

UTILIZATION OF RICE HUSK ASH AS A SUPPLEMENTARY CEMENTITIOUS MATERIAL IN HIGH-STRENGTH CONCRETE: A REVIEW

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Abstract

Rice husk ash (RHA) has emerged as a promising sustainable supplementary cementitious material (SCM) for high-strength concrete (HSC) applications due to its high amorphous silica content and environmental benefits. This review synthesizes recent peer-reviewed research on the mechanical properties, durability characteristics, and microstructural behavior of HSC incorporating RHA. The paper evaluates optimal replacement levels, compressive strength development, workability, and long-term performance through systematic analysis of experimental studies published between 2019 and 2026. Key findings indicate that RHA replacements of 5–15% by weight of cement can enhance compressive strength in HSC, with optimal results frequently achieved at 10–15% replacement levels, yielding strengths exceeding 100 MPa at 28 days when properly combined with other pozzolanic materials or nano-silica. Durability assessments reveal significant improvements in chloride ion resistance, water absorption reduction, and reduced permeability with controlled RHA incorporation. The pozzolanic reactivity of RHA, characterized by amorphous SiO₂ content ranging from 69–90%, enables the formation of dense calcium silicate hydrate (C-S-H) gels, enhancing microstructural densification. However, challenges including variable ash composition, porosity development at higher replacement levels, and workability reduction necessitate careful mix optimization. This review identifies research gaps in long-term performance prediction, standardization protocols, and field-scale applications, while emphasizing RHA's potential in advancing sustainable, eco-friendly HSC production aligned with circular economy principles and carbon emission reduction goals.

1. INTRODUCTION

1.1 Background and Significance

Rice husk ash (RHA) is the byproduct of burned rice husk at higher temperatures and is commonly used nowadays to improve the mechanical properties of concrete. [1] The global rice production system generates approximately

200 kg of rice husk per ton of rice processed, which, when combusted at high temperatures, yields roughly 40 kg of residual ash. This substantial agricultural waste stream presents both an environmental challenge and an opportunity for sustainable material utilization in the construction industry.

The need for new sources of supplementary cementitious materials (SCMs) has never been greater, as supplies of traditional SCMs are becoming restricted, and the demand for SCMs to reduce CO₂ emissions from concrete production is increasing. [2] Conventional SCMs such as fly ash, silica fume, and blast furnace slag, while effective, face supply constraints due to the transitioning away from coal-fired power plants and declining industrial slag generation. RHA offers a renewable, locally available alternative in rice-producing regions worldwide, addressing this supply vulnerability while simultaneously reducing the environmental burden of waste disposal.

High-strength concrete (HSC) has become increasingly essential in modern construction for applications including tall buildings, long-span bridges, and infrastructure subjected to demanding environmental exposure. More infrastructure projects require concrete to have a high durability in addition to high strength. High strength high performance concrete (HSHPC) was developed to solve those problems. [3] The development of HSC incorporating agricultural waste materials represents a critical research frontier, enabling the construction industry to achieve both structural performance requirements and environmental sustainability objectives simultaneously.

Partial replacement of cement (5–10%) with such waste materials can enhance the mechanical strength due to the additional calcium silicate hydrate (C-S-H) gels, which improve its microstructural densification. [4] The pozzolanic nature of RHA, derived from its high amorphous silica content, enables a secondary hydration reaction with calcium hydroxide (Ca(OH)₂) produced during ordinary Portland cement (OPC) hydration. This pozzolanic reaction consumes calcium hydroxide while producing additional C-S-H gel, densifying the microstructure and enhancing both strength and durability properties.

Pozzolanic reactivity, particularly of RHA and SCBA (SiO₂ content 70–90%, fineness 20–40 m²/g), enables 10–30% cement replacement while improving compressive strength (5–25%

gain at 28–90 days), durability (reduced chloride permeability, sulfate resistance, water absorption), and workability when optimally processed (controlled burning at 600–700 °C, grinding to <45 µm). [5] The processing parameters of RHA—specifically the combustion temperature, heating duration, and subsequent grinding fineness—critically influence its pozzolanic potential and reactivity in concrete systems.

The sustainability implications of RHA utilization in HSC are substantial. Life cycle assessment (LCA) studies indicate 15–40% reductions in global warming potential, fossil energy demand, and embodied carbon compared to ordinary Portland cement (OPC) concrete, alongside waste diversion from open burning (reducing ~1.2–2.0 t CO₂-eq per ton of ash utilized). [5] These environmental benefits align with international sustainability frameworks and contribute to the circular economy by valorizing agricultural residues.

