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# Exploring Rice Husk Ash in Uncontrolled Condition as Supplementary Cementitious Materials for Enhanced Performance in Construction Materials

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## Abstract

This study investigates the potential of Rice Husk Ash (RHA), an abundant agricultural byproduct in Bangladesh, as a sustainable supplementary cementitious material (SCM) in concrete. Ordinary Portland Cement (OPC) was partially replaced with locally produced, unprocessed RHA at proportions of 5%, 10%, 15%, and 20% by weight, with a control mix (0% RHA) for comparison. Mechanical performance was evaluated through compressive and tensile strength tests at 7, 14, and 28 days, complemented by durability assessments in saltwater conditions. Microstructural and chemical analyses were conducted using X-ray Diffraction (XRD), Energy Dispersive X-ray Spectroscopy (EDX), and Scanning Electron Microscopy (SEM). Results revealed that 10% RHA replacement achieved the optimal balance between strength and sustainability, with compressive strength reaching 22.06 MPa and tensile strength showing improved pozzolanic activity over time. Higher replacement levels (15–20%) significantly reduced strength due to dilution effects. Microstructural studies confirmed the high amorphous silica content and favorable morphology of RHA, supporting its pozzolanic reactivity. Incorporating RHA reduces cement demand, lowers emissions, and offers an environmentally friendly solution for

managing agricultural waste. The findings establish that a 10% substitution of OPC with unprocessed RHA provides an effective, eco-friendly, and cost-efficient pathway toward green construction in Bangladesh and other rice-producing regions.

**Introduction**

Concrete is a foundational material in the construction industry, globally valued for its robustness, versatility, and durability. Composed primarily of cement, water, fine and coarse aggregates, concrete's performance depends on the chemical interaction between cement and water, which initiates hydration and leads to hardening over time. Its widespread use across infrastructure, buildings, and industrial projects makes it indispensable in both developing and developed nations. However, the environmental cost of producing ordinary Portland cement (OPC), the most common binding agent in concrete is increasingly becoming a subject of global concern. Pollution from manufacturing of cement is a major concern [1]. Cement manufacturing is energy-intensive and emits large volumes of carbon dioxide ($CO_2$), with nearly one ton of $CO_2$ produced per ton of cement, significantly contributing to greenhouse gas emissions and climate change. The accumulation of dust and heavy metals around cement plants contributes to the deterioration of soil quality [2].

The outer protective layer of the rice grain, called the rice husk, is an agricultural byproduct generated during rice harvesting. In 2017, global rice consumption reached approximately 758.8 million tonnes [3]. The rice husk constitutes between 16.3% and 26% of the total weight of the rice grain [4]. Approximately 20% of the original weight of rice husks remains as rice husk ash (RHA) after the husks undergo combustion [5]. In light of these issues, the construction sector is actively seeking sustainable alternatives that can either reduce or replace the use of cement without compromising structural performance. RHA's high silica ($SiO_2$) concentration makes it a very reactive pozzolanic material. While its proportion may vary from 90% to 98% by weight of the total ash [6]. Another study states that the RHA can include up to 95% $SiO_2$ [7]. Amorphous silica is created when rice husk is burned at temperatures between 350°C and 750°C, while crystalline silica is created at temperatures higher than 800°C. Its silicon content, particle size, and specific surface area vary significantly depending on the treatment source, incineration temperature, and other factors [8]. As a rich source of amorphous silica, RHA exhibits pozzolanic behaviour, meaning it can chemically react with calcium hydroxide in concrete to form additional cementitious compounds, thereby enhancing strength and durability. Bangladesh, a leading rice-producing country, generates over 9.8 million tons of rice husk and approximately 2.5 million tons of RHA annually offering a substantial opportunity to repurpose this agro-waste into construction materials [9].

Several studies have demonstrated that highly reactive pozzolanic materials such as rice husk ash (RHA) can enhance the strength and long-term durability of concrete and mortar [10]. These properties make RHA a viable material for green construction, particularly when used in optimal proportions. Due to its physico-chemical characteristics and pozzolanic nature, RHA has the potential to serve as a substitute for supplementary cementitious materials (SCMs) in concrete [11].

