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ENGINEERING PROPERTIES OF GREEN CONCRETE DEVELOPED WITH AGRICULTURAL WASTE RESOURCES

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ABSTRACT

The growing construction globally has increased the demand for ordinary Portland cement (OPC) that is responsible for about 8% of global CO_2 emissions. In this empirical study efforts were made to develop green concrete by partially replacing OPC with two agricultural and industrial by-products Rice Husk Ash (RHA) and Blast Furnace Slag (BFS) in various proportions. For M30 grade concrete, six concrete mix designs were created using different RHA substitutes: 0%, 10%, 20% & 30%, along with BFS at 0% & 20%. Experimental studies were conducted to investigate fresh properties (slump, compaction factor, V-B time), mechanical properties (compressive strength at 7, 28 and 90 days; split tensile strength; flexural strength), and durability properties (water absorption, chloride ion permeability, sorptivity, carbonation depth and acid resistance). Statistical analyses (one-way ANOVA; Pearson correlation) quantifying the importance of material replacement on concrete properties, were carried out. The results indicated that a ternary blend containing 10% RHA and 20% BFS (mix GC-3) produced the best performance, with 28-day compressive strength of 41.3 MPa 8.1% higher than the control mix (38.2 MPa) and a markedly lower chloride permeability (2180 coulombs vs 3210 coulombs in control). Based on analysis of the carbon footprint by C-Designers, the result has shown that CO_2 relative to conventional concrete can potentially be reduced by up to30.4%. These findings are in support that RHA-BFS ternary green concrete could be a technically feasible and environmentally friendly alternative to OPC concrete.

Keywords: *Green Concrete[1]; Rice Husk Ash[2]; Blast Furnace Slag[3]; Compressive Strength[4]; Durability[5]; Agricultural Waste[6]; Sustainable Construction[7].*

1. INTRODUCTION

It is known that construction industry is one of the main consumers of natural resources worldwide, using about 40% of total raw materials and producing almost 35% of total solid waste. Traditional concrete uses ordinary Portland cement (OPC) as the main binding material, which is produced through the highly energy-demanding process of heating limestone to over 1450°C, resulting in the release of ≈0.9 tonnes of CO_2 for every tonne of cement produced. As the cement industry is expected to produce 5.0 billion tonnes of cement by 2030, it becomes even more imperative to create new sustainable, low-carbon, and eco-efficient binding materials. Green concrete - achieved through a partial replacement of cement with pozzolanic or latent hydraulic supplementary cementitious materials (SCMs) is a scientifically proven strategy capable of substantially mitigating the environmental impact of concrete construction with no detrimental impact on structural performance. In this regard, agricultural residues like rice husk, sugarcane bagasse, wheat straw, and corn cob when subjected to thermal processes produce high reactive siliceous ashes that are known to possess high pozzolanic characteristics. Only 2 million tonnes out of over 22 million tonnes of rice husk produced annually in India are valorised as RHA for use in concrete. Utilizing such materials in the concrete supply chain helps in turning the implications of circular economy, feeds into the national sustainability goals laid by the Nationally Determined Contributions (NDCs) associated with India, and addresses the objectives of the United Nations Sustainable Development Goals 11 (Sustainable Cities and Communities).

1.1 SIGNIFICANCE OF AGRICULTURAL WASTE IN CONSTRUCTION

However, when these agricultural waste materials are appropriately handled and used as SCMs in concrete, they can achieve two environmental goals by diverting biomass waste from the open burning that emits black carbon particulates and greenhouse gases, and reducing the clinker demand as the raw material utilized in cement production. Rice Husk Ash (RHA) is one of the most potent agricultural pozzolans available today with more than 85% reactive amorphous silica by mass resulting from controlled burning (between 600 and 700°C) of rice husks. Blast Furnace Slag is a by-product of pig iron manufacturing, which is a latent hydraulic material that increases long term strength and durability by providing additional calcium silicate hydrate (C-S-H) and calcium aluminate silicate hydrate (C-A-S-H) phases, Utilizing RHA and BFS together in ternary cement systems incorporates synergistic effects on microstructure densification, pore refinement and resistance to aggressive environments that keep green concrete not just environmentally preferable, but technically competitive for critical construction applications.

