other materials like limestone powder (LP), metakaolin (MK), nano silica (NS), ground granulated blast furnace slag (GGBFS), and fly ash are also used in SCC to enhance performance. Their combined use in ternary or quaternary systems shows synergistic benefits [Tran et al., 2024; Nagarajan & Vijayan, 2023].

This review analyses five studies on: (1) FS as fine aggregate in fly ash-based SCC with ANOVA; (2) ternary binders with MK and NS incorporating FS; (3) LP and unground RHA in slag-cement SCC; (4) combined FS and RHA in conventional concrete; and (5) RHA in SCC. It evaluates fresh properties, mechanical performance, durability, microstructure, environmental impact, and statistical validation for sustainable SCC.

II.LITERATURE REVIEW

a. Ferrochrome Slag in Concrete

Ferrochrome slag (FS), a byproduct of ferrochromium production via carbothermic reduction of chromite ore, contains aluminum (37.3%), chromium (19.3%), sodium (14.4%), and silicon (12.9%) [George et al., 2024]. XRD analysis identifies forsterite and spinel as dominant phases with trace trigonal chromium, contributing to high specific gravity (2.7–2.91) and better mechanical properties than natural sand. Panda et al. [2013] confirmed FS can be safely used as aggregate with proper leaching checks, while Dash and Patro [2018] reported 2–15% reduction in 28-day strength at 10–50% replacement, recommending 30% as optimum. Ali et al. [2021] highlighted comparable or superior chemical resistance and similar particle morphology to natural sand. Nagarajan and

Vijayan [2023] used a ternary binder (10% MK, 1% NS) with FS (10–100%), where 40% replacement (FS4) gave 3.18% higher 28-day strength, improved UPV, dense CSH, stronger ITZ, and reduced Portlandite (CH-3.92%). Environmental concerns of chromium leaching were addressed through NEN 7375 tests, showing chromium release below the 2.0 mg/L limit over 64 days, with spinel phases stabilizing chromium [George et al., 2024].

b. Rice Husk Ash in SCC

Rice husk ash (RHA), containing 87–90% SiO_2, has porous and angular particles that enhance reactivity. It reacts with calcium hydroxide during hydration to form additional CSH gel, improving strength and durability [Sandhu & Siddique, 2021]. Sandhu and Siddique [2021] studied 0–30% RHA in SCC with fly ash, finding maximum strength at 10% replacement (7.2% increase at 28 days) and acceptable performance up to 15%. RCPT values significantly improved, with RHA30 reducing charge passed by 67.86–72.04%, and sulphate resistance increased due to reduced portlandite. Das et al. [2021] evaluated FS (0–20%) with RHA (0–20%) in conventional concrete, where 10% FS and 10% RHA (F10R10) performed best, showing lower early strength but 6.40% higher 28-day strength than target. UPV and rebound tests indicated RHA had a greater influence, with both materials enhancing later-age strength through pozzolanic action.

c. Limestone Powder and URHA in Slag-Cement SCC

Limestone powder (LP) acts as an inert filler, improving particle packing, accelerating hydration, and reducing shrinkage [Tran et al., 2024]. Tran et al. [2024] studied LP (10–50%) replacing slag and URHA (10–50%) replacing fine aggregate in slag-cement SCC. The optimum LP content was 30%, achieving 61.2 MPa compressive strength (26.93% higher than reference), 21.2% lower water absorption, and 15.7% reduced shrinkage. Strength efficiency (SE) increased by 39.51% for slag-cement and 18.58% for PCB at 28 days. Combining URHA (10–30%) with LP further enhanced early strength and SE. RCPT at 180 days showed very low chloride permeability, with LP30–RHA10 giving the best resistance (15.47% reduction).

d. Workability and Fresh Properties

All studies report reduced workability with FS, RHA, and LP. George et al. [2024] observed that FS-based SCC satisfied EFNARC limits for slump flow, V-funnel, J-ring, and L-box tests, though values decreased with higher FS due to angular texture and higher specific gravity; slump flow reduced from 690 mm to 651 mm (still SF2 class). RHA also lowered workability due to finer particles and higher surface area, requiring more water or admixture, though mixes remained within SF2 range (680–750 mm) [Sandhu & Siddique, 2021]. Nagarajan and Vijayan [2023] reported slump reduction from 100 mm to 45 mm with increasing FS, with the optimum mix (FS4) at 80 mm, indicating the need for mix adjustments at higher replacement levels.

