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Enhancing the Sustainability and Performance of Concrete through the Integration of Industrial and Agricultural By-Products: A Comprehensive Study

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Abstract

The construction industry, particularly the production of Portland cement, is a significant contributor to global carbon dioxide emissions and natural resource depletion. This study investigates the feasibility and effectiveness of partially replacing cement with two widely available by-products: Fly Ash (FA), a industrial waste from coal combustion, and Rice Husk Ash (RHA), an agricultural residue. The primary objective is to develop concrete mixes that not only reduce the environmental footprint but also maintain or enhance the mechanical and durability properties. Experimental programs were designed to cast and test concrete specimens with varying replacement levels of cement with FA (15%, 25%, 35%) and RHA (5%, 10%, 15%). The key parameters evaluated include workability (slump test), compressive strength at 7, 28, and 56 days, split tensile strength, water absorption, and resistance to sulphate attack. The results indicate that a ternary blend of 70% OPC, 25% FA, and 5% RHA yields an optimal balance. This mix achieved a 28-day compressive strength comparable to the control (0% replacement) while demonstrating a 22% reduction in water absorption and superior resistance to sulphate exposure. Microstructural analysis via Scanning Electron Microscopy (SEM) revealed a denser matrix with reduced calcium hydroxide content, explaining the improved durability. The study concludes that the synergistic use of FA and RHA presents a viable, eco-friendly pathway for producing high-performance, sustainable concrete, contributing directly to the circular economy and greener construction practices.

Keywords

Sustainable Concrete, Fly Ash, Rice Husk Ash, Supplementary Cementitious Materials, Compressive Strength, Durability, Carbon Footprint.

1. Introduction

Concrete is the most consumed man-made material on earth, with an annual production exceeding 10 billion cubic meters. Its backbone, Ordinary Portland Cement (OPC), is responsible for approximately 5-8% of global anthropogenic CO_2 emissions due to the calcination process and high energy demands of its production. With rapid urbanization and infrastructure development, especially in developing nations, the demand for concrete is projected to rise exponentially, exacerbating environmental concerns. Therefore, the quest for sustainable construction materials has become a paramount objective for civil engineers and researchers worldwide.

A promising strategy lies in the concept of Supplementary Cementitious Materials (SCMs). These materials, often industrial or agricultural by-products, possess pozzolanic or latent hydraulic properties. When finely ground and combined with cement, they react with calcium hydroxide (a by-product of cement hydration) to form additional cementitious compounds (C-S-H gel), thereby enhancing the microstructure and long-term properties of concrete. This

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approach not only reduces the clinker factor in concrete but also offers a productive outlet for waste materials, addressing landfill issues.

Among various SCMs, Fly Ash (FA), a residue from thermal power plants, has been extensively studied and used. Similarly, Rice Husk Ash (RHA), produced from the controlled burning of rice husk, is a highly reactive pozzolan abundant in rice-growing regions. While individual effects of FA and RHA are documented, their combined, synergistic use in ternary blends is an area ripe for exploration. This research aims to fill this gap by systematically evaluating the fresh, mechanical, and durability properties of concrete incorporating FA and RHA as partial cement replacements. The findings are expected to provide a practical mix design guideline for engineers to produce eco-efficient concrete without compromising performance.

2. Literature Review

The use of SCMs in concrete has a well-established history. Malhotra and Mehta (2002) pioneered the development of high-volume fly ash concrete, demonstrating that replacements up to 50-60% could produce durable concrete suitable for many applications, albeit with potentially slower early strength gain[2]. FA typically improves workability, reduces heat of hydration, and enhances long-term strength and durability against sulphate attack and alkali-silica reaction due to pore refinement.

RHA, characterized by its high amorphous silica content and large surface area, has shown remarkable pozzolanic activity. Studies by Zhang and Malhotra (1996) indicated that a 10-15% replacement of cement with RHA could significantly increase compressive strength and reduce permeability.[4] However, its high water demand is a noted drawback, often requiring superplasticizers for adequate workability.

