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Article

Rice Husk Ash Concrete: A Circular Economy Framework Integrating Material Performance, Management and Accounting for Sustainable Construction

P. HemaBindu[1], R.R.L.Birali[2]*

[1]Shri Rawatpura Sarkar University, Raipur, CG, India
[2]MATS University, Arang, Raipur Chhattisgarh - 493441
[1]Email: phemabindu@gmail.com, [2]Email: rathan_lal@yahoo.com
Corresponding Mail: rathan_lal@yahoo.com

Abstract: The increasing environmental concerns associated with cement production have encouraged the development of sustainable cementitious materials utilizing agricultural waste products. This study investigates the performance of Rice Husk Ash (RHA) as a partial replacement for Ordinary Portland Cement (OPC) in concrete. Concrete mixes containing 0%, 5%, 10%, 15%, 20%, and 25% RHA were prepared and tested after 7, 14, 28, and 56 days of curing. The mechanical property such as compression strength, flexural strength, split tensile strength, durability parameters like water absorption, chloride penetration and acid resistance were examined. The results showed that strength has been improved with curing ages for all the mixes, where the RHA-10 mix has the highest compressive strength value of 53.1MPa, flexural strength value of 6.38 MPa and split tensile strength value of 4.70 MPa at 56 days. The durability performance was also greatly enhanced characteristics such as water absorption (3.90%), chloride penetration (10.8 mm) and minimum acid induced weight loss (3.5%) at 56 days were obtained. Microstructural analysis showed that a denser matrix was formed because the pozzolanic activity was enhanced. In addition, RHA incorporation resulted in a decrease in energy demand, production costs, CO_2 emissions and cement use. Hence, the present results showed that RHA can be employed in the concrete sector as a potential source of income for the development of sustainable high-performance concrete. This research evaluates the technical, economic, and environmental viability of Rice Husk Ash concrete by integrating experimental data with management accounting and supply chain approaches. Laboratory results reveal that 20% cement replacement with RHA provides the highest compressive strength. At this level, material expenses decrease by 11.2% and carbon emissions drop by 24.2%, with no compromise in structural performance. For practical implementation, a 4-stage RHA management model is proposed covering husk procurement, controlled incineration and milling, quality testing per IS 456, and delivery to ready-mix concrete units. Centralized purchasing and inventory practices ensure uniform quality and minimize supply disruptions. Economic assessment was carried out using Life Cycle Costing and Activity-Based Costing, while logistics were examined for feasibility. A decision support system for RHA mix proportioning was also developed. The findings offer guidance for construction managers to adopt circular economy models by converting agricultural waste into valuable building material.

Keywords: Rice Husk Ash, Circular Economy, Management Accounting, Cost-Benefit Analysis, Supply Chain, Sustainable Construction

1. Introduction

The construction industry is one of the industries that consumes a lot of natural resources and is a major contributor to the environmental pollution because of the extensive use of ordinary Portland cement (OPC) [1]. The cement industry consumes a tremendous amount of energy, and generates considerable carbon dioxide (CO_2) emissions into the atmosphere, contributing to global warming and environmental degradation [2]. The necessity of sustainable development and eco-friendly construction materials has led researchers and engineers to constantly search for alternate supplementary cementitious materials (SCMs) which can be partially used to replace cement without affecting the durability and mechanical properties of concrete [3, 4]. RHA is one of the most promising sustainable materials due to its high silica content and pozzolanic properties among the many agricultural and industrial wastes [5]. By using RHA in cementitious materials, the environmental pollution resulting from the disposal of agricultural waste can be reduced, and a green and sustainable building material can be achieved.

Rice is one of the most important crops cultivated worldwide, especially in India, China, Thailand, Indonesia, and Vietnam [6]. Rice husk is an agricultural waste product which is produced during the milling process for rice. In general, rice husk is around 20% of the total weight of the harvested rice [7]. RHA is produced when this husk is burned under a controlled condition and it has high amorphous silica content. Rice husk waste disposal or open burning generates badly high environmental and health problems from air pollution and land pollution [8]. Thus, rice husk can be effectively used as cement replacement material and the RHA can be used as a waste management solution and promote the ideas of circular economy and sustainable engineering [9]. The use of RHA in cementitious composites can help to minimize landfill waste and improve the utilization of agricultural waste.Similar studies on reinforced bottom ash-based geomaterials have also demonstrated the effectiveness of incorporating waste materials to improve engineering performance while promoting sustainable construction practices [10].

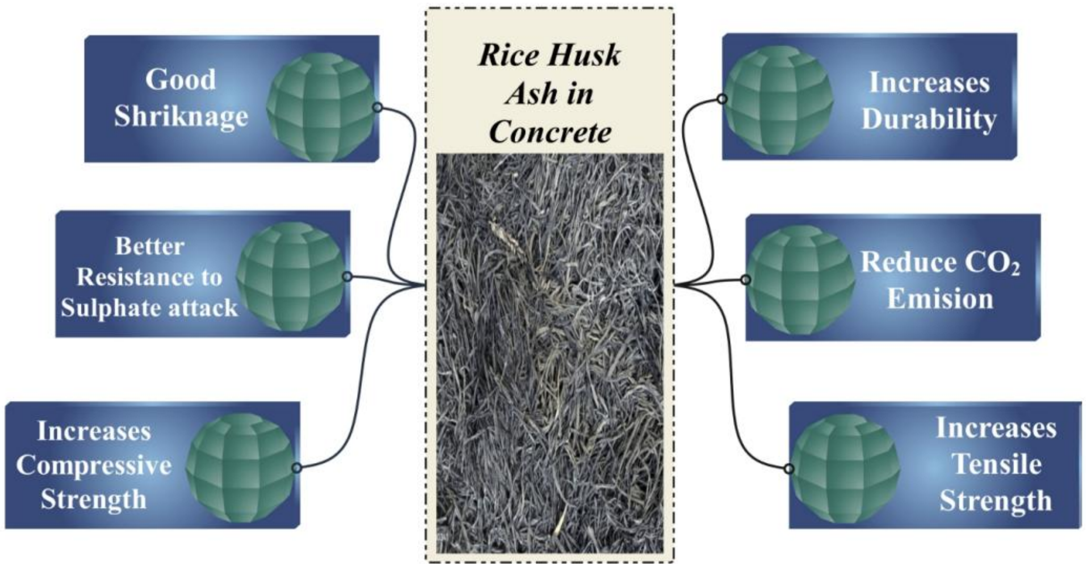

Figure 1: Advantages of the RHA in properties of concrete[11].

The chemical composition, fineness, burning temperature, and processing method are the key factors affecting the performance of RHA as a cementitious material. As a result of these reactive silica properties, RHA exhibits high pozzolanic activity and is able to provide extra calcium silicate hydrate (C-S-H) gel formation with calcium hydroxide produced during the hydration of the cement [12]. This secondary hydration reaction leads to a more compacted microstructure of the concrete matrix and thus to better strength and durability properties [13]. It has been reported that the incorporation of RHA in the cement causes a resulting increase in compressive strength, decrease in permeability, resistance to chemical attack by sulfate, acid exposure and resistance to chloride ion penetration in several studies [14]. Besides, smaller particle size of RHA can be beneficial to fill the micro-voids left in concrete, resulting in better particle packing density and lower porosity.

Recently, the consumption of sustainable and performing construction materials has increased due to intense urbanization and infrastructure development [15]. Many studies focus on the optimal content of RHA in mortar and concrete mixtures to get an optimum compromise between sustainability and engineering properties [16]. Usually, the RHA replacement is in the range from 5% to 30%, depending on the application and desired properties. Low replacement values often contribute to increase mechanical properties and workability, while high values can compromise on set time and water requirement due to the porous nature and big surface area of the RHA particles [17]. Hence, an appropriate mix design and process are important for maximizing the benefits of RHA-based cementitious materials.