The pozzolanic activity of RHA, however, is highly sensitive to its production process. While RHA produced at high temperatures (500–700°C) is known for high reactivity, this study investigates the effects of RHA produced at lower temperatures (110–120°C), a process that conserves energy and retains the organic structure of the husk to a greater extent. This research aims to investigate the pozzolanic properties of rice husk ash (RHA), evaluate its impact on the tensile and compressive strength of concrete, and promote sustainable development through its application as a partial cement replacement. Incorrect disposal of rice husk ash contributes to environmental pollution and soil degradation [12]. RHA mainly contains over 85% amorphous SiO2, along with oxides and trace CaO. Processes like incineration and grinding cause losses. Its amorphous nature aids high-strength concrete [13, 14]. High percentage of (SiO2) 80–85% which in turn confirms that it has pozzolanic character.

By examining the feasibility of using low-temperature RHA as a cement alternative, this study contributes to the broader effort of reducing the environmental footprint of construction while promoting the use of locally available, renewable resources. The results are expected to support more sustainable building practices, reduce dependence on traditional cement, and offer economically viable solutions for managing agricultural waste. Although numerous studies have investigated the use of rice husk ash (RHA) as a partial replacement for cement in concrete, its application as a mortar substitute remains relatively uncommon [15].

## Methodology

In this study, Rice Husk Ash (RHA) was investigated as a partial replacement for Ordinary Portland Cement (OPC) in concrete. OPC, fine aggregate (natural Domar sand), and coarse aggregate (crushed black stone chips of 6–20 mm size) were used as primary materials. RHA was collected from locally burnt rice husks at temperatures around 110–120°C and ground to fine powder. Concrete mixes were prepared with a constant 1:2:4 ratio and a water-cement ratio of 0.5, replacing OPC with RHA at 5%, 10%, 15%, and 20% by weight. Control mixes without RHA were also cast. Specimens were molded into standard cube and cylindrical forms, cured in water for 7, 14, and 28 days, and some were later exposed to saltwater for chloride resistance testing. Compressive strength was assessed using a Universal Testing Machine (ASTM C39), while split tensile strength was evaluated following ASTM C496. Additionally, X-ray Diffraction (XRD) and Scanning Electron Microscopy (SEM) were conducted to analyze the chemical and microstructural characteristics of RHA, conforming to ASTM C1365, C114, and C1723-16(2022). Pavement strength was tested using slab specimens after 28 days of curing. This comprehensive methodology aimed to assess both mechanical performance and durability of RHA incorporated concrete under varying conditions. Photo of collected RHA is shown in figure 1.


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Figure 1: Rice Husk Ash (RHA)

For mix design, a 1:2:4 ratio is used in this study. The water-cement ratio was 0.5. The mix designs for the respective ratios are shown in table 1.

**Table 1: Mixing Ratio for Testing**

| % of RHA | W/C Ratio | Cement (gm) | Sand (kg) | Stone chips(kg) | RHA (gm) | Water (gm) |
|---|---|---|---|---|---|---|
| **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 |

The specimens immersed in water for 7, 14, and 28 days and tested for compressive strength, as well as 7 and 28 days for tensile strength. Casting, molding, and curing shown in the figure 2.

