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Physicochemical Characterization and Performance Evaluation of Rice Husk Ash as a Sustainable Supplementary Cementitious Material in Mortar

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ABSTRACT: The high environmental cost of cement production has driven the search for sustainable supplementary materials. This study characterized Rice Husk Ash (RHA) and evaluated its feasibility as a partial cement replacement in mortar. RHA was produced by combusting rice husks at 650°C for two hours. X-ray Fluorescence (XRF) analysis confirmed its high pozzolanic quality, revealing a silica (SiO_2) content of 76.41%. Mortar cubes were prepared with 0% (control), 5%, 10%, 15%, and 20% cement replacement by RHA, and their compressive strength was tested after 7, 14, 21, and 28 days of curing. The results identified 10% as the optimal replacement level, achieving a 28-day compressive strength of 29.68 N/mm², which is comparable to the control mix (31.32 N/mm²). This indicates a successful pozzolanic reaction where RHA's silica consumed calcium hydroxide to form additional strength-giving C-S-H gel. Conversely, higher replacement levels (15% and 20%) resulted in a significant decline in strength due to cement dilution and increased water demand, leading to a less dense microstructure. The study concludes that RHA is an effective pozzolanic material, and its incorporation at 10% cement replacement enhances mortar strength while providing an eco-friendly solution for agricultural waste management.

KEYWORDS: Rice Husk Ash, Mortar, Cementous material, Pozzolanic material, Compressive Strength, and Physicochemical Evaluation

I. INTRODUCTION

The construction industry remains one of the largest consumers of natural resources globally, with Ordinary Portland Cement (OPC) being the principal binder used in concrete and mortar production. Despite its extensive applications, cement manufacturing contributes significantly to greenhouse gas emissions due to the calcination of limestone and high energy consumption during clinker production. Cement manufacturing accounts for approximately 5–8% of global carbon dioxide emissions, thereby intensifying concerns regarding environmental sustainability and climate change [1].

To mitigate these environmental impacts, researchers have increasingly focused on supplementary cementitious materials (SCMs) derived from industrial and agricultural wastes. These materials partially replace cement in mortar and concrete while improving mechanical and durability properties [2] (Neville & Brooks, 2010). Among the various agricultural wastes investigated, Rice Husk Ash (RHA) has emerged as a promising pozzolanic material due to its high silica content and global availability [3].

Rice husk is a by-product generated during rice milling operations and constitutes approximately 20% of the total weight of harvested rice. Improper disposal or open-air burning of rice husks contributes to environmental pollution and greenhouse gas emissions. However, controlled combustion of rice husks produces ash rich in amorphous silica, which can react with calcium hydroxide generated during cement hydration to form additional calcium silicate hydrate (C-S-H) gel [4].

The pozzolanic reaction occurring in RHA-blended cement systems enhances the microstructure and mechanical properties of cementitious composites through secondary hydration reactions [5]. Several studies have reported improved durability, permeability resistance, and compressive strength in mortar and concrete containing moderate amounts of RHA. Endale et al. (2022) observed enhanced compressive and tensile strength in concrete incorporating RHA [6], while [7] reported improved permeability resistance and strength performance due to pore refinement and microstructural densification.

The performance of RHA-blended mortar depends on several factors including combustion temperature, silica content, particle fineness, and replacement level. Previous investigations suggest that replacement levels between 10% and 20% can provide satisfactory mechanical performance while significantly reducing cement consumption and associated carbon emissions [8, 4].

Although numerous studies have investigated the use of RHA in concrete, limited information exists regarding the characterization and performance of locally produced RHA in mortar systems under controlled combustion conditions. Variations in rice husk source, combustion technique, and ash processing significantly influence the engineering properties of RHA.

The present study therefore evaluates the suitability of Rice Husk Ash as a sustainable supplementary cementitious material in mortar. The study focuses on producing RHA through controlled combustion at 650°C, characterizing its chemical composition using X-ray fluorescence (XRF), and assessing the compressive strength performance of mortar containing varying percentages of RHA.

