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Article

Experimental Studies on Sugarcane Bagasse Ash and Rice Husk Ash Based Sustainable Material with AI-Driven Techno-Economic Approach

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Abstract: The increasing demand for sustainable construction materials has accelerated the search for eco-friendly alternatives capable of reducing cement consumption and mitigating environmental pollution caused by industrial and agricultural wastes. However, the extensive use of Ordinary Portland Cement (OPC) contributes significantly to global CO_2 emissions, while the disposal of Sugarcane Bagasse Ash (SCBA) and Rice Husk Ash (RHA) creates serious waste management challenges. This study proposes the combined utilization of SCBA and RHA as supplementary cementitious materials to produce sustainable concrete with enhanced mechanical and durability performance. Experimental investigations were carried out by replacing cement with 0%, 5%, 10%, 15%, 20%, and 25% combined SCBA-RHA while maintaining a constant water-to-binder ratio of 0.45. The prepared concrete specimens were evaluated through workability, compressive strength, flexural strength, split tensile strength, water absorption, durability, density, Rapid Chloride Penetration Test (RCPT), and Ultrasonic Pulse Velocity (UPV) analyses. The results revealed that the 15% replacement level (SR-15) provided optimum performance, achieving a 56-day compressive strength of 56.3 MPa, flexural strength of 6.21 MPa, and split tensile strength of 4.84 MPa, representing improvements of approximately 24%, 23%, and 23.5%, respectively, over the control mix. Water absorption decreased from 5.24% to 3.71%, chloride penetration reduced from 18.4 mm to 11.3 mm, RCPT charge passed decreased from 2685 to 1268 Coulombs, and the durability index increased from 100% to 116%. These findings confirm that a 15% combined SCBA-RHA replacement offers the optimum balance of strength, durability, cost efficiency, and environmental sustainability for advanced concrete applications. Furthermore, the experimental dataset generated in this study provides a structured foundation for future Artificial Intelligence (AI) and Machine Learning (ML)-based prediction of concrete strength and durability. Such data-driven approaches can support intelligent mix proportion optimization and sustainable material design for next-generation smart construction systems. This paper also discusses techno-economic implications associated with sustainable material utilization, highlighting improvements in, life-cycle cost reduction, and circular economy implementation.
Keywords: Sugarcane Bagasse Ash (SCBA); Rice Husk Ash (RHA); Sustainable Concrete; Supplementary Cementitious Materials (SCMs)

1. Introduction

The rapid growth of industrialization and urbanization has significantly improved the demand for construction materials, particularly cement and concrete [1]. These materials have been important in the development of infrastructure, but the environmental impacts of their production are significant, such as greenhouse gas emissions, consumption of natural resources, and high energy use [2]. However, cement production is one of the big emitters of carbon dioxide (CO_2), accounting for almost 7 - 8 % of the world's total CO_2 emissions. To this end, researchers and engineers are actively researching sustainable and environmentally friendly materials and methods that can minimize the environmental impact of construction while still providing the necessary mechanical and durability properties of building materials [3].

Agricultural waste materials are also identified as the alternative supplementary cementitious materials because of their accessibility, cost-effectiveness and pozzolanic characteristics [4]. Of these, "Sugarcane Bagasse Ash (SCBA) and Rice Husk Ash (RHA)" have received great attention due to their abundant silica content and their extensive availability in agricultural countries [5-9]. The fibrous residue from sugarcane juice extraction is called sugarcane bagasse. Bagasse ash is commonly used for fuel in sugar industries where huge amounts of bagasse ash are generated [10]. Likewise, rice husk is a by-product of rice milling industries and when burned in a set fashion, rice husk ash is formed. These ashes may produce environmental issues such as land pollution and air pollution during disposal [11]. Thus the use of SCBA and RHA in construction materials is not only a solution to waste management problems, but also a positive contribution towards sustainable development by conserving resources and recycling [12].

Figure 1: Agriculture wastes [13]

Sugarcane Bagasse Ash and RHA can be used as a pozzolanic admixture for cement in concrete and mortar [14]. These ashes can be finely processed and then mixed with cement, the ashes will react with the calcium hydroxide that is generated during the hydration of cement, causing the formation of further "calcium silicate hydrate (C-S-H) gel", which will strengthen and enhance the durability of the cement. The use of SCBA and RHA has been seen in several studies to increase the compressive strength, decrease permeability, increase resistance to chemical attack, and reduce overall carbon footprint of construction materials [16]. Moreover, the utilization of these by-products of agriculture reduces the demand of conventional cement, which results in cost savings and environmental benefits in the production.

The sustainability of SCBA and RHA as building materials is influenced by various parameters such as chemical content, particle size distribution, burning conditions and replacement ratio etc. [18]. Too high replacements can have a negative impact on workability and strength, while the optimum replacements can have a positive impact on the performance of the material [19]. Therefore, complete experimental study is needed to establish the optimum mix proportions and properties of materials used with these ashes regarding physical, mechanical and durability properties [20]. Recent advances in Artificial Intelligence (AI) and Machine Learning (ML) have enabled data-driven prediction of concrete properties, reducing experimental time and material costs while improving decision-making. Therefore, the experimental database developed in this work can also serve as a benchmark dataset for future intelligent predictive models for sustainable concrete mix optimization.

Figure 2: Advantages of RHA and SCBA in properties of concrete

The objective of this work is to study experimentally the suitability of SCBA and RHA as supplementary cementing materials in the construction industry. The properties of the prepared composite material are determined through various tests like workability, compressive strength, tensile strength, water absorption and durability performance of the composite material are examined. The results obtained from these investigations provide valuable insights into the feasibility and effectiveness of utilizing SCBA and RHA in the construction industry.