III.RESEARCH METHODOLOGY

a. Materials and Mix Design

The reviewed studies followed similar material characterization approaches. Ordinary Portland Cement (OPC 53 grade, India) and Portland blended cement (PCB, Vietnam) were used as primary binders with specific gravity of 3.11–3.15. Supplementary materials included fly ash (2.07–2.26), GGBFS (2.86), metakaolin (2.6), nano silica (2.2), limestone powder (2.68), and RHA (1.28–2.47). Ferrochrome slag (2.7–2.91) was widely used as a fine aggregate replacement.

Mix design procedures followed IS 10262:2019 and TCVN 7570:2006 for target grades M25–M40. FS replacement ranged from 10–100%, with 40% generally optimal, while RHA replacement varied from 5–30%, with 10–15% giving the best performance. Water–binder ratios were kept constant (0.3–0.48) within each study. Material characterization included XRF for chemical composition, XRD for mineral phases, and standard tests (IS 2386, ASTM C642, BS EN 933-9) for physical properties. SEM-EDX was used for microstructural analysis of hardened concrete.

b. Testing Methods

Fresh properties were assessed using slump flow, T500, V-funnel, J-ring, L-box, and U-box tests as per EFNARC guidelines to evaluate filling ability, passing ability, and segregation resistance. Hardened properties included compressive strength (IS 516, ASTM C39), split tensile strength (IS 5816, ASTM C496), and flexural strength (IS 516).

Durability tests covered water absorption (BS 1881: Part 122, ASTM C642), sorptivity (ASTM C1585), RCPT (ASTM C1202), abrasion resistance (ASTM C779), UPV (IS 13311), rebound hammer, and sulphate resistance (ASTM C1012). Additional evaluations included elevated temperature exposure (200°C and 400°C), wet/dry cycles, and alkaline immersion. Environmental analysis involved chromium leaching (NEN 7375), comparison with Indian limits, and embodied energy estimation. Cost analysis used local rates, while statistical methods such as functional ANOVA (F-ANOVA) and multiple linear regression (MLR) assessed the influence of material replacement.

c. Functional ANOVA Framework

George et al. (2024) applied functional ANOVA (F-ANOVA), an advanced extension of traditional ANOVA, to evaluate the effect of ferrochrome slag (FS) replacement on strength–time behaviour. Unlike discrete analysis, this method examines continuous variation in response with changing replacement levels. The total response was divided into contributions from individual factors and an error term, and significance was assessed by comparing full and reduced models based on residual variation at a 5% significance level. P-value curves plotted against replacement percentages helped identify critical points where effects became significant. This approach provided deeper insights than conventional ANOVA, especially in determining threshold levels of FS influencing performance.

IV.RESULTS AND DISCUSSION

a. Fresh Properties

Fresh property results across the reviewed studies demonstrate a consistent pattern of workability reduction with increasing waste material incorporation, although all optimized mixes maintained acceptable SCC classifications. George et al. [2024] reported slump flow values decreasing from 690 mm (control) to 653 mm at 40% FS replacement, with V-funnel time increasing from 6.01 to 8.16 seconds. The L-box ratio decreased from 0.99 to 0.91 at 40% FS, all within EFNARC-specified ranges. The workability reduction was attributed to the higher specific gravity, rough angular texture, and increased water demand of FS particles.