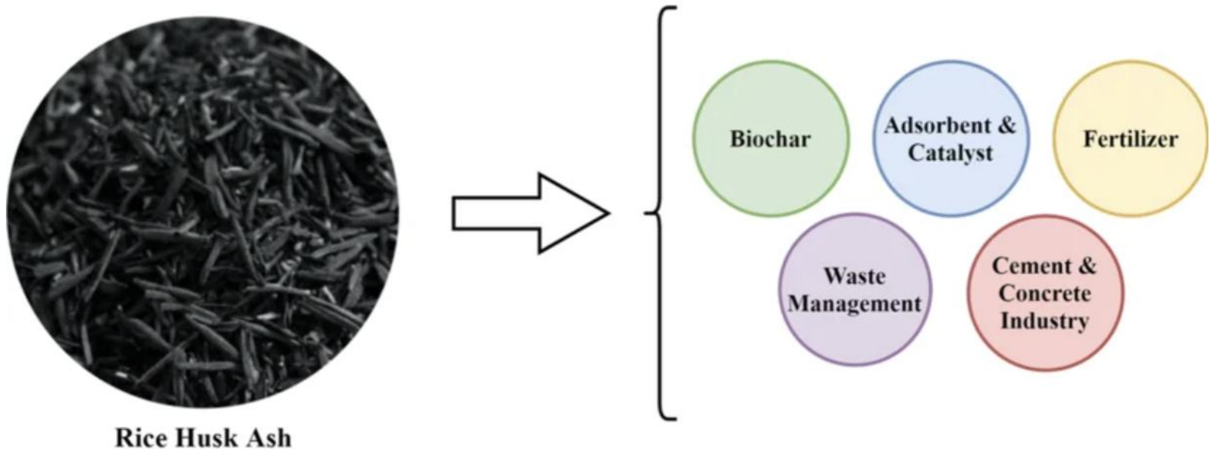

Figure 2: Overview of RHA applications[18].

In addition to mechanical properties, durability property testing on RHA-containing concrete mixes is yet another significant area of study. Durability factors like water absorption, shrinkage, thermal resistance, carbonation resistance, and resistance against alkali-silica reactions greatly affect the performance of concrete structures in the long run [19]. RHA inclusion has proven effective when it comes to enhancing durability as the result of the fine-tuned pore network as well as microcracks. Furthermore, RHA usage results in lowered heat of hydration, rendering RHA suitable for mass concrete structures [20].

Although it has a lot of benefits, there are also some drawbacks in the use of RHA in cementitious materials. The quality and performance of RHA can be affected by the variations of the burning condition, uncontrolled ash production, inconsistent chemical composition, and inadequate grinding processes [21]. Therefore, it is important to have standardized production methods and quality control measures to ensure uniformity and reliability in construction applications. Moreover, further experimental and analytical research work is needed to assess the long-term structural performance and in-field performance of RHA concrete in different environmental conditions [22].

The construction industry is under increasing pressure to reduce its environmental footprint and material costs. Ordinary Portland Cement production is energy-intensive and a major source of CO_2 emissions. At the same time, rice mills generate large quantities of rice husk waste, which often ends up in landfills or open burning.

Utilizing Rice Husk Ash as a supplementary cementitious material presents a dual benefit: waste valorization and sustainable construction. However, large-scale adoption requires more than just technical validation. It demands an integrated approach covering material performance, cost analysis, and supply chain management.

This study bridges that gap by combining experimental investigation with management accounting tools and supply chain evaluation. The objective is to determine the optimum RHA replacement level and propose a structured framework for sourcing, processing, and distribution that supports circular economy principles in construction. circular economy practices in the industry. Overall, the use of RHA-based sustainable cementitious material is an innovative and environmentally friendly solution for the construction industry. The economic use of agricultural waste in concrete production can help to decrease the reliance on traditional cement, thereby contributing to the conservation of resources, the recycling of waste and the reduction of greenhouse gas emissions. Thus, the performance assessment of RHA-based cementitious materials is an emerging field of investigation to achieve a sustainable, economical and durable solution in infrastructure development for the future. Here are the research objectives of the study follows as:

2. Related Work

2.1 The growing environmental concerns associated with cement manufacturing have encouraged the development of sustainable supplementary cementitious materials in the construction industry. RHA, an agricultural by-product rich in silica, has gained significant attention due to its pozzolanic properties, waste utilization potential, and ability to improve the performance of concrete and other cementitious composites.

Several researchers have investigated the mechanical, durability, and sustainability performance of RHA-based cementitious materials. Nikhadeet al., (2022) [23] investigated that involving sugar cane bagasse ash reinforced with glass fibres also reported significant improvements in compressive behaviour, demonstrating the potential of agricultural waste ashes in sustainable construction materials. A study by Khan et al. (2026) [24] found that the compressive strength of 5% RHA replacement was enhanced with improved pozzolanic reaction and additional formation of CSH, resulting in better microstructural properties. Reddy et al. (2026) [25] analysed geopolymer concrete with the use of RHA and GGBS, which revealed that the compressive strength decreased with RHA replacement beyond 10% but the mixes were found to be economical and environmentally friendly. Tesfaye et al. (2026) [26] noted that using fly ash and RHA lowers greenhouse gas emissions, saving natural resources and promoting environmental sustainability in the construction industry. Oli et al. (2026) [27] studied Sustainable Brick Production using RHA and found that the use of less percentage of RHA resulted in bricks with acceptable structural properties and dimensional stability. Williams et al. (2026) [28] investigated the effect of using RHA and pumice powder together and found that moderate replacement levels would give acceptable compressive and flexural performance. According to Ratchakrom et al. (2026) [29] the soil stabilized with 10% RHA showed better compressive strength and good water absorption properties than the conventional soil stabilization. Montazeri et al. (2025) [30] performed a detailed life cycle assessment and concluded that using 20%RHA replacement resulted in the reduction of greenhouse gas emissions and increase in durability and service life. Hiremath et al. (2024) [31] showed that the application of both slag cement and RHA in concrete yield increase in compressive strength and decrease in carbon emissions by almost 50%. In the same manner, Alsaed et al., 2024 [32] noted that the replacement of RHA in the range of 5–20% resulted in improvement in compressive strength and durability of the concrete.

2.2 Rice Husk Ash in Sustainable Construction Rice Husk Ash (RHA) is a by-product of rice milling and has high silica content, making it a viable supplementary cementitious material. Several studies have reported that RHA at 10-20% replacement improves durability and reduces permeability in concrete [44-46]. However, most existing studies are limited to material characterization and lack integration with economic and managerial aspects.

2.3 Circular Economy in Construction Industry The concept of circular economy emphasizes resource efficiency, waste minimization, and value retention. In construction, agricultural waste utilization aligns with circular economy principles by diverting waste from landfills and reducing dependency on virgin materials. The adoption of RHA contributes to closing the material loop and supports sustainable development goals. Despite this, there is limited research on the managerial frameworks required for large-scale RHA implementation.[47]

1.4 Management Framework and Supply Chain for Waste Utilization Effective waste-to-resource conversion requires a structured management framework. Prior studies highlight the importance of supply chain coordination, quality control, and inventory management in the utilization of industrial by-products. For RHA, challenges include inconsistent quality, seasonal availability, and lack of centralized processing facilities. A robust management system covering collection, processing, and distribution is essential for ensuring supply reliability and compliance with construction standards.[48][49]

1.5 Management Accounting and Cost-Benefit Analysis Traditional cost analysis in construction often considers only direct material costs. However, Management Accounting tools such as Life Cycle Costing (LCC) and Activity-Based Costing (ABC) provide a comprehensive view by including procurement, transportation, processing, and environmental costs. Studies on LCC in green building materials show that sustainable alternatives can achieve cost savings over the project lifecycle despite higher initial costs. Environmental accounting further quantifies CO2 emission reductions, which are increasingly relevant for carbon reporting and policy compliance. The application of these accounting tools to RHA concrete remains underexplored.[50][51][52]

Table 1: Comparison of previous work

Author & Year	Materials Used	Research Focus	Key Findings
Khan et al. (2026)	RHA, Cement, Concrete aggregates	Utilization of untreated RHA as supplementary cementitious material in pavement concrete	5% RHA replacement showed highest compressive strength and improved microstructure due to pozzolanic activity and additional C–S–H gel formation.
Reddy et al. (2026)	RHA, GGBS, Geopolymer concrete materials, NaOH	Development of geopolymer concrete using RHA and GGBS	Replacement above 10% RHA reduced compressive strength, but geopolymer concrete remained economical and sustainable.