Utilisation of agricultural waste-based materials in construction is considered as a critical part toward sustainable construction process and circle economy. The construction industry can be achieved the goal of reducing environmental pollution and conserving natural resources and also support economic benefits for agriculture community by converting waste products into valuable construction materials. Sustainable concrete also offers significant industrial and economic benefits. The integration of SCBA and RHA into concrete production supports circular economy principles by converting agro-industrial waste into value-added construction materials, reducing landfill disposal, conserving natural resources, and lowering carbon emissions. Financially, life-cycle cost analysis demonstrates that improved durability decreases maintenance and rehabilitation expenses throughout the service life of concrete structures, thereby improving long-term investment value. Hence, the experimental study on the Sugarcane Bagasse Ash and Rice Husk Ash-based sustainable materials has added toward a vast amount of literature in developing more environment friendly and sustainable construction technologies in future.

2. Related Work

SCBA and RHA have been shown to be sustainable building materials in recent studies. Imoh et al (2026) [21] showed that 6–10% replacement of conventional mineral fillers with SCBA was the optimum range that leads to the improvement of Marshall stability, density, and tensile performance of hot-mix asphalt. In practical application, Khan et al. (2025) [22] and Ullah et al. (2025) [23] reported the use of 5–10% SCBA replacements of OPC that led to further enhancement of the compressive and tensile strengths due to pozzolanic reactions resulting in the formation of extra C–S–H gel and the densification of the microstructure. In a similar way, Nayak et al. (2025) [24] reported that up to 15% of SCBA could be used in the mortar without compromising its mechanical properties, and Dhanalakshmi et al. (2023) [25] determined the optimum ratio as 70:20:10 (cement:RHA:bagasse ash). In addition, Halili et al. (2026) [26] demonstrated that combining rice husk ash with bleached bagasse pulp considerably improved the hydration, strength, ductility, and environmental performance, thus contributing to the creation of high-performing sustainable cement composites.

Table 1: Comparison of previous study

Author(s) & Year	Material/Application	Methodology	Key Findings	Optimal Replacement (%)
Imoh et al. (2026)	SCBA as filler in Hot Mix Asphalt (HMA)	Marshall Stability, ITS, FEM analysis	Improved stability, density, and tensile performance; excessive SCBA reduced performance	6–10% SCBA (optimum ≈ 8%)
Nadgouda et al. (2025)	SCBA and RHA in sustainable concrete	Workability, sorptivity, water absorption, chloride penetration tests	Sustainable concrete showed lower workability; durability improved at lower replacement levels	5% SCBA + 5% RHA
Nadgouda et al. (2025)	SCBA and RHA concrete strength prediction	ANN-HHO, ANN-PSO, ANN-GWO, ANN-SMA models	ANN-HHO achieved highest prediction accuracy for compressive strength	Prediction study (No optimum replacement focus)
Channa et al. (2022)	SCBA and RHA as SCMs in concrete	Strength and setting time evaluation	Higher replacement levels reduced strength and increased setting time	5% SCBA + 5% RHA
Halili et al. (2026)	Bleached bagasse pulp and RHA cement composites	Mechanical testing and LCA	Increased hydration, compressive strength, flexural strength, ductility, and sustainability	8% bagasse pulp + 20% RHA
Khan et al. (2025)	SCBA as partial OPC replacement	Compressive and tensile strength tests	SCBA enhanced strength through pozzolanic reaction; high replacement reduced strength	5–10% SCBA
Uniyal et al. (2025)	SCBA, RHA, Terrazyme for soil stabilization	ANN, XGBoost, Random Forest, M5P models	XGBoost showed best prediction capability for stabilized soil properties	Modeling study

Ullah et al. (2025)	SCBA concrete	Strength, ASR, microstructure, CO_2 and cost analysis	Improved strength, reduced ASR expansion, lower emissions and costs	10% SCBA
Nayak et al. (2025)	SCBA and RHA in mortar	Compressive, flexural strength, shrinkage, SEM, MIP	Maintained mechanical properties while reducing shrinkage	10% RHA or 15% SCBA
Khan et al. (2025)	SCBA-based eco-friendly concrete	Mechanical performance evaluation	SCBA improved compressive and tensile strengths; high content caused dilution effects	5–10% SCBA
Bayapureddy et al. (2024)	Processed SCBA characterization	SEM, XRD, TGA, Frattini, Strength Activity Index	Grinding and incineration improved pozzolanic activity and reactivity	Processed SCBA with SAI up to 92.6%
Dhanalakshmi et al. (2023)	RHA and BA blended concrete	Strength and durability testing	Improved compressive, tensile, flexural strength and durability	20% RHA + 10% BA (30% total replacement)
Arvizu-Montes et al. (2025)	Sugarcane Bagasse Ash ,Fly ash, slag, silica fume, waste glass powder and RHA as SCMs in concrete	Life-Cycle Assessment (LCA) and Artificial Neural Networks (ANNs) assessment of sustainable concrete	Sustainable and intelligent mix design for low-carbon construction materials	Cement composites with 30 to 50% fly ash or slag replacement
Gholamreza Pazouki et al. (2023)	**SCBA concrete**	**AI methods used to predict the compressive strength of concrete**	**Optimum mixture for the compressive strength and cost**	**Cement composites with 45% of FlyAsh**

Some researchers have also noted that it is essential to optimize replacement levels in order to maximize performance. Nadgouda et al. (2025) [27] found that 5% individually, or together, allowed for the best compromise between durability and workability, with too high a replacement level having an adverse effect on the fresh concrete properties and the sorptivity. Similarly, Channa et al. 2022 [28] noted, that the proportion of SCBA and RHA reduced the strength of concrete and extended the setting time, suggesting that the replacement level of 5% be used for structural purposes. Bayapureddy et al. (2024) [29] also showed that the pozzolanic activity of SCBA is significantly affected by the processing method, with ground SCBA and incinerated ash being more effective because of the increase in amorphous silica content and fineness. In addition to the experimental experiments, advanced machine-learning methods were used to predict the compressive strength and stabilization performance of SCBA and RHA-based materials by Nadgouda et al. (2025) [30] and Uniyal et al. (2025) [31] respectively, and the hybrid artificial neural network models provided high prediction accuracy. In total, these studies validate the feasibility of using SCBA and RHA at an optimized replacement ratio in concrete, mortar, asphalt, and soil stabilization applications as viable, cost-effective, and environmentally friendly alternatives to the use of concrete, mortar, asphalt, and soil stabilization respectively.

