Tropical Environment, Biology, and Technology

Research Article
Volume 4(1), 2026, 1−10
https://doi.org/10.53623/tebt.v4i1.870

Sustainable Concrete Production through Partial Cement Replacement Using Fly Ash and Rice Husk Ash

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SUBMITTED: 27 October 2026; REVISED: 17 January 2026; ACCEPTED: 19 January 2026

ABSTRACT: This study explores the utilization of fly ash and rice husk ash as supplementary cementitious materials to partially replace ordinary Portland cement (OPC) in concrete production. The increasing environmental impact of cement manufacturing, particularly its contribution to carbon dioxide emissions, has driven the search for alternative materials that promote sustainability without compromising performance. Fly ash and rice husk ash, both industrial and agricultural by-products, possess pozzolanic properties that enhance the mechanical and durability characteristics of concrete when properly incorporated. This paper reviews their chemical composition, particle morphology, and the effects of replacement levels on compressive strength, workability, and long-term durability. Additionally, the study discusses challenges such as variability in ash quality, optimal replacement percentages, and curing conditions that influence performance outcomes. By integrating these waste materials into concrete, significant environmental and economic benefits can be achieved, including reduced landfill disposal, conservation of natural resources, and lower greenhouse gas emissions. The findings highlight the potential of fly ash and rice husk ash as sustainable cement substitutes, supporting the development of eco-friendly construction materials aligned with green building standards and circular economy principles. This research contributes to advancing sustainable practices in the construction industry and provides insights for future studies focused on optimizing mix design, performance enhancement, and large-scale application of alternative cementitious materials.

Keywords: Eco-efficient concrete; sustainable infrastructure; cement replacement materials; fly ash-based concrete

1. Introduction

Concrete is the most widely used construction material worldwide due to its versatility, durability, and cost-effectiveness. It forms the backbone of modern infrastructure, including buildings, bridges, roads, and dams, with annual global production estimated at over 14 billion cubic meters [1]. However, the sustainability of concrete production has come under increasing scrutiny because its primary binding component, Portland cement, has a significant environmental footprint. Cement production alone contributes approximately 7–8% of global carbon dioxide (CO_2) emissions, primarily due to the calcination of calcium carbonate (limestone) and the burning of fossil fuels during clinker production [2]. The process not only emits CO_2 from fuel combustion but also from the chemical decomposition of limestone into calcium oxide and CO_2. This high carbon intensity has raised growing concerns over the long-term sustainability of cement-intensive construction practices, especially in the context of global climate change mitigation targets.

Moreover, the increasing demand for concrete driven by rapid urbanization and large-scale infrastructure development is putting additional pressure on natural resources, particularly limestone, clay, and sand [3]. This situation necessitates the search for alternative, eco-friendly supplementary cementitious materials (SCMs) that can partially replace Portland cement while maintaining or enhancing the performance of concrete. SCMs are materials that exhibit pozzolanic or latent hydraulic properties and can contribute to the strength development of concrete when used in combination with Portland cement [4].

Among the most promising SCMs are fly ash (FA) and rice husk ash (RHA). Fly ash is a by-product of coal combustion in thermal power plants, whereas rice husk ash is derived from the controlled burning of rice husks, an abundant agricultural residue in many rice-producing countries. Both FA and RHA are rich in amorphous silicon dioxide (SiO_2), which contributes to pozzolanic activity, the chemical reaction between silica and calcium hydroxide ($Ca(OH)_2$) in the presence of water to form additional calcium silicate hydrate (C–S–H), the primary strength-giving phase in concrete [5]. This pozzolanic reaction not only refines the pore structure but also enhances the long-term strength and durability of concrete.

Numerous studies have documented the beneficial effects of using FA and RHA as partial cement replacements. For instance, Siddique [6] reported that FA improves workability, reduces the heat of hydration, and enhances long-term compressive strength. Similarly, Ganesan et al. [7] demonstrated that incorporating RHA improves the resistance of concrete to sulfate attack and chloride ion penetration. RHA has also been shown to reduce permeability and enhance the durability of high-performance concrete due to its high silica content and ultrafine particle size [8]. Furthermore, the use of these ashes contributes to waste minimization and reduces the environmental burden associated with their disposal in landfills or open dumping sites [9].

Despite these advantages, the widespread adoption of FA and RHA in the construction industry remains limited, especially in developing regions. The barriers include variability in material properties due to different sources and combustion conditions, lack of standardized quality guidelines, and concerns about reductions in early-age strength that may delay formwork removal and construction schedules [10]. Therefore, there is a pressing need to optimize the replacement levels of these ashes to achieve a balance between mechanical properties, durability, and sustainability. Investigating the performance of FA- and RHA-blended concrete could contribute significantly to sustainable construction practices by reducing cement consumption, minimizing industrial and agricultural waste disposal problems, and lowering greenhouse gas emissions [11].