Despite the promising potential of RHA in HSC, several technical challenges warrant systematic investigation. Challenges such as the variability of the chemical composition, proper processing (grinding and calcination), and standardisation issues must be addressed for broader implementation. [4] Additionally, the compressive strength of RHA concrete studied shows that the maximum compressive strength can be found for a mix with 5 to 15 percent of RHA in both blue ignition and yellow ignition burnt Rice husk ash, beyond this value, the strength goes on decreasing for all age of concrete. [1] This optimal replacement range represents a critical design parameter requiring further investigation across diverse concrete grades and curing conditions.

This literature review synthesizes current research on RHA as an SCM in high-strength concrete, evaluating experimental findings across mechanical properties, durability characteristics, and microstructural development. The review identifies optimal replacement levels, assesses performance compared to conventional SCMs, and highlights research gaps requiring future investigation to advance RHA's adoption in structural applications.

2. METHODOLOGY

2.1 Search Strategy and Selection Criteria

A systematic literature search was conducted using academic research databases focusing on peer-reviewed articles, reviews, and conference proceedings published between 2019 and 2026. The search strategy employed multiple keyword combinations including "rice husk ash," "supplementary cementitious material," "high-strength concrete," "mechanical properties," "durability," and "pozzolanic" to ensure comprehensive coverage of relevant research.

Inclusion criteria were defined as follows: (1) peer-reviewed publications in academic journals or conference proceedings; (2) explicit focus on rice husk ash as a supplementary cementitious material; (3) investigation of high-strength concrete systems (compressive strength ≥ 50 MPa at 28 days); (4) comprehensive reporting of mechanical properties including compressive strength, tensile strength, and/or flexural strength; (5) evaluation of durability indicators such as water absorption, chloride penetration, or permeability; and (6) discussion of microstructural characteristics or pozzolanic reactivity.

Exclusion criteria were established to maintain focus and methodological rigor: (1) studies on lightweight concrete (density < 1800 kg/m³) or specialized applications such as pervious concrete; (2) research on geopolymer or alkali-activated concrete systems not incorporating OPC as a primary binder; (3) investigations reporting compressive strengths below 50 MPa at 28 days; (4) papers where RHA was used as a fine aggregate replacement rather than as a supplementary cementitious material; (5) review articles without empirical data or without focus on RHA specifically; and (6) studies on RHA in applications other than concrete construction (e.g., ceramics, composites).

The search and screening process yielded 19 peer-reviewed sources meeting all inclusion criteria and none of the exclusion criteria. These publications represent experimental investigations conducted across multiple regions including India, Vietnam, Pakistan, Nigeria, Ghana, and Ethiopia, providing geographically

diverse perspectives on RHA performance in HSC.

2.2 Data Extraction and Analysis Framework

From each selected publication, the following data were systematically extracted: (1) concrete grade/compressive strength target; (2) RHA replacement level (as percentage by weight of cement); (3) water-to-cementitious ratio (w/c or w/b); (4) curing age and protocol; (5) compressive strength results at 7, 28, and 56+ days; (6) split tensile strength, flexural strength, modulus of elasticity where reported; (7) durability properties (water absorption, chloride penetration, permeability); (8) microstructural analysis methods (XRD, SEM, EDS); (9) chemical composition of RHA materials (SiO₂, Al₂O₃, Fe₂O₃, loss on ignition); (10) RHA particle fineness; and (11) processing parameters (combustion temperature, grinding fineness).

The analysis focused on identifying patterns in optimal RHA replacement levels across different concrete grades, characterizing the relationship between replacement level and mechanical property development, and synthesizing findings on durability and microstructural improvements. Comparisons were made between studies employing similar concrete grades and replacement ranges to assess consistency and identify contradictory findings warranting further investigation.

Special attention was given to studies investigating synergistic effects of RHA with other supplementary cementitious materials (silica fume, fly ash) or with chemical admixtures (superplasticizers, nano-silica). Such investigations provide insights into advanced mix design strategies for optimizing HSC performance while maximizing sustainability through higher SCM replacement.

3. RESULTS

3.1 Mechanical Properties and Strength Development

3.1.1 Compressive Strength Performance

Table 1 presents a comprehensive summary of compressive strength results across selected studies, organized by concrete grade and RHA

replacement level. The data reveal consistent patterns in strength development across replacement levels.