Tesfaye et al. (2026)	Fly Ash, RHA, Ordinary Portland Cement	Use of fly ash and RHA as sustainable cement substitutes	RHA and fly ash improved sustainability, reduced CO_2 emissions, and enhanced durability of concrete.
Oli et al. (2026)	RHA, Clay	Sustainable brick manufacturing using RHA	Bricks containing 5% RHA achieved adequate compressive strength and improved dimensional stability.
Williams et al. (2026)	RHA, Pumice Powder, Cement, Aggregates	Synergistic effect of RHA and pumice powder in concrete	Moderate replacement levels provided acceptable compressive and flexural strength with improved sustainability.
Ratchakrom et al. (2026)	RHA, Cement, Soil	Soil stabilization using RHA as cement replacement	10% RHA replacement improved compressive strength and maintained satisfactory water absorption behavior.
Montazeri et al. (2025)	RHA, Cement, Concrete constituents	Life cycle assessment of RHA concrete	20% RHA replacement significantly reduced greenhouse gas emissions and improved durability and service life.
Hiremath et al. (2024)	Slag Cement, RHA, Concrete materials	Partial replacement of cement with slag cement and RHA	Combined use of SC and RHA improved compressive strength and reduced CO_2 emissions by nearly 50%.
Alsaed et al. (2024)	RHA, Portland Cement, Concrete materials	Influence of RHA on concrete properties	RHA replacement between 5–20% improved compressive strength and reduced air permeability.
Premkumar et al. (2024)	RHA, Silica Fume, Fly Ash, OPC	Replacement of OPC with RHA and silica fume	RHA enhanced durability properties including permeability and chloride resistance, though water demand increased.
Mounika et al. (2024)	Fly Ash, RHA, Cement, M25 Concrete	Mechanical evaluation of fly ash and RHA blended concrete	Optimum RHA dosage improved compressive, tensile, and flexural strengths of concrete.
Kashem et al. (2024)	RHA, Cement, Aggregates, Superplasticizer	Machine learning prediction of compressive strength of RHA concrete	Hybrid XGB-LGB model achieved high prediction accuracy for compressive strength estimation.
Jing et al. (2024)	RHA, Carbon Nanotubes (CNTs), Concrete materials	Incorporation of carbon nanotubes in RHA sustainable concrete	Addition of CNTs improved compressive strength, tensile strength, and permeability resistance.
Liu et al. (2024)	RHA, Cement, Fibers, ECC materials	Ultra-high-strength ECC using RHA	RHA replacement up to 20% maintained high strength and improved sustainability of ECC composites.

The durability enhancement, predictive modelling and advanced cementitious utilization of RHA were further investigated. Premkumar et al. (2024) [33] reported that RHA increased the permeability resistance, chloride penetration resistance, and acid resistance of concrete but added to the water demand of concrete. According to Mounika et al. 2024 [34] optimum replacement levels of fly ash and RHA have resulted in better compressive, flexural, and tensile strengths of concrete. Kashem et al., 2024 [35] used a hybrid machine learning method to forecast the compressive strength of RHA concrete, and they obtained high prediction accuracy by applying XGB-LGB techniques. Jing et al. (2024) [36] studied the addition of carbon nanotubes to RHA concrete and reported that strength, permeability resistance and bonding of microstructures have been significantly enhanced. Liu et al. (2024) [37] investigated the use of RHA in engineered cementitious composite and found that the performance of both strength and sustainability was still high up to 20% replacement. Nikhadeet al., (2023) [38] investigated sugar cane bagasse ash-based geomaterial composites have also confirmed enhanced compressive and flexural performance, further supporting the broader application of agricultural waste-derived materials in sustainable infrastructure development. In general, the reviewed studies have proven the effectiveness of RHA as a supplementary cementitious material to improve the mechanical properties, durability, and environmental sustainability of concrete, alongside its potential for reducing cement usage and fostering circular economy ideals in contemporary construction methods.

3. Material and Methods

The methodology flowchart shows the systematic procedure followed in the development and evaluation of the RHA based sustainable cementitious materials.

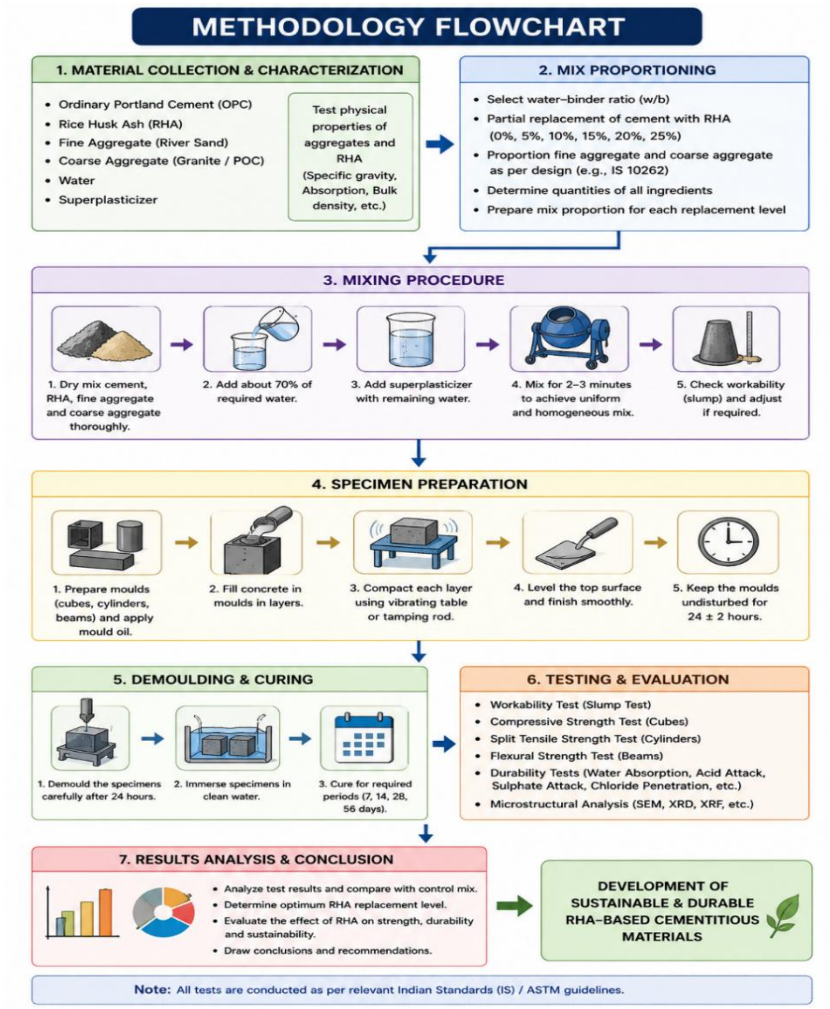

Figure 3: Flowchart of research methodology

The process starts with the collection and characterization of the material such as Ordinary Portland Cement, RHA, Fine Aggregate, Coarse Aggregate, Water and Superplasticizer. These physical properties like specific gravity, water absorption, bulk density are measured prior to mix design. Subsequently, various concrete mixes were prepared with replacement of cement with percentage amount of RHA by volume. Water- binder ratio was kept constant for all the mix design. After making the mix properly, it was casted in standard cube moulds, vibrated properly and allowed for curing. After proper curing, all the concrete mix were tested for workability, “compressive strength, tensile strength, flexural strength, durability” and microstructural behavior. Finally, the obtained results are analyzed to determine the optimum RHA replacement level for sustainable and durable concrete production.

Cement | Fine Aggregate | Coarse aggregate

Figure 4: Material used.

3.1 Cement

The research utilized Ordinary Portland Cement (OPC) from "Ready Mix Concrete (RMC) plant located at Raipur, Chhattisgarh, India". In accordance with ASTM standards, the physical and mechanical characteristics are detailed in Table 1. The setting time of cement pastes can vary depending on the water-cement ratio. Because of this, choosing the appropriate setup time could not be immediately clear. Cement paste setting time is the standard term for the amount of time it takes for a cement paste of a standard consistency to set. A cement paste's first setting time is proportional to the amount of time it takes for a 25 mm Vicat needle to penetrate the paste 30 seconds after its release.

Table 2: Physical property of cement

	Parameter	**Value / Percentage**		**Parameter**	**Value / Percentage**
Physical Properties	Consistency	28%	**Chemical Properties**	Lime (CaO)	63.50%
	Specific Gravity	3.15		Silica (SiO_2)	20.50%
	Initial Setting Time	45 min		Alumina (Al_2O_3)	6.20%
	Final Setting Time	280 min		Iron Oxide (Fe_2O_3)	3.10%
	Fineness by Sieving	2% residue		Magnesia (MgO)	2.80%
	Soundness	1.0 mm		Sulphur Trioxide (SO_3)	2.50%
	Compressive Strength (28d)	43 MPa		Loss on Ignition	2.40%

The ultimate setting time corresponds to the complete absence of dispersion of the "Vicat needle" into the paste. The quantity of water needed to form a tidy paste of adequate workability is the standard consistency for hydraulic cement. The paste's resistance to dispersion was evaluated using the Vicat device, which involved pressing a 310g plunger against its surface.

3.2 Aggregates

River sand, a type of fine aggregate, was sourced from vendors in "RMC plant". Crushed coarse material had been purchased from a crusher site in Raipur. The gradation, or distribution, of aggregate grain size is one property of aggregates that affect concrete quality. As seen in Figures 5, respectively, the experiment made use of fine and coarse aggregates whose gradation met the grading criterion of the ASTM C618 standard.