Therefore, this study aims to evaluate the effect of partially replacing Portland cement with FA and RHA on the fresh and hardened properties of concrete. The specific objectives are: (i) to determine the optimal replacement level of FA and RHA that yields comparable or improved compressive strength compared to control concrete; (ii) to assess the influence of these ashes on workability and setting time; and (iii) to analyze the potential environmental and economic benefits of incorporating FA and RHA in concrete. The outcomes of this research are expected to provide practical insights into the utilization of industrial and agricultural by-products in concrete, thereby supporting the transition toward sustainable and green construction materials.

2. Materials and Methods

2.1. Materials.

Ordinary Portland cement (OPC) conforming to ASTM International C150 Type I specifications was used as the primary binder. Class F fly ash (FA) was sourced from a local coal-fired thermal power plant, while rice husk ash (RHA) was obtained by controlled burning of rice husks at 600 °C for 6 hours in a muffle furnace, followed by grinding in a ball mill to achieve a particle size passing through a 75 µm sieve [12]. The chemical compositions of OPC, FA, and RHA were determined using X-ray fluorescence (XRF) analysis to verify their compliance with the requirements for supplementary cementitious materials (SCMs) [13]. Natural river sand with a fineness modulus of 2.6 was used as fine aggregate, and crushed granite with a maximum size of 20 mm was used as coarse aggregate. Both aggregates conformed to ASTM International C33 specifications. Potable tap water was used for mixing and curing all specimens.

2.2. Mix proportions.

Concrete mixtures were prepared with 0%, 10%, 20%, and 30% replacement of cement (by weight) with either FA or RHA. A control mix (0% replacement) was prepared for comparison. The water-to-binder ratio (w/b) was kept constant at 0.50, and the target compressive strength was 30 MPa at 28 days. The mix design followed the American Concrete Institute (ACI) 211.1 method. The binder content, fine-to-coarse aggregate ratio, and total water content were adjusted to maintain consistent workability among all mixtures [14].

2.3. Fresh properties.

The workability of the fresh concrete was assessed using the slump cone test according to ASTM International C143. Three replicate tests were conducted per mixture, and average slump values were recorded. The initial and final setting times of the cement pastes containing various FA and RHA levels were measured using a Vicat apparatus according to ASTM International C191 [15]. These tests were conducted at a room temperature of 25 ± 2 °C and 60 ± 5% relative humidity.

2.4. Hardened properties.

Compressive strength was evaluated using 150 mm × 150 mm × 150 mm cube specimens tested at 7, 28, and 56 days in accordance with ASTM International C39. For each mix and age, three specimens were tested, and the average compressive strength was calculated [16]. The density and water absorption of hardened concrete were determined using ASTM International C642 procedures. After 28 days of water curing, three specimens from each mix were oven-dried, immersed in water, and weighed to calculate apparent density and water absorption [17].

2.5. Statistical analysis.

All experimental data were subjected to statistical analysis to determine the significance of the effects of FA and RHA on concrete properties. One-way analysis of variance (ANOVA) was performed using IBM SPSS Statistics (version 28.0) to assess differences among mix groups at a 95% confidence level ($p < 0.05$) [18]. Post-hoc Tukey's Honestly Significant Difference (HSD) tests were conducted to identify pairwise differences between groups. The compressive strength results were also analyzed using regression modeling to establish relationships between replacement level and strength development [19]. Coefficient of variation (CV) was computed to assess data variability within each group.

3. Results and Discussion

3.1. Workability and setting time.

The results reveal that workability increased slightly at 10–20% FA content, as reflected by higher slump values compared to the control mix (Table 1). This improvement is attributed to the spherical morphology and smooth surface texture of FA, which acts as micro ball bearings, reducing internal friction and enhancing the flowability of fresh concrete [20]. The presence of FA particles allows better packing and dispersion of cement grains, reducing the water demand for achieving a given consistency. This phenomenon contributes to the improved slump observed in FA-containing mixes, particularly at moderate replacement levels where the dilution effect does not yet significantly hinder paste cohesion. Conversely, RHA led to a reduction in slump values with increasing dosage, likely due to its angular particle shape and high specific surface area, which increases water demand and internal friction within the mix [21]. The porous structure of RHA absorbs part of the mixing water, reducing the effective water available for lubrication, thereby decreasing the slump. This negative effect became more pronounced at 30% RHA replacement, where the mix exhibited noticeably stiff consistency and required additional compaction effort during casting.

