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Sustainable utilization of rice husk ash in concrete: A dual role as pozzolanic and filler material

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Abstract. The sustainable utilization of agricultural by-products in concrete production is essential for reducing environmental impact and enhancing material efficiency. Rice Husk Ash (RHA), a by-product of rice milling, serves a dual role in concrete as both a pozzolanic and filler material. This study investigates the influence of RHA on concrete properties, focusing on its pozzolanic activity and filler effect. RHA was incorporated into concrete at 0%, 5%, 10%, 15%, 20%, and 25% of the cement weight without replacing the cement. After thorough mixing, workability was evaluated through a slump test, while compressive strength was assessed after 7 and 28 days of curing. The results revealed that RHA significantly increased water demand to maintain workability and reduced the unit weight of hardened concrete. However, at an optimal dosage of up to 5%, RHA enhanced compressive strength and modulus of elasticity due to its pozzolanic reaction and particle packing effect. Higher replacement levels negatively impacted strength performance, highlighting the need for a balanced approach in mix design. This study underscores the potential of RHA as a sustainable alternative in concrete, reducing agricultural waste while improving material performance. By leveraging its dual functionality, RHA contributes to environmentally friendly construction practices by incorporating it into concrete production.

Keywords: filler effect; pozzolanic activity; rice husk ash; strength; sustainable concrete

1. Introduction

The construction industry faces mounting pressure to adopt sustainable practices amid growing environmental concerns, particularly regarding cement production's substantial carbon footprint, responsible for 7% of global CO_2 emissions (Shah *et al*. 2021, Rahman *et al*. 2020). Simultaneously, agricultural waste management presents a critical challenge, with approximately 150 million tons of rice husk generated annually from global rice processing (Ricehuskash 2021, Sandhu and Siddique 2017). This dual crisis has spurred interest in Rice Husk Ash (RHA), a silica-rich byproduct obtained from controlled combustion of rice husks, which demonstrates remarkable potential as a multifunctional concrete additive.

Unlike previous studies focusing on RHA as an additive material, this investigation explores its novel dual role as both the pozzolanic activator and a physical filler when incorporated alongside cement, offering fresh insights into sustainable concrete design. Traditional disposal methods for rice husk, either through open-air burning or landfilling, generate particulate matter and methane emissions while wasting a valuable silica resource (Zerbino *et al*. 2011). The utilization of rice husk ash (RHA) in concrete enables a practical way to both reduce environmental damage from the disposal of industrial byproducts and make sustainable use of agricultural waste (Annadurai *et al*. 2020).

RHA's composition (80-95% amorphous silica) enables it to address both challenges simultaneously through two key mechanisms: Pozzolanic Reactivity: Silica in RHA chemically reacts with calcium hydroxide from cement hydration, forming additional calcium-silicate-hydrate (C-S-H) gels. Microfiller Effect: Submicron RHA particles (10-75 μm) physically densify the cement matrix through improved particle packing (Cordeiro *et al*. 2009, Karthik *et al*. 2017, Panda and Prusty 2015). RHA's efficacy is mostly dependent on how it is prepared for burning, which has a big impact on the amount of amorphous silica and, in turn, its pozzolanic activity in concrete (Isberto *et al*. 2019). Concrete's three-phase structure: cement paste, aggregate, and interfacial transition zone (ITZ), undergoes significant modification with RHA incorporation. The ITZ, typically the weakest region due to porosity and crystalline hydroxide formation, becomes reinforced through the following three mechanisms: i) Pore refinement mechanism indicating RHA particles reduce average pore diameter from 50-100 nm to 10-30 nm. ii) The hydration acceleration mechanism indicates that nucleation sites on RHA surfaces promote early C-S-H formation. iii) The crack bridging mechanism indicates that angular RHA particles physically intercept microcracks in the ITZ.

The changes in pore structure and ITZ are directly linked to improvements in concrete strength. The addition of pozzolanic materials reduces concrete porosity, particularly in the weakest areas, such as the interfaces between the cement paste and aggregates. Reduced pore volume results from microaggregate filling and the

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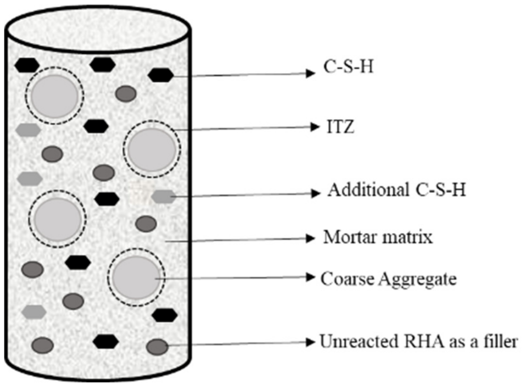


Fig. 1 Concrete matrix after the addition of RHA

pozzolanic reaction. It also helps to densify the microstructure, thereby reducing water permeability and chloride diffusivity. Fine RHA particles fill the spaces between cement grains, making the paste denser. The formation of additional C-S-H through the reaction between cement and pozzolanic additives further enhances the concrete's microstructure and strength (Meddah *et al*. 2010, Duan *et al*. 2013, Al-Amoudi *et al*. 2019). Fig. 1 illustrates the concrete matrix, mortar, aggregate, ITZ, and C-S-H gel, highlighting the additional C-S-H formation and filler effect following RHA incorporation.