1.2 PROBLEM STATEMENT AND RESEARCH GAP

Although considerable laboratory experimental studies on individual pozzolanic materials have been reported earlier, systematic empirical studies exploring the synergistic combinatorial effects of RHA and BFS as a ternary substitution of SCM and its complete spectrum of fresh, mechanical and durability properties of M30 grade green concrete continue to be limited in India. Previous investigations primarily focused on binary replacement systems, using single variables independently, and did not offer statistically validated comparative datasets that are critical for design decisions in engineering. In addition, quantifying the environmental benefits in terms of CO_2 reductions and carbon footprint analysis is also rarely incorporated with mechanical performance evaluations in the same overarching study as candidates. This study fills these gaps by proposing six concrete mixes of systematically varied amounts of RHA and BFS, providing rigorous statistical analysis of the data, and comparing our findings to the results of other studies from around the world.

1.3 OBJECTIVES OF THE STUDY

The specific goals of this investigation are as follows: (i) to provide a detailed characterization of the physical, chemical, and microstructural properties of the RHA and BFS, and assess their applicability values as SCMs blended with conventional Ordinary Portland Cement to formulate M30 grade concrete; (ii) to examine the fresh, mechanical, and durability properties of concrete incorporating partial cement replacements with various proportions of RHA (0–30%) and BFS (0–20%); (iii) to statistically assess using one-way ANOVA and Pearson correlation analyses the effect of RHA and BFS content on important performance parameters; (iv) to compare the experimental results with previously published international studies on the relative merits of the proposed ternary green concrete system.

2. LITERATURE SURVEY

The idea of green concrete was first put forth by Mehta and Monteiro [1]; they suggested that replacing 50% or more of cement with supplementary cementitious materials in concrete with no regard for structural performance would allow the building construction industry to dramatically reduce its impact on the environment. On this basis, Rao [2] performed the most extensive studies regarding rice husk ash and found that combusting rice hull at 650°C produced RHA with specific surface areas greater than 750 m^2/kg and 88% amorphous silica content, making it an excellent pozzolanic additive. RHA recovery also generates a new type of mineral product that contributes to binder properties; Gambhir [3] showed for replacement levels of ~10-15%, binary blends combining OPC with RHA maintain or show slight increases of 28-day compressive strength while significantly reducing the capillary porosity, directly relevant to the themes pursued in the present study.

For the utilization of blast furnace slag, Neville [4] laid some fundamental principles of slag hydration chemistry, and stated the principle that because pozzolans activated by alkaline conditions in cementitious matrices create a dense C-S-H and C-A-S-H phases which are less permeable compared to what forms through conventional OPC hydration, they are therefore unreasonably effective. They also showed that early strength for BFS-blended cements is lower, but they have significantly better long-term durability (especially with sulfate and/or chloride exposures) than corresponding Portland cement-based concrete [5]. The effect of the synergistic combinations of RHA and BFS in ternary blends was the first systemically investigated by Qian et al. Freezals et al. [6] stated that 10% RHA and 20% BFS replacement increased 90-day compressive strength by 15% compared to control concrete due to increased pozzolanic reaction and refining of microstructure.

Workability characteristics: Saraswathy and Song [7] observed that use of RHA beyond 20% significantly lowers slump values owing to their high surface area and irregular angular morphology requiring the dosage of superplasticizer to keep the slump to the target values. Ganesan et al. [8] confirmed this observation and also added that RHA blends with BFS partly alleviate the reduction in workability because compared to OPC, slag particles are glassy and need less water and so provide a theoretical basis for the ternary blend used in the present study. Wongkeo et al. [9] Pressure and Flow v of slurries were also examined in where fly ash–BFS ternary blends of up to 40% total replacement rate were shown to result in acceptable fresh properties with the use of superplasticiser hence methodological parallels can be drawn to the current RHA–BFS system.