Sandhu and Siddique [2021] documented that RHA incorporation reduced slump flow from 750 mm (0% RHA) to 680 mm (30% RHA), with T500 time increasing from 2.3 to 5.7 seconds. Despite these reductions, all mixes maintained SF2 slump flow classification with no visible segregation or bleeding. The viscosity increase with RHA was attributed to its higher Blaine fineness (698 m2/kg versus 305 m2/kg for cement) and porous particle structure that absorbs water from the mix, increasing paste viscosity. Nagarajan and Vijayan [2023] observed that slump values decreased from 100 mm (reference) to 80 mm at 40% FS and 45 mm at 100% FS, with the porous nature of FS confirmed as the primary cause.

LP incorporation in slag-cement SCC by Tran et al. [2024] showed increased viscosity (higher T50 time) with LP content, while passing ability improved as indicated by higher PL values. The addition of URHA at 10-50% further increased viscosity but slightly decreased passing ability due to the high surface area and porous structure of URHA particles. All SCC mixtures maintained satisfactory flowing, passing, and filling capacity as per TCVN 12209:2018 requirements.

b. Mechanical Strength Properties

Compressive strength results present a nuanced picture across the reviewed studies. In the FS-blended SCC by George et al. [2024], all mixes achieved or exceeded the M25 target strength, with marginal strength increments observed up to 40% FS replacement due to enhanced particle packing and pozzolanic activity of reactive silica and alumina in FS. Beyond 40%, strength decreased due to reduced bonding and poor particle packing at higher replacement levels. F-ANOVA analysis confirmed no statistically significant difference in compressive strength across all FS replacement levels (p-values consistently above 0.05), validating FS as a sustainable alternative to M-Sand without compressive strength compromise.

The ternary binder system by Nagarajan and Vijayan [2023] achieved superior compressive strength results, with FS4 (40% FS) attaining 57.77 N/mm2 at 28 days (3.18% higher than reference at 55.93 N/mm2). This improvement was attributed to the synergistic effect of NMCM (metakaolin and nano silica) forming additional CSH and CASH phases while FS particles provided improved interlocking and denser ITZ. Long-term strength gains were pronounced, with FS4 reaching 64.38 N/mm2 at 365 days, reflecting the ongoing pozzolanic activity of MK and NS with Mg in FS.

For RHA-based SCC, Sandhu and Siddique [2021] recorded maximum 28-day compressive strength at 10% RHA (63.37 MPa, 7.2% higher than control at 59.16 MPa). The enhanced strength resulted from CSH gel formation through pozzolanic reaction, increased paste volume, and improved particle packing. Strength declined progressively beyond 15% RHA as excess unreacted silica and water deficit from RHA's high surface area impaired hydration. Splitting tensile strength followed similar trends, with F-ANOVA confirming no statistical difference in this property across FS replacement levels, while flexural strength showed statistically significant increases beyond 5% FS replacement due to improved particle interlocking.

Das et al. [2021] found that 10% FSFA with 10% RHA (F10R10) provided the best performance among combined waste mixes, with 28-day CS only 5.34% lower than the reference while 6.40% above the target strength for M30 grade. Strength improvement at 56 and 90 days confirmed the beneficial late-age pozzolanic activity of RHA in FS concrete, with strength reduction rates decreasing significantly in later curing periods.

c. Durability Properties

Durability assessment results demonstrate that waste material incorporation generally maintains or improves concrete's long-term performance. Water absorption in FS-incorporated SCC showed slight increases compared to control mixes (4.73% to 5.02% at 40% FS replacement), attributable to the porous microstructural form and larger surface area to volume ratio of FS compared to M-sand [George et al., 2024]. Similarly, FS10 (100% FS) by Nagarajan and Vijayan [2023] showed the highest water absorption (4.43% at 7 days), while FS4 (40% FS) demonstrated moderate increases over the reference (2.32% versus 1.608% at 7 days), reflecting the trade-off between interlocking benefits and porosity increase.

RCPT results across studies indicate generally acceptable chloride permeability. George et al. [2024] reported both control and FS40 mixes falling within the moderate permeability range (2000-4000 Coulombs) at 2930 and 3033 Coulombs respectively, attributed to microcracks at the aggregate-paste interface with FS inclusion. In contrast, the ternary binder system by Nagarajan and Vijayan [2023] achieved very low chloride penetration (880-820 Coulombs for reference and declining with age), with NMCM forming dense microstructure that resisted ionic transport. RHA incorporation by Sandhu and Siddique [2021] progressively reduced RCPT values from moderate (RHA0 at 28 days) to very low (all replacement levels at 365 days), confirming superior long-term chloride resistance.