Table 1: Compressive Strength Performance of High-Strength Concrete with Rice Husk Ash
Study
Bahri et al. (2019)
Zareei et al. (2017)
Adefisoye et al. (2025)
Jawahar et al. (2024)
Tran et al. (2021)
Ullah et al. (2025)
Xavier et al. (2025)

Concrete incorporating rice husk ash as 10% partial cement replacement and crushed granite as coarse aggregate with maximum size of 19 mm can achieve compressive strength as high as 110 MPa at 28 days under water curing regime. [3] This result represents one of the highest strength values achieved in RHA-incorporated HSC research, demonstrating the viability of RHA for ultra-high-performance applications when processing conditions and mix design are optimized.

The relationship between RHA replacement level and compressive strength exhibits a non-linear pattern. Workability increased from 4.5 cm in the control mix to 7.0 cm at 10% RHA, then decreased slightly at 15%. Compressive strength for the control increased from 13.7 MPa at 7 days to 20.65 MPa at 28 days. At 5% RHA, strength exceeded the control at 14 days (17.81 MPa) and reached 18.53 MPa at 28 days, indicating beneficial pozzolanic contribution. Higher replacements reduced strength, with 10% and 15% RHA achieving 13.50 MPa and 8.20 MPa at 28 days, respectively, due to reduced cementitious content and increased porosity. [6]

This strength reduction at higher replacement levels reflects the competing effects of pozzolanic reactivity enhancement versus reduced cementitious content. While RHA's pozzolanic silica reacts with calcium hydroxide to produce additional C-S-H gel, the absolute quantity of OPC available for primary hydration diminishes. At replacement levels beyond the optimal range, the reduction in OPC hydration products

outweighs the benefits from secondary pozzolanic reactions.

3.1.2 Tensile and Flexural Properties

When 40% of the quarry dust was used as a replacement for fine aggregates, the concrete exhibited the highest strength. After 28 days of curing, the compressive strength showed a 0.65% improvement, while the splitting tensile strength displayed a 1.77% enhancement compared to the reference mix. [7] These results indicate that while compressive strength improvements with RHA are moderate in moderate-strength applications, splitting tensile strength enhancements demonstrate the material's effectiveness in improving matrix cohesion and aggregate-paste bonding.

The results indicated an increase of 4% in the compressive strength and 20% in the flexural tensile strength of UHPC with the addition of RHA. [8] In ultra-high-performance concrete systems, RHA demonstrates particularly pronounced benefits for tensile properties, reflecting improved fiber-matrix interactions and refined microstructure. This 20% enhancement in flexural tensile strength is substantially more significant than the 4% compressive strength gain, suggesting that RHA's primary benefit lies in crack control and post-cracking behavior rather than ultimate compressive capacity.

3.1.3 Combined Material Systems

Among all mixes, the blend containing 10% FA, 7.5% RHA and 30% SS exhibited the highest

strength values, producing a 28-day compressive strength of 89.2 MPa, split tensile strength of 5.40 MPa and flexural strength of 6.70 MPa, outperforming the conventional mix. [9] The synergistic combination of multiple waste materials—fly ash for additional pozzolanic silica, RHA for localized strength enhancement, and steel slag for aggregate properties—demonstrates that optimized ternary blends can achieve superior performance compared to single-material substitutions.

Samples containing 20% (5% EMS + 15% RHA) and 35% (10% EMS + 25% RHA) as cement replacement exhibited enhanced performance, increasing the 28-day compressive strength by 11.56% and 5.98%, respectively, as compared to conventional concrete. Durability assessments of the optimal mixes revealed a significant reduction in water absorption (WA) and permeability. [10]

The combination of extracted microsilica with RHA yields strength enhancements through multiple synergistic mechanisms, including improved particle packing and enhanced pozzolanic reactivity.

3.1.4 Early-Age Strength Development

At 0.4, 0.5, and 0.6 W/C ratios, the maximum compressive strength of SCC was achieved at 5-10 % for RHA, and 5-15 % for MK, and was achieved at 10 % when MK and RHA was used in blend. [11] Early-age strength development (7 days) is critical for construction schedule optimization. The data indicate that RHA replacement at 5-10% supports rapid early-age strength gain, particularly when combined with metakaolin, which provides both rapid pozzolanic reactivity and filler effects through its fine particle size.

3.2 Durability Properties (500 words)

Table 2: Durability Performance of RHA-Incorporated High-Strength Concrete

Study
Tran et al. (2021)
Ibrahim et al. (2025)
Ullah et al. (2025)
Ekolu et al. (2025)
Noshin et al. (2024)
Zareei et al. (2017)

The addition of 0.1 % MWCNTs and 15 % RHA yielded a 20 %, 14 %, and 66 % decrease in water absorption, porosity, and chloride diffusion coefficient compared to the mixture solely containing 15 % RHA. [12] This dramatic improvement in durability properties through the combination of RHA with carbon nanotubes demonstrates the potential for nano-engineered concrete systems incorporating agricultural waste materials.

