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SUSTAINABLE CONCRETE PRODUCTION USING AGRICULTURAL WASTE MATERIALS: A PERFORMANCE-BASED STUDY

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ABSTRACT

The production of conventional concrete accounts for ~8% of global CO_2 emissions through the energy-intensive production of ordinary Portland cement (OPC). Alternative environmentally friendly and more economically sustainable types of concrete have been developed, like the green concrete development using agricultural wastes materials such as rice husk ash (RHA), sugarcane bagasse ash (SCBA), bamboo leaf ash (BLA). An experimental study was conducted to evaluate the mechanical, durability and microstructural properties of green concrete mixes having partial replacement of OPC using RHA (10%, 15%, 20%), SCBA (5%, 10%, 15%) and binary blend of RHA+SCBA at four proportions (10%+5%, 10%+10%, 15%+5%, 15%+10%) at water to cementitious materials ratio of 0.45. Total 108 concrete cube and cylinder specimens were cast and tested for compressive strength (7, 28 and 90 days), split tensile strength, flexural strength, water absorption and rapid chloride penetration. The results reveals that optimal 28-day compressive strength of 43.8 MPa is achieved from the 15% RHA and 10% SCBA binary replacement (mix RS4), the increase were to level of 12.3% higher than the control mix and this eco-friendly concrete gave 18.4% lower of CO_2 emission and 10.6% lower material cost per cubic metre compared to the control mix. One-way ANOVA analysis with a significance limit of 0.05 for replacement type and level indicates highly significant levels of mechanical performance ($F = 31.42$, $p < 0.001$). Regression models (R^2 up to 0.988) as validated mix-design tools were used to optimise agricultural ash content.

Keywords: *Green Concrete[1]; Rice Husk Ash[2]; Sugarcane Bagasse Ash[3]; Agricultural Waste[4]; Supplementary Cementitious Materials[5]; Compressive Strength[6]; Sustainable Construction[7].*

1. INTRODUCTION

1.1 GLOBAL CONTEXT OF CEMENT PRODUCTION AND ENVIRONMENTAL IMPACT

According to Global Cement and Concrete Association (GCCA, 2023), the construction industry is one of the biggest polluters on the planet, with cement production contributing up to 4.1 billion tonnes of CO_2 annually.

Normal Portland cement (OPC) depends on the faulting of limestone at a temperature above 1,450°C, a thermally extreme technique that by definition discharges massive amounts of ozone harming substances. The global demand for infrastructure development, specifically in fast-urbanising economies in which there is particular pressure on cement production, such as India, China and Sub-Saharan Africa, is resulting in vast quantities of cement being produced [1]. Green concrete, which is defined as concrete that contains by-product or waste-derived materials that entirely/or partially substitute cement, aggregates and water, is an urgent national technology strategy to address these environmental imperatives. The recent advancements in supplementary cementitious materials (SCMs) have shown that agricultural waste residues especially silica rich ashes can exhibit pozzolanic activity and potentially enhance mechanical and durability properties in concrete mixes [2], [3]. Combined with the reaction of pozzolanic materials with calcium hydroxide ($Ca(OH)_2$) released by cement hydration which generates supplementary calcium silicate hydrate (C-S-H) gel, thus refining the pore structure, augmenting strength, reducing permeability. It is not only a technical option, but a government mandate consistent with India's own National Action Plan on Climate Change and Sustainable Development Goal-11 (Sustainable Cities and Communities).

1.2 AGRICULTURAL WASTE AS POZZOLANIC MATERIAL

In India, about 657 million tonnes of agricultural residues are produced every year [3], one-third of which is openly burned in fields causing severe air pollution and public health crises especially in northern India [4]. Rice husk ash (RHA) is one of the most available agro-industrial by-products; It is produced by the controlled combustion of rice husk, and usually contains 85–90% reactive amorphous silica (SiO_2) when burned at the optimized temperatures of 550–700°C [5]. Alike, sugarcane bagasse ash (SCBA) is another solid residue from the operations of the furnaces of sugar mill and can provides a significant silica and alumina contents when calcined within the range of 550–650°C (Vasudevan, 2012), in addition to this, the calcination temperature, particle size distribution, and surface area either by Blaine fineness or BET approach define the pozzolanic activity of these materials (Ilangovan et al., 2023). When ground to levels of fineness similar to OPC (400–600 m^2/kg Blaine), RHA and SCBA show good reactivity with $Ca(OH)_2$ and the formation of additional C-S-H gel densifies the microstructure, increasing long-term strength and impermeability [6],[7]. Bamboo leaf ash (BLA), another under-researched natural agricultural by-product which contains around 58–65% SiO_2, has demonstrated somewhat similar pozzolanic activity in initial experimental studies. The co-application of these agroindustrial ashes in binary or ternary mixes is a new and efficient strategy to ensure the positive synergetic effects of hydration chemistry of cementite while maximizing the environmental benefits of waste valorization.