II. LITERATURE REVIEW

A. Rice Husk Ash as a Supplementary Cementitious Material

The increasing demand for sustainable construction materials has stimulated research into the utilization of agricultural wastes as supplementary cementitious materials (SCMs). Among these materials, rice husk ash (RHA) has attracted considerable attention due to its high silica content, abundance, and potential to partially replace ordinary Portland cement (OPC) in mortar and concrete production. The use of RHA not only reduces the environmental burden associated with agricultural waste disposal but also contributes to the reduction of carbon dioxide emissions generated during cement manufacture [9, 10].

Rice husk is a by-product of rice milling, representing approximately 20% of the weight of harvested rice. When properly combusted under controlled conditions, the husk produces ash rich in amorphous silica, which exhibits significant pozzolanic activity. The pozzolanic behaviour of RHA results from the reaction between reactive silica and calcium hydroxide released during cement hydration, leading to the formation of additional calcium silicate hydrate (C-S-H) gel that enhances the strength and durability of cementitious materials [11] (Saad et al., 2015).

B. Chemical Composition and Pozzolanic Properties of RHA

The effectiveness of RHA as a pozzolanic material is largely dependent on its chemical composition and combustion conditions. Several studies have reported that high-quality RHA contains more than 70% silica, making it suitable for use as a supplementary cementitious material in accordance with ASTM C618 requirements. Karim et al. (2012) [12] reported that the high silica content of RHA contributes significantly to its pozzolanic reactivity and subsequent strength development in cement-based systems. Similarly, [9] observed that RHA produced under controlled burning conditions possesses a high proportion of amorphous silica, which improves the mechanical and durability properties of concrete.

The combustion temperature employed during RHA production plays a critical role in determining the form of silica present in the ash. Studies have shown that burning rice husks within the temperature range of approximately 500–700°C promotes the formation of amorphous silica, whereas excessively high temperatures may convert silica into crystalline forms with lower pozzolanic reactivity. Consequently, controlled combustion is essential for producing RHA with desirable cementitious properties.

C. Effect of RHA on Compressive Strength of Mortar and Concrete

Numerous researchers have investigated the influence of RHA incorporation on the compressive strength of mortar and concrete. The strength development of RHA-modified cementitious materials is generally attributed to both the filler effect and the pozzolanic reaction. The fine particles of RHA improve particle packing within the cement matrix, while the reactive silica contributes to the formation of additional C-S-H gel, resulting in a denser microstructure and enhanced mechanical performance [12].

Previous studies have demonstrated that moderate replacement levels of cement with RHA can produce compressive strengths comparable to or greater than those of conventional cement mixtures. A review by [13] Nisa and Sitanggang (2024) indicated that RHA replacement levels between 10% and 20% often provide optimum performance in concrete, depending on the fineness and quality of the ash. Likewise, [14] reported that partial replacement of cement with RHA can improve the mechanical properties of concrete when appropriate replacement levels are used.

However, excessive replacement of cement with RHA may adversely affect compressive strength due to the dilution effect. As the proportion of cement decreases, the quantity of hydration products generated becomes insufficient to maintain strength development, particularly when the pozzolanic reaction cannot fully compensate for the reduced cement content. Several studies have therefore identified optimum replacement levels ranging from 10% to 15%, beyond which a decline in strength is commonly observed.

D. Sustainability Benefits of RHA Utilization

The incorporation of RHA in cementitious materials offers significant environmental and economic benefits. Cement production is responsible for substantial greenhouse gas emissions, accounting for a considerable proportion of global industrial CO_2 emissions. The partial replacement of cement with RHA reduces clinker consumption, thereby lowering the carbon footprint of construction materials. Furthermore, the utilization of rice husk ash provides an effective waste management strategy by converting agricultural residues into valuable construction resources [15].

In addition to environmental benefits, the use of RHA can improve the durability characteristics of concrete, including resistance to sulphate attack, chloride penetration, and aggressive environmental conditions. These advantages contribute to the production of sustainable and durable infrastructure while promoting circular economy principles within the construction industry.

III. EXPERIMENTAL

A. Sample preparation

Rice husks were obtained from a local rice mill in Bauchi and used as the raw material for the production of rice husk ash (RHA). Ordinary Portland Cement (OPC), fine aggregate (sand), and potable water were used in the preparation of mortar specimens.