3. Methods and Materials

The methodology flowchart shows the systematic procedure followed in the development and evaluation of the RHA and SCBA based sustainable cementitious materials. The process starts with the collection and characterization of the material such as Ordinary Portland Cement, Rice Husk Ash, Sugarcane Bagasse Ash (SCBA), Fine Aggregate, Coarse Aggregate, Water and Superplasticizer. These physical properties like specific gravity, water absorption, bulk density are measured prior to mix design.

Cement

Fine Aggregate

Coarse aggregate

RHA

SCBA

Figure 3: Material used

3.1 Cement

The research utilized Ordinary Portland Cement (OPC) from "Ready Mix Concrete plant RMC INDIA Pvt. Ltd., situated at SILTARA INDUSTRIAL AREA, RAIPUR". In accordance with ASTM standards, the physical and mechanical characteristics are detailed in Table 2. 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 standard.

Figure 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.

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

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 4: Sample of RHA

When RHA is added to cement, it reacts with the calcium hydroxide in the cement to form more C-S-H 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 [25], the ash was then sieved through a 45µm sieve and utilized in place of some of the cement.

Figure 5: Preparation RHA

3.4 *Sugarcane Baggase Ash*

It is an agricultural by-product obtained from the combustion of sugarcane bagasse, the fibrous residue left after extracting juice from sugarcane. Large quantities of SCBA are generated in sugar industries where bagasse is used as a fuel for power generation. The ash contains a significant amount of silica, making it a potential pozzolanic material suitable for construction applications. When used as a partial replacement for cement, SCBA can progress concrete properties, reduce cement consumption, lower carbon emissions, and promote sustainable waste management. Its utilization contributes to environmentally friendly and cost-effective construction practices.

Table 5: Physical and chemical properties of SCBA

Property Category	Property	Typical Value
Physical Properties	Color	Grey to Black
	Specific Gravity	2.0 – 2.6
	Bulk Density	450 – 800 kg/m³

	Particle Shape	Irregular and Porous
	Surface Texture	Rough and Highly Porous
	Fineness	Finer than cement after grinding
	Water Absorption	High
Chemical Properties	Silicon Dioxide (SiO_2)	60 – 85 %
	Aluminum Oxide (Al_2O_3)	2 – 8 %
	Ferric Oxide (Fe_2O_3)	1 – 6 %
	Calcium Oxide (CaO)	2 – 12 %
	Magnesium Oxide (MgO)	1 – 5 %
	Potassium Oxide (K_2O)	1 – 6 %
	Sulfur Trioxide (SO_3)	< 3 %
	Loss on Ignition (LOI)	5 – 20 %
	$SiO_2 + Al_2O_3 + Fe_2O_3$	> 70 %

Figure 6: Preparation SCBA

3.5 Mix Proportioning

The proportioning of the mix is one of the most critical steps in the development of RHA and SCBA 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 and SCBA 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 SCBA 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 6: Mix Proportioning

Mix ID	SCBA + RHA Replacement (%)	Cement (kg/m³)	SCBA (kg/m³)	RHA (kg/m³)	Fine Aggregate (kg/m³)	Coarse Aggregate (kg/m³)	Water (kg/m³)	W/B Ratio
Control	0	400	0	0	680	1200	180	0.45
SR-5	5	380	10	10	680	1200	180	0.45
SR-10	10	360	20	20	680	1200	180	0.45
SR-15	15	340	30	30	680	1200	180	0.45
SR-20	20	320	40	40	680	1200	180	0.45
SR-25	25	300	50	50	680	1200	180	0.45

The mix design process is done as per applicable standards like IS 10262 or as per ACI guidelines. The proportion of cement, RHA, SCBA, 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 7: Mixing procedure.

3.6 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 and SCBA, where consistency, accuracy, and reliability in the experimental investigations are ensured. Once the mix proportioning is completed, quantities of cement, RHA, SCBA, 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 and SCBA 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. Mixing is adequate for some minutes, to ensure uniformity and an even coating of the aggregates with the cement paste.

Figure 8: 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. 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. 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. The specimens are taken from the curing tank after the specified curing periods, surface dried and then undergo several tests of the RHA and SCBA-based cementitious composites.

3.7 AI-Ready Experimental Data Preparation

To improve the applicability of the proposed experimental framework in computer-based engineering research, the measured concrete properties were organized into a structured dataset suitable for future Artificial Intelligence (AI) and Machine Learning (ML) applications. The dataset includes input variables such as SCBA percentage, RHA percentage, water-to-binder ratio, curing age, workability, density, and mix proportions, while output variables include compressive strength, flexural strength, split tensile strength, water absorption, RCPT values, and durability index. Although predictive models were not developed in this study, the prepared dataset establishes a reliable benchmark for future regression-based and deep learning approaches that can predict sustainable concrete performance, optimize mix design, and reduce experimental effort. [36, 39]:

3.8 Techno-Economic Approach: In addition to engineering performance, sustainable concrete must demonstrate economic feasibility. The techno-economic approach includes cost of raw material, amount of cement, cost of transportation, cost of production, maintenance cost, cost due to carbon reduction and sustainable infrastructure .