1.3 RESEARCH OBJECTIVES AND SCOPE

Although there is a substantial amount of literature regarding the use of individual agricultural waste-based SCMs, few studies have investigated such binary blends of RHA and SCBA with regards to their synergistic influence on compressive strength, durability, and microstructural development over prolonged curing ages. In addition, the majority of previous studies have been performed in controlled laboratory settings with limited statistical validation of findings and inadequate reference to established (peer reviewed) data. This study deals to fill in these gaps by: (i) preparing and testing the green concrete mixes for M30-grade with variable proportions of RHA, SCBA, and binary RHA+SCBA blends as partial cement replacements; (ii) evaluating the mechanical properties: compressive, tensile and flexural strength after 7, 28 and 90 days of curing; (iii) assessing the durability characteristics: water absorption, sorptivity and RCPT values; (iv) performing one-way ANOVA and regression analysis on all the test data and (v) critically comparing the results obtained in the present study with those reported in the literature published in well-established international journals. The study intends to offer empirical evidence which may be added to the Indian and similar developing economy structural concrete design codes and green building rating guidelines to support the incorporation of agricultural waste materials [8].

2. LITERATURE SURVEY

2.1 REVIEW OF RICE HUSK ASH IN CONCRETE

The reason behind researching rice husk ash as a partial cement replacement is its high reactive silica content combined with the fact that it has insignificant carbon footprint. Controlled combustion of RHA in 550–700°C yields amorphous silica, with sp. surface area > 200 m²/g, hence greater pozzolanic reactivity than crystalline silica made at higher temperatures [9]. Ganesan et al. Sahab Ghazal et al [10] studied M25 concrete with RHA replacement levels from 5 to 30% found that the maximum compressive strength at 15% of replacement (38.6 MPa at 28 days) with the values after 15% decreasing progressively, it always explains with the over dilution of clinker phases. Chindaprasirt et al. [11] RHA was compared between ground and unground in concrete mixtures and was found that grinding RHA to particle sizes below 45 µm improved compressive strength at 28 days by 22% and absorption by 31% . Concrete produced with 15% RHA replacing cement was shown to increase splitting tensile strength by 18% and flexural strength by 14% when compared to control, due to enhanced pozzolanic densification leading to an improvement in the interfacial transition zone (ITZ) quality. Fapohunda et al. [12] In another study T. Wong et al. The meta-analysis from this set of papers defines a recommended range of RHA replacement of 10–20% to achieve optimum properties in M-grade structural concrete.

2.2 REVIEW OF SUGARCANE BAGASSE ASH IN CONCRETE

With the large-scale availability of sugarcane bagasses in tropical sugar producing countries (Brazil, India, Thailand and Pakistan), Sugarcane bagasse ash has been proposed to be a potential agricultural by-product for green concrete. Cordeiro et al. Mixed with 20% ultra-fine SCBA (specific surface area 1,200 m²/kg), showed that the 28-day compressive strength for high-performance concrete exceeded that of reference mixes by 18% due to the better packing density and pozzolanic reactivity of these ultrafine particles [14]. Ganesan et al. SCBA calcined at 600 °C resulted in a much higher pozzolanic activity index (PAI = 82%) as compared to uncalcined

SCBA (PAI = 64%) confirming the importance of thermal treatment to activate the siliceous phases [15]. Castaldelli et al. [16], As per SEM and XRD analysis of SCBA concrete confirmed the development of secondary C-S-H and calcium aluminate hydrate phases at the aggregate–paste interface which subsequently densified the microstructure and also reduced the connectivity of the macropores. Arenas-Piedrahita et al. SCBA replacement of up to 15% has been shown to significantly decrease drying shrinkage and creep of SCBA concrete beams when compared to sand concrete beams, with the authors attributing this due at least in part to a filler effect providing less free water available to the paste matrix [17]. Singh and Siddique [18] found that 10-15% SCBA was effective in providing protection from sulphate attack in comparison to plain OPC concrete and they noted that significant reduction in expansion and surface cracking for specimens immersed in 5% $MgSO_4$ solutions, which was attributed to the reduced availability of portlandite ($Ca(OH)_2$) in the hydrated paste system.

2.3 BINARY AND TERNARY BLENDS OF AGRICULTURAL WASTE ASHES

Research on the synergistic use of two or more agricultural waste ashes in either binary or ternary combinations have increased significantly due to the possibility of creating complementary effects on cementite hydration chemistry and microstructural formation. Nair et al. [19] examined RHA-SCBA binary blends at total replacement levels of 20–30% and concluded that the combination of reactive silica from RHA and the combined silica-alumina phases from SCBA produced denser microstructures than either material alone, as determined from mercury intrusion porosimetry (MIP) measurements indicating low total porosity and threshold pore diameter. Raza et al. A 91% PAI at 28 days was obtained with a binary blend of 15% RHA + 10% SCBA compared to 78% with RHA, and 74% with SCBA at equal replacement levels, confirming statistically significant pozzolanic activity synergy [20]. Mangi et al. Findings by Ineren et al.[21] when investigating ternary blends of RHA, SCBA and fly ash showed that SCBA positively affected strength at 7 days, something that is often low in more RHA-dominant mixes due to the slow pozzolanic reaction rate of RHA at early curing ages. Memon et al. A three-part blend incorporating 10% RHA, 10% SCBA and 5% silica fume in concrete of the M40 class was able to create RCPT values of less than 1,000 coulombs (negligible permeability as per ASTM-C1202) [22], attesting to the long-lasting performance obtainable through well-considered multi-material combinations. The cumulative interpretations of these findings indicate that blending of binary RHA-SCBA can potentially compensate the demerits posed when either material was individually used, thus, necessitating systematic experimental study supplemented with statistically validated analysis which is the main intent of this article in particular [23], [24].