Extensive research has examined the use of RHA as a partial cement replacement in concrete, primarily focusing on its effects on mechanical properties and durability (Sathawane *et al*. 2013, Al-Alwan *et al*. 2024, Umasabor and Okovido 2018). In the context of self-healing concrete, the incorporation of bacteria has emerged as a promising bio-based approach for autonomously repairing cracks and sustaining structural integrity over time (Shadhar *et al*. 2023). When combined with Rice Husk Ash (RHA), the bacterial concrete exhibits improved compressive strength characteristics (Solarte *et al*. 2024). Most studies have explored 10–30% cement substitution, potentially overlooking the benefits of RHA-cement synergy in combined systems where RHA acts as an additional component rather than a replacement. The addition of RHA to concrete introduces a dual mechanism: fine RHA particles contribute to the pozzolanic reaction at the micro level, while larger particles enhance crack bridging at the macro level and improve the filler effect.

Despite its potential versatility in structural applications, the optimal RHA content for maximizing concrete strength remains unexplored. Determining the RHA percentage that delivers the best overall performance requires further investigation through systematic variation of RHA content in concrete. By systematically varying the RHA content within the mix, this research aims to assess its impact on key concrete properties, contributing to the sustainable utilization of RHA waste in construction materials.

As discussed, critical knowledge gaps persist regarding RHA's optimal utilization without cement replacement. This study breaks new ground by investigating RHA's dual functionality as a cement complement rather than a substitute. Through systematic incorporation of 0–25% RHA (by cement weight), we evaluated workability trade-offs versus strength gains, microstructural evolution via ITZ modification, and sustainability metrics, including compressive strength, modulus of elasticity, and cracking behavior.

1.1 Research significance

This study is significant for several reasons. Firstly, it contributes to sustainable waste management by promoting the beneficial use of RHA, thereby mitigating the environmental issues associated with its disposal. Secondly, it offers an eco-friendly pathway for improving the structural performance of conventional concrete. By evaluating both the pozzolanic and filler characteristics of RHA, the study supports a more eco-efficient approach to concrete mix design that aligns with global sustainability goals. The novelty of this research lies in its dual-perspective evaluation of RHA, where it is incorporated in addition to cement (rather than as a replacement). Unlike traditional studies, this research focuses solely on RHA as an additive and reveals how optimized RHA dosages (particularly up to 5%) can enhance the mechanical properties of concrete through improved particle packing and secondary cementitious reactions. This nuanced approach advances existing knowledge by providing new insights into mix optimization strategies that harness both the chemical and physical benefits of RHA. Additionally, the identification of performance thresholds beyond which RHA negatively affects strength offers critical guidance for practical implementation in the field. This research not only advances the scientific understanding of RHA's multifunctional role in concrete but also provides actionable pathways toward sustainable and high-performance construction materials.

2. Materials and methods

The materials used were cement, fine aggregate, coarse aggregate, rice husk ash, and water.

2.1 Cement

Locally available Ordinary Portland Cement (OPC) was used for the experiment. Table 1 shows the physical and chemical properties of cement. The particle size distribution curve of OPC is shown in Fig. 2.

2.2 Rice Husk Ash (RHA)

The rice husk ash production process was operated in a factory building of the Make Integrated Technology (M.I.T.) company in Osaka, Japan, using an industrial machine device. Unlike traditional incinerators, this machine operates as a natural-type silica generator, eliminating the need for combustible materials such as gas, kerosene, or electricity. Instead, solid methanol fuel is used to ignite and burn the rice husks. This innovative process is environmentally friendly, as it does not produce dioxins, making it exempt from the Fire Services Act. The burning speed and temperature are meticulously controlled by a computer,