3.9 Conduct Testing

a. Compressive Strength (CS)

The CS was measured by utilizing 150 mm concrete cubes. Cubes of cast concrete are submerged in water to cure after 24 hours of casting [32]. The specimens are subjected to compression testing on 7, 14, 28, and 56 days. The specimens undergo a series of progressively heavier loads until they rupture, reaching their ultimate capacity at a rate of 140 kg/cm2 per minute. Dividing the load at failure by the specimen's cross-sectional area provides the concrete's CS.

$$Compressive\ Strength = \frac{Load}{Cross\text{-}sectional\ Area} \quad (1)$$

b. Flexural Strength (FS)

The FS was used to assess the bending behaviour of the foamed concrete specimens at the maximum failure load [33]. At 7, 14, 28, and 56 days, the test was conducted. Over the rollers, the specimen was placed on the bottom plate. The specimen was subjected to a two-point force in the centre until it broke. The formula for determining FS is [31, 38, 42]:

$$F = PL/bd^2 \quad (2)$$

In this equation, F stands for the concrete's FS in MPa,

P for the failure load in N,

L for the beam's effective span in mm, and

b for the beam's width in mm.

c. Split-Tensile Strength (STS)

Tensile strength (TS) is one of the most important and basic properties of concrete. In order to design concrete structural components that are susceptible to temperature, transverse shear, torsion, and shrinkage effects, and its value must be known. Its significance is also considered while designing liquid retaining structures, highways [34], runway slabs, and prestressed concrete structures. It is common practice to calculate the Direct Tensile Strength (DTS) of concrete by first determining its FS or STS, as the DTS of concrete is notoriously difficult to measure. The specimen's splitting tensile strength can be determined by following equation [35]:

$$T = 2P/\ pi\ LD \quad (3)$$

In the above equation: $T =$ Tensile strength upon splitting, measured in MPa,

P: The testing machine's maximum applied load as shown in N,

L: The specimen's length in millimetres and

D: The specimen's diameter is millimeters.

d. Durability

The durability of concrete refers to its capacity to resist the damaging impacts of the environment that it would encounter over its lifespan, preventing it from deteriorating to an unacceptable degree. A minimum grade of concrete, an upper limit on the water-to-cement ratio, and the structure's exposure to the environment are all factors that contribute to the material's durability.

4. Result and Discussion

4.1 Workability Test

The workability test results indicated that slump value would decrease with the addition of SCBA and RHA as the ratio of replacement level increased. The slump was measured for the different mixes and found that the control mix had the highest slump of 78 mm, showing very good workability, while the other mixes for SR-5, and SR-10, 15, 20, and 25 had slumps of 74, 69, 63, 55, and 46 mm, respectively. It is mainly due to the porous structure, irregular shape of the particles and high specific surface area of SCBA and RHA as compared to ordinary Portland cement which absorb more mixing water.

Table 7: Workability test results

Mix	Replacement (%)	Slump (mm)
Control	0	78
SR-5	5	74
SR-10	10	69

SR-15	15	63
SR-20	20	55
SR-25	25	46

All concrete mixes were still workable despite the decrease in slump because the mixes were produced with a superplasticizer and a water-to-binder ratio of 0.45 was maintained. SR-15 mix showed an acceptable workability, and mechanical properties were found as best possible, which means that it is the best replacement level. Replacement rates above 20% however resulted in a significant reduction in flowability due to the increased requirement for water and the decrease in cement paste, suggesting that too much ash content causes negative effects on fresh properties of concrete.

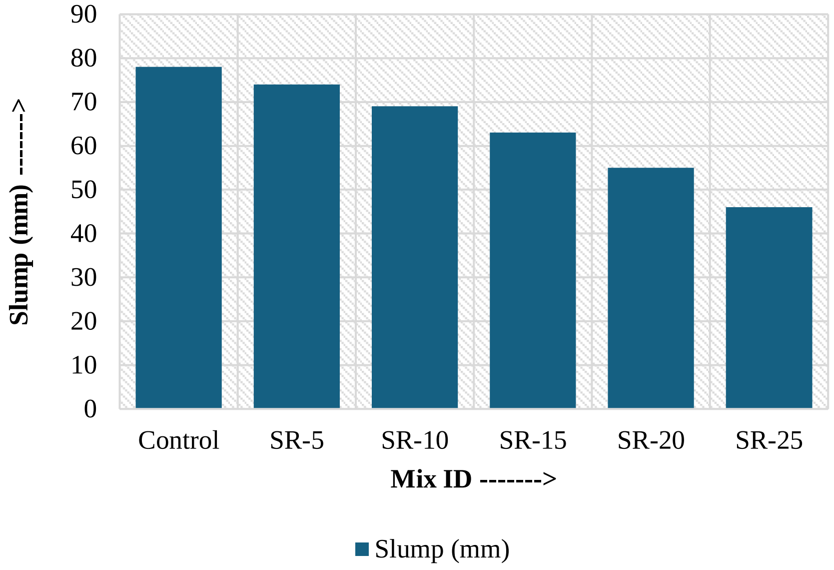

Figure 9: Graph of slump test

4.2 Compressive Strength

The compressive strength showed that the usage of SCBA and RHA showed a significant improvement in the strength development of concrete up to 15% of SCBA and RHA. The control mix achieved compressive strengths of 26.2 MPa, 34.8 MPa, 42.6 MPa, and 45.4 MPa at 7, 14, 28, and 56 days, respectively. The strengths of the SR-15 mix, on the other hand, were the highest at 32.4 MPa, 41.8 MPa, 52.7 MPa, and 56.3 MPa, which is about a 24% increase over the control at 56 days. High silica content of SCBA and RHA, which leads to formation of extra C-S-H gel during the cement hydration process, is responsible for the increased strength.