The collected rice husks were washed to remove impurities and air-dried prior to combustion. The dried husks were subjected to controlled burning in a muffle furnace at a temperature of 650°C for 2 h to produce rice husk ash. After combustion, the ash was allowed to cool to room temperature and subsequently sieved to obtain a uniform particle size as shown in Figure 1.

Figure 1: Rice Husk Ash after combustion for 2 hours at 650^{0}C and Sieving

B. Characterization and Curing

The chemical composition of the produced RHA was determined using X-ray Fluorescence (XRF) analysis. The test was conducted to identify and quantify the major and minor oxide constituents present in the ash. Particular attention was given to the silica (SiO_2) content and the combined percentage of SiO_2, Al_2O_3, and Fe_2O_3, which are commonly used to evaluate the pozzolanic potential of supplementary cementitious materials.

Figure 2: RHA-Cement Mortar Mold

Mortar specimens were prepared, as in Figure 2, by partially replacing cement with RHA at replacement levels of 0%, 5%, 10%, 15%, and 20% by weight of cement. The constituent materials were thoroughly mixed to achieve a homogeneous mixture before the addition of water. The fresh mortar was then cast into moulds and compacted to eliminate entrapped air. After 24 h, the specimens were demoulded and transferred to a curing tank containing clean water.

The mortar specimens were cured under water for periods of 7, 14, 21, and 28 days (see Figure 3). The curing process was maintained throughout the specified periods to ensure adequate hydration and strength development.

Figure 3: Curing Of RHA-Cement Mold Samples

C. Mechanical Strength Test

At the end of each curing period, the mortar specimens were removed from the curing tank and tested for compressive strength using a compression testing machine. The test was conducted in accordance with the relevant standard procedure for mortar strength determination. The maximum load sustained by each specimen prior to failure was recorded, and the compressive strength was calculated and expressed in N/mm^2. The results were used to evaluate the effect of RHA content on the mechanical performance of the mortar.

IV. RESULTS AND DISCUSSION

A. Proximate and Ultimate Analysis of Rice Husk

The proximate analysis revealed a relatively high volatile matter content of 67%, indicating that the rice husk possesses significant combustible organic components suitable for ash production. The proximate and ultimate analyses of the rice husk used for ash production are presented in Table 1 where the ash content of 21.50% confirms the substantial mineral residue available after combustion, which is mainly composed of silica.

In other hand, the ultimate analysis showed appreciable carbon and oxygen contents, which are characteristic of lignocellulosic biomass materials. The calorific value of 12.76 MJ/kg further confirms the suitability of rice husk for thermal processing and controlled combustion.

The moderate fixed carbon content indicates that controlled burning can effectively produce ash with low residual carbon content. This observation agrees with the low Loss on Ignition (LOI) obtained from the XRF analysis of the produced RHA.

Table I. Proximate and Ultimate Analysis of Rice Husk

Proximate Analysis	
Parameter	**Value (wt %)**
Moisture Content (%)	6.50 ± 0.14
Ash Content (%)	21.50 ± 0.71
Volatile Matter (%)	67.00 ± 0.00
Fixed Carbon (%)	11.50 ± 0.71
HHV (MJ/kg)	12.76 ± 0.27
Ultimate Analysis	
Parameter	**Value (wt %)**
Carbon (%)	31.44 ± 0.47
Hydrogen (%)	4.87 ± 0.07
Oxygen (%)	32.33 ± 0.50

B. XRF Analysis

The XRF analysis was employed to determine the elemental composition of the sample. It is a rapid, non-destructive analytical technique that identifies and quantifies elements based on the characteristic fluorescent X-rays emitted when the sample is irradiated with primary X-rays. The technique provides reliable information on the major and minor elemental constituents of the material, making it suitable for compositional characterization. The results obtained from the XRF analysis are presented in Table II.

The XRF analysis, conducted on the RHA at 650^0C for 2 hour, revealed that the produced rice husk ash (RHA) contained a high concentration of SiO_2 (76.41 wt.%), confirming that silica is the predominant constituent of the ash. The elevated silica content indicates a strong potential for pozzolanic reactivity, as amorphous silica readily reacts with calcium hydroxide generated during cement hydration to form additional calcium silicate hydrate (C–S–H) gel. Furthermore, the combined content of SiO_2, Al_2O_3 (1.53 wt.%), and Fe_2O_3 (2.32 wt.%) was approximately 80.26 wt.%, exceeding the minimum requirement of 70% specified in ASTM C618 for pozzolanic materials. This result confirms the suitability of the produced RHA as a supplementary cementitious material.