Regarding setting time, FA addition delayed the initial and final setting, with the final setting time increasing from 210 min in the control mix to 260 min at 30% FA content. This can be explained by the lower reactivity of FA, which slows the early hydration reactions and reduces the early availability of calcium hydroxide for pozzolanic reaction [22]. In contrast, RHA slightly accelerated the setting time, suggesting that its high amorphous silica content and finely divided particles promote early nucleation and growth of calcium silicate hydrate (C–S–H) [23]. However, excessive RHA may reduce the amount of free water available, which can shorten the setting time by accelerating the stiffening process [24]. These findings support prior evidence that the particle morphology and reactivity of supplementary cementitious materials (SCMs) strongly influence fresh properties and hydration kinetics [25].

Table 1. Slump and setting time of concrete mixes with partial FA and RHA replacement.

Mix ID	FA (%)	RHA (%)	Slump (mm)	Initial Setting Time (min)	Final Setting Time (min)
Control	0	0	75	120	210
FA10	10	0	82	130	225
FA20	20	0	85	145	240
FA30	30	0	70	165	260
RHA10	0	10	65	110	200
RHA20	0	20	50	105	190
RHA30	0	30	38	100	185

3.2. Compressive strength development.

The compressive strength results show that FA replacement up to 20% enhanced long-term strength (28 and 56 days), with the FA20 mix achieving 44.8 MPa at 56 days, about 14% higher than the control (Table 2). This improvement can be attributed to the pozzolanic reaction of FA, which consumes calcium hydroxide released during cement hydration and forms additional calcium silicate hydrate (C–S–H). The secondary C–S–H fills the pore spaces and refines the microstructure, leading to a denser and stronger cement matrix over time. However, the initial strength at 7 days was lower in FA mixes, which is expected since FA has low early reactivity and contributes mainly through pozzolanic activity that becomes significant only after sufficient calcium hydroxide has accumulated. This delay explains why the FA mixes lag behind the control mix at early ages but outperform it at later curing stages.

RHA showed a slight strength gain at 10% replacement, surpassing the control mix at all ages. This behavior is likely due to the highly reactive amorphous silica in RHA, which reacts rapidly with calcium hydroxide to form C–S–H even at early ages. Additionally, the fine particle size and high surface area of RHA provide a filler effect, improving particle packing and reducing voids, which further enhances strength development. However, higher RHA content (20–30%) led to reduced strength compared to the control. The reduction can be linked to the increased water demand caused by RHA's porous nature, which effectively lowers the water-to-cement ratio available for hydration. This condition may cause incomplete hydration of cement particles, resulting in weaker early and later age strength. The overall trend confirms that optimal replacement levels are critical to harnessing the benefits of FA and RHA, where moderate dosages promote synergistic pozzolanic reaction and microstructural densification, while excessive amounts hinder cement hydration.

Table 2. Compressive strength of concrete mixes at different curing ages.

Mix ID	FA (%)	RHA (%)	7-day (MPa)	28-day (MPa)	56-day (MPa)
Control	0	0	26.2	34.5	39.3
FA10	10	0	24.1	36.0	42.7
FA20	20	0	22.8	37.2	44.8
FA30	30	0	19.5	33.1	39.0
RHA10	0	10	27.0	35.8	40.6
RHA20	0	20	23.6	32.5	36.8
RHA30	0	30	20.3	29.0	32.1

3.3. Durability indicators.

Concrete incorporating 10–20% FA showed lower water absorption and porosity than the control, indicating improved pore refinement and microstructure densification due to the secondary C–S–H formed by the pozzolanic reaction (Table 3). The FA20 mix had the lowest absorption (4.0%), which also correlated with its highest compressive strength at 56 days. This reduction in water absorption suggests that FA particles effectively fill voids and capillary pores within the cement matrix, thereby reducing permeability. The spherical shape and fine size of FA enhance the packing density of the paste, while the pozzolanic reaction gradually consumes calcium hydroxide to produce additional C–S–H that blocks pore connectivity. These combined effects contribute to a denser, less permeable microstructure, which directly enhances the durability of the concrete by limiting the ingress of water and potentially harmful agents such as chlorides and sulfates.

Table 3. Water absorption and porosity of concrete mixes.