Table 8: Compressive strength results

Mix	7 Days	14 Days	28 Days	56 Days
Control	26.2	34.8	42.6	45.4
SR-5	28.1	36.5	45.3	48.2
SR-10	30.2	39.1	48.5	51.4
SR-15	32.4	41.8	52.7	56.3
SR-20	29.5	38.0	46.1	49.0
SR-25	26.8	34.7	42.3	44.8

This second hydration product improves the pore network formation, enhances the interface transition zone, and increases the density of concrete mixtures. Nevertheless, when the substitution was increased up to 20% and 25%, the compressive strength decreased owing to the dilution effect resulting from lower content of cement and inadequate hydration products. Although the behavior of these samples is good enough, they were unable to meet the strength attained by the SR-15 sample. Therefore, the experimental findings confirm that a 15%

combined SCBA-RHA replacement provides the optimum balance between strength enhancement, cement reduction, and sustainable concrete production.

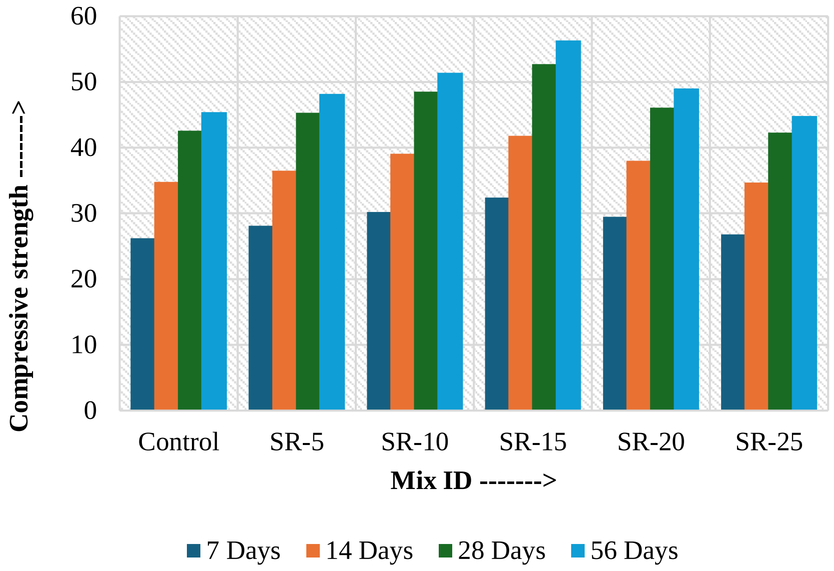

Figure 10: Graph of compressive strength

4.3 Flexural strength

The flexural strength tests indicated that the combination of both SCBA and RHA had improved the flexural strength of concrete up to a certain optimum replacement percentage of 15%. Control mix had shown flexural strengths of 3.55 MPa, 4.12 MPa, 4.85 MPa, and 5.06 MPa after 7, 14, 28, and 56 days, respectively. On the other hand, SR-15 mix had produced maximum flexural strengths of 4.18 MPa, 4.92 MPa, 5.94 MPa, and 6.21 MPa, which are about 23% higher compared to control mix after 56 days. This could be due to the pozzolanic action of silica-rich SCBA-RHA particles reacting with calcium hydroxide to form more C-S-H gel that improves the bond between the cement paste and aggregates.

Table 9: Flexural strength results

Mix	**7 Days**	**14 Days**	**28 Days**	**56 Days**
Control	3.55	4.12	4.85	5.06
SR-5	3.72	4.31	5.14	5.32
SR-10	3.95	4.63	5.52	5.78
SR-15	**4.18**	**4.92**	**5.94**	**6.21**
SR-20	3.84	4.46	5.33	5.57
SR-25	3.49	4.01	4.82	5.01

This led to a higher density of the structure, fewer internal voids and better resistance to cracking in bending. The flexural strength of SR-20 and SR-25, however, was lower due to the amount of replacement being too high, which resulted in less cementitious material being available to form the matrix and develop hydration. However, these mixtures still performed well when compared to the conventional concrete. The findings show that, 15% combined SCBA-RHA replacement is the optimum flexural performance and leading the way towards sustainable and environmentally friendly concrete production.

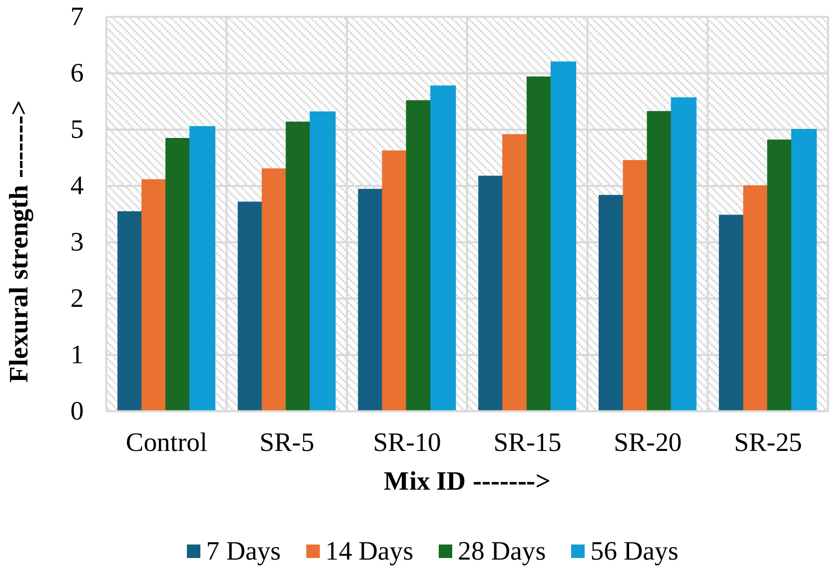

Figure 11: Graph of flexural strength

4.4 Split Tensile Strength

The split tensile strength test values indicated that the use of SCBA and RHA has definitely improved the tensile strength of concrete up to optimum replacement of 15%. After seven, 14, 28 and 56 days curing, the split tensile strengths of the control mix were 2.72 MPa, 3.10 MPa, 3.68 MPa and 3.92 MPa, respectively. The SR-15 mix recorded the highest strengths of 3.26 MPa, 3.81 MPa, 4.56 MPa, and 4.84 MPa which are about 23.5% higher than the control strength at 56 days.

