Green Pavement Materials: Effects of Rice Husk Ash on the Properties of Cement-Concrete Mixtures

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Abstract

This study investigates the potential of rice husk ash (RHA) as a supplementary cementitious material (SCM) in cement–concrete mixtures for pavement applications. The rice husk ash used in this study was applied without further processing, whereas in most other studies, RHA was processed before being mixed with concrete. Laboratory tests including X-ray diffraction (XRD), scanning electron microscopy (SEM), energy dispersive X-ray spectroscopy (EDX), and compressive strength analysis were conducted to evaluate the chemical, microstructural, and mechanical behavior of RHA-modified concrete. Results revealed that RHA consists predominantly of amorphous silica, displaying high pozzolanic reactivity. Incorporation of 5% RHA as a partial cement replacement yielded the highest compressive strength, surpassing the control mixture. Higher substitution levels (10–20%) resulted in strength reduction due to dilution and unreacted RHA. Microstructural analyses confirmed the ability of RHA to refine the concrete matrix by consuming calcium hydroxide and generating additional calcium silicate hydrate (C-S-H). Overall, the findings demonstrate that low-level RHA incorporation enhances strength and sustainability of pavement concrete, contributing to waste valorization and reduction of CO_2 emissions from cement production.

Keywords

Rice husk ash (RHA); supplementary cementitious materials (SCMs); green pavement; compressive strength; pozzolanic reaction; sustainable construction.

INTRODUCTION

Concrete is among the most widely used construction materials globally, valued for its durability, rigidity, and adaptability to a broad range of structural applications. It is typically composed of cement, fine aggregates, coarse aggregates, and water, forming a hardened mass through the process of hydration [1, 2, 3]. When water is added to cement, it produces a paste that coats each aggregate particle and undergoes chemical hydration, gradually solidifying into a stone-like composite material. The ability of concrete to provide structural stability, strength, and long-term performance has made it indispensable in infrastructure development, from residential buildings to industrial complexes, highways, and high-rise structures [4, 5]. A thorough understanding of concrete behavior is therefore essential for ensuring the longevity, safety, and economic viability of civil engineering projects.

Cement, the binding component of concrete, plays a critical role in determining its strength and durability. Ordinary Portland Cement (OPC) has historically been the most common binder due to its availability, high compressive strength, and versatility. Cement-based concrete has been central to human development, shaping modern cities and supporting industrialization. However, its benefits come at a significant environmental cost. Cement production is both energy-intensive and environmentally damaging, contributing substantially to global greenhouse gas emissions, dust pollution, and the depletion of non-renewable natural resources. For every ton of cement manufactured, nearly one ton of carbon dioxide (CO_2) is released into the atmosphere, making cement production responsible for approximately 7–8% of global anthropogenic CO_2 emissions [6, 7, 8].

The cement industry, while critical to economic growth, is a major polluter. Multiple forms of environmental degradation are linked with cement manufacturing [9, 10]. During clinker production and material handling, significant dust and carbon emissions are released into the air, contributing to air pollution and respiratory health issues in surrounding communities. Wastewater generated during cement production is often contaminated with alkaline compounds, suspended solids, and toxic elements, contributing to water pollution and ecological imbalance [11]. Additionally, heavy metals and fine dust particles deposited around cement plants deteriorate soil fertility, while noise and thermal pollution from heavy machinery further degrade the living environment. These environmental impacts, combined with the rising global demand for construction materials, underscore the urgent need for sustainable alternatives to cement in concrete production. The growing emphasis on reducing carbon footprints, achieving circular economies, and meeting global Sustainable Development Goals (SDGs) has spurred research into supplementary cementitious materials (SCMs) derived from industrial by-products and agricultural residues.

