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Rice Husk Ash-Infused Concrete for Seismic Resilience: Experimental Evaluation of Mechanical Durability, Microstructural Enhancements, and Sustainable Integration in Retrofitted Structures

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Abstract- Rice husk ash (RHA), an agricultural waste rich in reactive silica, has shown strong potential as a supplementary cementitious material. This research investigates the effect of partial replacement of ordinary Portland cement with rice husk ash on the fresh properties, mechanical performance, durability, microstructure, with the aim of developing durable materials suitable for earthquake-resistant structures. In this study, cement was partially replaced with RHA at 5%, 10%, 15%, and 20% by weight. The fresh properties of concrete, including slump, compacting factor, density, and initial surface absorption, were evaluated. Mechanical properties such as compressive strength, splitting tensile strength, and flexural strength were determined at curing ages of 7, 28, and 60 days. Concrete containing 10% RHA exhibited the highest compressive, splitting tensile, and flexural strengths, with maximum improvements of approximately 7.16%, 7.03%, and 3.82%, respectively, compared to conventional concrete. Overall, the findings of this study demonstrate that rice husk ash can be effectively used as a sustainable supplementary cementitious material to produce high-strength, durable, cost-effective, and environmentally friendly concrete.

Keywords: Agricultural waste, Rice husk ash, Sustainable concrete, Cement replacement.

I. INTRODUCTION

The construction industry is currently facing serious challenges due to the environmental impacts associated with conventional cement production. Cement manufacturing requires large quantities of raw materials and energy, which results in high carbon dioxide (CO_2) emissions and depletion of natural resources. Globally, cement production is responsible for nearly 8% of total CO_2 emissions, making it one of the major contributors to climate change.

As urbanization and infrastructure development continue to increase, the demand for cement-based materials is expected to rise further, intensifying environmental concerns.

In countries such as India, where seismic activity is frequent and infrastructure development is rapid, there is an increasing demand for construction materials that can provide both high durability and earthquake resistance. Structures located in seismic regions must be capable of withstanding repeated dynamic loads, limiting crack formation, and maintaining structural integrity during and after earthquake events.

At the same time, these materials should be environmentally sustainable and economically feasible to ensure their long-term use in large-scale construction.

Rice husk ash is an agricultural byproduct obtained from the controlled burning of rice husk, which is abundantly available in rice-producing countries. It contains a high percentage of amorphous silica, typically in the range of 85 to 95 percent, which gives it strong pozzolanic properties. When rice husk ash is used as a partial replacement for cement, it reacts with calcium hydroxide produced during cement hydration and forms additional cementitious compounds. This reaction improves the density and compactness of the concrete matrix, leading to better strength and durability.

The incorporation of rice husk ash in concrete provides several technical advantages. At optimum replacement levels, it enhances compressive, tensile, and flexural strengths, which are essential properties for earthquake-resistant structures. Improved tensile and flexural strengths help control crack development and improve the ability of concrete to dissipate energy during seismic loading. In addition, rice husk ash reduces concrete permeability by refining the pore structure, which limits the ingress of water and harmful chemicals. This reduction in permeability improves resistance to reinforcement corrosion and increases the service life of structures.

This study focuses on the application of rice husk ash–based concrete in earthquake-proof construction, with special attention to its use in retrofitting existing structures. Retrofitting requires materials that are compatible with existing concrete, provide improved mechanical performance, and enhance long-term durability without causing adverse effects. Rice husk ash–modified concrete meets these requirements by improving bonding characteristics, reducing microcracking, and increasing resistance to environmental degradation. Moreover, the use of rice husk ash supports sustainable construction by reducing cement consumption, lowering carbon emissions, and promoting the effective utilization of agricultural waste.

Overall, the use of rice husk ash in concrete offers a sustainable and practical solution for developing high-performance materials suitable for earthquake-resistant and retrofitted structures. By combining improved mechanical properties, enhanced durability, and reduced environmental impact, rice husk ash–based concrete contributes to resilient and environmentally responsible infrastructure development.

