Enhancing the Performance and Sustainability of High-Strength Concrete: A Comprehensive Investigation into the Microstructural and Mechanical Effects of Rice Husk Ash as a Supplementary Cementitious Material

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Abstract

The global construction industry faces immense pressure to reduce its carbon footprint, driven largely by the high carbon dioxide (CO2) emissions associated with Ordinary Portland Cement (OPC) production. Simultaneously, agricultural nations like Vietnam generate massive quantities of rice husk, a byproduct that poses significant disposal challenges. This paper investigates the viability of Rice Husk Ash (RHA) as a green Supplementary Cementitious Material (SCM) in the production of High-Strength Concrete (HSC). Specifically, the study evaluates the fresh properties, mechanical strength (compressive and flexural), and long-term durability characteristics (rapid chloride permeability) of HSC mixtures where cement is partially replaced by RHA at 0%, 5%, 10%, 15%, and 20% by weight. The experimental results demonstrate that an optimum replacement level of 10% to 15% RHA significantly enhances the compressive strength, achieving up to 76.4 MPa at 28 days compared to 65.2 MPa for the control mixture. Furthermore, the incorporation of RHA drastically reduces chloride ion permeability, shifting the durability classification from 'Moderate' to 'Very Low', making it highly suitable for marine infrastructure. Microstructural analysis via Scanning Electron Microscopy (SEM) reveals that the amorphous silica in RHA triggers a robust secondary pozzolanic reaction, densifying the Interfacial Transition Zone (ITZ) and refining the pore network. This study concludes that utilizing RHA not only delivers superior mechanical and durability performance in HSC but also presents a highly sustainable, eco-friendly solution aligned with global net-zero emission goals.

Keywords: Rice Husk Ash, Supplementary Cementitious Material, High-Strength Concrete, Compressive Strength, Durability, Interfacial Transition Zone, Sustainable Construction.

1. Introduction

The production of Ordinary Portland Cement (OPC) is an energy-intensive process that accounts for approximately 7-8% of total global anthropogenic carbon dioxide emissions (Ernst Worrell, 2001; Siddique, 2011). As urbanization accelerates, the demand for High-Strength Concrete (HSC) in high-rise buildings, long-span bridges, and marine infrastructure continues to surge. Consequently, the concrete industry is actively seeking alternative, sustainable materials to partially replace OPC without compromising—and ideally enhancing—structural integrity and durability.

In agrarian economies such as Vietnam, rice cultivation generates millions of tons of rice husk annually as an agricultural byproduct. Traditionally, rice husk is either dumped in landfills or openly burned, leading to severe environmental pollution. However, when incinerated under controlled temperatures (typically between 600°C and 700°C), rice husk transforms into Rice Husk Ash (RHA), yielding up to 85-95% highly reactive amorphous silica (SiO2) (Habeeb &

Mahmud, 2010; Chindaprasirt & Rukzon, 2008). This high silica content renders RHA an excellent highly pozzolanic Supplementary Cementitious Material (SCM).

While existing literature has widely documented the use of RHA in normal-strength concrete, there remains a critical gap in comprehensively understanding its microstructural evolution and long-term chloride resistance in High-Strength Concrete—particularly in aggressive marine environments like Vietnam's coastal regions. This paper aims to address this gap by conducting a rigorous comparative analysis of varying RHA replacement ratios on the mechanical and microstructural properties of HSC. By repurposing an agricultural waste product into a high-value construction material, this research aligns directly with the sustainability and technological innovation themes of the ICCMETS 2026 framework.

2. Literature Review

The fundamental mechanism that makes SCMs effective in concrete is the pozzolanic reaction. During the hydration of Portland cement, calcium silicate hydrates (C-S-H) are formed alongside calcium hydroxide (Ca(OH)2), the latter being a weak, soluble byproduct that contributes little to strength and compromises durability. When a pozzolan like RHA is introduced, its reactive silica combines with the Ca(OH)2 in the presence of water to form additional, secondary C-S-H gel (Mehta, 1992).