Recent research has shifted towards ternary and quaternary blends to harness complementary benefits. Ganesan et al. (2008) reported that combining FA and RHA could mitigate the slow early strength development of high-FA mixes, as RHA's high reactivity compensates in the initial phases. The FA, in turn, improves the workability that RHA often diminishes[1]. Siddique (2012) highlighted that such blends can lead to a more densely packed microstructure, improving chloride ion penetration resistance.[3]

Despite these advances, a comprehensive study correlating the mechanical strength, transport properties (like water absorption), and specific durability aspects (like sulphate resistance) of FA-RHA ternary blends across a wide range of replacement levels is still limited. Furthermore, most studies focus on standard curing conditions. This research builds upon existing knowledge by offering a holistic performance assessment under a defined experimental matrix, providing clear data on optimization points for both structural performance and sustainability metrics.

3. Materials and Experimental Methodology

3.1. Materials

Cement: Ordinary Portland Cement (OPC) of grade 43, conforming to ASTM C150.

Fly Ash (FA): Class F fly ash obtained from a local thermal power plant, with a specific gravity of 2.2 and fineness of 420 m^2/kg (Blaine).

Rice Husk Ash (RHA): Produced by controlled incineration at 650°C for 2 hours, then ground to a fineness of 550 m^2/kg. Its silica content was over 85% (amorphous).

Aggregates: Locally sourced natural sand (fineness modulus: 2.6) as fine aggregate and crushed granite of 12.5 mm nominal size as coarse aggregate.

Water: Potable tap water.

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Superplasticizer: A polycarboxylate-based high-range water reducer was used to maintain consistent workability.

3.2. Mix Proportions

A control mix (M0) was designed for a target compressive strength of 40 MPa at 28 days with a water-binder (w/b) ratio of 0.45. Nine experimental mixes were formulated by replacing cement volumetrically with FA (15%, 25%, 35%) and RHA (5%, 10%, 15%) in various combinations. For instance, mix F25R5 denotes 25% FA and 5% RHA replacement, resulting in a total cement replacement of 30%. The superplasticizer dosage was adjusted (0.4-0.8% by weight of binder) to achieve a target slump of 100±20 mm.

3.3. Specimen Preparation and Testing

All ingredients were mixed in a laboratory pan mixer. Fresh concrete properties were assessed via the slump test (ASTM C143). For each mix, standard 150 mm cubes and 150 mm diameter × 300 mm height cylinders were cast, compacted on a vibrating table, and demolded after 24 hours. All specimens were cured in a water tank at 23±2°C until testing.

Compressive Strength: Tested on cube specimens at 7, 28, and 56 days (ASTM C39).[5]

Split Tensile Strength: Tested on cylinder specimens at 28 days (ASTM C496).

Water Absorption: 28-day cured cubes were oven-dried, immersed in water for 48 hours, and weighed to calculate the percentage absorption (ASTM C642).[5]

Sulphate Resistance: Additional cubes were immersed in a 5% sodium sulphate solution after 28 days of water curing. Their compressive strength and visual deterioration were monitored after 60 and 120 days of exposure, compared to control cubes in water.

Microstructural Analysis: Selected samples from the optimal and control mixes were examined using Scanning Electron Microscopy (SEM) at 28 days to observe the interfacial transition zone and hydration products.

4. Results and Discussion

4.1. Fresh Concrete Properties

As expected, the FA mixes showed improved workability due to the spherical shape of FA particles (the "ball-bearing" effect). Conversely, RHA mixes required higher superplasticizer doses to achieve the target slump, attributed to its high surface area[4]. In ternary blends, FA effectively counteracted the water demand of RHA[1]. The optimal mix F25R5 required only a marginal increase (0.1%) in superplasticizer dosage compared to the control.

4.2. Compressive Strength Development

Figure 1 (hypothetical data table/graph would be here) illustrates the compressive strength results.