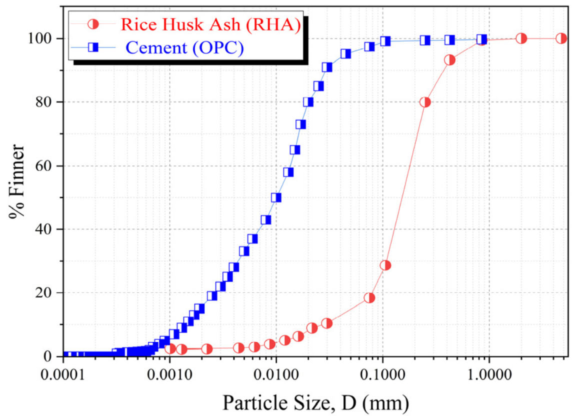


Fig. 2 Particle size distribution of rice husk ash and ordinary Portland cement

Table 1 Physical and chemical properties of OPC

Physical properties	Values
Initial setting time (minutes)	170
Final setting time (minutes)	225
Specific gravity (g/cm^3)	3.15
Specific surface area (m^2/kg)	340
28-day compressive strength (MPa)	33-35
Loss of ignition (%)	<4
Chemical properties	**Values (%)**
Silica (SiO_2)	63.40
Calcium Oxide (CaO)	21.6
Iron Oxide (Fe_2O_3)	5.35
Alumina (Al_2O_3)	4.45
Magnesium oxide (MgO)	1.65
Others	3.55

Table 2 Physical and chemical properties of RHA

Physical properties	Values
Specific gravity	1.47
Average particle size (mm)	0.001 to 0.30
Loss of ignition	4.00 to 6.00
Chemical properties	**Values (%)**
Silica (SiO_2)	91.10
Carbon dioxide (CO_2)	4.35
Potassium Oxide (K_2O)	2.40
Calcium Oxide (CaO)	0.57
Iron Oxide (Fe_2O_3)	0.05
Alumina (Al_2O_3)	0.03
Others	1.50

reducing labor costs and minimizing personnel requirements. Additionally, the system can be remotely controlled, offering further convenience in managing the incineration process. Fig. 2 shows the Particle size distribution curve, and Table 2 shows the physical and chemical composition of RHA.

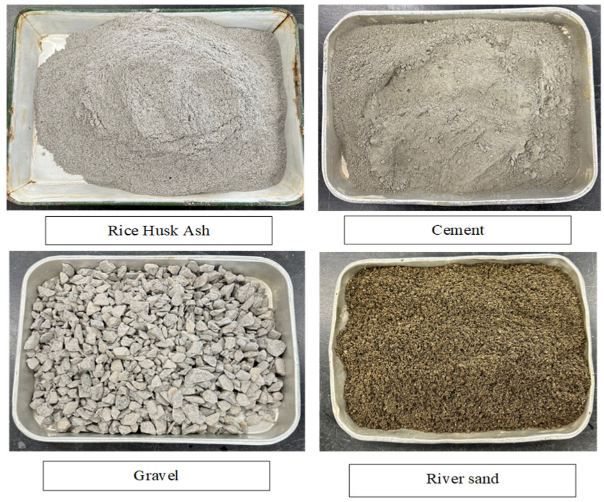


Fig. 3 Raw materials for the concrete mixture

2.3 Aggregates

River sand was used as fine aggregate, and gravel was used as coarse aggregate. The maximum size of coarse aggregate was 19 mm. Both were purchased at a home center in Tsu City, Japan. The raw materials are shown in Fig. 3.

2.4 Mixture proportioning

In this study, the concrete mixture was prepared using a mix ratio of 1:1:3 by weight for cement, fine aggregate (sand), and coarse aggregate (gravel). Rice husk ash (RHA) was added to the concrete mix at percentages of 0%, 5%, 10%, 15%, 20%, and 25% of the total weight of the cement. The water-cement ratio was precisely calibrated to achieve a consistent slump of 8 ± 1 cm, ensuring the concrete mixture exhibited medium workability. Table 3 presents the mixing amount of concrete materials. The experimental procedures are illustrated in Fig. 4.

2.5 Testing program

2.5.1 Slump test

The slump test was done to evaluate the workability of fresh concrete. A slump cone with standardized dimensions (300 mm in height, a bottom diameter of 200 mm, and a top diameter of 100 mm) was used for this test. The cone was filled in three layers, with each layer being tamped 25 times using a rod with a diameter of 16 mm. After filling the cone, the surface was leveled off. Then, the cone was lifted vertically, and the vertical difference between the height of the cone and the highest point of the slumped concrete was measured as the slump value.

2.5.2 Unit weight

The unit weight of hardened concrete was calculated using the following equation.