Figure 2: Casting, Molding, and Curing

According to ASTM 39, compressive strength involves casting and curing concrete, then crushing cubes in a compression machine. The process includes conditioning molds, preparing and depositing concrete, curing specimens, then testing. To ensure failure under tension normal to the loading direction, a compressive load is applied in the diametral plane of the cylinder until it splits. The splitting tensile strength is then calculated using the maximum load and the cylinder's dimensions. XRD test is used to define and quantify crystalline portions. The method involves preparing the sample, collecting diffraction data, and performing pattern analysis. His standard provides a procedure and calculations for determining the phase composition of hydraulic cements, including Portland cement and clinker, using X-ray diffraction in accordance with ASTM C1365. ASTM C1723-16(2022) provides guidance for observing hardened concrete using SEM, which can be applied to cement and ash within concrete. This well-known reference focuses on using SEM to analyze hardened concrete and related materials such as fly ash and cement. The chloride test to assess the risk of corrosion in reinforced concrete structures. Concrete is permeable to salt and susceptible to cracking and spalling caused by chlorides, which can pose problems during construction or in exposed conditions. A complementary concrete cube is prepared during the compressive strength test for each percentage (5%, 10%, 15%, 20%) of RHA. When made, these cubes are submerged in salty water and cured for 28 days. After curing, the cubes are removed and tested for compressive strength. Photo of compressive strength test and tensile strength test is shown in figure 3 and figure 4.

Figure 3: Compressive Strength Test

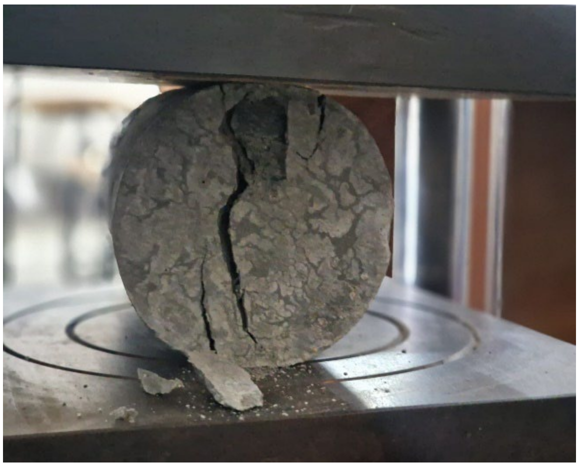


Figure 4: Tensile Strength Test

**Result and Discussions**

Compressive strength is the ability of a material or structural component to withstand axial loads that tend to decrease its size. It is an important mechanical property that shows how much compressive stress a material can handle before failing or deforming. In concrete testing, compressive strength is determined by applying a uniaxial load to a test specimen, usually a cube or cylinder until it breaks. This property is measured in megapascals (MPa), where one MPa equals one million pascals. The test provides vital data about the load-bearing capacity of concrete, helping engineers and inspectors evaluate if the material meets the structural and safety standards for a project. The performance of concrete with RHA partially replacing cement was assessed through a compressive strength test. With RHA replacement levels of 0% (control), 5%, 10%, 15%, and 20%, the study tested five mix proportions. Compressive strength was measured at 7, 14, and 28 days of curing. The results are presented in Figure 5.