Among the promising alternatives to reduce cement dependency is rice husk ash (RHA), an agricultural waste product generated from burning rice husks [12, 13]. Rice is one of the most widely consumed staple foods worldwide, and its cultivation produces vast amounts of by-products. When rice is milled, approximately 20% of its weight becomes husk, and upon burning, around 15–20% of this husk is converted into ash [14, 15]. Globally, an estimated 750 million tonnes of paddy are produced annually, resulting in over 160 million tonnes of rice husk and more than 30 million tonnes of rice husk ash [16, 17]. In Bangladesh alone, rice production yields nearly 9.83 million tonnes of rice husk and 2.5 million tonnes of rice husk ash annually [18, 19].

The primary advantage of RHA lies in its pozzolanic characteristics [20, 21, 22]. Its high silica content allows it to improve the microstructure of concrete by reducing porosity and refining the interfacial transition zone (ITZ) between cement paste and aggregate. As a result, RHA-modified concrete often demonstrates enhanced compressive strength, tensile strength, and durability compared to conventional mixes.

The exploration of rice husk ash as a partial replacement for cement aligns with the global push toward green construction practices [23. 24, 25, 26]. Its application supports multiple United Nations Sustainable Development Goals [27], including:

- **SDG 11: Sustainable Cities and Communities** – through resource-efficient infrastructure development.
- **SDG 12: Responsible Consumption and Production** – by converting agricultural waste into valuable materials.
- **SDG 13: Climate Action** – by reducing CO_2 emissions from cement production.

By leveraging RHA, countries like Bangladesh, India, China, and others with large rice production capacities can simultaneously address agricultural waste disposal problems and reduce dependence on energy-intensive cement production. Thus, RHA represents not only a technical innovation but also a socio-economic opportunity to support sustainable development.

Partial cement replacement with RHA produces comparable compressive strength and abrasion resistance for pavement applications [28, 29, 30]. But previous researches were based on processed RHA in a fixed temperature. Objective of this research was to evaluate the compressive strength of concrete pavement incorporating rice husk ash without further process as a partial replacement for cement.

METHODS AND MATERIALS

Ordinary Portland Cement (OPC) conforming to ASTM C595 was used in this study. OPC is a fine, powdery material produced by the calcination of limestone, clay, and other raw substances. It acts as a binder by forming a paste when mixed with water, ensuring cohesion between sand and aggregates. Cement was procured from the local market and stored under dry conditions prior to use.

Domar natural river sand was employed as fine aggregate. This sand consists primarily of silica, feldspar, and other minerals, with low clay and silt content. It is light grey in color, well-graded, and exhibits good binding properties, making it suitable for use in reinforced cement concrete and mortar. The sand was oven-dried and sieved before mixing to ensure uniformity and remove impurities.

Locally available black stone chips (basalt/granite) were used as coarse aggregate. The stone chips ranged in size from 6 mm to 20 mm and were selected for their high compressive strength, weather resistance, and durability. They were washed, dried, and sieved prior to use.

Rice husk ash was obtained by uncontrolled burning of rice husk at local auto rice mills, with combustion temperatures ranging from 110–120 °C. The ash contained significant amounts of amorphous silica (SiO_2), contributing to its pozzolanic reactivity. The ash was ground to adequate fineness and used to partially replace cement at replacement levels of 5%, 10%, 15%, and 20% by weight. Potable tap water was used for mixing and curing, consistent with ASTM C1602 standards for mixing water in concrete.

The concrete was prepared with a mix ratio of 1:2:4 (cement : sand : stone chips) and a water-cement ratio (w/c) of 0.5. Cement was partially replaced with RHA at levels of 0%, 5%, 10%, 15%, and 20% by weight. The detailed mix proportions are provided in Table 1.

Table 1: Mix Proportions for Different RHA Replacement Levels

% of RHA	W/C Ratio	Cement (gm)	Sand (kg)	Stone chips(kg)	RHA (gm)	Water (lit)
0	0.5	5000	13	20	0	2650
5	0.5	4750	13	20	250	2750
10	0.5	4500	13	20	500	2900
15	0.5	4250	13	20	750	3050
20	0.5	3950	13	20	1050	3300

All materials were oven-dried before mixing, and mechanical mixing was carried out to ensure homogeneity. For pavement simulation, rectangular concrete slabs were cast using the same mix design (1:2:4, w/c = 0.5, with 0–20% RHA). Pavement size was 195mm x 165mm x 38mm as shown in below figure 1.