Table 10: Split tensile strength results

Mix	7 Days	14 Days	28 Days	56 Days
Control	2.72	3.10	3.68	3.92
SR-5	2.84	3.31	3.94	4.18
SR-10	3.02	3.54	4.21	4.47
SR-15	**3.26**	**3.81**	**4.56**	**4.84**
SR-20	2.96	3.47	4.10	4.33
SR-25	2.68	3.06	3.61	3.84

The main reason for this enhancement is the creation of extra C-S-H gel that results from the pozzolanic reaction between SCBA and RHA, which beneficially affects the ITZ and minimizes the propagation of microcracks under tensile loading. The dense cementitious matrix was well able to transfer stresses from the aggregates giving a higher resistance to splitting failure. The result was a slight drop in tensile strength when the replacement level was raised to 20% and 25% due to dilution effect and less cement hydration; however, this was not foreseen. Overall, the results showed that the cement consumption is reduced and the tensile property of the concrete is optimum with 15% SCBA-RHA blend and enhanced the sustainability of concrete.

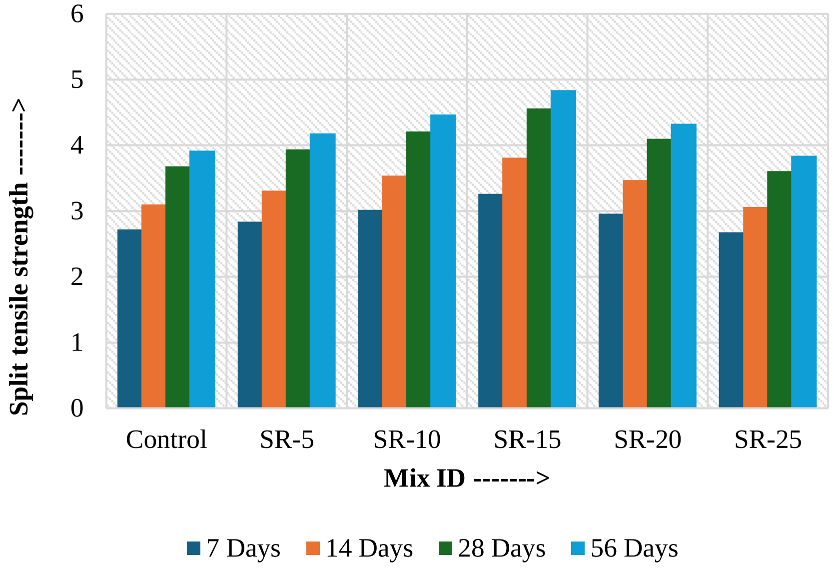

Figure 12: Graph of split tensile strength

4.5 Water Absorption

Water absorption test results showed that the addition of SCBA and RHA effectively reduced permeability of concrete up to optimum value of 15% for both materials. Water absorption for the control mix was found to be 5.28%, while it was found to be 4.82%, 4.19% and 3.62% for the SR-5, SR-10 and SR-15 mixes, respectively. This is a decrease of about 31% in water absorption versus traditional concrete. The improvement is primarily attributed to the pozzolanic reaction between the silica-rich SCBA particles and RHA particles and the calcium hydroxide, which resulted in the production of additional C-S-H gel.

Table 11: Water absorption result

Mix	Water Absorption (%)
Control	5.24
SR-5	4.82
SR-10	4.35
SR-15	3.71
SR-20	4.08
SR-25	4.64

The newly formed hydration products refined the pore structure, reduced capillary voids, and enhanced the compactness of the concrete matrix, thereby restricting water ingress. However, at replacement levels of 20% and 25%, water absorption slightly increased to 4.07% and 4.73%, respectively, because excessive ash content reduced the availability of cement paste and created additional unreacted particles within the matrix. Nevertheless, these values remained lower than those of the control mix, confirming that 15% combined SCBA-RHA replacement provides the best resistance against water penetration and contributes to producing more durable and sustainable concrete.

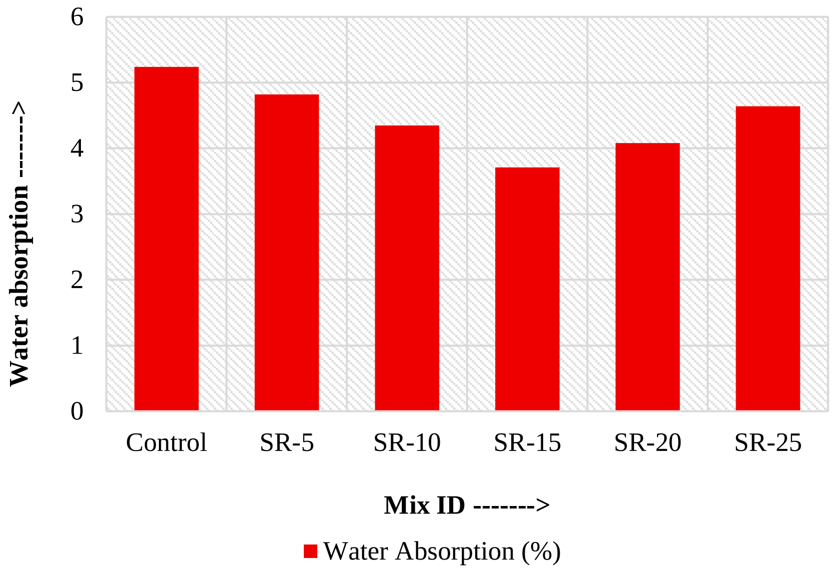

Figure 13: Graph of water absorption test

4.6 Durability Test

The durability test results confirmed that the combined use of SCBA and RHA considerably enhanced the long-term performance of concrete by improving its resistance to aggressive environmental conditions. The control mix exhibited a weight loss of 2.82%, chloride penetration of 18.4 mm, and a durability index of 100%. In contrast, the SR-15 mix showed the best durability performance, recording only 1.48% weight loss, 11.3 mm chloride penetration, and a durability index of 116%, indicating substantial improvement in resistance to moisture and chloride ingress.