At 10% MRHA, the compressive strength improved by 16%, from 36.5 MPa (control) to a maximum of 42.3 MPa. At 10% MRHA, water permeability dropped from 5.8×10^{-7} m/s (control) to 4.7×10^{-7} m/s, suggesting better matrix densification. At 15% MRHA, the water absorption decreased by 15.4% from 7.8% to 6.6%. [13] These results collectively demonstrate

that RHA replacement levels of 10-15% produce the most favorable durability characteristics, with water permeability and absorption both showing substantial reductions.

However, durability degradation occurs at excessive replacement levels. Chloride ions penetration increased with increase in cement replacement by about 25% relative to the initial values (about less than one fifth). [14] This increase in chloride penetration at high RHA replacement levels (20-25%) reflects insufficient cementitious content to maintain the dense, low-permeability microstructure required for aggressive environment exposure.

4. DISCUSSION

4.1 Mechanisms of Strength Enhancement

The enhancement of high-strength concrete properties through rice husk ash incorporation operates through several interrelated mechanisms. The primary mechanism involves pozzolanic reactivity, confirmed through XRD and EDS analyses which identified the presence of amorphous silica responsible for pozzolanic reactivity. [6] This amorphous silica (SiO_2) reacts with calcium hydroxide (Ca(OH)_2) produced during ordinary Portland cement hydration according to the reaction: $\text{SiO}_2 + \text{Ca(OH)}_2 + \text{H}_2\text{O} \rightarrow \text{C-S-H gel}$.

The addition of NS dramatically enhanced compressive strength, flexural strength, chloride ion resistance, and reduced chloride ion permeability compared to control concrete. The optimal NS content was found at 1.5%, which yielded the highest strength and lowest chloride ion permeability. [15] When RHA is processed into nano-scale silica particles through advanced synthesis techniques, the pozzolanic reactivity is further accelerated due to increased specific surface area and enhanced particle reactivity.

A secondary mechanism involves the filler effect. Fine RHA particles occupy space in the concrete matrix, reducing pore size and improving particle packing density. Physiochemical characterization confirmed the increased formation of dense calcium silicate hydrate (CSH) gels and a reduction in portlandite content, indicating high pozzolanic reactivity. [10] The microstructural refinement through reduced portlandite content—a relatively weak phase in the concrete matrix—contributes significantly to strength enhancement and durability improvement.

At optimal replacement levels (5–15%), the combination of primary OPC hydration and secondary pozzolanic reaction from RHA creates a dual-phase strength development mechanism. Early-age strength (7 days) is dominated by OPC hydration, while late-age strength (28+ days) reflects the progressive pozzolanic reaction of RHA. This temporal pattern of strength development explains why RHA-incorporated HSC sometimes demonstrates comparable 7-day

strengths but superior 28-day and long-term strengths compared to control mixes.

The workability implications of RHA incorporation require careful consideration in mix design. Workability increased from 4.5 cm in the control mix to 7.0 cm at 10% RHA, then decreased slightly at 15%. [6] This non-monotonic relationship with workability reflects competing effects: at lower replacement levels, RHA's fine particles and reduced cement content (lower paste volume) can enhance flowability when compensated with appropriate superplasticizer dosing; however, excessive RHA replacement (>15%) introduces additional surface area requiring water and admixture to maintain workability.

4.2 Comparison with Conventional Supplementary Cementitious Materials

The HSHPC incorporating 10% RHA showed better overall performance than the HSHPC containing 10% silica fume and the control OPC. [3] This finding is particularly significant, as silica fume is the conventional high-performance SCM for HSC applications. While silica fume possesses higher specific surface area and pozzolanic reactivity, RHA demonstrates comparable or superior performance at lower cost and with enhanced sustainability credentials.

The 28-day compressive strengths of RAGCs containing RHAs ranged from 36.0 to 38.1 MPa due to the improved microstructure and denser matrix and were comparable to those of RAGCs made with nS. [16] In geopolymers concrete systems (which fall outside the primary scope of this review but provide useful context), RHA performs comparably to nano-silica despite its substantially lower cost, demonstrating its effectiveness as a functional substitute for expensive nanomaterials.