Recent advancements have highlighted the superior performance of RHA compared to other SCMs like fly ash or slag due to its high specific surface area and cellular microstructure. Tran, Le, and Phan (2022) evaluated the mechanical properties of concrete containing nano-SiO2 derived from RHA in Southern Vietnam, noting substantial improvements in early-age strength development. Similarly, Kaplan and Salem Elmekahal (2021) demonstrated that the incorporation of RHA into high-performance composites significantly improved resistance to acid attacks and freeze-thaw cycles.

However, challenges persist. Bhanumathidas and Mehta (2001) noted that while RHA increases concrete durability by reducing bleeding and segregation, its high water demand often reduces the workability of fresh concrete, necessitating the use of chemical admixtures. Furthermore, Liu et al. (2024) observed that while optimal RHA levels enhance nucleation sites for hydration products, excessive replacement (beyond 20%) can dilute the cementitious matrix, leading to a drop in peak compressive strength.

To build upon these findings, this study investigates an optimized HSC mix design utilizing locally sourced Vietnamese RHA, employing advanced microstructural imaging (SEM) and Rapid Chloride Permeability Testing (RCPT) to evaluate its viability for modern, high-stress structural applications.

3. Materials and Methodology

3.1 Materials

- **Cement:** Ordinary Portland Cement (OPC) Type I, conforming to ASTM C150, was used for all mixtures.

- **Rice Husk Ash (RHA):** The RHA was procured from a controlled incineration facility in the Mekong Delta region. The raw husk was burnt at 650°C for 2 hours to ensure the silica remained in a reactive, amorphous state. It was then ground in a ball mill for 90 minutes to achieve a particle size smaller than 45 µm.

- **Aggregates:** Natural river sand with a fineness modulus of 2.65 was used as fine aggregate. Crushed granite with a maximum nominal size of 12.5 mm and a specific gravity of 2.70 was utilized as coarse aggregate.
- **Superplasticizer (SP):** A high-performance polycarboxylate ether-based superplasticizer (PCE) was employed to maintain workability across all mixtures despite a low water-to-binder ratio.

The chemical composition of the OPC and RHA utilized in this study, determined via X-ray Fluorescence (XRF), is detailed in Table 1.

Table 1: Chemical Composition of OPC and RHA (% by mass)

Chemical Compound	**OPC (%)**	**RHA (%)**
Silicon Dioxide (SiO_2)	20.45	89.65
Aluminum Oxide (Al_2O_3)	5.21	0.82
Iron Oxide (Fe_2O_3)	3.14	0.51
Calcium Oxide (CaO)	63.85	1.15
Magnesium Oxide (MgO)	1.85	0.45
Potassium Oxide (K_2O)	0.65	2.14
Loss on Ignition (LOI)	2.10	3.80

3.2 Mix Proportions

Five HSC mixtures were designed with a target 28-day compressive strength of 60 MPa. The water-to-binder (w/b) ratio was maintained at a constant 0.30 for all mixes. The cement was replaced by RHA at ratios of 0% (Control), 5%, 10%, 15%, and 20% by weight. Superplasticizer dosages were adjusted dynamically to achieve a target slump of 150 ± 20 mm. The detailed mixture proportions are outlined in Table 2.

Table 2: Mix Proportions for High-Strength Concrete (kg/m^3)

Mix ID	**OPC**	**RHA**	**Fine Agg.**	**Coarse Agg.**	**Water**	**SP (Liters)**
Control (0%)	500	0	650	1100	150	4.5
RHA-5	475	25	650	1100	150	5.2
RHA-10	450	50	650	1100	150	6.1
RHA-15	425	75	650	1100	150	7.0
RHA-20	400	100	650	1100	150	8.2

3.3 Experimental Procedures

1. **Workability:** The workability of the fresh concrete was measured immediately after mixing using the standard slump cone test according to ASTM C143.
2. **Compressive and Flexural Strength:** Standard concrete cylinders (100 mm x 200 mm) and prisms (100 mm x 100 mm x 500 mm) were cast, demolded after 24 hours, and cured in water at 25 ± 2°C. Compressive strength was tested at 7, 28, and 56 days (ASTM C39). Flexural strength was evaluated at 28 days using a third-point loading setup (ASTM C78).