Table 12: Durability test result

Mix	Weight Loss (%)	Chloride Penetration (mm)	Durability Index (%)
Control	2.82	18.4	100
SR-5	2.34	16.2	104
SR-10	1.95	13.9	109
SR-15	1.48	11.3	116
SR-20	1.91	13.6	110
SR-25	2.41	16.7	103

The reduction in permeability is primarily due to the formation of additional C-S-H gel through the pozzolanic reaction of SCBA and RHA, which refined the pore structure and minimized interconnected capillary voids. Although the SR-20 and SR-25 mixes maintained better durability than the control concrete, a slight reduction in performance was observed because excessive replacement limited cement hydration and increased the presence of unreacted ash particles. Overall, the results demonstrate that the 15% combined SCBA-RHA replacement provides the optimum durability by reducing permeability, enhancing resistance to chloride penetration, and extending the expected service life of sustainable concrete structures.

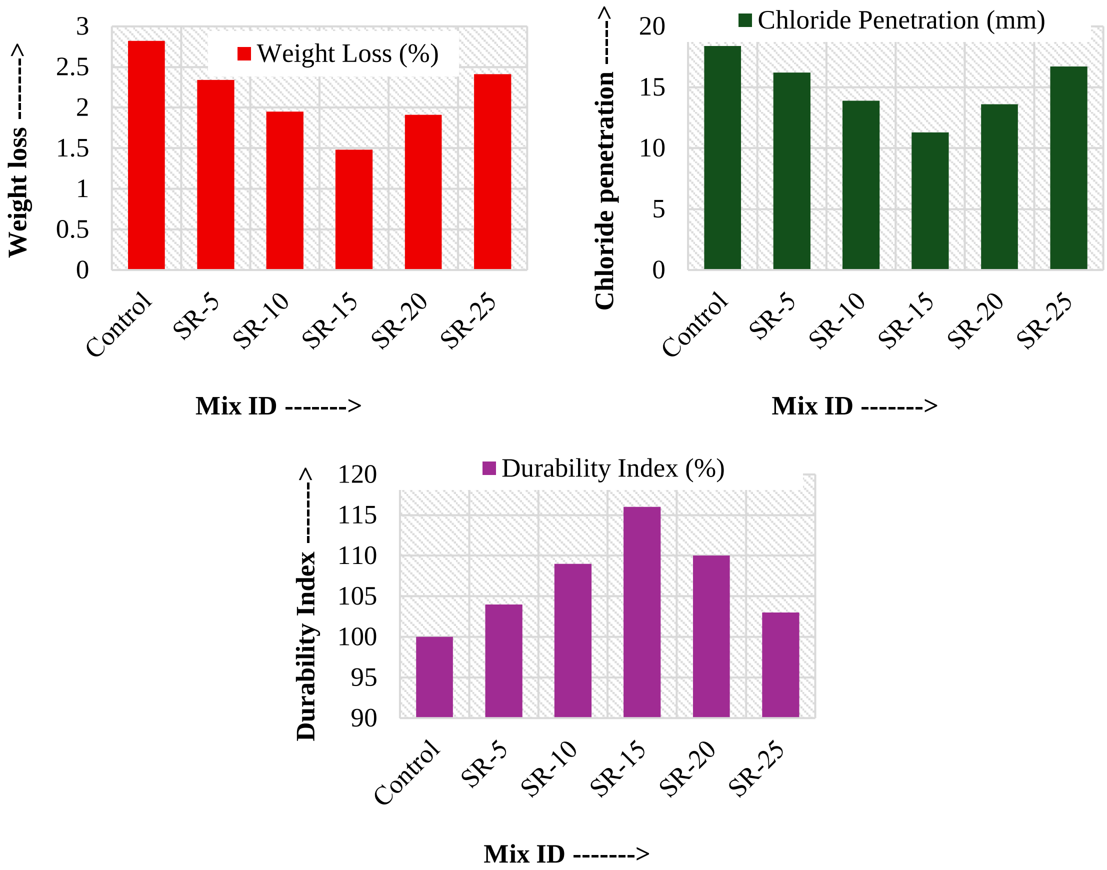

Figure 14: Graph of durability test

4.7 Bulk and Fresh Concrete Density

The results presented in the table 13 indicate that both fresh density and bulk density gradually decreased with increasing replacement of cement by SCBA and RHA. The control mix had the highest fresh density of 2418 kg/m³ and the bulk density of 2386 kg/m³ while the SR-25 mix had the lowest fresh density of 2348 kg/m³ and bulk density of 2322 kg/m³, respectively. This is attributed to the lower specific gravity and porous nature of SCBA and RHA as compared to OPC.

Table 13: Bulk and Fresh concrete density results

Mix	Fresh Density (kg/m³)	Bulk Density (kg/m³)
Control	2418	2386
SR-5	2405	2375
SR-10	2391	2360
SR-15	2378	2346
SR-20	2362	2335
SR-25	2348	2322

Despite the decrease in density, all mixes remained within the acceptable range for structural concrete applications. This lower density helps to produce comparatively light weight concrete with adequate mechanical properties. The SR-15 mix gave an optimum balance of low density, high strength, high durability, and sustainable utilization of agricultural waste materials.