Table 3 Mix design for concrete

Specimen identity	RHA (%)	W/C ratio	Cement (kg/m^3)	RHA (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)
CRHA0	0	0.50	290	0	308	852
CRHA5	5	0.60	290	14.5	308	852
CRHA10	10	0.70	290	29	308	852
CRHA15	15	0.75	290	43.5	308	852
CRHA20	20	0.80	290	58	308	852
CRHA25	25	0.95	290	72.5	308	852

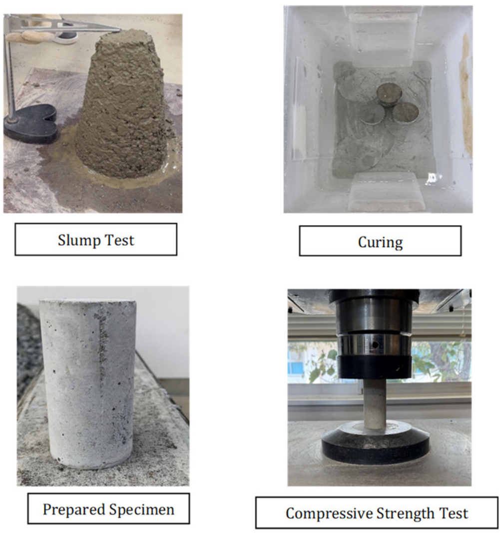


Fig. 4 Specimen preparation and testing

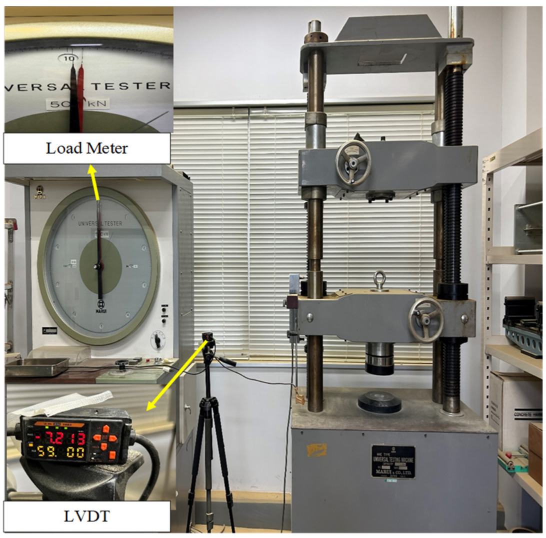


Fig. 5 Universal testing machine for compressive strength test

$$\text{Unit wight} = \frac{M}{V}$$

Where
M is the dry weight (g) and
V is the dry volume (cm^3) of the sample.

Table 4 Slump value, water/cement ratio at Different RHA content

RHA (%)	W/C ratio	Slump value (cm)
0	0.50	8 ± 1
5	0.60	8 ± 1
10	0.70	8 ± 1
15	0.75	8 ± 1
20	0.80	8 ± 1
25	0.95	8 ± 1

2.5.6 Compressive Strength Test

Concrete cylinders 50 mm by 100 mm were used to determine the compressive strength. Tap water was used to cure these cylinders, which were immersed in water throughout the curing process. The test was conducted at 7 and 28 days of curing, and compressive strengths were determined according to ASTM C39 using the Universal Testing Machine shown in Fig. 5. Three cylindrical specimens were used for each test condition. The data presented in the graph represents the mean value obtained from three specimens.

3. Results and discussion

3.1 Workability of concrete

After thoroughly mixing the fresh concrete, a slump test was performed to assess its workability. Table 4 represents the slump value and water-cement ratio at different RHA percentages. Adding rice husk ash (RHA) significantly reduced the slump value. As a result, the water-cement (W/C) ratio had to be increased continuously with the rising percentages of RHA to attain a targeted slump. The slump of concrete was maintained at 8 ± 1 mm. For every 5% increase in RHA, the required amount of water increased by about 8%. The linear relationship between the required W/C ratio and RHA percentage is shown in Fig. 6. The RHA content varied from 0% to 25%, while the corresponding W/C ratio ranged from 0.50 to 0.95. This trend indicates a notable increase in water requirements at higher levels of RHA. This finding is consistent with other studies (Khan *et al*. 2012, Singh *et al*. 2021) that showed a rising water demand as the proportion of RHA in concrete increases. The higher water requirements for RHA concrete can be