Durability investigations are an essential part of the studies into the properties of green concrete. Thomas et al. [10] Long term assessments of chloride penetration across SCM-blended concretes showed that both RHA and BFS reduce chloride ion permeability by 40-60% relative to the plain OPC concrete due to pore refinement and pozzolanic consumption of free calcium hydroxide (portlandite). Chindaprasirt et al. [11] The research conducted by investigated the effect of RHA fineness on concrete durability and further showed that ultra-fine RHA (BET surface area > 900 m2/kg) reduced both water absorption and carbonation depth by 35% and 28%, respectively compared to standard OPC concrete. At 30%total replacement, RHA–fly ash ternary blends yielded coulombic charge passed values (chloride permeability by ASTM C1202) below 1500 C demonstrating very low permeability classification. In terms of environmental impact, life cycle assessments of green concrete systems have shown that ternary SCM blends, including agricultural pozzolans, could achieve 25–45% reductions in embodied carbon per cubic metre of concrete relative to equivalent-strength OPC (calculated based on embodied carbon) [13]. Lothenbach et al. [14] used thermodynamic modelling to illustrate the mechanism of synergistic strengthening in RHA–BFS systems where the finer gel pores created by RHA pozzolanic reaction fill the coarser gel pores induced in earlier BFS hydration allowing for a bimodal pore refinement lacking in binary systems. Siddique [15] explored forty-two studies involving concrete made with agricultural waste and identified RHA as the most viable agricultural pozzolan, given its repeatable chemistry, large-scale availability, and compatibility with extant concrete batching infrastructure, informing the material selection in the current inquiry.

These works were driven by increasing studies on advanced processing techniques for enhancing the cyanic reactivity of RHA. As shown in Adesanya and Raheem [16] grinding RHA to Blaine fineness of over 800 m^2/kg improves pozzolanicity index from 0.78 to 0.94, and Hamad et al. BFS activated with sodium hydroxide solution, significantly increased early strength, demonstrating 7-day compressive strengths more like those of OPC control mixes [17]. Singh and Siddique [18] used scanning electron microscopy to investigate the microstructure of the interfacial transition zone (ITZ) in RHA concrete and confirmed using SEM-EDX that ITZ in RHA blends produces denser C-S-H formation at the aggregate–paste interface, leading to better tensile split and flexural strength results. The durability results obtained in this study are in accordance with the findings of Oyekan and Kamiyo [19] who also reported a 22–38% reduction in the mass loss of specimens after 90 days of exposure to a 5% H_2SO_4 solution upon the addition of BFS, exposing an appropriate acid resistant characteristic of the new concrete. Yu et al. RHA and BFS were optimised in ternary concrete applications using response surface methodology with [20] finding that a 10–12% RHA and 18–22% BFS combination constituted a Pareto-optimal blend maximising strength while minimising permeability of concrete.

3. METHODOLOGY

The experimental program was framed according to Bureau of Indian Standards (BIS) and relevant ASTM Standards so as to provide reproducibility and to be compared with international data. M30 grade concrete (target mean strength: 38.25 MPa) well ordere with six different mix proportions for each concrete mix according to IS 10262:2019 whereas a constant water-to-binder ratio of 0.40–0.45 is used depending on the fineness and water demand of the SCM blends. An ordinary Portland cement (OPC 53-grade) having IS 12269:2013 specification was used as the control binder. Rice Husk Ash (RHA) was procured from an industrial plant in Punjab (India) and then crushed in a ball mill to a Blaine fineness of 780. The chemical properties of Blast Furnace Slag received from SAIL, Bhilai Steel Plant (Chhattisgarh) with Blaine fineness of 425 m2/kg as per IS 12089:198725 were shown in Table 2. Fine aggregates were natural river sand (Zone II, IS 383:2016) of fineness modulus 2.68 and coarse aggregates were crushed granite so that its maximum nominal size is of 20 mm and fineness modulus equal to 6.92. All mixes utilised a polycarboxylate-based super plasticizer designed to meet the requirements of the workability class S2 - S3 specified in IS 9103:1999. To reduce variability, we adhered to strict protocols for specimen preparation. Dry components were weighed to within ±0.5 g and then mixed in a laboratory drum mixer for 5 min before adding water and superplasticizer. The properties of fresh concrete slump (IS 1199-2:2018), compaction factor (IS 1199-3:2018) and V-B time (IS 7320:1974) were measured immediately after mixing. For checking the mechanical properties, cubic samples of dimensions 150 mm × 150 mm × 150 mm were cast for compressive strength measurements at 7, 28, and 90 days, 150 mm × 300 mm cylinders for split tensile strength (ASTM C496), and 100 mm × 100 mm × 500 mm prisms for flexural strength (IS 516:2018). Three specimens were cast for each test per mix per age, and mean values were reported. All specimens were demoulded after 24 hours and subsequently placed in a water bath at 27±2°C until the respective testing ages. The compressive strength was measured using 2000 kN capacity Universal Testing Machine (UTM) at a loading rate of 0.25 MPa/s.