II. MATERIAL AND METHODS

Ordinary Portland Cement of 43 grade, conforming to Indian Standard specifications, was used as the primary binding material. Rice husk ash was employed (Figure 1) as a supplementary cementitious material to partially replace cement. \\

The rice husk ash contained approximately 90 percent silica and was finely ground, with the majority of particles smaller than 45 micrometers (Figure 2). Due to its porous nature, rice husk ash exhibited higher water absorption, which influenced the workability of fresh concrete. Natural river sand and crushed stone aggregates conforming to Indian Standard grading limits were used as fine and coarse aggregates, respectively. Potable water was used for mixing and curing of all concrete specimens.

Figure 1: Rice Husk Ash

Concrete mixes were proportioned for M20 grade with a low water–cement ratio of 0.35 to achieve high strength and a dense matrix. Cement was replaced with rice husk ash at 0, 5, 10, 15, and 20 percent by weight, designated as RHA0, RHA5, RHA10, RHA15, and RHA20 as shown in Table 1. Concrete was mixed mechanically to ensure uniform distribution of materials. Standard cube specimens of 100 mm were prepared for compressive strength tests, cylindrical specimens of 100 mm diameter and 200 mm height were cast for splitting tensile strength tests, and prism specimens of 100 × 100 × 500 mm were used for flexural strength evaluation. All specimens were demolded after 24 hours and water cured for 7, 28, and 56 days.

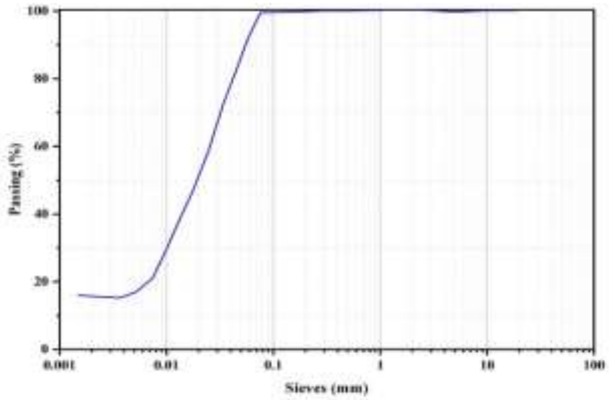


Figure 2: Particle size distribution of RHA

Fresh concrete properties were assessed using slump, compacting factor, and density tests. Mechanical performance was evaluated through compressive, splitting tensile, and flexural strength tests conducted at different curing ages in accordance with Indian Standards. Durability was examined using the initial surface absorption test to evaluate permeability characteristics. Microstructural analysis was performed using scanning electron microscopy at a scale of 10 micrometers to observe pore structure and hydration products. The environmental impact of RHA incorporation was assessed by estimating global warming potential based on material-specific carbon dioxide emission factors.

Table 1: Details of fresh mix concrete

Mix ID	**Replacement (%)**	**Binder**		**Fine Aggregate (kg/m3)**	**Coarse Aggregate (kg/m3)**	**Water (kg/m3)**	**SP (kg/m3)**
		Cement (kg/m3)	RHA (kg/m3)				
RHA 0	0% (plain concrete)	600	-	477	1113	165	3
RHA 5	5%	570	30	477	1113	165	3
RHA 10	10%	540	60	477	1113	165	3
RHA 15	15%	510	90	477	1113	165	3
RHA 20	20%	480	120	477	1113	165	3

III. RESULTS AND DISCUSSIONS

Fresh Properties of RHA-Concrete

The experimental results show a clear reduction in workability with the increase in rice husk ash (RHA) content. The control mix (RHA0) exhibited the highest slump value, while mixes with higher RHA replacement showed progressively lower slump and compacting factor values. This reduction is mainly attributed to the porous and cellular structure of RHA particles, which absorb part of the mixing water and reduce free water availability. Similar observations were reported by Habeeb and Mahmud, who linked reduced workability to the high surface area and water demand of RHA.

Despite the reduced workability, the mixes remained within an acceptable range for high-strength concrete when a constant dosage of superplasticizer was used as shown in Figure 3. This indicates that RHA can be incorporated without compromising constructability, provided appropriate mix control is ensured.