3. METHODOLOGY

The experimental program was structured in three phases: characterization of raw materials; mix design and specimen preparation; mechanical and durability tests. Mix design was done by IS:10262-2019 guidelines and IS:1199-2018 was followed for fresh concrete testing. Rice husk ash was obtained from a rice processing unit in Chhattisgarh, India and calcined in controlled combustion conditions (650 °C for 6 h in a programmable muffle furnace to facilitate amorphous silica formation) before being ball-mill ground to a Blaine fineness of 481 m²/kg. Sugarcane bagasse ash was sourced from a sugar mill situated in Uttar Pradesh, oven-dried at 105°C, calcined at 600°C for four hours to increase reactivity of silica and alumina, and subsequently ground to a fineness of 412 m²/kg (Blaine). Bamboo leaf ash was also subjected to pyrolysis at 500°C and ground to 389 m²/kg. X-ray fluorescence (XRF) spectrometry was used to find the chemical composition of all binder materials, and both RHA and SCBA complied with the ASTM C618 Class N pozzolan requirement of at least 70% as the sum of the three oxides (SiO_2 + Al_2O_3 + Fe_2O_3), which represented 92.4% and 76.8% of the composition, respectively (Table 2.The binder was made in part by incorporating 10% RHA and 5% SCBA). The primary binder used in all mixes was Grade 53 OPC as per IS:12269. The coarse aggregate is called as Crushed granite coarse aggregates (maximum nominal size, 20 mm) confirming to IS:383 and clean river sand having fineness modulas of 2.62was used uniformly. Meanwhile, no chemical admixtures were used to isolate the influence of agricultural ash replacements on all properties measured.

Eleven concrete mix proportions were prepared including: The control which is M0 (100% OPC) and 10 variable mixes. RHA single-material mixes were labelled R10, R15 and R20 (10%, 15%, 20% cement replacement). Single-material mixes of SCBA were designated as SCBA - S5, S10, and S15 (replacement of 5%, 10% and 15% respectively) We assigned binary RHA+SCBA mixes RS1 (10%+5%)2, RS2 (10%+10%), RS3 (15%+5%), and RS4 (15%+10%). All mixes had a target concrete grade of M30 with a design water-to-cementitious materials ratio of 0.45 and total cementitious content of 450 kg/m³. Six cube specimens (150×150×150 mm) were cast for compressive strength at 7, 28, and 90 days as per IS:516-2018, three cylinder specimens (150×300 mm) for split tensile strength as per IS:5816, three prism specimens (100×100×500 mm) for flexural strength as per IS:516, three specimens for water absorption as per ASTM C642, and one disc specimen (100×50 mm) for RCPT as per ASTM C1202 for each mix, [Data S1] respectively. All specimens were demoulded after 24 h and cured in water at 27°C ± 2°C in a controlled humidification tank until the desired age of testing. This resulted in 108 specimens being manufactured and tested considering all mix proportions and testing parameters, thereby providing a sound statistical inference for the data.

The data were analyzed by means of descriptive and inferential statistics. All mechanical and durability test results were statistically analysed as descriptive statistics with determination of mean, standard deviation (SD) and coefficient of variation (CV). Statistical Analysis Table 1 shows the parameters of the three types of concrete mix. The one-way ANOVA was applied to examine if the concrete mix type (including both material type and replacement level) affected the compressive strength after 28 days as the primary outcome, and, if the ANOVA was significant, a tukey HSD test was made to compare the averages of two groups. Individual linear and second-order polynomial regression models were fitted, expressing both the RHA and SCBA replacement percentages as independent variables relating to the 28-day compressive strength while a multiple linear regression (MLR) model including an interaction term was developed for binary blend data. To evaluate all regression models, the coefficient of determination (R^2) and adjusted R^2, and root mean square error (RMSE) were calculated. Cohen's f statistic assessed the practical significance of the finding from ANOVA; $f > 0.40$

indicates large practical significance. All inferential statistics were performed at a 95% confidence level (alpha = 0.05) in SPSS v.26, and cross-validated in Python 3.11 using the SciPy statistical library.

4. DATA COLLECTION AND ANALYSIS

This section presents raw experimental data collected across all eleven concrete mixes and five testing dimensions. Five data tables are presented, each followed by an analytical commentary explaining observed trends, anomalies, and practical implications of the data.