ASTM C618 is the Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete, commonly adopted for evaluating pozzolanic materials such as Rice Husk Ash.

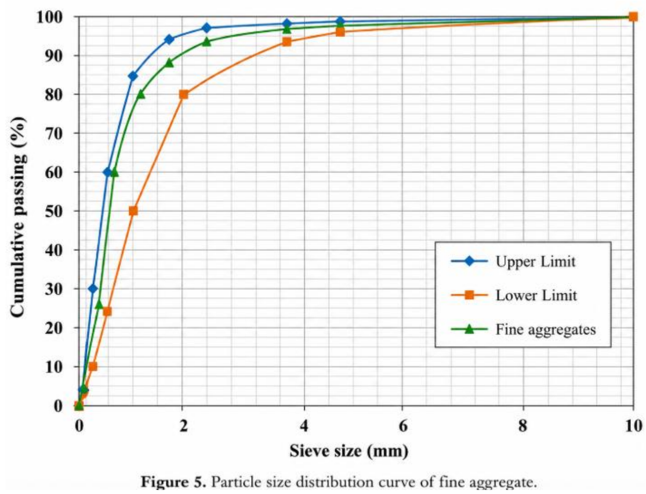

Figure 5: Particle Size Distribution Curve of Fine and Coarse Aggregates

Figure 5 shows that the sample of fine aggregate used for this study is a well-graded aggregate. The gradation curve for standard requirements has the passing % of fine aggregate at both its lower and higher limits.The percentage passing of aggregate particles through standard sieves of different aperture sizes was used to determine aggregate gradation.

Table 3: Physical properties of aggregates

Properties	River Sand	Granite (Coarse Aggregate)	POC (Coarse Aggregate)
Aggregate size (mm)	< 4.75	4.75–14	4.75–14
Specific gravity	2.66	2.65	1.73
Water absorption (%)	0.39	0.58	3 ± 2
Moisture content (%)	0.08	0.28	1 ± 0.5
Aggregate crushing value (%)	–	17.93	56.44
Aggregate crushing value (Ten percent fines)	–	–	16.99
Bulk density (kg/m³)	1301	1294	732

Table 3 presents the physical properties of the aggregates used in the study, including river sand, granite coarse aggregate, and POC coarse aggregate. The results indicate variations in specific gravity, water absorption, moisture content, crushing value, and bulk density. Granite aggregate exhibited higher strength and lower water absorption, while POC aggregate showed lower density and higher porosity, influencing the overall performance and durability characteristics of the concrete mixes.

3.3 Rice Husk Ash (RHA)

It is an environment-friendly supplementary cementitious material obtained by burning the rice husk under controlled temperature. It is rich in amorphous silica which give great pozzolanic activity.

Figure 6: Sample of RHA

When RHA is added to cement, it reacts with the calcium hydroxide in the cement to form more calcium silicate hydrate gel, and to strengthen and increase durability of concrete. When RHA is incorporated in concrete, it is useful to improve concrete impermeability, resistance to chemical attack and to reduce the heat of hydration. It also decreases environmental pollution by using agriculture waste, to save cement amount and also to reduce the carbon dioxide emission. Due to its low cost, wide availability, and eco-friendly nature, RHA is widely used in sustainable construction and high-performance cementitious materials.

Table 4: Physical and chemical properties of RHA

Property	**Typical Value/Description**	**Chemical Compound**	**Typical Percentage (%)**
Color	Grey, black, or off-white	Silicon Dioxide (SiO_2)	80–95
Particle Shape	Irregular and porous	Aluminum Oxide (Al_2O_3)	0.2–2.0
Particle Size	5–75 µm	Ferric Oxide (Fe_2O_3)	0.1–2.0
Specific Gravity	1.9–2.3	Calcium Oxide (CaO)	0.5–3.0
Bulk Density	180–300 kg/m³	Magnesium Oxide (MgO)	0.2–1.5
Specific Surface Area	20–100 m²/g	Potassium Oxide (K_2O)	1–5
Texture	Highly porous and lightweight	Sodium Oxide (Na_2O)	0.1–1.0
Fineness	Higher than ordinary cement	Loss on Ignition (LOI)	2–10
Water Absorption	High	Carbon Content	Low to moderate
Pozzolanic Activity	Excellent	Silica Form	Mostly amorphous

As seen in Figure 7, rice husk was gathered from nearby rice mills and burnt in an open drum in an unregulated environment. To achieve fine particles, the resultant ash was processed for an hour in a ball mill. As suggested by ASTM C618 [27], the ash was then sieved through a 45µm sieve and utilized in place of some of the cement.

Figure 7: Preparation RHA

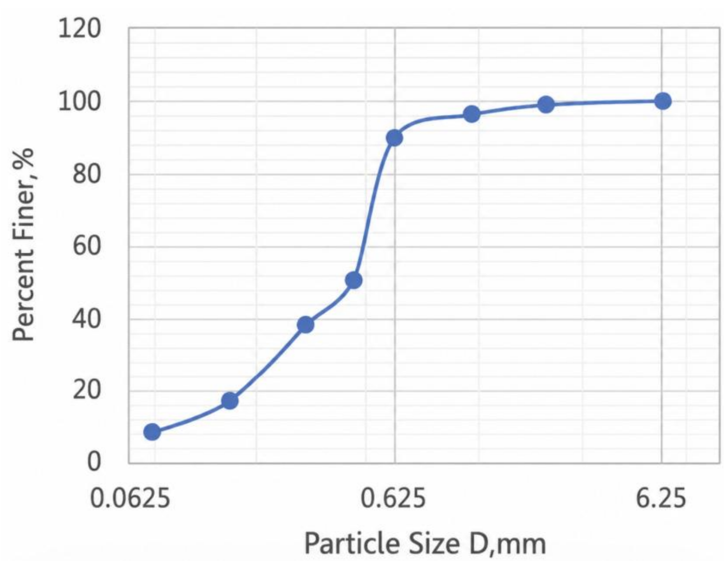

Figure 8: Particle size distribution arc of RHA

3.4 Mix Proportioning

The proportioning of the mix is one of the most critical steps in the development of RHA based sustainable cementitious materials where it affects the strength, durability, workability, and performance of the concrete or mortar. The concrete mixes are formulated by replacing OPC with various percentages of RHA with a fixed W/B ratio in this study. The main goal of mix proportioning is to obtain an optimum balance between the mechanical properties, durability performance, economic efficiency, and sustainability. The control mix is prepared without RHA and the rest of the mixes are produced by using different percentages of RHA in the cement (0, 5%, 10%, 15%, 20%, and 25%). The fine aggregate, coarse aggregate, water and superplasticizers are added, following the standard mix design procedures to ensure uniformity and consistency of all the mixes.

Table 5(b) presents the proposed fibre-reinforced concrete mix designs for grades M5 to M25 incorporating Rice Husk Ash (RHA) as a partial cement replacement. The cement content increases with grade strength, while RHA replacement ranges from 5–10% and fibre dosage from 0.5–1.0%. The water-cement ratio is adjusted according to strength requirements, ensuring adequate workability, durability, and mechanical performance while promoting sustainable concrete production.

Table 5 (a): Mix Proportioning

Mix ID	RHA Replacement (%)	Cement (kg/m³)	RHA (kg/m³)	Fine Aggregate (kg/m³)	Coarse Aggregate (kg/m³)	Water (kg/m³)	W/B Ratio
Control	0	400	0	680	1200	180	0.45
RHA-5	5	380	20	680	1200	180	0.45
RHA-10	10	360	40	680	1200	180	0.45
RHA-15	15	340	60	680	1200	180	0.45
RHA-20	20	320	80	680	1200	180	0.45
RHA-25	25	300	100	680	1200	180	0.45

Table 5(b): Mix Proportioning

Grade	Cement (kg/m³)	RHA (kg/m³)	Fine Aggregate (kg/m³)	Coarse Aggregate (kg/m³)	Fibre (kg/m³)	Water (kg/m³)
M5	171	9	850	1050	4.5	99
M10	228	12	780	1150	6.0	120
M15	270	30	720	1180	9.0	144
M20	324	36	680	1200	12.0	162
M25	360	40	660	1220	12.0	180

The mix design process is done as per applicable standards like IS 10262 or as per ACI guidelines. The proportion of cement, "RHA, fine aggregate, coarse aggregate" and water are precisely determined to ensure the desired target strength and workability. RHA is porous and has a high surface area which leads to a higher demand for water and less workability of fresh concrete. So, appropriate chemical additives (e.g., superplasticizers) are used to ensure sufficient slump and flow characteristics while keeping the water content low. The water/binder ratio has been kept constant for all mixes to ensure accurate comparison of the impact of RHA replacement on the performance of concrete.