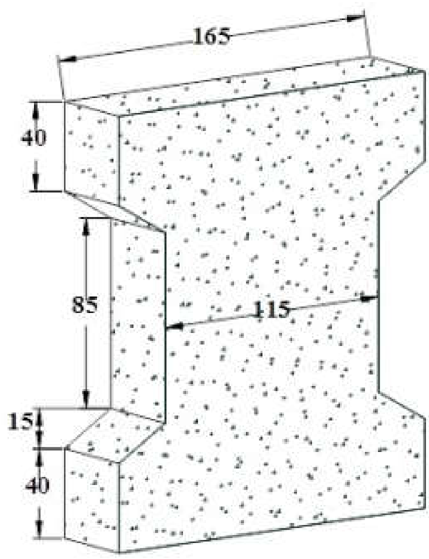

Figure 1: Pavement

After 28 days of curing, compressive strength was evaluated using a UTM machine by applying load until failure. Strength was calculated based on applied load and crosssectional area. The compressive strength was determined according to ASTM C39. Samples were surface-dried, placed in a compression testing machine (UTM), and loaded at a uniform rate until failure. The maximum load carried by each specimen was recorded, and compressive strength was calculated. Figure 2 shows compressive Strength test of pavement concrete.

Figure 2: Compressive Strength Test of Pavement Concrete

XRD analysis was conducted in accordance with ASTM C1365 to determine the crystalline and amorphous phases of RHA and cement. Samples were finely ground, scanned using X-ray diffraction, and analyzed for mineralogical composition. The analysis helped confirm the presence of amorphous silica in RHA and the hydration products in cementitious mixes.

Microstructural analysis was performed using SEM following ASTM C1723-16 guidelines. Hardened concrete samples were sectioned, polished, and gold-coated before imaging. SEM images were analyzed to observe the morphology, porosity, and bonding characteristics of the hydrated products in RHA-modified concretes.

RESULT AND DISCUSSION

The normal consistency of the Ordinary Portland Cement (OPC) sample was found to be 29%, which falls within the standard range of 26–33%. This indicates that the cement used in this study possessed acceptable workability and was suitable for preparing comparative mixtures with Rice Husk Ash (RHA). The consistency values also ensured proper hydration and setting characteristics, which is important when blending with supplementary cementitious materials (SCMs).

The fine aggregate showed an average apparent specific gravity of 1.22 and water absorption capacity of 19.1%. These values indicate higher porosity compared to conventional fine aggregates (typically 2.4–2.7 for specific gravity and 0.5–2% for absorption). Such properties influence water demand in concrete mixtures, suggesting that mix adjustments were necessary to achieve desired workability when RHA was incorporated.

The XRD profile of OPC confirmed the presence of crystalline phases such as alite (C_3S), belite (C_2S), aluminate (C_3A), and ferrite (C_4AF), which are responsible for strength development in cementitious systems. In contrast, the XRD pattern of RHA displayed a broad hump between 22–25° 2θ, a signature of amorphous silica, with negligible crystalline peaks shown in figure 3. The amorphous silica phase is critical for pozzolanic activity, as it reacts with calcium hydroxide ($Ca(OH)_2$), a byproduct of cement hydration, to produce additional calcium silicate hydrate (C-S-H) gel [31]. This reactivity makes RHA a valuable SCM for concrete applications, improving long-term strength and durability.