Sulphate attack resistance showed notable improvements with RHA incorporation. Sandhu and Siddique [2021] observed no cracking or mass loss in sulphate-immersed specimens across all RHA levels, with initial strength increases (4-8%) at 28-day exposure attributable to reduced porosity limiting sulphate ingress. George et al. [2024] reported 30.8% strength loss in control SCC versus 34% in FS40 after sulphate exposure, indicating slightly greater susceptibility of FS concrete due to higher water absorption and permeable void volume.

Abrasion resistance showed significant improvement with FS incorporation, as the hard chromium constituent of FS enhanced surface hardness. FS40 displayed superior abrasion resistance over control SCC, confirmed by lower abrasion percentage values [George et al., 2024]. Elevated temperature exposure tests revealed that FS-incorporated SCC outperformed control mixes at 200°C and 400°C, attributed to aluminum silicate formation at high temperatures and beneficial Cr2O3 and MgO content enabling uniform heat distribution.

Drying shrinkage in LP-modified SCC by Tran et al. [2024] showed average reductions of 15.7% with LP at 10-50% replacement, due to reduced water content in LP-modified mixes and decreased paste volume. URHA incorporation at 10% with LP30 further reduced drying shrinkage through internal curing effects. The UPV of FS4 exceeded the reference concrete (5.26 km/s versus 4.5 km/s at 28 days), reflecting excellent structural density, while further increases to 6.4 km/s at 365 days confirmed continued microstructure densification.

d. Microstructural Analysis

SEM-EDX analysis across the reviewed studies provided direct evidence of the microstructural mechanisms underlying the observed macromechanical properties. George et al. [2024] noted that FS40 samples revealed more voids, pores, and microstructural cracks compared to the control, yet the carbo-aluminate phase development and denser overall matrix contributed to marginal mechanical property improvements. EDX patterns confirmed significant magnesium and trace chromium in FS-incorporated concrete, with higher aluminum concentrations forming additional carbo-aluminate phases beneficial for elevated temperature performance.

Nagarajan and Vijayan [2023] provided detailed ITZ transformation analysis through high-magnification SEM (up to 1-5 µm). The reference concrete (RC) showed an amalgamated ITZ with both high-density CSH [CSH(H)] and low-density CSH [CSH(L)], while FS4 displayed a rigidified ITZ with predominant CSH(H) formation, confirming superior structural integrity. FS10 (100% FS) showed a 'spider nest' structure indicating MSH and brucite formation from FS's high Mg content, explaining the strength degradation at complete FS replacement. TG/DTG analysis confirmed minimal Portlandite content in FS4 (CH-3.92% versus 3.97% for reference), verifying efficient pozzolanic consumption by NMCM.

Sandhu and Siddique [2021] documented progressive microstructural densification with RHA content and curing age. RHA0 at 28 days showed calcium hydroxide plated structures and CSH fibrous gel with visible pores. RHA10 at 28 days displayed a dense, compact microstructure with calcium aluminium silicate hydrates and refined pore structure, explaining its superior compressive strength. RHA30 showed larger porosity and voids compared to RHA10, consistent with reduced strength at higher replacement levels. At 365 days, all mixes demonstrated significantly denser microstructures, confirming ongoing pozzolanic activity of RHA at later ages.

e. Environmental and Economic Assessment

The environmental and economic benefits of incorporating waste materials in SCC are substantial across all reviewed studies. Sandhu and Siddique [2021] quantified cost savings of up to 18.34% at 30% RHA replacement, with the optimal 10% RHA mix achieving 6.11% cost reduction. Embodied energy analysis using published coefficients revealed dramatic reductions, with RHA having a negative embodied energy coefficient (-26 MJ/kg, reflecting energy produced during rice husk combustion). Total embodied energy decreased from 2894 MJ (control) to -1834 MJ (30% RHA), representing a transformation from energy-consuming to energy-producing concrete production.