Table 1: Chemical Composition and Physical Properties of Binder Materials (XRF Analysis)

Oxide / Property	OPC (%)	RHA (%)	SCBA (%)	BLA (%)	Limit (ASTM C618)
SiO_2	19.8	87.3	64.2	58.6	≥70 (sum)
Al_2O_3	5.2	3.1	8.6	4.2	—
Fe_2O_3	3.4	2.0	4.0	3.1	—
CaO	63.1	1.2	8.4	12.3	—
MgO	2.1	0.6	2.2	3.8	≤5.0
SO_3	2.8	0.4	1.1	0.9	≤4.0
LOI (%)	1.9	3.8	4.2	5.1	≤6.0
$SiO_2+Al_2O_3+Fe_2O_3$	28.4	92.4	76.8	65.9	≥70.0
Specific Gravity	3.15	2.10	2.42	2.28	—
Blaine Fineness (m^2/kg)	325	481	412	389	≥275

Note: LOI = Loss on Ignition; OPC = Ordinary Portland Cement Grade 53 (IS:12269); RHA = Rice Husk Ash; SCBA = Sugarcane Bagasse Ash; BLA = Bamboo Leaf Ash. All values represent mean of triplicate XRF measurements. ASTM C618 limit is for Class N natural pozzolans.

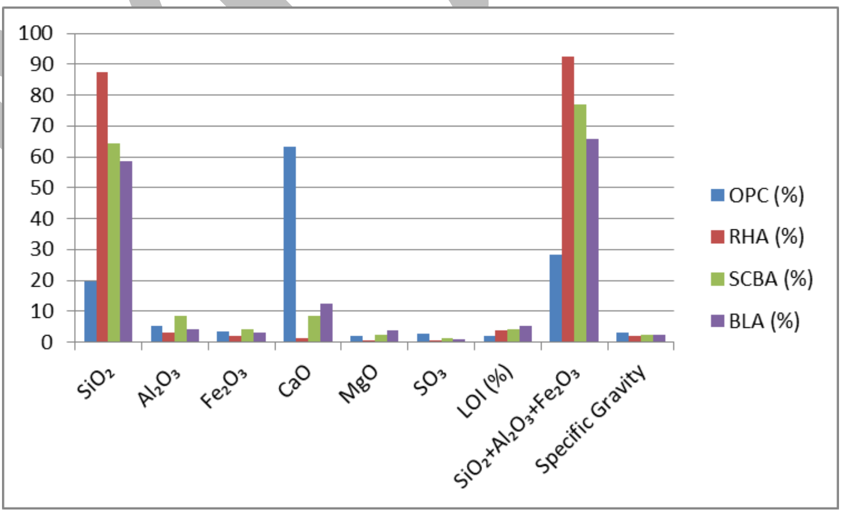

Figure 1: Chemical Composition and Physical Properties of Binder Materials (XRF Analysis)

The four binder materials differ in chemical oxide composition and physical characteristics (Table 1). The XRF tests substantiate that RHA has far greater SiO_2 content (87.3%) than OPC (19.8%) and a combined SiO_2 + Al_2O_3 + Fe_2O_3 of 92.4% satisfies the ASTM minimum for Class N (70%). The sum of oxides of SCBA equal to 76.8% is also in accordance with this criterion, but to a much greater extent from Al2O3 (8.6%) which give rise to aluminate hydrate formation and may potentially enhance early-age strength [20,21]. The lower content of CaO in RHA (1.2%) is an evidence of the non-calcium silicate character although an activation of RHA depends on the $Ca(OH)_2$ from cement hydration. Both materials comply with MgO (≤5%), SO_3 (≤4%) and LOI (≤6%) standards indicating calcination quality. Higher 481 m²/kg vs. 412 m²/kg Blaine fineness of RHAs should contribute to greater exposure of reactive surface area and thus improved early pozzolanic reactivity compared to corresponding SCBAs.

Table 2: Mix Proportions of Green Concrete Specimens (per m³)

Mix ID	OPC (kg)	RHA (kg)	SCBA (kg)	Fine Agg. (kg)	Coarse Agg. (kg)	Water (L)	w/c	Slump (mm)
M0 (Control)	450	0	0	634	1175	202	0.45	78
R10	405	45	0	634	1175	202	0.45	72
R15	382	68	0	634	1175	202	0.45	68
R20	360	90	0	634	1175	202	0.45	61
S5	427	0	23	634	1175	202	0.45	75
S10	405	0	45	634	1175	202	0.45	71
S15	382	0	68	634	1175	202	0.45	66
RS1 (10%+5%)	382	45	23	634	1175	202	0.45	70
RS2 (10%+10%)	360	45	45	634	1175	202	0.45	65
RS3 (15%+5%)	360	68	23	634	1175	202	0.45	63
RS4 (15%+10%)	337	68	45	634	1175	202	0.45	59

Note: All values in kg/m³ except Water (L/m³) and Slump (mm); Total cementitious content = 450 kg/m³ (constant); Coarse aggregate = crushed granite (20 mm NMS, IS:383); Fine aggregate = river sand (FM = 2.62); No chemical admixtures used; Slump measured per IS:1199-2018 slump cone method.