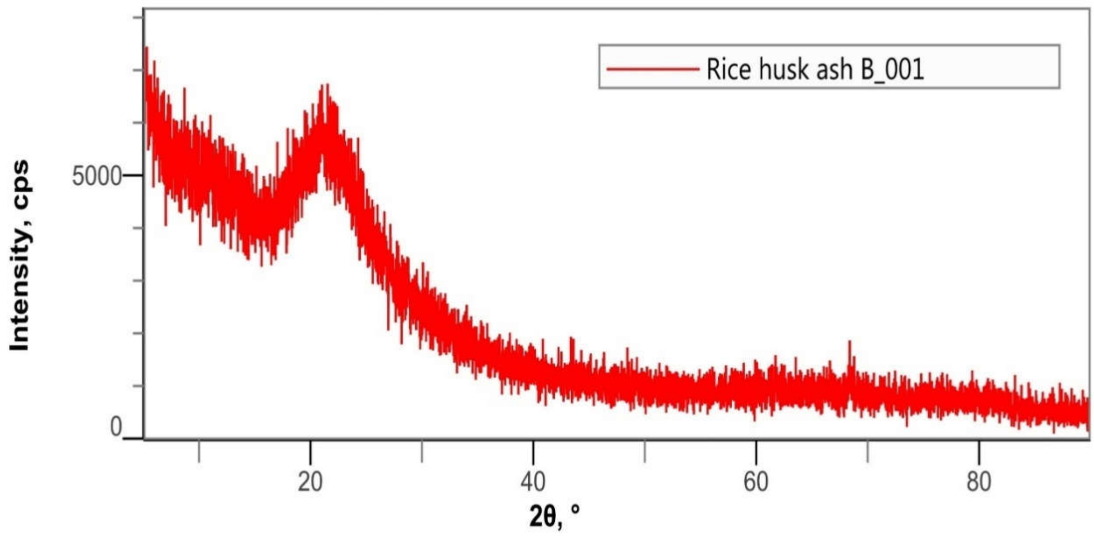

Figure 3: Measured Profile view of RHA

SEM images of RHA revealed an irregular, rough, and porous morphology. Such a high surface area accelerates pozzolanic reactivity by facilitating greater contact between reactive silica and cement hydration products (Ganesan et al., 2008). EDX results confirmed that the RHA sample contained 48–54% silica by mass, alongside oxygen (32–34%) and minor carbon residues, consistent with other studies on well-burnt RHA [32]. By contrast, OPC exhibited a microstructure dominated by hydration products, with EDX identifying high calcium content (31–37%), oxygen, and moderate silica. The high Ca content indicates abundant Ca $(OH)_2$, which can be effectively consumed by pozzolanic RHA, thereby refining pore structure and enhancing durability. Previous studies suggest that such microstructural refinement leads to reduced porosity, improved ITZ bonding, and enhanced resistance to deleterious chemical attacks [33].

The compressive strength of pavement concrete mixtures incorporating RHA at different cement replacement levels (5%, 10%, 15%, and 20%) was measured after 28 days of curing. Test result is shown in figure 4.