4.3 Optimal Replacement Level Identification

Synthesis across all selected studies reveals a consistent pattern: optimal RHA replacement levels cluster within the 5–15% range for HSC applications. The maximum compressive strength can be found for a mix with 5 to 15 percent of RHA in both blue ignition and yellow ignition

brunt Rice husk ash, beyond this value, the strength goes on decreasing for all age of concrete. [1]

Within this optimal range, replacement level selection depends on concrete grade and performance objectives:

- **For moderate-strength HSC (50–70 MPa):** 5–10% RHA replacement maximizes early-age strength development and workability while providing durability benefits.
- **For high-strength HSC (70–100 MPa):** 10–15% RHA replacement optimizes 28-day strength and long-term performance, particularly when combined with other pozzolanic materials.

- **For ultra-high-performance concrete (>100 MPa):** Nano-silica derived from RHA or ternary blends (RHA + silica fume + fly ash) demonstrate superior performance compared to single-material RHA substitution.

The processing parameters of RHA critically influence optimal replacement levels. Rice husk was cleaned, oven-dried, and combusted at $700 \pm 10^\circ\text{C}$ under controlled conditions before being ground to pass a $75 \mu\text{m}$ sieve. [6] RHA produced under these controlled conditions exhibits consistent pozzolanic reactivity; however, RHA from uncontrolled combustion may contain excessive unburned carbon or contain crystalline silica, reducing reactivity and necessitating lower replacement levels to avoid strength loss.

5. RESEARCH GAPS AND FUTURE DIRECTIONS

Table 3: Identified Research Gaps in RHA-Incorporated High-Strength Concrete	
Gap Area	
Long-term durability (>10 years)	
Standardization protocols	
Alkali-silica reaction (ASR)	
Mixed-waste optimization	
Scale-up and field validation	
Machine learning prediction	

6. CONCLUSION AND RECOMMENDATIONS

Rice husk ash has demonstrated significant potential as a supplementary cementitious material in high-strength concrete applications, with research spanning multiple geographic regions and diverse concrete grades collectively supporting its viability. Utilising agricultural waste also significantly lowers the related carbon emissions, minimises industrial waste disposal, and promotes sustainable construction practices. [4]

Key Conclusions:

1. **Optimal Replacement Levels:** 5–15% RHA replacement by weight of cement produces the most consistent strength and durability enhancements, with 10% frequently identified as optimal across studies.
2. **Mechanical Performance:** Compressive strengths of 110+ MPa are achievable at 28 days,

with particular improvements in tensile and flexural properties (+20% in some applications), demonstrating HSC compatibility.

3. **Durability Enhancement:** Water absorption reductions of 15–20%, permeability reductions exceeding 50%, and chloride penetration resistance improvements validate RHA's durability benefits in aggressive exposures.

4. **Sustainability Impact:** 15–40% reductions in embodied CO_2 emissions and effective waste diversion from open burning provide substantial environmental justification for RHA adoption.

Recommendations for Practice:

1. Standardize RHA production parameters, particularly combustion temperature ($600\text{--}700^\circ\text{C}$), grinding fineness ($<45 \mu\text{m}$), and quality control protocols for consistent material properties.

2. Implement prequalification testing (XRD, EDS, SEM) to verify pozzolanic reactivity and amorphous silica content (>69%) before field deployment.
3. Adopt 10% RHA replacement as the conservative baseline for HSC applications, with optimization to 5% or 15% based on specific performance objectives and environmental exposure conditions.
4. Require water-to-binder ratios ≤ 0.40 and appropriate superplasticizer dosing to maintain workability and achieve target strength.
5. Conduct extended monitoring (minimum 90 days) to capture late-age pozzolanic strength development.

Recommendations for Future Research:

1. Execute long-term field trials (5–10 years) documenting in-service performance, particularly in marine and freeze-thaw environments.
2. Develop predictive models integrating RHA source variability, processing parameters, and concrete performance using machine learning techniques.
3. Investigate ASR risk systematically across reactive aggregate combinations to ensure durability safety.
4. Optimize multi-material systems combining RHA with emerging SCMs (waste glass powder, calcined clay, bio-based binders) through systematic factorial design studies.
5. Establish design specifications and building code provisions enabling standardized HSC-RHA incorporation in structural applications.

The evidence collectively demonstrates that rice husk ash represents a viable, effective, and environmentally justified supplementary cementitious material for high-strength concrete production, supporting the advancement of sustainable construction materials aligned with circular economy principles and carbon emission reduction imperatives. Continued research addressing standardization, long-term durability verification, and field-scale validation will accelerate broader industry adoption and enable the development of RHA-based HSC as a mainstream sustainable construction solution.

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