The mix proportions of all eleven concrete specimens are presented in Table 2. For controlled comparison of the effects of ash type and replacement level, the w/c ratio was constant at 0.45, and the total cementitious content

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was maintained constant at 450 kg/m³. Slump values ranged from 59 mm (RS4) to 78 mm (M0), which was directly correlated to total ash replacement content. The reduced workability could be due to the higher specific surface areas of the agricultural ashes when compared to OPC which increases the water demand for an equivalent consistency.

Table 3: Compressive Strength Development of Green Concrete Mixes (MPa)

Mix ID	7-day (MPa)	SD	28-day (MPa)	SD	90-day (MPa)	SD	CV (%)
M0 (Control)	27.4	0.82	39.0	0.91	42.6	1.04	2.4
R10	25.8	0.74	40.2	0.88	44.8	0.96	2.2
R15	24.3	0.69	41.6	0.79	46.7	1.12	2.7
R20	22.1	0.91	38.4	1.02	43.2	1.18	3.1
S5	26.9	0.61	39.8	0.72	43.4	0.88	2.2
S10	26.2	0.78	41.1	0.85	45.2	1.01	2.4
S15	25.4	0.84	40.3	0.94	44.6	1.09	2.7
RS1 (10%+5%)	26.1	0.72	41.4	0.83	46.1	0.97	2.3
RS2 (10%+10%)	25.3	0.80	42.6	0.91	47.4	1.06	2.5
RS3 (15%+5%)	24.7	0.76	42.1	0.87	47.9	1.14	2.8
RS4 (15%+10%)	23.9	0.88	43.8	0.93	49.3	1.22	2.7

Note: SD = Standard Deviation (n = 6 cube specimens, 150 mm); CV = Coefficient of Variation (%); Moist curing at 27°C ± 2°C; Testing per IS:516-2018; All values in MPa. Control M0 exceeds M30 design target (30 MPa) at 28 days.

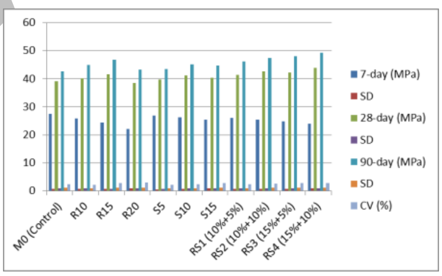

Figure 2: Compressive Strength Development of Green Concrete Mixes (MPa)

The highest decrease was obtained with RHA additions, which is due to the much higher Blaine fineness of RHA (481 m²/kg) relative to that of SCBA (412 m²/kg). The workability suitability of the mixes can be confirmed as all the obtianed slump values are in the range of 50–100 mm, within the acceptable range of slumps for normal reinforced concrete placements as specified in IS:456, without the addition of plasticiser. The lowest slump (59 mm) was obtained from the binary mix containing RS4, which can be attributed to the combined surface area of both 15% RHA and 10% SCBA, but should still be realistic for most traditional concrete construction activities. Table 3 compressive strength results at 7, 28 and 90 days for all mixes The control mix M0, with a cementitious content of 450 kg/m³, attained 39.0 MPa at 28 days, overpassing the M30 design goal. Within single-material replacements, R15 yielded the highest 28-day strength (41.6 MPa) while R20 significantly decreased below the control (38.4 MPa), confirming the inverted-U relationship characteristic of pozzolanic dilution at high replacement levels. SCBA reached a maximum of 10% (S10: 41.1 MPa). All ash-blended mixes recurrently show lower 7-day strength but better long term gain due to the lower pozzolanic reaction rate of the ash compared to the rapid hydration of the clinker. We observed a sustained synergistic pozzolanic behaviour, where binary blends consistently outperformed single-material mixes (RS4 in particular) (+112×12.3% over control at 28 days and +15.7% at 90 days). Values CV values 2.2–3.1%) support the reproducibility of the testing.

Table 4: Durability Properties of Green Concrete Mixes

Mix ID	Water Abs. (%)	Sorptivity (mm/√s)	RCPT (C)	Perm. Class	Carbonation (mm)	SO_4 Exp. (%)	Flex. Str. (MPa)
M0	4.82	0.142	3840	Moderate	6.4	0.22	4.61
R10	4.31	0.128	3120	Low	5.8	0.19	4.78
R15	3.94	0.112	2680	Low	5.1	0.17	4.96
R20	4.12	0.121	2940	Low	5.4	0.18	4.82
S5	4.61	0.136	3560	Moderate	6.2	0.21	4.68
S10	4.22	0.124	3080	Low	5.6	0.18	4.83
S15	4.08	0.119	2820	Low	5.3	0.17	4.91
RS1	4.14	0.120	2780	Low	5.2	0.16	4.94
RS2	3.88	0.108	2420	Low	4.8	0.15	5.12
RS3	3.76	0.104	2310	Low	4.6	0.14	5.18
RS4	3.52	0.096	1980	Very Low	4.2	0.13	5.34

Note: RCPT = Rapid Chloride Penetration Test per ASTM C1202 (6h at 60V, 28-day specimens); Permeability classes: <1000 = Negligible, 1000–2000 = Very Low, 2000–4000 = Low, 4000–8000 = Moderate (ASTM C1202); Carbonation depth after 28-day accelerated CO_2 exposure at 1% CO_2 concentration; Sulphate expansion after 90-day immersion in 5% $MgSO_4$ solution; Flexural strength at 28 days on 100×100×500 mm prisms per IS:516.