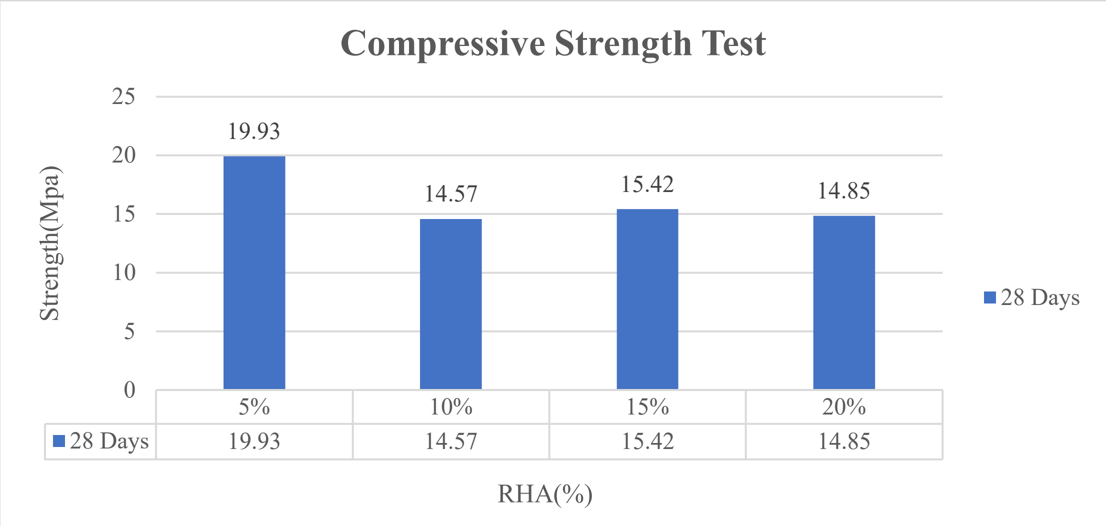

Figure 4: Compressive Strength Test of Pavement

At 5% RHA replacement, the mixture exhibited the highest compressive strength, exceeding the control OPC mix. This enhancement can be attributed to the synergistic effect of filler action and pozzolanic reactivity. The fine RHA particles act as nucleation sites, accelerating C-S-H formation, while the amorphous silica reacts with Ca $(OH)_2$, leading to a denser matrix [34].

At 10–20% replacement levels, compressive strength gradually decreased relative to the control. The reduction is due to the dilution effect, wherein excessive cement replacement reduces clinker content and leaves a portion of RHA unreacted, limiting the overall strength development. This trend aligns with the findings of Givi et al. (2010), who reported that RHA is most effective at low to moderate replacement levels (<10%). Despite the decline at higher substitution levels, the observed strengths remained within acceptable ranges for pavement applications, indicating that RHA can still be a viable sustainable binder in non-structural or medium-strength concrete.

The findings of this study emphasize that the optimal RHA replacement level is 5%, which maximizes compressive strength while reducing cement consumption. This performance enhancement is directly linked to the amorphous silica content and microstructural refinement confirmed by SEM and EDX analyses. Beyond this threshold, the pozzolanic contribution of RHA is insufficient to offset the loss of cementitious material, resulting in reduced strength.

From a sustainability perspective, the use of RHA addresses two critical challenges; recycling of agricultural waste (rice husk), which otherwise contributes to environmental pollution if improperly disposed of, and reduction in cement consumption, which lowers CO_2 emissions associated with cement production. These outcomes are in line with global efforts to transition towards greener construction materials [35].

In pavement applications, RHA-modified mixtures can offer additional durability advantages, such as improved resistance to chloride penetration, reduced permeability, and better long-term performance in aggressive environments. Future work should focus on durability studies, life-cycle cost analysis, and field-scale performance of RHA concrete to fully establish its potential as a green pavement material.

CONCLUSION

This research demonstrates that rice husk ash (RHA) is a highly effective supplementary cementitious material for pavement-grade concrete when used at controlled, low replacement levels. The rice husk ash used in this study was applied without further processing, whereas in most other studies, RHA was processed before being mixed with concrete. Characterization through XRD, SEM, and EDX confirmed that RHA is rich in amorphous silica, ensuring strong pozzolanic reactivity that contributes to the formation of additional calcium silicate hydrate (C–S–H) gel and a denser microstructure. At an optimal replacement level of around 5%, RHA significantly improved the compressive strength of concrete compared to control OPC mixtures, primarily due to the combined effects of pozzolanic reactions that refine the pore structure and the filler action of fine RHA particles that enhance packing density. However, replacement levels beyond 10% resulted in strength reduction, attributed to the dilution effect and reduced availability of clinker phases, highlighting the importance of dosage optimization. Beyond mechanical performance, the use of RHA in pavement concrete contributes to sustainable construction by lowering cement consumption, reducing CO_2 emissions, and transforming agricultural waste into a valuable resource for infrastructure, thereby promoting the development of green pavement technologies that balance structural performance with environmental responsibility.

Future studies should investigate long-term durability properties, life-cycle cost assessments, and large-scale pavement performance to validate the practical applicability of RHA concrete.

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