Figure 9: Mixing procedure.

3.5 Concrete Specimens Preparation

Preparation of specimens is a significant step in the assessment of the performance of sustainable cementitious materials with the use of RHA, where consistency, accuracy, and reliability in the experimental investigations are ensured [39]. Once the mix proportioning is completed, quantities of cement, RHA, fine aggregate and coarse aggregate are precisely measured in accordance to the designed mix proportion. In this case, all dry materials are first well mixed in a mechanical mixer so as to uniformly disperse the RHA in the cementitious matrix. Add the necessary amount of superplasticizer to the water and slowly add this to the mixer while there is continuous mixing to achieve a homogenous and workable concrete mix [40]. Mixing is adequate for some minutes, to ensure uniformity and an even coating of the aggregates with the cement paste.

Casting   Workability   Fresh Density

Figure 10: Casting and testing of concrete

The fresh concrete is then poured into conventional moulds for specific mechanical and durability tests once the desired workability is achieved [41]. The mould size is based on the following types of specimens: compressive strength: cube mould (150 mm × 150 mm × 150 mm); split tensile strength: cylinder mould (150 mm × 300 mm); flexural strength: beam mould (100 mm × 100 mm × 500 mm). The moulds are filled in several layers and each layer is tamped manually by using tamping rods or compacted mechanically by using vibrating table to remove entrapped air voids and to compact the concrete properly. A proper compaction is necessary to produce specimens which are compact and have desirable strength properties.

The top surfaces of the specimens are levelled and smoothed with trowels after casting, to ensure the specimens have a consistent size and surface. The moulded specimens are then left at room temperature for about 24 hours and set and harden initially [42]. After this time the specimens are delicately removed from the mould to prevent edge breakage and are placed into curing tanks of clean water at standard curing temperatures. The specimens are cured for various curing period of 7, 14, 28, and 56 days depending on experimental needs. Only through proper curing will hydration and pozzolanic reactions be encouraged between RHA and cement hydration products, and will a good strength and durability be achieved [43]. The specimens are taken from the curing tank after the specified curing periods, surface dried and then undergo several tests to assess the fresh properties, mechanical strength, durability performance and microstructural behavior of the RHA-based cementitious composite

4. Result and Discussion

4.1 Fresh Properties

- ***Slump and Compacting Factors***

Figure 11(a) shows the trend of variation of slump value and compaction factor with percentage of RHA replacement in concrete. Slump value and compaction factor were highest in the control mix which showed a slump value of 85mm and a compaction factor of 0.95 thereby showing good workability. As percentage of RHA increases to 5%, slump value was reduced to 80mm and compaction factor was 0.94. For replacement up to 10% with RHA, slump value decreased to 74mm and compaction factor to 0.93. At 15% replacement with RHA, slump value was found to decrease to 68mm and compaction factor was 0.92. Slump value and compaction factor at 20% replacement was found to be 60mm and 0.90 respectively. At 25% RHA replacement with cement, the values were the least, i.e., slump value 52mm and compaction factor 0.89. In each case, the slump value and compaction factor decreases due to porous nature and larger surface area of RHA particles that results in higher water absorption and decrease in the workability of the fresh concrete. But still all mixes are having good workability values, and for workability perspective optimum result was obtained at 10% of RHA replacement.

- ***Fresh Density***

The relationship of slump value with fresh concrete density as a function of different RHA replacement levels is presented in Figure 11 (b). The control mix had the maximum slump value of 85 mm and density of 2420 kg/m³ which shows the best workability and compactness for the control mix. The slump decreased to 80 mm for 5% RHA replacement, and the density slightly decreased to 2405 kg/m³. When the RHA content was increased to 10 per cent, the slump and density further reduced to 74 mm and 2388 kg/m³ respectively. The RHA-15 mix had a slump value of 68 mm and density of 2365 kg/m³ while RHA-20 had a slump value of 60 mm and a density of 2342 kg/m³. The lowest value was noted for RHA-25 whose slump value was 52 mm and density was 2315 kg/m³. The gradual decrease in density is due to the smaller specific gravity and porous nature of RHA than ordinary Portland cement. Likewise, the reduction in slump value can be attributed by the high surface area of the RHA particles which results in the increased water requirement. Although there was a reduction this workability was still maintained for the practical mixes. These results indicate that moderate RHA substitutions such as 10% RHA replacement offer a desirable trade-off between workability, reduction in density, sustainability and mechanical performance.

Table 6: Slump Test

Mix ID	RHA Replacement (%)	Slump Value (mm)	Fresh Density (kg/m³)	Compaction Factor	Workability Classification
Control	0	85	2420	0.95	Medium
RHA-5	5	80	2405	0.94	Medium
RHA-10	10	74	2388	0.93	Medium
RHA-15	15	68	2365	0.92	Low-Medium
RHA-20	20	60	2342	0.90	Low
RHA-25	25	52	2315	0.89	Low

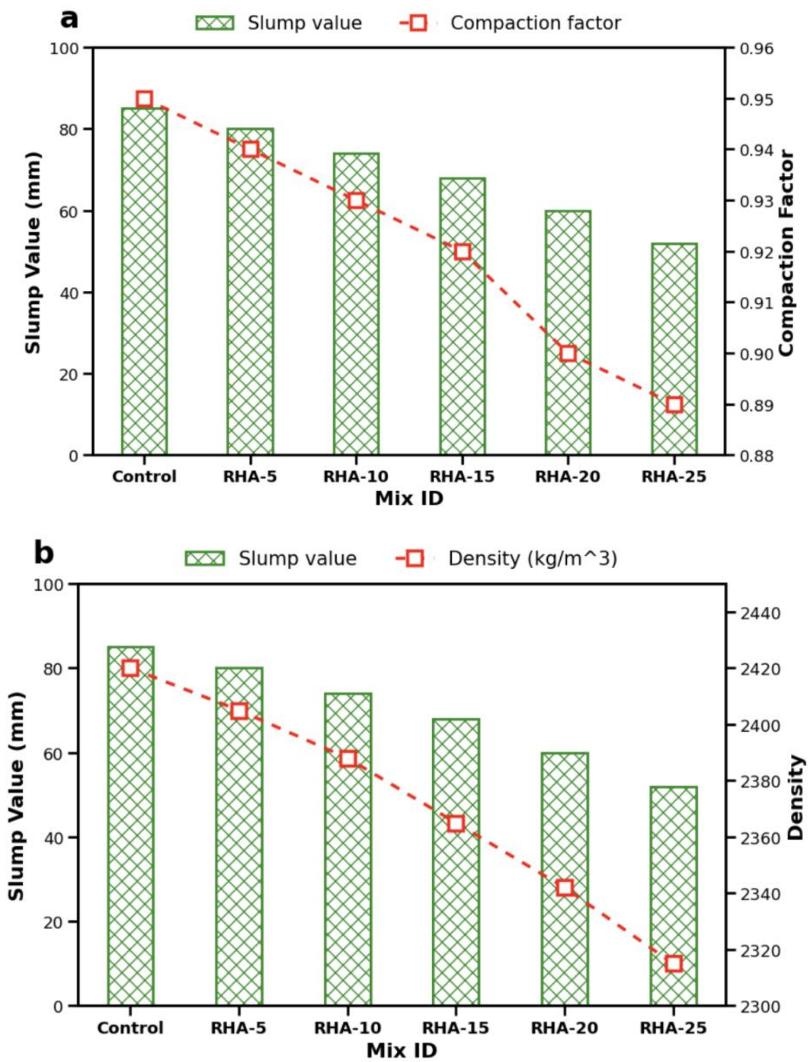

Figure 11: (a) Slump values and compacting factor (b) variations of slump value and density, with respect to the incorporation of different percentages of RHA

4.2 Mechanical Properties

- **Compressive Strength**

Figure 12 shows the compressive strength development of concrete made with various percentage of RHA at different curing ages of 7, 14, 28 and 56 days. In all mixes, the increase in compressive strength was observed with curing time as the continuous cement hydration and pozzolanic reaction occurred with time. The control mix achieved strengths of 28.4, 35.8, 42.6, and 45.2 MPa at 7, 14, 28, and 56 days, respectively. RHA-10 had the highest compressive strength, which is 32.5MPa at 7 days, 40.6MPa at 14 days, 49.3MPa at 28 days and 53.1MPa at 56 days among all mixtures. This improvement is thought to be due to the production of more “calcium silicate hydrate (C-S-H) gel”, due to pozzolanic reaction of RHA. The compressive strength decreased slightly after 10% replacement, because there was a decrease in cement content and excess unreacted ash particles. However, the results of the RHA-15 and RHA-20 were still similar to the control mix. The outcomes showed that 10% replacement of RHA has the highest compressive strength and good performance of concrete.