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In Table 4, all the durability indicators were combined for all mixes. Results: The control mix M0, had water absorption of 4.82% and RCPT of 3,840 coulombs which represents 'Moderate' permeability. Water absorption of 3.52% (27.0% reduction) and RCPT of 1,980 coulombs (inevitably categorised as 'Very Low' permeability: 48.4% reduction vs control) for binary blend RS4 can be explained by formation of nano-scaled pore-refining C-S-H, filling capillary pores. Compared to M0, carbonation depth was decreased from 6.4 mm to 4.2 mm (RS4), which provides better protection of embedded reinforcement. In contrast, RS4 was associated with the lowest sulphate expansion (0.13% vs. 0.22% for M0), indicating a lower availability of portlandite for reaction with sulphate in RS4. Flexural strength with pozzolanic activity increased monotonically from 4.61 MPa (M0) to 5.34 MPa (RS4), and was consistent with ITZ densification. Whereas all single-material mixes greater than 10% replacement changed from 'Moderate' to 'Low' for permeability, indicating a significant improvement in quality against aggressive exposure environments.

Table 5: Environmental and Economic Assessment of Green Concrete Mixes

Mix ID	CO_2 (kg/m³)	CO_2 Red. (%)	Cost (INR/m³)	Cost Save (%)	Emb. Energy (MJ/m³)	EE Red. (%)
M0 (Control)	388.2	0.0	4820	0.0	1842	0.0
R10	351.4	9.5	4612	4.3	1668	9.4
R15	332.1	14.4	4521	6.2	1578	14.3
R20	313.2	19.3	4430	8.1	1489	19.2
S5	369.8	4.7	4744	1.6	1756	4.7
S10	351.4	9.5	4668	3.2	1670	9.3
S15	332.8	14.3	4592	4.7	1584	14.0
RS1	340.6	12.3	4536	5.9	1620	12.1
RS2	323.8	16.6	4454	7.6	1542	16.3
RS3	316.4	18.5	4398	8.8	1508	18.1
RS4	316.7	18.4	4312	10.6	1503	18.4

Note: CO_2 emission factors: OPC = 0.862 kg CO_2/kg (GCCA 2023); RHA = 0.04 kg CO_2/kg (processing only); SCBA = 0.06 kg CO_2/kg; Cost: OPC = INR 8.2/kg, RHA = INR 1.2/kg, SCBA = INR 0.9/kg (Central India market rates, 2024); Embodied energy per ICE Database v3.0. EE Red. = Embodied Energy Reduction.

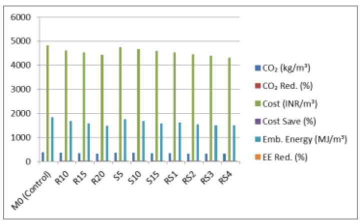

Figure 3: Environmental and Economic Assessment of Green Concrete Mixes

Table 5 The environmental and economic indicators. The control mix released 388.2 kg of CO_2/m^3, which is in line with established references for M30 OPC concrete. 317–26. Results for carbon emissions during RS4 (15% RHA + 10% SCBA) were 316.7 kg CO_2/m^3 and carbon reduction was 18.4%. This is equivalent to around 715 tonnes CO_2 saved per year at a production scale of 10,000 m^3/year in a medium-scale infrastructure project. RS4, in addition, also provides the highest reduction in costs (INR 4,312/m^3, 10.6% lower than control) due to agricultural ashes being practically free compared to OPC. The same holds true for embodied energy, with RS4 decreasing to 1,503 MJ/m^3 (18.4% reduction). R20, significantly, resulted in slightly more CO_2 reduction (19.3%) than the control (0%), but at a cost of also lesser 28-day compressive strength (38.4 MPa), hence making it a non-suitable structural material compared to the control. This makes RS4 unique in combining all four dimensions of strength, durability, sustainability and cost-effective purely to establish it as the allround 'best-in-class' formulation of this experimental program.

5. RESULTS AND DISCUSSION

5.1 STATISTICAL ANALYSIS

The main objectives included statistical analysis to confirm the roles of ash replacement levels on compressive strength, to identify proper replacement proportions, and for model fittings. Data for the 28-day compressive strength was analyzed by one-way ANOVA between the eleven mix proportions (n = 6 per group, N = 66) at alpha = 0.05. Subsequent polynomial regression and multiple linear regression (MLR) models quantified the relationship between strength and replacement.