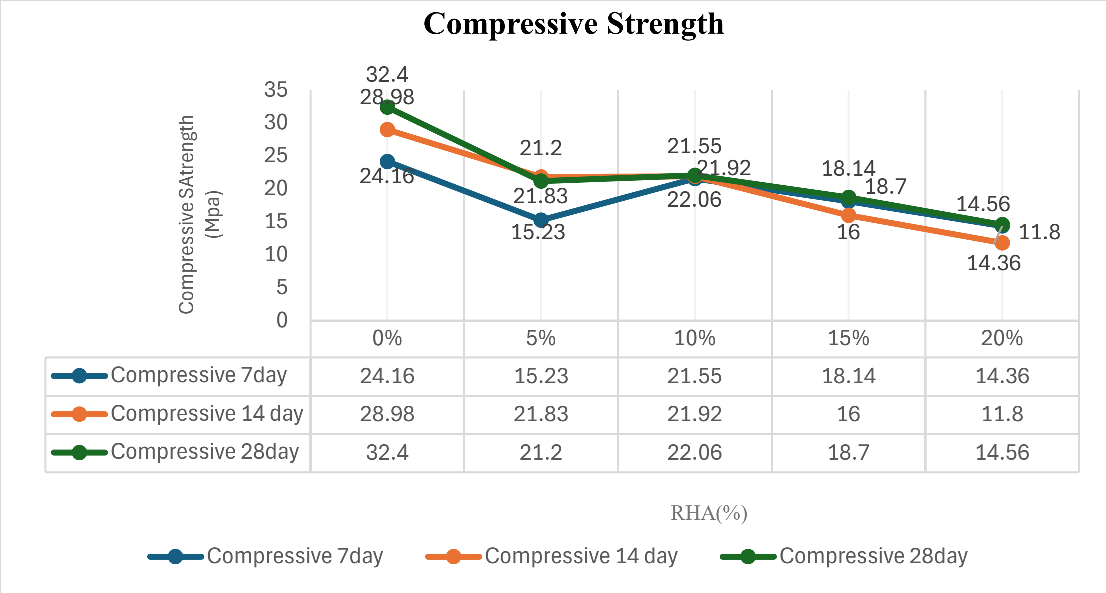
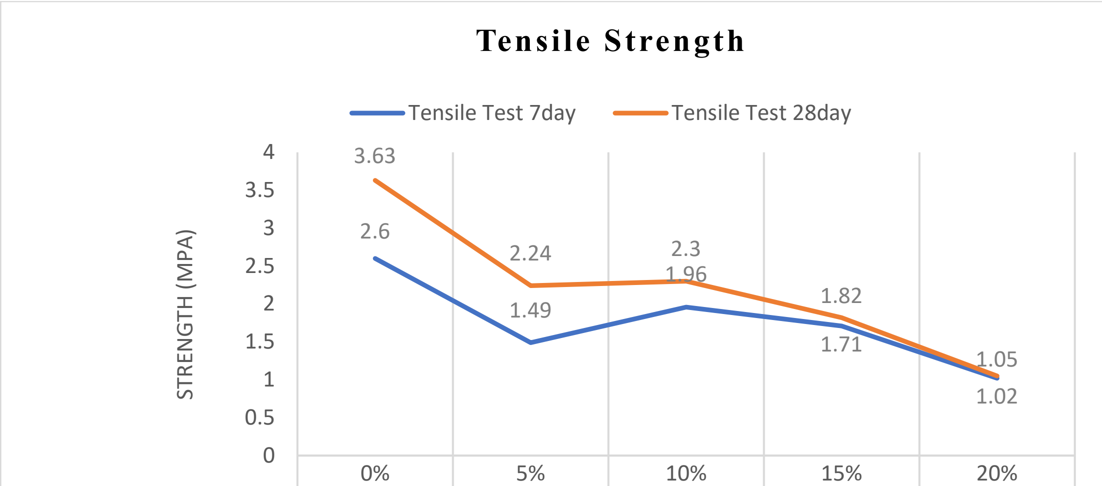



Figure 5: Compressive Strength Test Result

According to the test results, at 28 days, the control mix (0% RHA) had the highest compressive strength of any age, measuring 32.40 MPa. With a 28 days strength of 22.06 MPa and consistent strength gain over time, the 10% RHA replacement mix outperformed the other RHA blended mixes. The strength of the 5% RHA mix was moderate initially, but it did not increase as the curing process continued. At all ages, mixes with higher RHA contents (15% and 20%) showed a significant decrease in compressive strength, indicating that excessive RHA replacement negatively affects the concrete's load-bearing capacity. The 15% and 20% mixes recorded strengths of 18.70 MPa and 14.56 MPa at 28 days, respectively. The findings suggest that 10% RHA replacement is the optimal level to maintain respectable compressive strength while enhancing sustainability. Higher replacement levels are not recommended for structural applications due to their adverse effect on strength development.

The 28 days compressive strength established that the incorporation of RHA enhances the strength of concrete with an optimum percentage of replacement. The best substitution level was a 10% concentration of RHA (62.3 N/mm²), which indicated a greater pozzolanic reactivity, and thus more densification of the matrix greater at 0% RHA, (54.0 N/mm²). For 15% and 20% replacements, the strengths were 60.3 N/mm² and 60.2 N/mm², respectively, but lower than the control. This indicates that the 10% RHA is the most effective percentage for enhancing 28 days compressive strength.