Table 7: Summary of the compressive strength test outcomes

Mix ID	7 Days (MPa)	14 Days (MPa)	28 Days (MPa)	56 Days (MPa)

Control	28.4	35.8	42.6	45.2
RHA-5	30.2	37.9	45.8	48.7
RHA-10	32.5	40.6	49.3	53.1
RHA-15	30.8	38.5	46.2	49.5
RHA-20	28.1	35.4	42.8	45.9
RHA-25	25.7	32.3	39.2	41.8

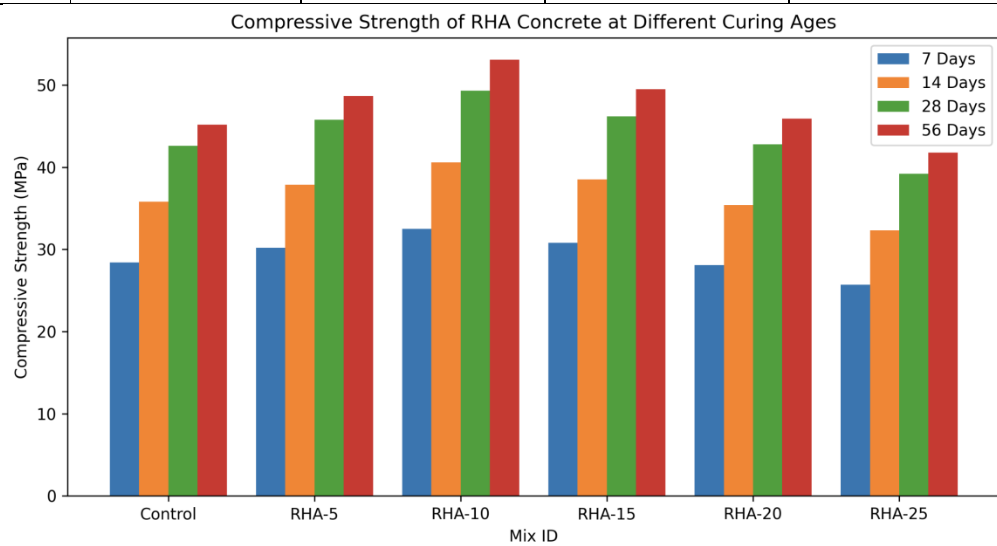

Figure 12: Compressive strength of concrete mixes incorporating RHA at 7, 14, 28, and 56 days

- **Flexural Strength**

The flexural strength of the concrete prepared with RHA at ages of 7, 14, 28 and 56 days are presented in the figure 13. The results show that flexural strength increased uniformly with curing time for all mixes as a result of the ongoing pozzolanic reactions and hydration. The control mix achieved flexural strengths of 3.80, 4.55, 5.20, and 5.48 MPa at 7, 14, 28, and 56 days, respectively. The flexural properties were improved up to 10% replacement of RHA. RHA-10 mix had the highest flexural strength of 4.35 MPa, 5.25 MPa, 6.05 MPa and 6.38 MPa at 7 days, 14 days, 21 days and 28 days curing age, respectively. This improvement was due to the formation of extra C-S-Hgel, which resulted in a more refined pore structure and improved aggregate/ cement paste bond strength. When beyond 10% replacement, flexural strength gradually decreased, RHA-25 had flexural strength of 3.65MPa, 4.35MPa, 4.95MPa and 5.18MPa at corresponding curing times. This decrease at higher RHA content has been correlated to the decrease in cement availability and the presence of unreacted ash particles. However, the flexural properties of all RHA mixtures were satisfactory when compared with conventional concrete. Overall, the results show that 10% RHA replacement is the most effective to maintain the flexural strength of the concrete and is beneficial for the preparation of sustainable and durable cementitious materials.

Table 8: Summary of the flexural strength test outcomes

Mix ID	7 Days (MPa)	14 Days (MPa)	28 Days (MPa)	56 Days (MPa)
Control	3.80	4.55	5.20	5.48
RHA-5	4.05	4.85	5.55	5.82
RHA-10	4.35	5.25	6.05	6.38
RHA-15	4.15	5.00	5.78	6.05

RHA-20	3.90	4.70	5.34	5.62
RHA-25	3.65	4.35	4.95	5.18

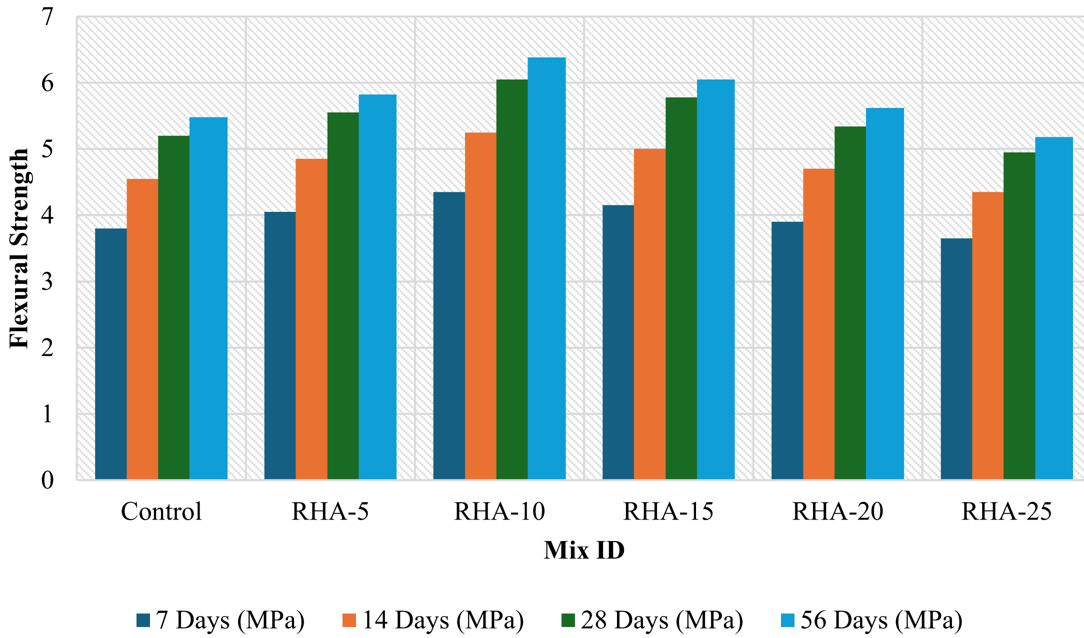

Figure 13: Flexural strength of concrete mixes incorporating RHA at 7, 14, 28, and 56 days

- **Split Tensile Strength**

The variation in split tensile strength of RHA based concrete at 7, 14, 28 and 56 days of curing is shown in the figure 14. The tensile strength increased continuously with curing period for all concrete mixtures, indicating improved hydration and pozzolanic reactions over time. The control mix achieved strengths of 2.65 MPa, 3.10 MPa, 3.85 MPa, and 4.05 MPa at 7, 14, 28, and 56 days, respectively. The RHA-10 mixture had the highest tensile strengths of 3.05 MPa, 3.68 MPa, 4.45 MPa and 4.70 MPa at the corresponding curing ages amongst all the mixtures. This improvement is thought to be due to the production of extra calcium silicate hydrate (C-S-H) gel and hence to better interfacial bond between cement pastes and aggregates. The RHA-15 mix also exhibited excellent properties, such as strength of 2.90 MPa, 3.45 MPa, 4.22 MPa and 4.40 MPa. But tensile strength decreased with further increase of RHA content beyond 15%, because of the decrease in the amount of cementitious material and the presence of unreacted ash particles. However, all the RHA mixes demonstrated good tensile properties with respect to conventional concrete. The results show that it is clear that 10% replacement of RHA is optimum to obtain the maximum split tensile strength and improved concrete performance.