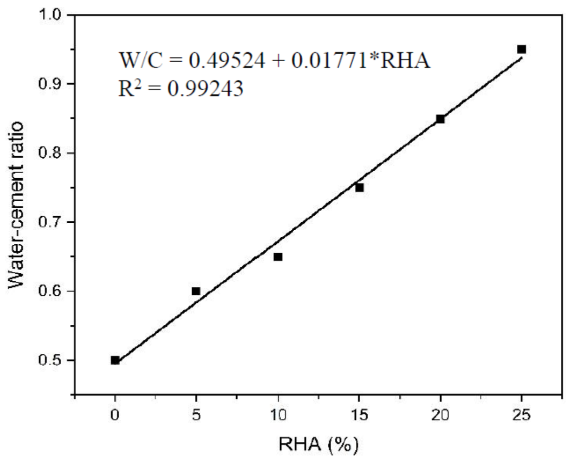


Fig. 6 Relationship between RHA content and the water-cement ratio

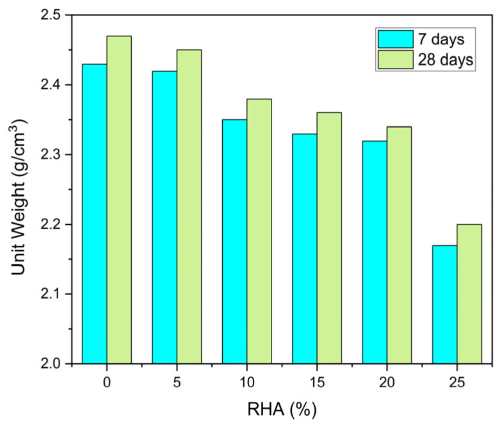


Fig. 7 Effect of the addition of RHA on the unit weight of concrete

attributed to the fine particle size, large surface area, and irregular shape of the RHA particles.

3.2 Unit weight

The changes in the unit weight of the concrete resulting from the addition of rice husk ash (RHA) are shown in Fig. 7. As the RHA content increased, the unit weight of the concrete decreased significantly. Specifically, at 7 days, the unit weight decreased from 2.43 to 2.17 g/cm³, and at 28 days, it dropped from 2.47 to 2.20 g/cm³ as the RHA content increased from 0% to 25%. The addition of 25% RHA led to an approximate 11% reduction in unit weight. This trend is also supported by previous research. The reduction in unit weight can be attributed to the lower density of RHA compared to Portland cement (Ameri *et al.* 2019). Additionally, the pozzolanic reaction between RHA and the hydrated products of cement produces calcium silicate hydrates (CSH) that have a lower density. Consequently, this lower-density CSH gel fills the pores, further contributing to the reduced unit weight of the final concrete (De Sensale 2010, Monteiro 2006).

3.3 Compressive strength

The influence of RHA content on the compressive strength of concrete after 7 and 28 days of curing, as presented in Fig. 8. Incorporating up to 5% RHA significantly enhanced compressive strength, surpassing that of the control specimen (CRHA0) at both 7 and 28 days of curing. Beyond this optimal threshold, strength exhibited a progressive decline across both curing periods. Although CRHA10 and CRHA15 maintained strengths above the minimum structural requirement, higher RHA ratios (CRHA20 and CRHA25) showed notable reductions. While previous studies (Adnan *et al.* 2022, Ganesan *et al.* 2008) have demonstrated that RHA is an adequate cement substitution at 5–15%, with 15% achieving a 26% increase in compressive strength, this study highlighted that adding up to 5% RHA without replacing cement improved strength by 48.5%, after which a decremental trend was observed. The enhancement in strength may be attributed to the filling effect and pozzolanic reactions of RHA, which reduce porosity and decrease the interfacial transition zone (ITZ) width between the cement paste and the aggregate, thereby improving the concrete's strength performance. However, excessive RHA increases water demand, exacerbating capillary porosity and impairing strength.

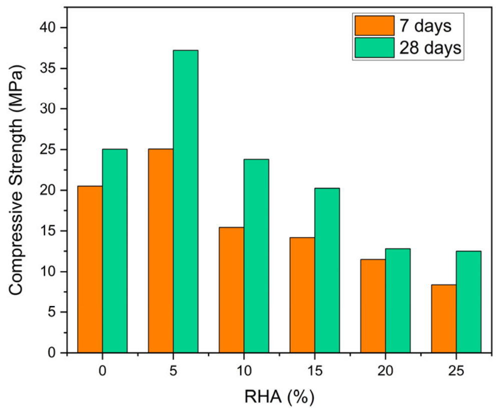


Fig. 8 Effect of the Addition of RHA on the Compressive Strength of Concrete

3.4 Correlation among W/C ratio, RHA content, and compressive strength

The comparison among the Rice Husk Ash (RHA) percentages, water-cement ratio, and compressive strength at 28 days of curing is displayed in Fig. 9. The water-cement ratio showed an increasing trend with an increment of RHA percentage, whereas the strength increased up to 5% of RHA and then continuously reduced. The rising water-cement ratio contributes to lower strength at higher RHA percentages due to increased porosity in the mix. RHA contains a high amount of silica and is highly porous with a large surface area. This increases the demand for water to ensure proper workability in the mix. Small amounts of RHA contribute to the pozzolanic reaction. The silica in RHA reacts with calcium hydroxide produced during cement hydration to form additional calcium silicate hydrate (C-S-H), which improves strength. Around 5% RHA is ideal for maximizing compressive strength while