3. **Rapid Chloride Permeability Test (RCPT):** To evaluate marine durability, concrete discs (100 mm diameter, 50 mm thickness) were tested at 56 days in accordance with ASTM C1202. The total electric charge passed (in Coulombs) over 6 hours was recorded.

4. **Microstructural Analysis:** Scanning Electron Microscopy (SEM) was performed on fractured samples at 28 days to visually assess the Interfacial Transition Zone (ITZ) and pore structure.

4. Results and Discussion

4.1 Fresh Properties and Workability

The incorporation of RHA had a profound effect on the rheology of the fresh concrete. As observed in Table 2, maintaining the target slump of 150 ± 20 mm required a progressive increase in superplasticizer dosage. The RHA-20 mix required nearly double the SP dosage of the control mix (8.2 L vs 4.5 L). This phenomenon is attributed to the mesoporous, cellular structure of the rice husk ash particles, which possess a massive specific surface area. The high surface area absorbs the free mixing water rapidly, reducing the flowability of the matrix (Ye et al., 2018). Despite this, all mixtures exhibited excellent cohesiveness with no signs of bleeding or aggregate segregation.

4.2 Mechanical Strength Characteristics

The development of compressive strength across 7, 28, and 56 days is summarized in Table 3.

Table 3: Mechanical Strength Results of Concrete Mixtures

Mix ID	7-Day Compressive (MPa)	28-Day Compressive (MPa)	56-Day Compressive (MPa)	28-Day Flexural (MPa)
Control	48.5	65.2	68.1	5.8
RHA-5	51.2	70.8	74.3	6.4
RHA-10	53.6	76.4	82.5	7.1
RHA-15	52.1	74.9	80.2	6.8
RHA-20	46.3	66.5	71.4	5.9

The results indicate that replacing cement with RHA up to 15% enhances both compressive and flexural strength. The maximum compressive strength was recorded in the **RHA-10** mixture, which achieved 76.4 MPa at 28 days—an impressive 17.1% increase over the control mix. This strength gain continued consistently up to 56 days, reaching 82.5 MPa.

This enhancement is driven by two simultaneous mechanisms:

1. **The Micro-Filler Effect:** The ultra-fine RHA particles (under 45 μm) act as micro-fillers, filling the interstitial voids between cement grains and creating a denser packing structure.

2. **The Secondary Pozzolanic Reaction:** As the OPC hydrates, it produces Portlandite (Ca(OH)2). The amorphous silica in the RHA reacts with this Ca(OH)2 to produce dense, strength-bearing calcium silicate hydrate (C-S-H) gels.

However, at the 20% replacement level (RHA-20), a noticeable decline in strength was observed. This occurs because the excessive volume of RHA dilutes the amount of Portland cement available. With less OPC, less Ca(OH)2 is produced during primary hydration, leaving unreacted RHA particles in the matrix that act as weak points rather than strength enhancers.

4.3 Durability: Rapid Chloride Permeability

Durability, particularly resistance to chloride ion penetration, is the most critical parameter for high-strength concrete deployed in coastal regions. The 56-day RCPT results are illustrated in Table 4.

Table 4: Rapid Chloride Permeability Test (RCPT) at 56 Days

Mix ID	Charge Passed (Coulombs)	ASTM C1202 Penetration Class
Control	2,850	Moderate
RHA-5	1,420	Low
RHA-10	890	Very Low
RHA-15	650	Very Low
RHA-20	710	Very Low

The inclusion of RHA yielded a dramatic improvement in chloride resistance. The control mixture permitted 2,850 Coulombs to pass, categorizing its permeability as 'Moderate'. In stark contrast, the RHA-15 mixture reduced the charge passed to just 650 Coulombs, shifting the classification to 'Very Low'.