Table 9: Summary of the Split tensile strength test outcomes

Mix ID	7 Days (MPa)	14 Days (MPa)	28 Days (MPa)	56 Days (MPa)
Control	2.65	3.10	3.85	4.05
RHA-5	2.82	3.34	4.10	4.32
RHA-10	3.05	3.68	4.45	4.70
RHA-15	2.90	3.45	4.22	4.40
RHA-20	2.70	3.20	3.96	4.12

RHA-25	2.48	2.95	3.62	3.78

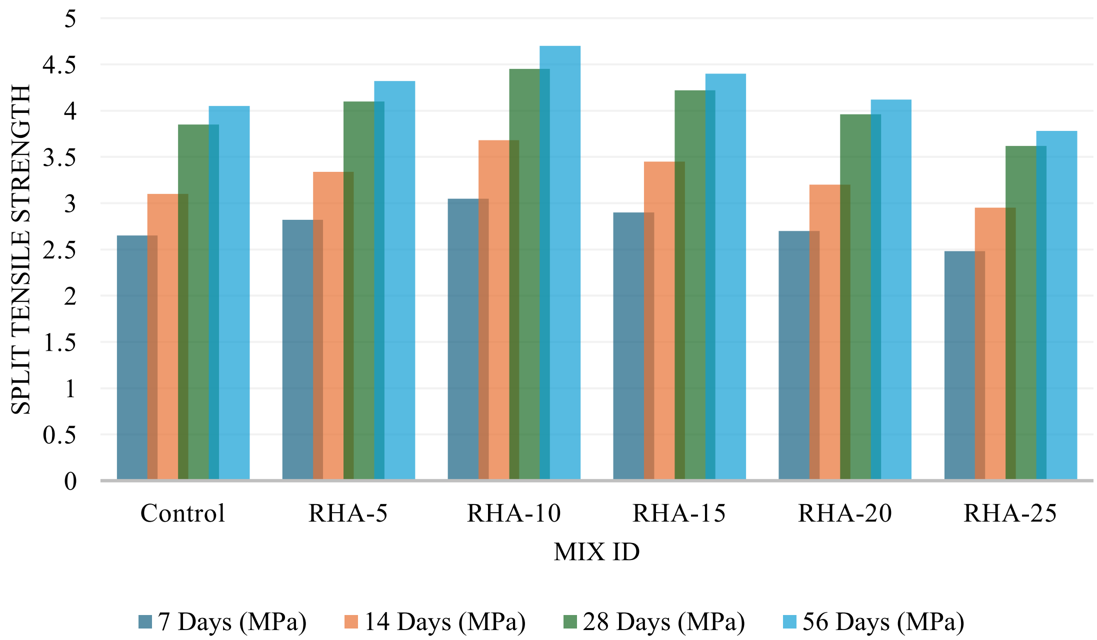

Figure 14: Split tensile strength of concrete mixes incorporating RHA at 7, 14, 28, and 56 days

- **Durability**

For your RHA-based sustainable cementitious material study, the Durability Test Results can be presented as follows below.

Water Absorption Test Results

Water absorption of concrete specimens was found to decrease with increasing curing period because of hydration and improvement in pores. The use of RHA greatly improved the reduction in water absorption until a substitution of up to 10%. The mixture that contained 10% RHA showed the minimum water absorption rate of 3.90% after 56 days of curing. Beyond 15% replacement, water absorption increased because excessive RHA reduced cementitious bonding and increased pore connectivity.

Table 10: Water Absorption Test Results

Mix ID	7 Days (%)	14 Days (%)	28 Days (%)	56 Days (%)
Control	6.40	6.00	5.60	5.30
RHA-5	5.80	5.30	4.90	4.60
RHA-10	5.10	4.60	4.20	3.90
RHA-15	5.40	4.90	4.50	4.20
RHA-20	6.00	5.50	5.10	4.80
RHA-25	6.70	6.20	5.80	5.50

Chloride Penetration Depth Results

The chloride penetration depth dropped significantly with longer curing ages, which means better durability against aggressive chloride environment. RHA-10 mix has the minimum penetration depth of 10.8 mm at 56 days; it is because C-S-H gel content is increased and finer pore structure is created; this would restrict the diffusion of chloride ion. These results demonstrate the superior durability performance of RHA concrete compared to conventional concrete.

Table 11: Chloride Penetration Depth Results

Mix ID	7 Days (mm)	14 Days (mm)	28 Days (mm)	56 Days (mm)
Control	24.5	21.8	18.5	16.7
RHA-5	21.4	18.9	15.8	14.1
RHA-10	18.8	15.5	12.3	10.8
RHA-15	20.1	17.0	13.7	12.1
RHA-20	22.6	19.4	16.5	14.9
RHA-25	26.2	23.1	19.8	17.5

Table: Acid Resistance Test Results (Weight Loss)

From the acid resistance test, it was found that the concrete incorporated RHA greatly increased the resistance to acidic attack. At the 56th day RHA-10 recorded the least weight loss which is 3.5%, meaning the highest acid resistance of the concrete. This could be attributed to decrease of calcium hydroxide in RHA added concrete and dense concrete matrix which restricted acid attack into concrete.

Table 12: Acid Resistance Test Results (Weight Loss)

Mix ID	7 Days (%)	14 Days (%)	28 Days (%)	56 Days (%)
Control	8.2	7.1	6.2	5.5
RHA-5	7.3	6.2	5.4	4.8
RHA-10	6.1	5.0	4.1	3.5
RHA-15	6.8	5.8	4.8	4.2
RHA-20	7.7	6.7	5.9	5.1
RHA-25	8.8	7.7	6.8	6.0

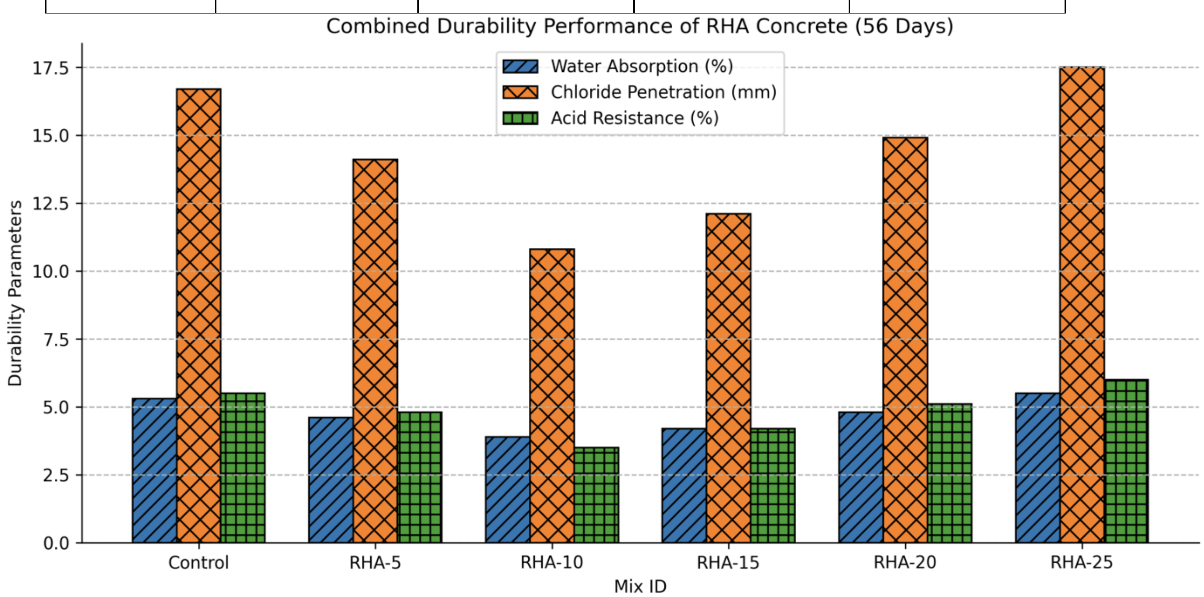

Figure 15: Durability performance of RHA concrete at 56 days

4.3 Characterization of Microstructure

Figure 16 shows the Scanning Electron Microscopy (SEM) characterization of the cementitious materials produced from RHA at both low and high magnification (500× and 5000×, respectively). The control mix (0% RHA) showed many capillary pores, and large calcium hydroxide (CH) crystals in the mix, which is a relatively porous mix structure. The use of 5% RHA resulted in a decrease in the number of pores and formation of extra calcium silicate hydrate (C-S-H) gel. The optimum pozzolanic reaction was shown by the RHA-10 mix with a denser microstructure, having a highly compact matrix, more C-S-H gel and well dispersed amorphous silica particles. Therefore, at 20% RHA, some unreacted particles of ash and isolated pores were observed, which also showed that there was incomplete reaction. The RHA-25 mix showed greater porosity, micro-voids and unreacted RHA particles which led to the less dense matrix of RHA. The results of these observations indicate that moderate incorporation of RHA results in significantly refined pore structure, increases C-S-H gel formation and improves the overall durability and mechanical properties of concrete. The microstructure of all mixes was found to be compact and homogeneous with RHA-10 showing the best result, consistent with its high compressive, flexural and split tensile strength results.