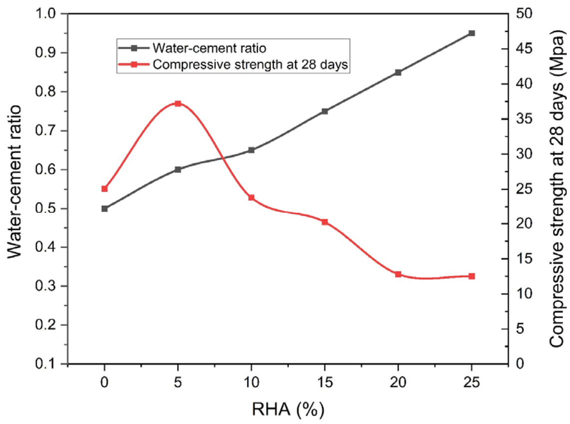


Fig. 9 Relationship between compressive strength and water-cement ratio at different RHA content

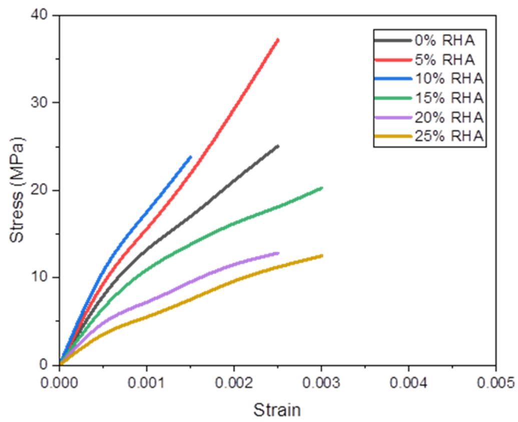


Fig. 10 Stress-strain relationship under uniaxial compression

maintaining a manageable water-cement ratio.

3.5 Stress-strain relationship

The stress-strain behavior of a cylindrical concrete sample measuring 50×100 mm was evaluated under uniaxial compression after 28 days of curing. Fig. 10 compares stress-strain curves between ordinary and RHA blended concrete up to the ultimate stress. The control specimen (CRHA0) exhibited a two-stage linear response, with peak stress occurring at a strain of 0.0025. When 5% RHA was added, the curve became steeper than that of the control sample and achieved the highest peak stress of 37.2 MPa. The CRHA10 showed more steeping behavior, but its peak stress was lower than that of the 5% RHA and the control sample. Beyond 10% RHA, a distinctly different behavior emerged. Adding 15% RHA improved ductility but with lower stress-bearing capacity compared to the control, 5%, and 10% RHA samples. When the RHA content increased to 20% and 25%, the concrete exhibited a more ductile nature, albeit with reduced stress values. Overall, incorporating RHA increases the material's stress-bearing capacity by up to 5% RHA. The superior performance of the CRHA5 specimen can be attributed to optimizing particle packing, pozzolanic reactivity, and

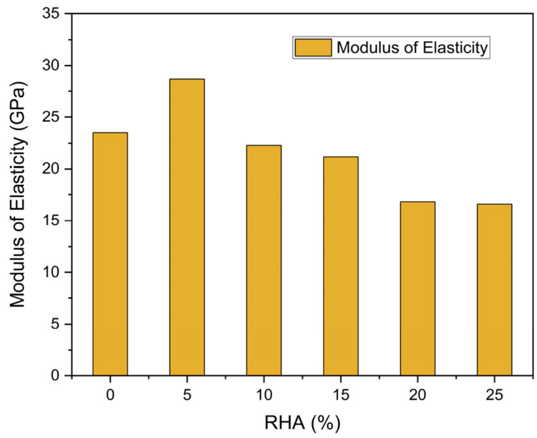


Fig. 11 Effect of the addition of RHA on the modulus of elasticity of concrete

microstructural enhancements.

3.6 Modulus of elasticity

The modulus of elasticity is an important parameter for evaluating a structure's behavior under stress. According to the American Concrete Code (ACI 318 M-95), the Modulus of elasticity can be obtained from Eq. (1) where f_c = Maximum stress. The trend of modulus of elasticity variation with RHA percentage after 28 days of curing is shown in Fig. 11.

Modulus of Elasticity,

$$Ec = 4700\sqrt{fc}$$

Where,

fc = Compressive strength
Ec = Modulus of Elasticity

The modulus of elasticity increased with the level of rice husk ash (RHA) up to 5%, after which it began to decline. When 5% RHA was added, the modulus of elasticity increased by approximately 22%. In contrast, introducing 25% RHA resulted in a decrease of around 30% compared to the control sample. The improvement in modulus of elasticity with a small amount of RHA can be attributed to the amorphous silica in RHA, which enhances the pozzolanic reaction, resulting in a denser and stiffer matrix. However, concrete with a high RHA content tends to exhibit more non-linear stress-strain behavior, leading to softer deformation under stress and, consequently, a lower modulus of elasticity. Previous research (Raisi *et al.* 2018) has also shown that using RHA as a cement substitute initially increases the modulus of elasticity by 5%, but this effect tends to decline with higher concentrations.