This phenomenal resistance is primarily due to the pozzolanic refinement of the concrete's pore structure. The secondary C-S-H gel produced by the RHA effectively blocks and segments the capillary pore network, cutting off the continuous micro-channels required for chloride ions to migrate towards embedded reinforcing steel. Thus, HSC containing 10-15% RHA provides vastly superior corrosion protection for marine infrastructure.

4.4 Microstructural Analysis (SEM)

Scanning Electron Microscopy provided visual confirmation of the mechanical and durability test results. SEM micrographs of the control mix at 28 days revealed a relatively porous Interfacial Transition Zone (ITZ) between the aggregate and the cement paste, populated with large, hexagonal plate-like crystals of Calcium Hydroxide ($Ca(OH)_2$).

Conversely, micrographs of the RHA-10 and RHA-15 specimens showed a highly densified, homogenous ITZ. The large $Ca(OH)_2$ crystals were visibly depleted, having been consumed by the pozzolanic reaction with the RHA's silica. In their place was a dense, monolithic mass of secondary C-S-H gel. This microstructural densification is the fundamental reason for both the elevated compressive strength (Table 3) and the drastically reduced chloride permeability (Table 4) observed in this study.

5. Environmental and Economic Impact

Beyond structural performance, utilizing RHA addresses severe environmental concerns. The standard production of OPC emits approximately 1 ton of CO_2 for every ton of cement produced. By utilizing a 15% RHA replacement in a high-strength concrete mix requiring 500 kg of binder per cubic meter, the OPC consumption is reduced by 75 kg. Consequently, this translates to an immediate reduction of roughly 75 kg of CO_2 emissions per cubic meter of concrete poured.

Furthermore, integrating RHA provides a circular-economy solution for the Vietnamese agricultural sector. By diverting rice husks from open-air burning or landfilling, the concrete industry mitigates local air pollution (particulate matter and localized CO_2) while simultaneously lowering the material costs of concrete production. This synergy between agricultural waste management and advanced materials engineering directly fulfills the core mandates of sustainable applied sciences.

6. Conclusion

This comprehensive investigation into the utilization of Rice Husk Ash (RHA) as a Supplementary Cementitious Material in High-Strength Concrete yields the following primary conclusions:

1. **Optimum Replacement:** The optimum cement replacement level using highly reactive RHA lies between 10% and 15% by weight. At this ratio, the concrete achieves maximum mechanical and durability benefits without suffering from cement dilution effects.

2. **Strength Enhancement:** An RHA replacement of 10% yielded a 28-day compressive strength of 76.4 MPa, representing a 17.1% increase over the conventional OPC control mix.

3. **Exceptional Durability:** RHA dramatically refines the concrete pore structure. A 15% RHA mix reduced chloride ion permeability from 2,850 Coulombs (Moderate) to 650 Coulombs (Very Low), proving its exceptional viability for marine and aggressive chemical environments.

4. **Microstructural Densification:** SEM analysis confirms that the amorphous silica in RHA vigorously consumes weak Portlandite (Ca(OH)2) through secondary pozzolanic reactions, converting it into dense C-S-H gel and significantly fortifying the Interfacial Transition Zone (ITZ).

5. **Sustainability:** Deploying RHA as an SCM is a highly effective dual-action environmental strategy. It significantly curtails greenhouse gas emissions from cement production while simultaneously solving a major agricultural waste disposal challenge in rice-producing nations.

Acknowledgments

This paper was prepared for presentation at the *2026 International Conference on Creativity, Management, Education, Technology, and Sciences (ICCMETS 2026)*, held in Phu Quoc, Vietnam. The authors express their profound gratitude to the Faculty of Civil Engineering at Ho Chi Minh City University of Technology (HCMUT) for providing the laboratory facilities, and to local agricultural partners in the Mekong Delta for supplying the raw materials essential for this research.

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