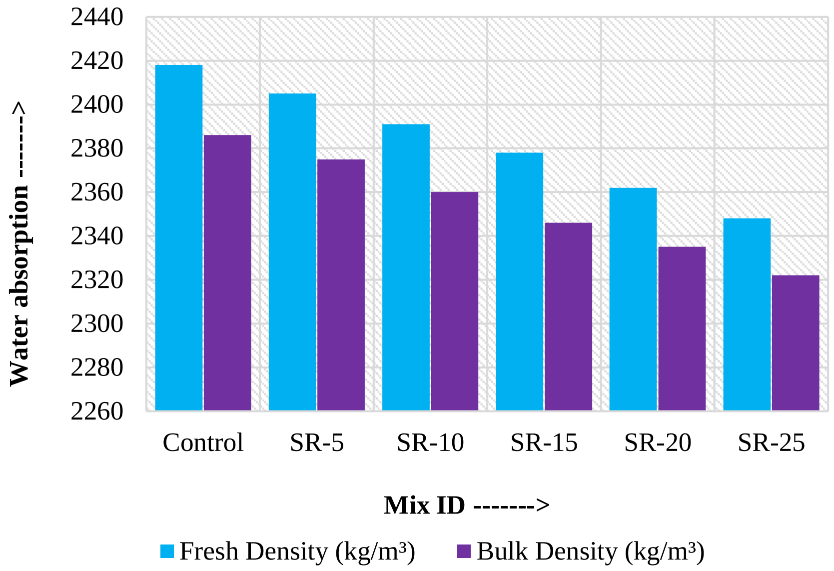

Figure 15: Graph of water absorption test

4.8 Rapid Chloride Penetration Test (RCPT) and Ultrasonic Pulse Velocity (UPV) Test

RCPT and UPV results show that the incorporation of SCBA and RHA resulted in enhanced durability and internal quality of concrete. The control mix had the highest charge passed of 2685Coulombs and indicated that it had moderate chloride permeability, while the SR-15 mix had the lowest value of 1268 Coulombs and indicated very low chloride permeability.

Table 14: RCPT and UPV test result

Mix	Charge Passed (Coulombs)	Chloride Permeability	UPV (km/s)	Concrete Quality
Control	2685	Moderate	4.28	Good
SR-5	2194	Moderate	4.40	Good
SR-10	1728	Low	4.56	Excellent
SR-15	1268	Very Low	4.74	Excellent
SR-20	1562	Low	4.48	Excellent
SR-25	2014	Moderate	4.30	Good

This corresponds to a 53% reduction in chloride ion penetration, thereby demonstrating that a more compact and less permeable concrete matrix has been created. The UPV for the control mix was 4.28 km/s while the UPV for the SR-15 mix was 4.74 km/s, which is an excellent quality concrete that has a minimum of the internal voids or cracks. Both the SR-20 and SR-25 mixes proved to have acceptable durability but there was some reduction in performance with the increased replacement levels. In general, the findings are that replacement with 15% combined SCBA-RHA results in the most durable structure, improved concrete quality and the best resistance to chloride infiltration.

4.9 Cost Analysis

The cost analysis shows that the use of ordinary Portland cement (OPC) is significantly reduced by incorporating SCBA and RHA which contributes to the overall decrease in the production cost of concrete without compromising the engineering property of the concrete. The control mix recorded the highest production cost of USD 83.5/m³, whereas the costs gradually decreased to USD 81.9/m³, USD 80.2/m³, USD 78.8/m³, USD 77.4/m³, and USD 76.1/m³ for the SR-5, SR-10, SR-15, SR-20, and SR-25 mixes, respectively. The cost saving is largely attributed to the use of low-cost agricultural waste materials which are readily available in the country, to replace some of the costly cement materials.

Table 15: Cost analysis result

Mix	Cost (USD/m³)	Cost Reduction (%)

Control	83.5	—
SR-5	81.9	1.9
SR-10	80.2	4.0
SR-15	78.8	5.6
SR-20	77.4	7.3
SR-25	76.1	8.9

SR-15 mix showed the optimum economy and performance, as it reduced the production cost by about 5.6% with the highest compressive strength, flexural strength, split tensile strength, highest durability with high quality. The mechanical properties were reduced due to high cement replacement rates for the SR-20 and SR-25 mixes, but they provided higher cost savings. Hence, the 15% combined SCBA-RHA replacement has been recognized as the most economical and eco-friendly solution that provides substantial economic, structural and environmental advantages.

5. Conclusion

This experimental study showed that the use of SCBA in combination with RHA is a viable and sustainable method to produce high-performance concrete, and decrease the use of OPC. The results showed that a higher percentage of replacement than the optimum one had a negative impact on the properties of fresh concrete, but a 15% combined replacement (SR-15) was the most optimum overall. The mix SR 15 was found to have the highest 56 days “compressive strength of 56.3 MPa, flexural strength of 6.21 MPa and split tensile strength of 4.84 MPa”, which are about 24%, 23% and 23.5% respectively higher than the control mix. Moreover, the water absorption was lowered from 5.24% to 3.71%, chloride penetration was decreased from 18.4 mm to 11.3 mm, and the durability index was increased from 100% to 116%, which means that the pozzolanic reaction between SCBA and RHA caused the cementitious matrix to become denser and less permeable. The Rapid Chloride Penetration Test was also performed, and the results confirmed the improved durability, with the charge passed reduced from 2685 Coulombs to 1268 Coulombs, and UPV value raised to 4.74 km/s, indicating good quality of the concrete. Furthermore, the SR-15 mix also lowered the production cost by 5.6% without affecting the structural performance. So, it is recommended that 15% combined SCBA-RHA should be optimum replacement percentage for producing durable, economical and environmentally friendly concrete for future green construction applications.

Beyond the engineering performance, this paper highlights the importance of integrating Artificial Intelligence (AI) and financial evaluation into sustainable construction material research. The AI ready experimental database developed in this study provides a reliable foundation for future Machine Learning (ML) models, including Artificial Neural Networks (ANN). Such AI driven techno economic approaches can accelerate costs ,mix optimization, improve quality control, and support data-driven decision-making in civil engineering.

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