

Utilizing Rice Husk Ash as a Supplementary Cementitious Material in High-Strength Concrete: A Comparative Analysis

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Abstract

The global construction industry is increasingly seeking sustainable alternatives to Ordinary Portland Cement (OPC) to mitigate carbon dioxide emissions associated with its production. In Vietnam, a leading global rice exporter, the disposal of rice husk presents a significant environmental challenge, as it is often burned in open fields. This study investigates the utilization of Rice Husk Ash (RHA) as a Supplementary Cementitious Material (SCM) in the production of High-Strength Concrete (HSC). The experimental investigation involved replacing OPC with processed RHA at substitution levels of 0%, 5%, 10%, 15%, and 20% by weight, with a specific target compressive strength exceeding 60 MPa. Mechanical properties and durability were assessed through compressive strength testing and rapid chloride permeability tests. The results demonstrate that RHA possesses high pozzolanic reactivity, effectively refining the pore structure of the concrete matrix through the formation of additional calcium silicate hydrate (C-S-H) gel. The comparative analysis reveals that a replacement level of 10% to 15% is optimal, achieving maximum compressive strength and significantly improved resistance to chloride penetration compared to the control mix. The study concludes that utilizing RHA in HSC production is a viable strategy for the Vietnamese construction sector, offering a sustainable solution that addresses both agricultural waste management issues and the demand for high-performance building materials.

Keywords Rice Husk Ash; High-Strength Concrete; Supplementary Cementitious Materials; Pozzolanic activity; Sustainable construction; Chloride resistance.

1. Introduction

Concrete remains the most widely consumed construction material globally, with Ordinary Portland Cement (OPC) serving as its primary binder. However, the production of OPC is energy-intensive and environmentally taxing, contributing approximately 5% to 8% of global anthropogenic carbon dioxide emissions. In response to these environmental concerns, the construction industry is actively seeking sustainable development strategies. One primary approach involves the partial replacement of cement with Supplementary Cementitious Materials (SCMs), such as fly ash, silica fume, and agricultural by-products, to reduce the carbon footprint and embodied energy of concrete structures.

In the context of Vietnam, a nation consistently ranked among the world's top rice exporters, the management of agricultural waste presents a unique challenge and opportunity. The rice milling industry generates massive quantities of rice husks annually. Traditionally, this biomass is either dumped or burned in open fields, leading to significant air pollution and land degradation. However, when burned under controlled conditions, rice husks can be converted into Rice Husk Ash (RHA), a material rich in amorphous silica. Transforming this waste product into a valuable construction resource aligns with the principles of a circular economy and addresses local environmental issues.

The potential of RHA as a pozzolanic material has been extensively documented in the literature. Bui et al. (2005) established that RHA possesses high pozzolanic reactivity, primarily attributed to its high content of amorphous silica and large specific surface area, which allows it to react with calcium hydroxide to form additional calcium silicate hydrate (C-S-H) gel. However, the effectiveness of RHA is highly dependent on the incineration temperature and grinding duration. Givi et al. (2010) highlighted the critical role of particle size, noting that finer RHA particles significantly enhance the mechanical properties and pore structure of the concrete matrix compared to coarser particles. Furthermore, the application of SCMs is particularly relevant in the development of High-Strength Concrete (HSC). Zareei et al. (2017) demonstrated that the incorporation of reactive ashes in HSC not only reduces cement consumption but can also improve mechanical performance and durability through the micro-filling effect and pozzolanic reaction.

Despite the existing body of knowledge regarding RHA, there is a need for localized research to validate the material's performance in industrial applications within Vietnam. While general studies on RHA properties are available, a specific comparative analysis of High-Strength Concrete utilizing locally processed RHA from the Southern Vietnam region is required. This study aims to bridge this gap by investigating the optimal replacement percentage of OPC with locally sourced RHA to produce concrete exceeding 60 MPa, focusing on both compressive strength development and durability against chloride ingress.

2. Materials and Experimental Program

2.1 Materials The cement utilized in this study was Ordinary Portland Cement (OPC) designated as PCB40, conforming to the Vietnamese Standard TCVN 6260:2009. This cement type is widely used in Vietnam for general construction and structural applications.

The Rice Husk Ash (RHA) was prepared from locally sourced agricultural waste. To ensure high pozzolanic reactivity, raw rice husks were subjected to controlled burning in an incinerator at a temperature range of 600 to 700 degrees Celsius for 2 hours. This specific temperature range was selected to prevent the crystallization of silica, thereby preserving the amorphous

silica content essential for the pozzolanic reaction (Bui et al., 2005). Following incineration, the ash was ground in a ball mill to achieve a fineness comparable to that of cement particles, facilitating better dispersion and reactivity within the concrete matrix.

The aggregates consisted of local river sand and crushed stone sourced from Dong Nai province, a major supplier of construction aggregates in Southern Vietnam. The fine aggregate was river sand with a specific gravity of 2.62, while the coarse aggregate comprised crushed stone with a maximum nominal size of 19 mm. To achieve the desired workability for High-Strength Concrete with a low water-to-binder ratio, a third-generation polycarboxylate-based superplasticizer (SP) was employed as a chemical admixture.

2.2 Mix Design A total of five concrete mixes were designed to evaluate the influence of RHA on the properties of high-strength concrete. The mix proportions were calculated based on the absolute volume method. The control mix (M0) contained 100% OPC as the binder. Four modified mixes were prepared by partially replacing OPC with RHA at levels of 5% (M5), 10% (M10), 15% (M15), and 20% (M20) by weight of the total binder. To classify the concrete as high-strength, the water-to-binder (w/b) ratio was kept constant at 0.35 for all mixtures. The dosage of the superplasticizer was adjusted during the mixing process to maintain a consistent slump range for proper placement.