Table II: XRF analysis of RHA

Components	Composition (%)
Fe2O3	2.3172
SiO2	76.410
Al2O3	1.528
MgO	1.750
P2O5	2.840
SO3	0.1812
TiO2	0.03642
MnO	0.24728
CaO	2.4224
K2O	2.5159
CuO	0.00187
ZnO	0.10540
Cr2O3	0.00111
PbO	0.00568
Rb2O	0.00780
NiO	0.00210
Cl	0.0598
LOI	3.34758

Minor quantities of CaO (2.42 wt.%), K_2O (2.52 wt.%), MgO (1.75 wt.%), and P_2O_5 (2.84 wt.%) were also detected. These oxides are commonly present in rice husk ash and originate from the natural mineral composition of the rice plant. The presence of calcium and magnesium oxides may contribute to secondary hydration reactions, while potassium oxide is characteristic of agricultural biomass ashes.

The Loss on Ignition (LOI) value of 3.35 wt.% indicates a relatively low amount of residual unburnt carbon, suggesting that the combustion process was effective in producing a well-burnt ash. The low LOI value is advantageous because excessive carbon content can increase water demand and adversely affect the performance of cementitious systems. Additionally, the very low concentrations of trace metal oxides such as CuO, ZnO, Cr_2O_3, PbO, Rb_2O, and NiO indicate that the ash contains negligible levels of potentially undesirable impurities.

Overall, the chemical composition obtained from the XRF analysis demonstrates that the produced RHA possesses the characteristics of a high-silica pozzolanic material and is therefore suitable for use as a supplementary cementitious material in cement and concrete-based applications.

Figure 4 is also the presentation of the XRF analysis result directly obtained from the XRF equipment.

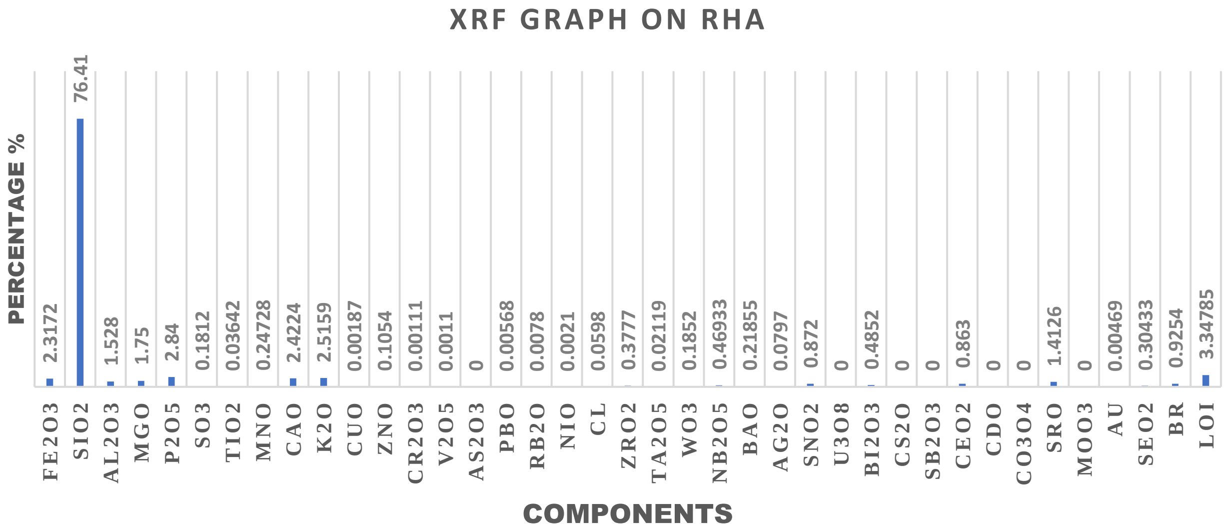

Figure 4: XRF Analysis Of RHA @ 650°C For 2 Hours

C. Compressive Strength

The compressive strength test was conducted to evaluate the mechanical performance of mortar specimens containing varying percentages of rice husk ash (RHA) as a partial replacement material. Compressive strength is one of the most important parameters used to assess the load-bearing capacity and durability of cementitious materials. The specimens were cured for 7, 14, 21, and 28 days before testing to investigate the strength development with curing age. The results obtained provide insight into the influence of RHA incorporation on the hydration process and the overall structural performance of the mortar.