Tensile strength is a key material property that measures the maximum load a material can handle when pulled, divided by its original cross-sectional area. This test determines the material's ability to resist deformation or breakage under tension. Tensile strength is expressed in force per unit area, usually in megapascals (MPa) according to the International System of Units (SI). In this system, 1 MPa equals 1 N/mm² or 145 psi. Measuring tensile strength helps evaluate the material's durability and its suitability for various structural uses where tension is involved. The performance of concrete with different percentages of Rice Husk Ash (RHA) as a partial cement substitute was evaluated through tensile strength tests. Mixtures containing 0% (control), 5%, 10%, 15%, and 20% RHA were tested at curing ages of 7 and 28 days. The results are shown in figure 6.




| RHA(%) | 0% | 5% | 10% | 15% | 20% |
|---|---|---|---|---|---|
| Tensile Test 7day | 2.6 | 1.49 | 1.96 | 1.71 | 1.02 |
| Tensile Test 28day | 3.63 | 2.24 | 2.3 | 1.82 | 1.05 |

Figure 6: Tensile Strength Test Result

According to the test results, the control mix (0% RHA) exhibited the highest tensile strength at 7 days, 2.6 MPa, demonstrating a strong matrix development and early bonding. Strength significantly decreased to 1.49 MPa with the addition of 5% RHA, likely due to the cement's dilution effect and slower pozzolanic reaction. A partial recovery was observed at 10% RHA, reaching 1.96 MPa, indicating that pozzolanic activity began to have a beneficial effect. However, increases of 15% and 20% once again reduced tensile strength, most likely because excessive replacement left insufficient cementitious content for early strength development. A similar pattern persisted at 28 days, with the control mix still showing the highest strength at 3.63 MPa. As the mix aged, pozzolanic reactions improved, as reflected by the strength for 10% RHA (2.3 MPa) surpassing that of 5% RHA (2.24 MPa). Nonetheless, at 15% and 20%, strength decreased further to 1.82 MPa and 1.05 MPa, respectively, indicating that too much replacement negatively affects long-term strength by reducing the available calcium hydroxide and potentially causing poor particle packing.

XRD, EDX, and SEM Analysis of Cement and Rice Husk Ash (RHA) investigates the mineralogical, chemical, and microstructural properties of Ordinary Portland Cement (OPC) and Rice Husk Ash (RHA) through X-ray Diffraction (XRD), Energy Dispersive X-ray Spectroscopy (EDX), and Scanning Electron Microscopy (SEM), aiming to evaluate RHA's potential as a supplementary cementitious material (SCM).

X-ray Diffraction (XRD):

- Cement: Sharp peaks between 2θ = 25°–40°, with the highest at 29.4° 2θ (~11,000 cps), confirmed crystalline phases typical of OPC, alite ($C_3S$), belite ($C_2S$), aluminate ($C_3A$), and



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ferrite ($C_4AF$). This indicates strong crystallinity and structural integrity suitable for construction.

- RHA: A broad peak at $2\theta = 22°–25°$ (6200 cps) revealed predominantly amorphous silica with negligible crystalline quartz, crucial for pozzolanic reactivity. Mild heat treatment (110–120°C) effectively stabilized the reactive silica phase.

Energy Dispersive X-ray Spectroscopy (EDX):

- Cement: High levels of calcium (31–37%) and oxygen (23–36%), along with significant silicon (4–4.5%), aluminum (1.1%), sulfur (2–6%), and trace magnesium and potassium. These compositions confirm the presence of hydration products like C-S-H, gypsum, and ettringite.
- RHA: Dominated by silicon (48–53%) and oxygen (32–34%), with moderate carbon content (12–19%). The high $SiO_2$ proportion supports strong pozzolanic potential.

Scanning Electron Microscopy (SEM):

- Cement: Revealed dense microstructures with hydration products (C-S-H, $Ca(OH)_2$, ettringite). Elemental mapping aligned with EDX data, verifying a typical cementitious matrix.
- RHA: Exhibited irregular, porous, and rough surfaces, providing a high surface area beneficial for pozzolanic reactions. Morphology supports enhanced reactivity when blended with cement.