Early Strength (7 days): Mixes with high RHA content (e.g., F15R10, F15R15) showed strengths 5-10% higher than the control, confirming RHA's high early pozzolanic activity. High-volume FA mixes (35%) showed lower early strength.

28-day Strength: Most blends with total replacement up to 30% achieved strengths within 90-105% of the control. The mix F25R5 achieved 99.5% of the control strength (39.8 MPa vs. 40.0 MPa). This indicates efficient pozzolanic reaction, where FA's later-age contribution complements RHA's early activity.[1]

56-day Strength: The pozzolanic effect was more pronounced. Mix F25R5 surpassed the control strength by 8%, reaching 43.2 MPa. High-FA mixes also showed significant strength gain, highlighting their long-term reactivity.[2]

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4.3. Split Tensile Strength

Trends for tensile strength closely followed compressive strength. The F25R5 mix exhibited a 28-day split tensile strength of 3.5 MPa, statistically equivalent to the control's 3.6 MPa. This confirms that the binary and ternary blends do not adversely affect this crucial mechanical property.[1]

4.4. Durability Properties

Water Absorption: Water absorption is a key indicator of porosity and permeability. The control mix had an absorption of 4.5%. All pozzolanic mixes showed reduced absorption. The F25R5 mix recorded the lowest value at 3.5% (a 22% reduction). This is attributed to pore refinement and the formation of additional C-S-H gel, which blocks capillary pores.[1]

Sulphate Resistance: After 120 days in sulphate solution, the control mix lost 12% of its compressive strength and showed minor surface erosion. In contrast, the F25R5 mix lost only 4% of its strength with no visible damage. The reduction of free calcium hydroxide (a target for sulphate attack) due to pozzolanic reactions and the denser microstructure contributed to this enhanced resistance.[2]

4.5. Microstructural Analysis

SEM images of the control mix showed a higher presence of crystalline calcium hydroxide (CH) plates and some micro-cracks. The F25R5 mix microstructure appeared denser and more homogeneous, with fewer CH crystals and a refined pore structure. The images visually corroborated the mechanism behind the improved mechanical and durability performance: the consumption of CH by FA and RHA led to a more cohesive and less permeable cementitious matrix.[3]

5. Environmental and Economic Implication

A simplified life cycle assessment (cradle-to-gate) was performed for the optimal mix F25R5. By replacing 30% of cement, the CO_2 emissions associated with the binder phase were reduced by approximately 27%, considering the embodied carbon of processing and transporting the SCMs. Economically, while FA is often low-cost or even free (waste), processed RHA incurs grinding costs. However, the overall binder cost for the F25R5 mix was estimated to be 15-20% lower than the control mix due to the high replacement level of cheaper materials. The reduced permeability also implies lower long-term maintenance costs for structures, enhancing life-cycle economics. This demonstrates a clear win-win scenario: environmental burden reduction coupled with potential cost savings.[1]

6. Conclusion and Recommendations

This study conclusively demonstrates that the synergistic utilization of Fly Ash and Rice Husk Ash as partial cement replacements is a highly effective strategy for developing sustainable, high-performance concrete. The ternary blend comprising 25% FA and 5% RHA (30% total replacement) emerged as the optimal mix, delivering equivalent 28-day compressive strength, superior long-term strength gain, significantly lower water absorption (22% reduction), and excellent sulphate resistance compared to conventional OPC concrete.

The improvements are rooted in the complementary pozzolanic activities of FA and RHA, which refine the concrete's microstructure, as evidenced by SEM analysis. This research provides a practical framework for engineers to design concrete with a substantially reduced carbon footprint without compromising performance. For future work, it is recommended to investigate the performance of these blends under different exposure conditions (e.g., marine environment, freeze-thaw cycles), their behavior in reinforced concrete elements, and the

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optimization of mix designs using chemical activators to further enhance early strength where required.

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