The compressive strength results indicate that both the RHA content and curing duration significantly influenced the strength development of the mortar specimens. The control specimen (0% RHA) exhibited the highest compressive strength at all curing ages, increasing progressively from 28.32 N/mm² at 7 days to 31.32 N/mm² at 28 days. This trend is expected as continued cement hydration produces additional calcium silicate hydrate (C-S-H) gel, leading to a denser microstructure and improved strength.

Table III shows the compressive strength results of the RHA based on the curing time and the percentage replacement, while Figure 5. compare the strength of percentage replacement samples based on the curing time.

Table III: Compressive strength of RHA replacement in mortar

% RHA	Curing Time (days)	Strength (N/mm^2)
0 %	7	28.32
	14	29.20
	21	30.44
	28	31.32
5 %	7	13.08
	14	16.12
	21	22.28
	28	17.08
10 %	7	22.32
	14	25.68
	21	24.04
	28	29.68
15 %	7	16.88
	14	12.44
	21	18.86
	28	12.12
20 %	7	16.48
	14	11.20
	21	17.84
	28	10.92

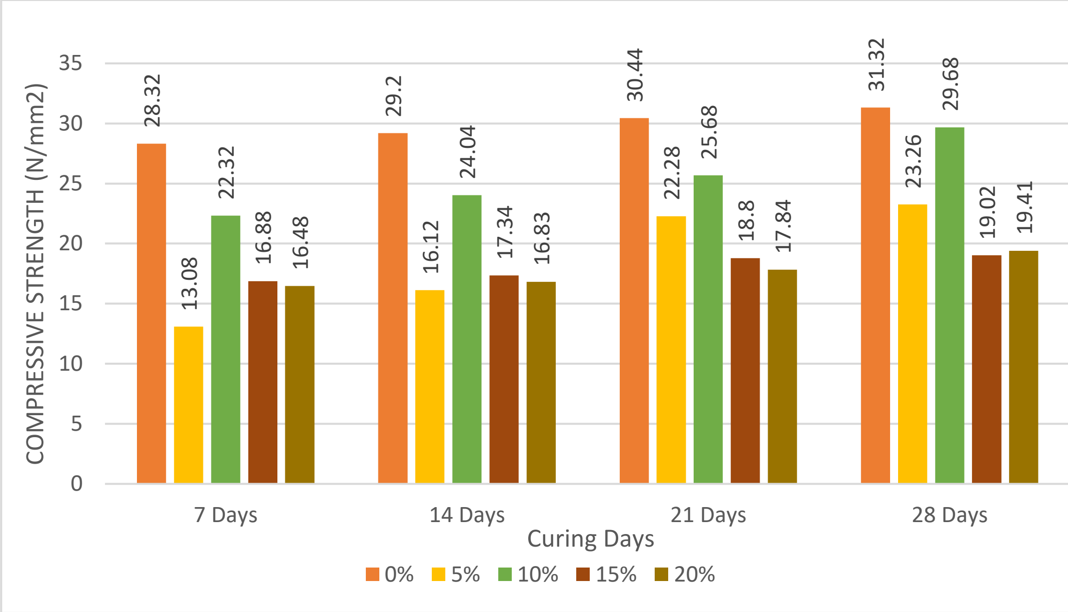

Figure 5: Graph of Compressive Strength

The incorporation of RHA generally resulted in lower compressive strengths compared with the control mix. At 5% RHA replacement, the compressive strength increased from 13.08 N/mm² at 7 days to 22.28 N/mm² at 21 days before decreasing to 17.08 N/mm² at 28 days. Similarly, the 10% RHA mixture exhibited a steady increase in strength with curing age, achieving 29.68 N/mm² at 28 days, which was the highest strength among all RHA-containing mixtures and closely approached the strength of the control specimen. This behaviour suggests that a 10% replacement level may represent the optimum RHA content for the mortar system investigated.