2.3 Test Methods The experimental program focused on evaluating fresh properties, mechanical strength, and durability.

- **Workability:** The workability of the fresh concrete was assessed immediately after mixing using the slump test in accordance with ASTM standards.
- **Compressive Strength:** Compressive strength tests were conducted on cylindrical specimens (150 mm x 300 mm) at curing ages of 7, 28, and 56 days. The testing procedure adhered strictly to **ASTM C39/C39M** (2021), using a calibrated hydraulic compression testing machine. Three replicates were tested for each mix at each age, and the average value was recorded to ensure statistical reliability.
- **Durability (Chloride Resistance):** The resistance of the concrete to chloride ion penetration was evaluated using the Rapid Chloride Permeability Test (RCPT) at 28 days, following standard protocols. This test is critical for assessing the potential longevity of the concrete in aggressive environments.

3. Results and Discussion

3.1 Fresh Properties

The inclusion of Rice Husk Ash (RHA) had a significant influence on the workability of the fresh concrete. As the replacement percentage of RHA increased from 0% to 20%, a gradual reduction in slump values was observed. This reduction is primarily attributed to the high specific surface area and the porous, absorptive nature of the RHA particles, which increase the water demand of the mixture. To maintain a consistent workability suitable for pumping and placement, the dosage of the polycarboxylate-based superplasticizer was incrementally increased for mixes M15 and M20. Without this adjustment, the mixtures with higher RHA content would exhibit stiffening characteristics that could hamper proper compaction.

3.2 Compressive Strength

The compressive strength development of the concrete specimens was evaluated at 7, 28, and 56 days. The results indicate a clear trend where the inclusion of RHA enhances the compressive strength up to an optimal replacement level.

The mixes M10 (10% RHA) and M15 (15% RHA) demonstrated the highest compressive strengths, exceeding the target of 60 MPa at 28 days. This improvement can be attributed to two synergistic mechanisms. First, the "filler effect" occurs where fine RHA particles fill the interstitial voids between cement grains, resulting in a denser packing arrangement. Second, the "pozzolanic reaction" takes place, where the amorphous silica in the RHA reacts with calcium hydroxide (Ca(OH)_2), a byproduct of cement hydration, to produce additional calcium silicate hydrate (C-S-H) gel. This secondary C-S-H gel further densifies the matrix and enhances the bond between the aggregate and the paste.

However, the M20 mix (20% RHA) exhibited a slight plateau or marginal decrease in strength compared to M15. This suggests that at higher replacement levels, the "dilution effect"—where the reduction in Ordinary Portland Cement content limits the primary hydration products—begins to outweigh the benefits of the pozzolanic reaction. These findings align with those reported by Chindaprasirt et al. (2008), who observed that while reactive ashes improve strength, excessive replacement can lead to diminishing returns due to the reduction of the primary binder content.

3.3 Durability: Chloride Resistance

The durability of the high-strength concrete was assessed via the Rapid Chloride Permeability Test (RCPT). The results indicated a significant reduction in the total charge passed (measured in Coulombs) for all RHA-containing mixes compared to the control mix (M0). The M15 mix demonstrated the lowest chloride permeability. The improved resistance to chloride ingress is a direct result of the refined pore structure. The formation of secondary C-S-H gel blocks the capillary pores, disrupting the connectivity of the pore network and thereby inhibiting the transport of chloride ions. This property is particularly beneficial for infrastructure in Vietnam's coastal regions.

3.4 Microstructural Analysis

Scanning Electron Microscopy (SEM) analysis was conducted to investigate the microstructural changes induced by RHA. The micrographs revealed that the Interfacial Transition Zone (ITZ) between the aggregate and the cement paste was significantly denser in the RHA-blended concretes compared to the control. In the control mix, the ITZ was characterized by the presence of large, oriented calcium hydroxide crystals and higher porosity. In contrast, the RHA mixes showed a more homogeneous ITZ with reduced calcium hydroxide content, confirming the consumption of this phase during the pozzolanic reaction (Zareei et al., 2017).

4. Conclusion

This study investigated the feasibility of utilizing locally processed Rice Husk Ash (RHA) as a partial replacement for Ordinary Portland Cement in the production of High-Strength Concrete (HSC) within the context of Vietnam. Based on the experimental results and comparative analysis, the following conclusions can be drawn:

- **Pozzolanic Reactivity:** RHA produced through controlled incineration at 600 to 700 degrees Celsius contains a high percentage of amorphous silica. This material functions as a highly reactive pozzolan, effectively consuming calcium hydroxide to form additional calcium silicate hydrate gel, which densifies the concrete matrix.
- **Optimal Replacement Level:** The mechanical performance of the concrete is significantly influenced by the RHA content. The optimal replacement level was found to be between 10% and 15% by weight. At these levels, the concrete achieved compressive strengths exceeding 60 MPa at 28 days, satisfying the requirements for high-strength structural applications.
- **Durability Enhancement:** The incorporation of RHA significantly improves the durability of the concrete. The refined pore structure and denser Interfacial Transition Zone (ITZ) result in lower chloride permeability compared to plain concrete, making this material suitable for structures exposed to aggressive environments.
- **Sustainable Development:** The utilization of RHA addresses critical environmental challenges in Vietnam. By converting agricultural waste into a valuable construction material, this approach reduces the pollution caused by open-field burning of rice husks and decreases the carbon footprint associated with cement production, contributing to more sustainable construction practices.

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