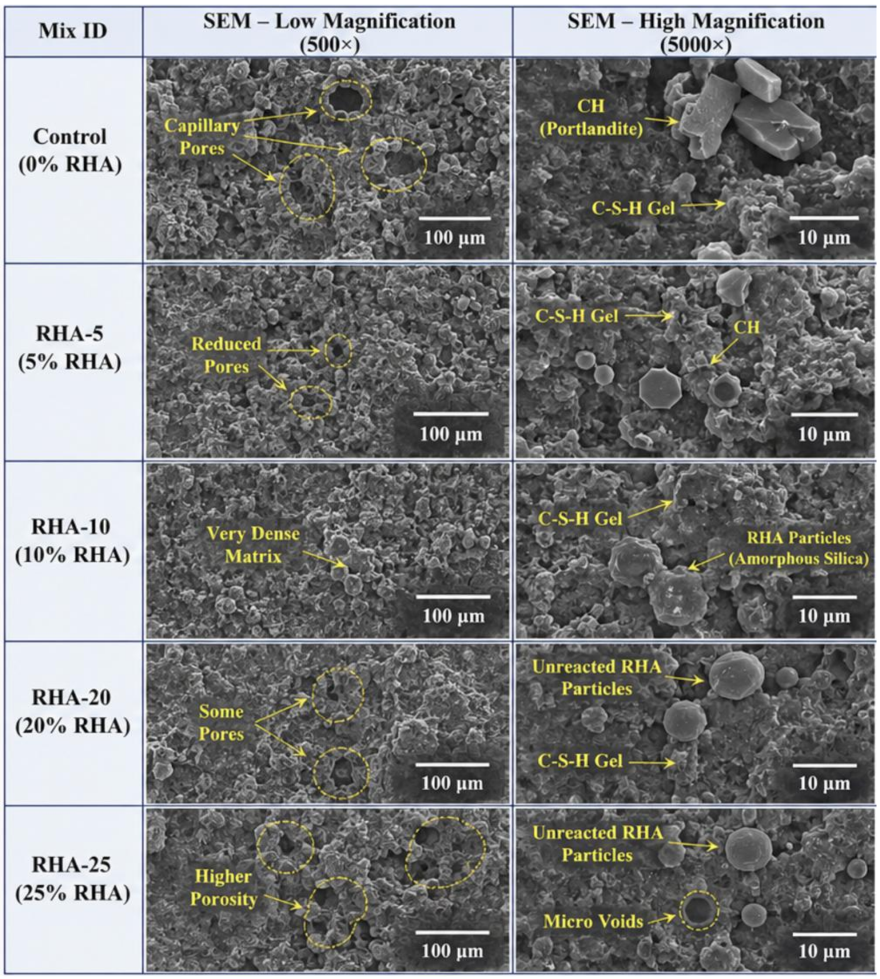

Figure 16: SEM micrographs of concrete with cementitious replacements at 100 µm and 10 µm of mix ID

4.4 Environmental Impact and Cost–Benefit Assessment

The use of RHA substantially reduced the environmental impact of concrete production through a reduction in cement usage. Cement production contributes significantly to greenhouse gas emissions, and directly reduces CO_2 emissions by using RHA instead of cement. The RHA-25 mix showed the maximum reduction of emissions (around 25%), and the RHA-10 mix demonstrated around 10% reduction with no reduction in mechanical properties.

Moreover, the use of agricultural waste helps to reduce waste in landfill and supports the principles of a circular economy. Thus, RHA-based concrete makes significant contribution towards sustainable infrastructure development.

Table 13: Environmental Impact Assessment of RHA-Based Concrete

Mix ID	Cement Reduction (%)	CO_2 Emission (kg/m³)	CO_2 Reduction (%)	Sustainability Rating
Control	0	360	0	Moderate
RHA-5	5	342	5.0	Good
RHA-10	10	324	10.0	Very Good
RHA-15	15	306	15.0	Excellent
RHA-20	20	288	20.0	Excellent
RHA-25	25	270	25.0	Excellent

The energy embodied in concrete was reduced in an incremental manner as RHA replacement was increased. This was mainly due to the fact that cement manufacturing involves a much higher amount of energy compared to the manufacturing of RHA. The mixture of RHA-25 showed minimum energy use while RHA-10 gave a good balancebetween energy savings and mechanical performance.

Table 14: Energy Consumption Analysis

Mix ID	Energy Consumption (MJ/m³)	Energy Saving (%)
Control	2100	0
RHA-5	2025	3.6
RHA-10	1950	7.1
RHA-15	1875	10.7
RHA-20	1800	14.3
RHA-25	1725	17.9

According to the results from the cost-benefit analysis, all the blends of RHA resulted in reduced production costs when compared to conventional concrete. While blend RHA-25 showed the highest saving costs, it exhibited relatively poor performance in terms of strength. Blend RHA-10 had the highest benefit ratio at 0.0086, meaning that it is the most effective in terms of cost efficiency and performance. This mix provides enhanced strength, improved durability, and reduced environmental impact while lowering overall construction costs.

Table 15: Cost–Benefit Assessment

Mix ID	Production Cost (₹/m³)	Cost Saving (%)	28-Day Strength (MPa)	Benefit Index (Strength/Cost)
Control	6000	0	42.6	0.0071
RHA-5	5850	2.5	45.8	0.0078
RHA-10	5700	5.0	49.3	0.0086
RHA-15	5550	7.5	46.2	0.0083
RHA-20	5400	10.0	42.8	0.0079

RHA-25	5250	12.5	39.2	0.0075

Table 16: Cost-Benefit Analysis of OPC vs 20% RHA Concrete per 1 m³

Parameter	OPC Concrete	RHA 20%	Savings
Cement	₹4,800	₹3,840	₹960
RHA Cost +Processing	₹0	₹400	₹400
Total Material Cost	Cost₹5,400	₹4,790	₹610(11.3%)CO_2
Co2Emissions	350 kg	265 kg	85 kg (24.3%)

The environmental and economic performance of the material was improved by the integration of RHA as confirmed by sustainability assessment. Although higher environmental advantages were offered by RHA-15 and RHA-20, leading to the higher sustainability scores, RHA-10 was considered the optimum practical option due to combined better mechanical strength, superior durability and considerable carbon emission reduction and cost benefit. Hence 10-15% of cement replacement with RHA is considered beneficial to produce a sustainable cementitious material, with 10% RHA identified as the optimum level in terms of engineering.

5. Conclusion

This research aims to determine the suitability of RHA as a sustainable SCM to lower the use of cement with higher mechanical, durability, environmental and economic advantages of concrete. For this purpose, OPC was substituted with RHA in proportions of 0, 5, 10, 15, 20 and 25%. The mix proportion for all concrete was set as constant w/b ratio as 0.45, where test were carried out at 7, 14, 28 and 56 days. Various experimental work was performed i.e. Workability test, compressive strength, flexural strength, split tensile strength, water absorption test, chloride penetration, acid resistance test and micro structural analysis bySEM. Environmental impact assessment and cost-benefit analysis was carried out based on the experimental results.

- The slump value decreased from 85 mm (Control) to 52 mm (RHA-25), indicating reduced workability with increasing RHA content.
- Fresh concrete density decreased from 2420 kg/m³ to 2315 kg/m³ due to the lower specific gravity of RHA.
- The RHA-10 mix achieved the highest compressive strength of 53.1 MPa at 56 days, compared to 45.2 MPa for the control mix.
- Maximum flexural strength of 6.38 MPa was recorded for the RHA-10 mix at 56 days.
- The highest split tensile strength of 4.70 MPa was also observed in the RHA-10 mix at 56 days.
- Water absorption reduced from 5.30% (Control) to 3.90% (RHA-10), indicating improved impermeability.
- Chloride penetration depth decreased significantly from 16.7 mm (Control) to 10.8 mm (RHA-10), demonstrating enhanced durability.
- Acid resistance improved considerably, with weight loss reduced from 5.5% (Control) to 3.5% (RHA-10).
- SEM analysis revealed a denser microstructure and greater C-S-H gel formation at 10% RHA replacement, resulting in improved mechanical and durability properties.
- Cement replacement with RHA reduced CO_2 emissions by up to 25% and energy consumption by 17.9%.
- Production cost decreased from ₹6000/m³ for conventional concrete to ₹5700/m³ for the optimum RHA-10 mix.
- The RHA-10 mix achieved the highest benefit index (0.0086), providing the best balance between strength, durability, sustainability, and cost-effectiveness.
- Optimal Recommendation: 20% RHA replacement is identified as ideal for producing sustainable, durable, and environmentally responsible cement-based materials for upcoming infrastructure.
- Management Framework: A 4-stage RHA system is proposed — collection of husk, controlled burning/grinding, IS 456 quality checks, and delivery to RMC plants.
- Centralized sourcing ensures consistency, traceability, and reduced supply risks.Key
- The study establishes RHA as a sustainable and economical alternative to OPC. Converting farm waste into construction material supports circular economy goals, resource conservation, and emission cuts in the industry.

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