The improved performance observed at 10% RHA can be attributed to the pozzolanic activity of the ash. The high silica content identified by the XRF analysis (76.41% SiO_2) enables the RHA to react with calcium hydroxide released during cement hydration, producing additional C-S-H gel that contributes to strength development, particularly at later curing ages. Furthermore, the fine particles of RHA may improve particle packing and reduce pore spaces within the mortar matrix, resulting in a denser microstructure.

In contrast, higher replacement levels of 15% and 20% RHA produced significantly lower compressive strengths throughout the curing period. The 15% RHA specimens attained strengths of 16.88, 12.44, 18.86, and 12.12 N/mm² at 7, 14, 21, and 28 days, respectively, while the 20% RHA specimens recorded the lowest strengths, ranging from 10.92 to 17.84 N/mm². The reduction in strength at these replacement levels may be attributed to the dilution effect, whereby the amount of cement available for hydration becomes insufficient to compensate for the increased RHA content. Consequently, the pozzolanic reaction alone could not generate enough cementitious products to maintain strength levels comparable to the control mixture.

Overall, the results demonstrate that moderate incorporation of RHA can contribute positively to mortar strength development, while excessive replacement adversely affects mechanical performance. Among the mixtures investigated, the 10% RHA replacement level exhibited the most favourable compressive strength characteristics and may therefore be considered the optimum dosage for achieving a balance between sustainability and mechanical performance.

V. CONCLUSIONS

This study investigated the potential of rice husk ash (RHA) as a sustainable supplementary cementitious material for mortar production. Controlled combustion of rice husks at 650°C for 2 hours successfully produced a silica-rich ash with desirable pozzolanic characteristics. The XRF analysis revealed that the ash contained 76.41% SiO_2, while the combined content of SiO_2, Al_2O_3, and Fe_2O_3 exceeded 80%, satisfying the ASTM C618 requirements for pozzolanic materials. In addition, the low loss on ignition (LOI) value of 3.35% indicated efficient combustion and a low residual carbon content, which is beneficial for cementitious applications.

The compressive strength performance of mortar incorporating different RHA replacement levels demonstrated that the percentage of RHA significantly influences the mechanical properties of the hardened mortar. While all mixes containing RHA developed measurable strength with curing age, the 10% replacement level exhibited the most favourable performance, attaining a 28-day compressive strength of 29.68 N/mm². This value was comparable to that of the control mortar and indicates that the pozzolanic activity of the RHA effectively contributed to strength development through the formation of additional calcium silicate hydrate (C-S-H) gel.

Conversely, replacement levels above 10% resulted in reduced compressive strengths. This reduction can be attributed to the dilution effect associated with the decrease in cement content, as well as the increased water demand commonly associated with high volumes of RHA. At these higher replacement levels, the amount of cementitious products generated was insufficient to compensate for the reduction in cement, leading to lower strength values.

The findings of this study demonstrate that properly processed rice husk ash can be effectively utilized as a partial cement replacement in mortar without significant loss of mechanical performance when used at moderate replacement levels. Among the replacement levels investigated, 10% RHA was identified as the optimum dosage, providing the best balance between strength performance and material sustainability.

From an environmental perspective, the utilization of RHA offers a viable pathway for converting agricultural waste into a value-added construction material. Its incorporation in mortar can reduce cement consumption, lower the environmental burden associated with cement production, minimize agricultural waste disposal challenges, and contribute to the development of more sustainable and eco-friendly construction practices. Therefore, rice husk ash possesses considerable potential as an alternative supplementary cementitious material for sustainable construction applications.

RECOMMENDATIONS

Based on the findings of this study, the following recommendations are made:

i. Rice husk ash (RHA) should be utilized as a partial replacement for cement at a replacement level of approximately 10%, as this proportion exhibited the most favourable compressive strength performance.
ii. Future research should evaluate the effects of different combustion temperatures and burning durations on the chemical composition and performance of rice husk ash in cementitious materials.
iii. Long-term strength development and the performance of RHA in concrete applications should be investigated to determine its suitability for large-scale sustainable construction projects.

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