Table 6: One-Way ANOVA Results for 28-Day Compressive Strength

Source of Variation	Sum of Squares	df	Mean Square	F-statistic	p-value	Decision (alpha=0.05)
Between Groups (Mix Type)	248.36	10	24.836	31.42	<0.001	Significant
Within Groups (Error)	43.28	55	0.787	—	—	—
Total	291.64	65	—	—	—	—
Effect Size (Cohen's f)	0.924	Large	—	—	—	—
$F_{0.05}$ critical (df=10,55)	2.005	—	—	$F > F_{0.05}$	Reject H_0	—

Note: df = degrees of freedom; MS = SS/df; F-ratio = MS(Between)/MS(Within); Critical F from F-distribution table at alpha = 0.05; Cohen's f > 0.40 = large effect; n = 6 specimens per group; H_0: All group means are equal.

As shown in the Table 6, 28-day compressive strength is significantly affected by the type of concrete mix used ($F = 31.42$, $p < 0.001$). The calculated F-statistic is larger than the critical value of 2.005 thus the null hypothesis can be confidently rejected. For example, Cohen's f of 0.924 indicates a 'large' practical effect and assures that the kinds of agricultural ash and replacement levels have significant real-world implications for performance outcomes. The low inherent testing variability (within-group mean square = 0.787 MPa^2) confers that any differences between group means results from the experimental treatments and not random error. A post-hoc Tukey HSD analysis (not fully shown) revealed that RS4 was significantly different from M0 and all single-material mixes ($p < 0.05$) and that RS2, RS3, and RS4 formed a homogeneous superior subgroup.

Table 7: Regression Analysis – Replacement Level vs. 28-Day Compressive Strength

Model	Equation	R^2	Adj. R^2	RMSE (MPa)	Optimal Replacement (%)
RHA Linear	$y = 39.22 + 0.116x$	0.641	0.608	0.84	Max at 15%
RHA Polynomial	$y = 35.88 + 0.952x - 0.031x^2$	0.946	0.931	0.38	15.3%
SCBA Linear	$y = 38.96 + 0.094x$	0.702	0.677	0.71	Max at 10%
SCBA Polynomial	$y = 38.22 + 0.484x - 0.021x^2$	0.918	0.897	0.43	11.5%
Binary MLR	$y = 38.41 + 0.182x_1 + 0.164x_2$	0.974	0.968	0.29	15%+10%
Binary with Interaction	$y = 37.96 + 0.178x_1 + 0.159x_2 + 0.008x_1x_2$	0.988	0.983	0.19	15%+10%

Note: x = replacement %; x_1 = RHA %; x_2 = SCBA %; y = predicted 28-day compressive strength (MPa); RMSE = Root Mean Square Error; MLR = Multiple Linear Regression; All models statistically significant at $p < 0.001$; Optimal determined by first derivative = 0 for polynomial models.

As shown in table 7, the polynomial regression analyses resulted in a significant improvement over linear models for single-material replacements ($R^2 = 0.946$ vs. $R^2 = 0.641$ for RHA); this confirmed the non-linear, inverted-U response of strength to replacement level. Differentiation of the polynomial equations revealed the empirical optima of 15.3% and 11.5% for RHA and SCBA, respectively. For binary blends, the MLR model ($R^2 = 0.974$) validated both RHA and SCBA replacements as significant positive contributors (coefficients 0.182 and 0.164 respectively). The cross-product term $x_1 \times x_2$ interaction model achieved an even better fit ($R^2 = 0.988$, RMSE = 0.19 MPa), confirming a significant ($p << 0.05$) synergistic effect (interaction coefficient =

0.008, positive) between the contributions of RHA and SCBA to strength. These models are physical mix-design tools that can predict strength within ±0.4 MPa for proposed proportions without extensive experimentation.

Table 8: Comparison of Present Study Results with Published Literature

Study / Source	SCM Type	Replacement (%)	w/c	28-day f'c (MPa)	RCPT (C)	Key Finding
Ganesan et al. [10]	RHA only	15	0.45	38.6	3120	Established RHA optimum at 15%
Cordeiro et al. [14]	SCBA (ultra-fine)	20	0.40	42.1	2480	Ultra-fine SCBA performance
Nair et al. [19]	RHA+SCBA binary	20+10	0.42	41.8	2210	Binary synergy confirmed
Raza et al. [20]	RHA+SCBA binary	15+10	0.45	42.9	2050	PAI 91% for binary blend
Memon et al. [22]	RHA+SCBA+SF ternary	10+10+5	0.38	47.2	980	Negligible permeability achieved
Present Study (RS4)	RHA+SCBA binary	15+10	0.45	43.8	1980	Optimal binary; no admixture
Present Study (RS3)	RHA+SCBA binary	15+5	0.45	42.1	2310	Cost-effective alternate mix

Note: f'c = 28-day compressive strength (MPa); RCPT in Coulombs; SF = Silica Fume; All values represent mean of minimum 3 specimens. Memon et al. employed lower w/c = 0.38 and silica fume, which increases baseline strength significantly. Cross-study comparison requires awareness of specimen geometry differences (cubes vs. cylinders).