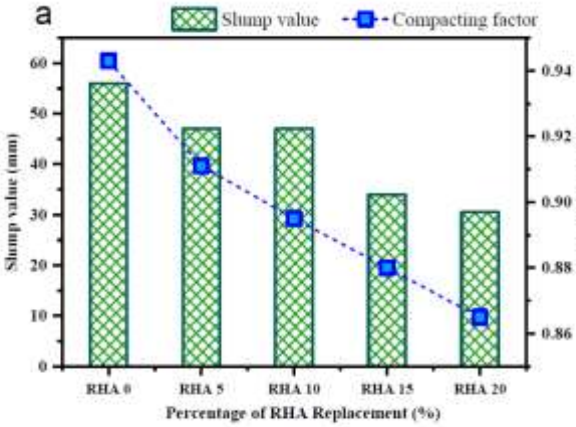


Figure 3: Percentage replacement of RHA

A gradual reduction in fresh concrete density was observed as the RHA replacement level increased.

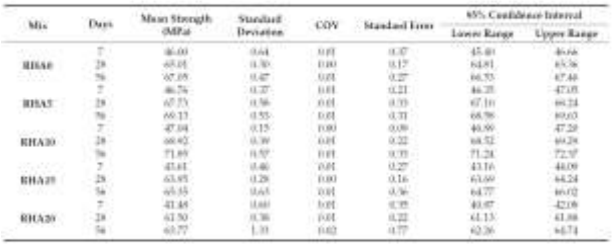
The decrease in density is due to the lower specific gravity of RHA compared to ordinary Portland cement. This trend confirms that RHA contributes to producing slightly lighter concrete, which can be advantageous for seismic applications where reduction in self-weight leads to lower inertia forces during earthquakes. Similar density reductions were noted by Ephraim et al. and Dong et al. for RHA-based concretes.

Compressive strength results demonstrate that RHA significantly influences strength development. Strength increased with RHA replacement up to 10%, after which a decline was observed. The RHA10 mix achieved the highest compressive strength at all curing ages (7, 28, and 56 days), outperforming the control mix.

This improvement is attributed to the pozzolanic reaction between the amorphous silica in RHA and calcium hydroxide released during cement hydration. This reaction produces additional calcium–silicate–hydrate (C–S–H) gel, which fills capillary pores and refines the microstructure (Table 2). Similar mechanisms were reported by Ganesan et al. and Bouzoubaâ and Fournier, who observed enhanced strength and reduced permeability at optimal RHA levels.

At higher replacement levels (15–20%), the reduction in strength is linked to insufficient calcium hydroxide to react with excess silica and increased water demand, as discussed by Chopra and Siddique.

Table 2: Compressive strength results



Mix	Days	Mean Strength (MPa)	Standard Deviation	COV	Standard Error	95% Confidence Interval	
						Lower Range	Upper Range
RHA0	7	46.00	0.64	0.01	0.37	45.41	46.66
	28	65.01	0.30	0.00	0.17	64.81	65.36
	56	67.05	0.47	0.01	0.27	66.53	67.44
RHA5	7	46.74	0.37	0.01	0.21	46.35	47.05
	28	67.73	0.56	0.01	0.33	67.10	68.24
	56	69.13	0.55	0.01	0.31	68.78	69.63
RHA10	7	47.04	0.15	0.00	0.09	46.99	47.29
	28	68.92	0.39	0.01	0.22	68.52	69.28
	56	71.89	0.57	0.01	0.33	71.24	72.37
RHA15	7	43.61	0.46	0.01	0.27	43.16	44.09
	28	63.95	0.28	0.00	0.16	63.69	64.24
	56	65.35	0.63	0.01	0.36	64.77	66.02
RHA20	7	41.48	0.60	0.01	0.35	40.87	42.06
	28	61.50	0.38	0.01	0.22	61.13	61.88
	56	63.77	1.33	0.02	0.77	62.26	64.74

The splitting tensile strength followed a trend similar to compressive strength. An increase was recorded up to 10% RHA replacement, followed by a decrease at higher levels. The improvement in tensile strength at lower RHA contents is due to better interfacial bonding between aggregates and cement paste, caused by pore refinement and micro-filling effects of RHA particles.

These findings are consistent with the observations of Saraswathy and Song, who reported enhanced tensile resistance due to improved microstructural density in RHA-modified concrete as shown in Figure 4.