3.7 Strength efficiency of cement and environmental sustainability

Cement strength efficiency, expressed in MPa/kg/m^3 of cement, represents the amount of strength gained per unit weight of cement used (Chao-Lung *et al.* 2011). Fig. 12 illustrates how cement efficiency changes with increasing percentages of rice husk ash (RHA) after 7 and 28 days of

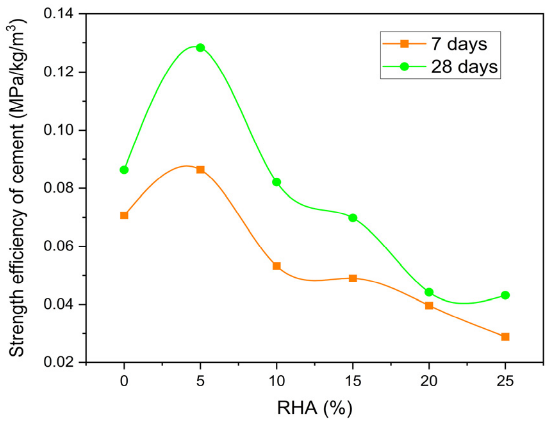


Fig. 12 Modification of the strength efficiency of cement with the addition of RHA

curing. Incorporating up to 5% RHA had a positive impact,significantly enhancing cement efficiency at both curing periods. This improvement can be ascribed to the synergistic effect of the silica-rich RHA admixtures. However, further increases in RHA content led to a gradual decline in the strength efficiency of cement. This reduction may be attributed to the detrimental effects of a higher water-cement ratio and a shortage of calcium hydroxide produced in cement hydration that reacts with RHA silica in the pozzolanic reaction. This result also highlights the environmental and sustainability benefits of integrating RHA into concrete. Attaining an equivalent level of compressive strength without incorporating RHA would require a higher cement dosage, leading to an increase in overall cement consumption. This elevated cement production contributes to greater CO_2 emissions, which represents a critical environmental concern (Shadhar *et al.* 2024). Moreover, the inadequate formation of calcium silicate hydrate (C–S–H) in conventional cement concrete results in a relatively weak and porous microstructure, thereby compromising its mechanical performance. Conversely, the addition of RHA into concrete enhances strength performance by refining the microstructure through pozzolanic reactions that generate additional C–S–H gel, as well as by filling microvoids with unreacted silica particles. This approach not only strengthens the matrix but also promotes sustainable waste management by utilizing agricultural by-products. Consequently, the use of RHA can significantly reduce the reliance on cement, mitigate environmental impact, and advance sustainable construction practices.

3.8 Failure mode

Fig. 13 shows the failure patterns of concrete made with Ordinary Portland Cement (OPC) and concrete containing 5% rice husk ash under uniaxial compression test after 28 days of curing. Significant damage has been observed in the OPC concrete, which is characterized by widespread cracking. On the other hand, the RHA-treated concrete exhibits fewer fractures and maintains more structural stability. The improved performance of the RHA concrete can be attributed to calcium silicate hydrate (C-S-H) gel by the pozzolanic effect and filling the pores with small particles of RHA. This resulted in a denser microstructure and increased resistance to crack propagation.

3.9 Scanning Electron Microscopy (SEM) Analysis

The microstructure of concrete containing 0% RHA (control) and 5% RHA is shown in Fig. 14. The control concrete exhibited a relatively porous microstructure with noticeable voids, indicating weakly bonded interfacial transition zones (ITZ) between the aggregates and cement paste. The porous structure of concrete matrix reflects the absence of pozzolanic activity, resulting in inadequate formation of calcium silicate hydrate (C–S–H) around the aggregate interfaces. In contrast, the incorporation of RHA contributed to a reduced porous nature and formed a densified matrix through the synergistic effects of pozzolanic reactions and filler action. The reactive silica in RHA interacted with $Ca(OH)_2$ to form a substantial amount of calcium silicate hydrate (C–S–H) gel, which effectively bridged internal voids. Meanwhile, the unreactive portion of RHA served as a micro-filler, further reducing porosity. This led to the development of a refined and compact interfacial transition zone (ITZ) and a denser cementitious matrix, which collectively enhanced the overall strength performance of the concrete.