Key Findings from XRD, EDX, and SEM analysis are as below-

- RHA Properties: High amorphous silica content, favorable morphology, and suitable chemical composition make RHA an effective SCM for partially replacing cement.
- Sustainability Impact: Incorporating RHA can reduce cement consumption, lower $CO_2$ emissions, and improve concrete durability without compromising strength.
- Compatibility: The chemical and microstructural compatibility of RHA with OPC supports its use in blended cements.

RHA used as a partial replacement for cement in concrete has demonstrated good mechanical behavior and sustainability benefits, along with economic advantages. RHA is a waste from rice production. Use of RHA in concrete decrease the amount of waste, an important part of sustainable development. Also, the replaced amount of cement led to decrease the production and pollution from such amount of cement. Its high silica content (53.48% by mass) indicates strong pozzolanic properties, although its low calcium content and larger particle size compared to OPC contribute to a slower reaction rate and lower early strength. Compressive and tensile strengths decreased with the inclusion of RHA, but 10% substitution showed the best overall performance in strength and the supplementary cementitious effect. Regarding sustainability, RHA applications can help save cement, which reduces cement consumption in the final product, thereby decreasing atmospheric pollution and carbon dioxide emissions, supporting green construction. From an economic perspective, RHA can be cost-effective due to its nutrient-rich lignocellulosic ash, requiring less energy to produce and consuming fewer resources such as fuel, energy, and raw materials. Green, low-cost concrete with lower strength can be achieved with only a slight decrease in performance by considering RHA at a 10% replacement level.

Another study focused on determining the optimal replacement level of rice husk ash (RHA) to improve the physical properties of concrete. The researcher experimented with substitution ratios ranging from 5% to 35% by mass of cement. The results suggested that up to 30% of ordinary Portland cement (OPC) can be replaced with reburnt RHA without negatively impacting the strength performance of the concrete [16, 17, 18]. A study investigated the improvement of cement mortar strength using rice husk ash produced under controlled temperature conditions, with the highest compressive strength observed at a 20% replacement level [19, 20]. Both of these studies used processed RHA during research. As cement, the binder is the costliest component of concrete, partially replacing it with a more affordable, natural, and locally available material like RHA not only aids waste management but also reduces the overall cost of concrete and housing [21, 22, 23]. the possible benefits remain, although the overall financial impact is complex and varies depending on local and practical conditions. [10].

It was observed from this research that, 10% replace of cement by RHA showed satisfactory result considering compressive strength and tensile strength of concrete. RHA used in this research was unprocessed. The improper disposal or uncontrolled burning of rice husk contributes to air pollution and land degradation. Utilizing RHA as a supplementary cementitious material (SCM) not only reduces environmental harm but also adds value to agricultural waste, aligning with global sustainability goals such as reduced industrial emissions, waste valorisation, and circular economy practices.

**Conclusions**

The study establishes that Rice Husk Ash (RHA) can be effectively utilized as a supplementary cementitious material in concrete, with 10% replacement of cement yielding the most favorable balance between strength and sustainability. At this level, concrete demonstrated satisfactory compressive and tensile strengths, enhanced pozzolanic reactivity, and improved microstructural densification, while higher replacement levels led to significant strength reduction due to dilution effects. XRD, EDX, and SEM analyses confirmed the high amorphous silica content, favorable morphology, and strong chemical compatibility of RHA with Ordinary Portland Cement (OPC), validating its potential as a sustainable alternative. Beyond mechanical performance, incorporating RHA reduces cement consumption, lowers emissions, and promotes waste valorization, aligning with sustainable development and circular economy practices. Therefore, use of unprocessed RHA commonly found in Bangladesh, particularly at 10% replacement, provides an eco-friendly, cost-effective, and technically viable solution for green construction. This study was conducted to evaluate the potential of using RHA as a partial replacement for OPC in concrete, aiming to promote sustainable construction.

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