Mix ID	FA (%)	RHA (%)	Water Absorption (%)	Apparent Porosity (%)
Control	0	0	5.2	14.6
FA10	10	0	4.3	12.7
FA20	20	0	4.0	12.0
FA30	30	0	5.0	14.0
RHA10	0	10	4.5	13.1
RHA20	0	20	5.5	15.4
RHA30	0	30	6.2	17.0

RHA at 10% also lowered water absorption and porosity compared to the control, demonstrating its potential to improve durability at low replacement levels. This can be attributed to its high amorphous silica content, which reacts quickly to form C–S–H, and its filler effect, which helps refine the pore structure. However, when the RHA content increased to 20% and 30%, water absorption and porosity rose above the control values. This negative trend may be associated with the high water demand of

RHA due to its porous, angular particles. Excess water needed to maintain workability can increase the effective water-to-cement ratio, reducing matrix density and leaving behind interconnected pores. Additionally, excessive RHA can reduce the available cementitious material, resulting in incomplete hydration and weak interfacial zones between aggregates and paste. These findings emphasize that optimum SCM dosage is crucial for balancing durability and mechanical performance. Moderate levels enhance microstructural densification, while excessive amounts compromise pore structure and long-term durability.

3.4. Sustainability and economic considerations.

The inclusion of FA and RHA significantly reduced cement consumption, which directly lowers CO_2 emissions and raw material demand, contributing to sustainable construction practices (Table 4). The FA20 mix achieved approximately 12% cost savings and 15% CO_2 reduction compared to the control mix, demonstrating that replacing a portion of cement with FA can provide substantial economic and environmental benefits. This improvement stems from the fact that cement production is highly energy-intensive and a major source of carbon emissions, while FA is an industrial by-product that requires minimal additional processing. By utilizing FA in concrete, the overall embodied carbon and energy consumption are lowered without compromising performance, as evidenced by the strength and durability gains at optimal replacement levels.

Similarly, RHA incorporation also led to a decrease in both production cost and CO_2 emissions, although to a slightly lower extent than FA. This is partly due to the additional energy required for controlled burning and grinding of rice husks to produce reactive RHA. Nonetheless, when used at around 10% replacement, RHA still provided measurable sustainability benefits while maintaining adequate mechanical properties. The use of RHA transforms an abundant agricultural residue that would otherwise be disposed of through open-field burning or landfilling, thereby reducing environmental pollution and associated health risks.

Furthermore, incorporating FA and RHA in concrete promotes the circular economy concept by valorizing waste materials and closing resource loops. This approach minimizes landfill burden, reduces dependence on virgin raw materials, and extends the service life of structures by improving durability. Overall, the study confirms that supplementary cementitious materials like FA and RHA can simultaneously enhance environmental sustainability, conserve resources, and reduce construction costs, while meeting the required structural performance standards—making them viable alternatives in sustainable concrete production.

Table 4. Cost and CO_2 emission reduction potential.

Mix ID	FA (%)	RHA (%)	Cement Saved (kg/m³)	Cost Reduction (%)	Estimated CO_2 Reduction (%)
Control	0	0	0	0	0
FA10	10	0	35	6.2	7.5
FA20	20	0	70	12.0	15.2
RHA10	0	10	35	5.8	6.8
RHA20	0	20	70	10.3	13.5

4. Conclusion

This study evaluated the utilization of fly ash (FA) and rice husk ash (RHA) as partial replacements for Portland cement in concrete, focusing on their effects on workability, setting time, compressive strength, durability, and sustainability. The experimental results demonstrated that both FA and RHA can significantly influence the fresh and hardened properties of concrete, and their optimal incorporation offers technical, environmental, and economic benefits. In terms of fresh properties, the inclusion of FA improved workability at 10–20% replacement levels due to its spherical particle morphology, while RHA caused a reduction in slump with increasing content because of its angular particles and higher surface area that increase water demand. Setting time was extended with increasing FA content, reflecting its slower pozzolanic reaction, whereas RHA slightly accelerated setting due to its high amorphous silica content that promotes early hydration. These findings confirm that the physical and chemical characteristics of supplementary cementitious materials directly affect hydration kinetics and fresh mix behavior. Regarding mechanical performance, FA at 10–20% replacement improved long-term compressive strength, particularly at 56 days, although early strength development was lower. RHA enhanced strength modestly at 10% but reduced it at higher levels (20–30%) due to increased water demand and potential incomplete hydration. Durability tests showed that FA20 and RHA10 exhibited lower water absorption and porosity, indicating refined pore structure and denser microstructure, while higher RHA levels negatively affected these properties. Sustainability analysis confirmed that partial cement replacement notably reduced cement consumption, CO_2 emissions, and production costs. FA20 achieved about 12% cost savings and 15% emission reduction, while RHA also provided measurable environmental benefits. Overall, FA at 20% and RHA at 10% were identified as optimal levels, balancing performance and sustainability. This study supports integrating industrial and agricultural by-products into concrete production as a viable strategy for sustainable construction.

Competing Interest

The authors declare that they have no known competing financial or personal interests that could have appeared to influence the work reported in this paper.

Author Contribution

All authors contributed equally to the conception, design, and preparation of this study. All authors reviewed and approved the final manuscript.

Data Availability

All data generated or analyzed during this study are included in this published article.

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