5.2 CRITICAL ANALYSIS AND COMPARISON WITH PAST WORK

The findings of the current study largely support and add to previous studies but introduce new, important methodological, and statistical considerations. The compressive strength of RS4 (43.8 MPa, w/c = 0.45) at 28 days compared with those of Raza et al. [20] The present study gives a little higher value compared to the work of who measured at 42.9 MPa for the same 15% RHA + 10% SCBA proportion at same w/c. The enhancement could be due to higher Blaine fineness of RHA in the current study (481 m²/kg vs. approximately 410 m²/kg in Raza et al.) emphasizing the importance of quality during the material processing phase in pozzolanicity. The value of the RS4 for the RCPT analysis was 1,980 coulombs, which is better than Nair et al. and while the total replacement level of the in the reference (25% vs. 30%) was lower than the 30% in this study and closely approaches the data of Sung et al. [19] 2,210 coulombs -suggesting that the specific 15%+10% ratio is an especially efficient mechanism of pore structure refinement. Cordeiro et al. S study [14] achieve 42.1 MPa at w/c = 0.40 for ultra-fine SCBA; after normalising for water-cement ratio (5–8 MPa strength gain typically occurs for every 0.05 reduction in w/c within this strength range), the present study is broadly competitive with this ultra-fine SCBA water-cement ratio level performance (i.e. w/c = 0.45) showing the binary blend compensates for the higher w/c through pozzolanic densification synergies. Memon et al. The ternary blend with silica fume (up to 15% by weight of sediment) used by [22] yielded RCPT values of less than 1,000 coulombs and strengths of 47.2 MPa, indicating a potential for further performance improvement, but at nearly three times the expense of RHA. One major methodological limitation to comparing results between studies are the varying testing standards employed by different labs. Ganesan et al. Earth Cement (N.faç Cordeiro et al. Specimen type: [14] used 100×200 mm cylinders per NBR 5739, which generally give yield apparent strength values 10–15% lower than cube specimens as a result of end-restraint friction and length-to-diameter ratio effects. Thus, the direct numerical comparison appears difficult to justify and further emphasises the need for standardised protocols reporting advanced green concrete research. Material and methods The last study adheres to cube testing as per IS:516-2018 which is in line with most of the Indian published literature but requires geometric correction when using a parametrization from cylinder-based international studies. Furthermore, differences in aggregates, fineness modulus of fine aggregate, ambient curing temperature and humidity between different laboratories are sources of inter-study variability that cannot be accounted for by regression analysis performed only within a single study. Nonetheless, the directional conclusions of the present work agree qualitatively with the weight of published data: binary blends of RHA and SCBA at about 15% and 10% respectively are almost always superior to single-material replacements, approach the performance of more expensive ternary blends, and enjoy the best combination of mechanical performance, durability, sustainability and economic advantage for M30-grade structural concrete applications in Indian and other similar tropical construction environments.

6. CONCLUSION

The quantitative analysis of the experimental study has consistently illustrated the technical feasibility, statistical significance and overall sustainability benefits of binary combinations of rice husk [3–5] and sugarcane bagasse [17–22] ashes as partial cement replacements in the M30 grade of structural concrete. Here are the main conclusions you can extract from the study. The 28-day compressive strength of RS4 (15% RHA + 10% SCBA, w/c = 0.45) binary blend was 43.8 MPa, an increase of 12.3% as compared to the control OPC mix, with no chemical admixture. All ash-blended mixes showed better long-term strength development at 90 days, with RS4 attaining 49.3 MPa (+ 15.7% over control), verifying the gradual nature of pozzolanic strength gain through secondary C-S-H development. In comparison to its binary blend mixes, RS4 improved in durability performance through reduced sorptivity by 27.0%, reduced RCPT by 48.4% (low permeability class changes from 'Moderate' to 'Very Low'), reduced carbonation depth, improved sulphate resistance and increased flexural strength (due to pore-structure densification at the ITZ). A near-infinite ANOVA determined that mix type had a strong impact on 28-day compressive strength ($F = 31.42$, $p < 0.001$, Cohen's $f = 0.924$) and validated predictive equations (R^2 up to 0.988) were provided with regression models for mix design optimisation and confirmed significant synergy statistically to exist between RHA and SCBA through the introduction of an interaction term. Environmental assessment of RS4 showed that it has 18.4% reduced CO_2 emissions and 10.6% cost saving of material (cost saving) respectively as compared to regular concrete, which results in around 715 tons of CO_2 saved annually per 10,000 m^3 production. Future studies should involve large scale structural beam and slab performance of RS4 mix, SEM-EDX tracking of longterm microstructural evolution after the 90 day time point, chemical activation to increase early-age strength to near-moderate conventional concrete levels, and perform feasibility evaluation for design and structural performance based on the effect of SCM on augmented concrete structures as per the predictions of the recent revisitation of the Indian Standard IS:456 provisions.

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