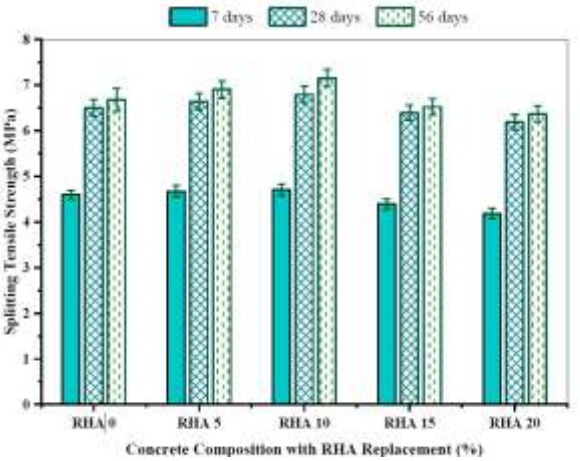


Figure 4: Split tensile test result

Flexural strength results also peaked at 10% RHA replacement. The RHA10 mix showed superior resistance to bending stresses compared to the control mix. This behavior is critical for earthquake-resistant structures, where flexural capacity governs crack control and energy dissipation.

The reduction in flexural strength beyond 10% RHA is again linked to reduced cementitious content and increased porosity at higher replacement levels. Giaccio et al. similarly reported that optimal RHA content improves the interfacial transition zone, while excess replacement weakens it.

Initial surface absorption tests showed a significant reduction in water absorption for RHA-modified concrete, particularly at 10% replacement. Lower absorption values indicate reduced permeability and improved durability. This enhancement is mainly due to pore refinement caused by the pozzolanic reaction and micro-filler effect of fine RHA particles.

Dhir et al. reported similar reductions in surface absorption for pozzolanic concretes, confirming the durability advantage of RHA incorporation SEM images revealed a denser and more homogeneous microstructure in RHA10 concrete compared to the control mix. The presence of well-distributed C–S–H gel and reduced microcracks confirm improved matrix integrity. At higher RHA contents, particle agglomeration was observed, which explains the reduction in mechanical strength.

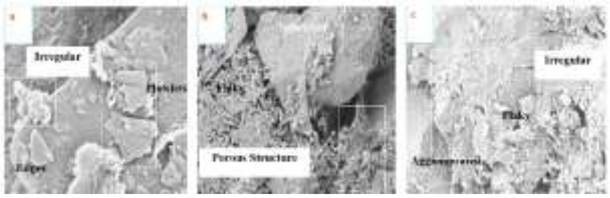


Figure 5: SEM result

These microstructural observations strongly support the mechanical and durability results and align with findings by Yu et al. and Nehdi et al. regarding silica-driven pore refinement in RHA concretes.

Replacing cement with RHA led to a substantial reduction in embodied CO_2 emissions. The RHA20 mix achieved the highest reduction in Global Warming Potential, while the RHA10 mix offered the best balance between strength and environmental efficiency. This eco-strength efficiency concept aligns with the framework proposed by Damineli et al., where strength per unit CO_2 emission is considered a key sustainability indicator.

IV. CONCLUSION

Based on the experimental study and detailed analysis, it can be concluded that the use of rice husk ash affects both the fresh and hardened properties of concrete in a meaningful way. The addition of rice husk ash reduces the workability of fresh concrete because of its porous nature and higher water absorption; however, this issue can be effectively managed by using suitable superplasticizers. As the amount of rice husk ash increases, the density of concrete decreases, which can be advantageous for earthquake-resistant structures since lighter structures experience lower seismic forces. The study identified that replacing 10% of cement with rice husk ash gives the best overall performance, resulting in higher compressive, tensile, and flexural strengths due to improved pozzolanic reactions and better pore filling. Durability of concrete also improves with rice husk ash addition, as shown by reduced surface water absorption and a denser internal structure. Microstructural analysis using SEM confirmed that rice husk ash enhances particle packing and leads to the formation of a compact cement matrix with more binding gel. In addition, the use of rice husk ash significantly lowers carbon dioxide emissions associated with cement production, with the 10% replacement level showing the best balance between strength and environmental benefit. Overall, rice husk ash–based concrete is a sustainable, economical, and practical option for producing high-strength concrete suitable for earthquake-resistant construction.

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