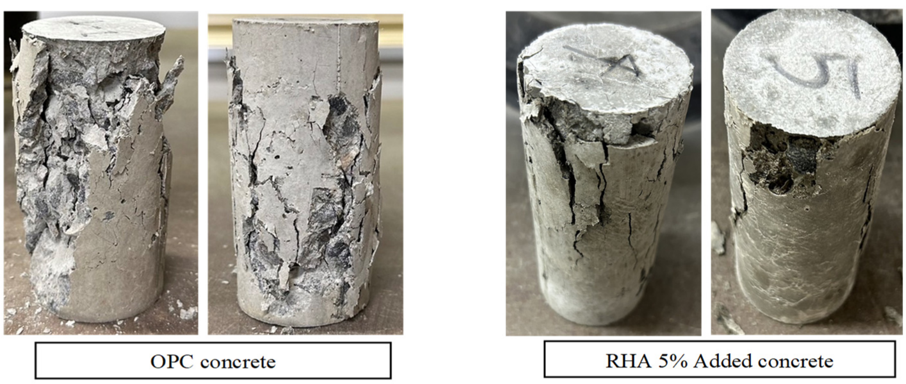
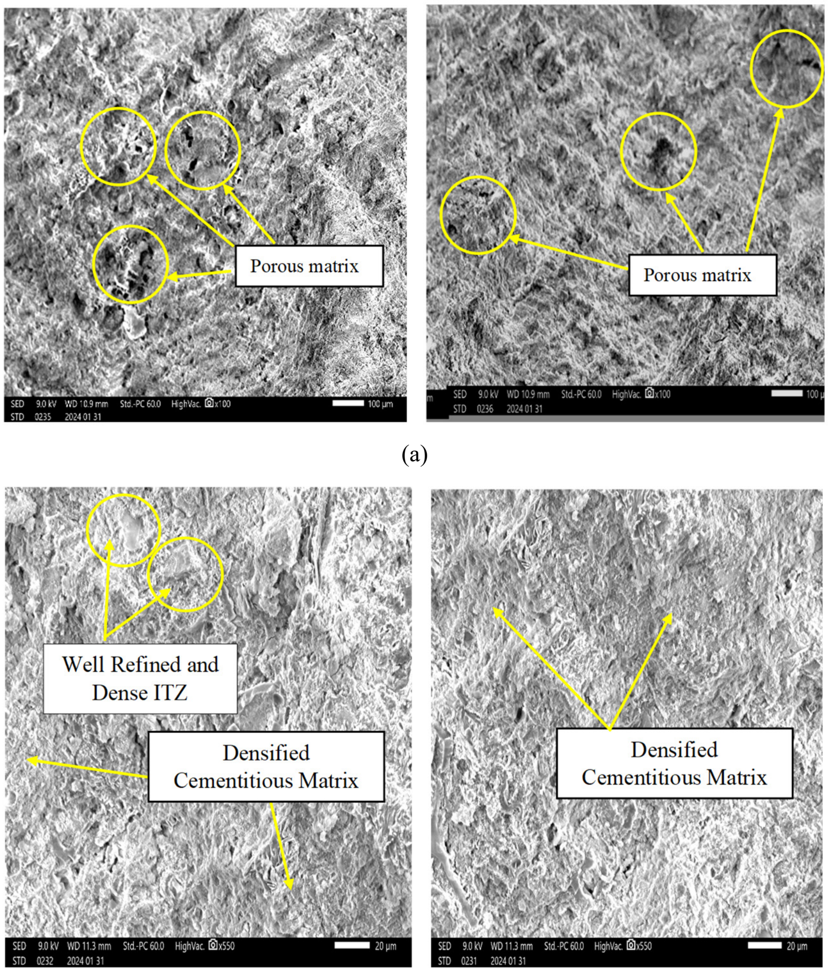


Fig. 13 Failure modes of the specimen under compression test



(a) (b)

Fig. 14 Microstructure of (a) 0% RHA (control); and (b) 5% RHA concrete after 28 days of curing

4. Conclusions

Based on the investigations into the properties of concrete incorporating rice husk ash (RHA), the following conclusions can be drawn:

- The incorporation of rice husk ash (RHA) in small quantities significantly enhances the concrete microstructure, resulting in a marked improvement in mechanical properties with resistance to cracking.
- However, the fine particle nature of RHA increases water demand to achieve the desired workability, which leads to a reduction in strength performance. This challenge can be effectively mitigated by the addition of superplasticizers, which optimize water usage while preserving both workability and strength.
- Additionally, as RHA content increases, a reduction in unit weight is observed, highlighting its potential for producing lightweight concrete.
- Utilization of RHA as an additive in cementitious materials has a significant positive impact on the strength efficiency of cement.
- Therefore, utilizing the pozzolanic properties of rice husk ash (RHA) provides an effective solution to address environmental and disposal challenges linked to rice husk ash waste, fostering an eco-friendly and sustainable approach to construction materials.

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