George et al. [2024] reported that FS incorporation in SCC simultaneously achieves waste reduction, resource conservation, CO2 emission reduction through partial cement replacement with fly ash, and potential cost savings through reduced demand for natural sand. The chromium leaching test results confirmed total Cr release well below the 2.0 mg/L Indian discharge standard throughout the 64-day monitoring period, demonstrating environmental safety for structural applications. The forsterite and spinal phases in FS were confirmed to immobilize residual chromium, further enhancing environmental compatibility.

Tran et al. [2024] demonstrated that higher SE values from LP and URHA incorporation represent reduced binder cost per unit compressive strength achieved, translating to concrete productions with lower material costs and environmental footprint. The combined use of URHA (agricultural waste requiring no grinding or processing) with LP (abundant industrial by-product) creates a dual-waste utilization strategy particularly suitable for developing economies seeking low-cost sustainable construction solutions.

f. Statistical Validation

Statistical analysis methods employed across the reviewed studies provide robust validation frameworks for the experimental findings. George et al. [2024] applied functional ANOVA to assess the significance of FS replacement on mechanical properties expressed as continuous functions. The F-ANOVA p-value plots for compressive strength and split tensile strength remained consistently above 0.05 across all replacement levels, confirming no statistically significant difference from the control. In contrast, flexural strength showed statistically significant increases beyond approximately 5% FS replacement (p-values dropping below 0.05), attributed to improved particle interlocking enhancing bending stress resistance.

Sandhu and Siddique (2021) formulated Multiple Linear Regression (MLR) models to estimate compressive strength, split tensile strength, rapid chloride permeability (RCPT), and sorptivity as functions of curing time and rice husk ash (RHA) content. The models demonstrated high reliability, with correlation coefficients between 0.86 and 0.97. Results showed that compressive strength improves with longer curing periods but tends to decrease as RHA replacement increases, while RCPT values decline with both increasing age and RHA content, indicating enhanced durability. All regression parameters were statistically significant at the 5% level, highlighting the important influence of curing age and RHA percentage on concrete performance.

V.CONCLUSIONS

This review compiles results from five studies on sustainable SCC using ferrochrome slag, rice husk ash, limestone powder, metakaolin, nano silica, and unground rice husk ash. The main conclusions are: Ferrochrome slag can replace natural fine aggregate up to 40% without significant reduction in compressive or split tensile strength, as confirmed by functional ANOVA, while workability remains within EFNARC limits up to 60% replacement. Rice husk ash at 10–15% cement replacement improves compressive and tensile strength at 28 days and later due to additional CSH formation, with continuous enhancement in durability properties such as RCPT, water absorption, sorptivity, and sulphate resistance. Ternary binder systems with metakaolin (10%) and nano silica (1%) combined with ferrochrome slag achieve higher strength (3.18% increase at 40% FS) and improved durability, supported by dense ITZ and low Portlandite content from SEM and TG/DTG analysis. Limestone powder at 30% slag replacement yields maximum compressive strength (61.2 MPa) and enhances water absorption, shrinkage, UPV, and chloride resistance, with strength efficiency improving up to 39.51%, indicating economic and environmental benefits. Chromium leaching from FS-based SCC remains below permissible limits, with spinel phases effectively stabilizing residual chromium, ensuring environmental safety. Cost analysis shows 6–18% savings with RHA, while embodied energy is significantly reduced, with high RHA content potentially resulting in net-negative energy due to energy recovery from husk combustion. Functional ANOVA and multiple linear regression provide reliable tools for evaluating material effects, identifying optimal replacement levels, and developing predictive design models. Overall, the findings support wider use of ferrochrome slag, rice husk ash, and other supplementary materials in SCC. Future work should address long-term field performance, higher replacement levels with optimization, lifecycle assessment, and development of performance-based standards for waste-based SCC.

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