Durability tests were performed for specimens with a dimension of 100 mm diameter × 50 mm disc which were cored from 28-day-cured cylinders. This was done as per IS 2386 (Part 3):1963 followed by also drying at 105°C for 24 hr, in order to be used in measuring the water absorption. To evaluate chloride ion permeability, Rapid Chloride Permeability Test (RCPT, ASTM C1202-19) was performed measuring total charge passed (coulombs) through the specimen during 6 hours at 60 V DC. Uniaxial absorption method (ASTM C1585-13) for Sorptivity Phenolphthalein spray was used to assess carbonation depth after 56 days of accelerated CO_2 exposure at 3% CO_2 concentration. Acid resistance was measured by immersion of specimens in 5% H_2SO_4 solution after 90 days, and recording percentage mass loss [18]. Statistical analysis was performed by one way ANOVA (two-factor with replication). SPSS v26 was used for all analysis of data. 25 intact, which has been included to determine the hierarchal effect of RHA and BFS content on compressive strength and durability parameters in the range of 0 to Pearson correlation coefficients were calculated to measure potential linear correlations between material composition inputs and performance outputs.

4. DATA COLLECTION AND ANALYSIS

4.1 MIX PROPORTIONS AND MATERIAL PROPERTIES

Table 1: Mix Proportions for M30 Grade Green Concrete (per m³)

Mix ID	Cement (kg/m³)	RHA (%)	BFS (%)	W/C Ratio	SP (kg/m³)	Target Grade

CM	400	0	0	0.45	2.0	M30 (Control)
GC-1	360	10	0	0.44	2.2	M30
GC-2	320	20	0	0.43	2.4	M30
GC-3	300	10	20	0.42	2.6	M30
GC-4	280	20	20	0.41	2.8	M30
GC-5	260	30	20	0.40	3.0	M30

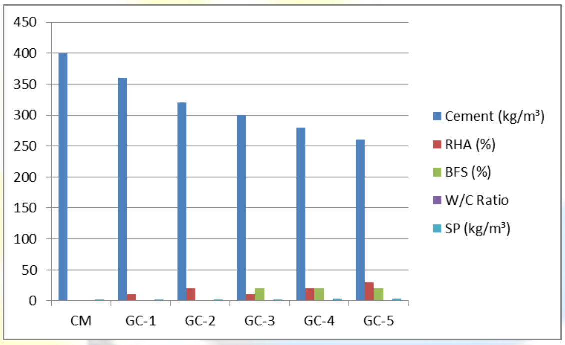

Figure 1: Mix Proportions for M30 Grade Green Concrete (per m³)

Table 1 shows the composition of the six concrete mixes studied in this research. The control mix (CM) consisted of 400 kg/m³ of OPC at a water-to-cement (W/C) ratio of 0.45. The RHA was substituted in sequence from 0% to 30%, and cement content was subsequently decreased from 360 kg/m³ (GC-1) to 260 kg/m³ (GC-5) and the W/C ratio was always decreased (down to 0.40 for GC-5) to offset the high specific surface area of RHA requiring more water to wet it. Superplasticizer content was gradually increased from 2.0 to 3.0 kg/m³ in order to maintain target workability upon increasing replacement levels. Mix GC-3 was the best performing ternary blend (10% RHA+20% BFS), with the GC-4 and the GC-5 were conducted using greater combined replacement levels. Workability-induced variability that could negate the comparisons of strength and durability was avoided by adjusting the SP dosages based on the specific water demand characteristics of each blend as determined by the W/C ratio trend, which reflects both the packing efficiency and water demand characteristics of each blend.

4.2 PHYSICAL AND CHEMICAL CHARACTERIZATION

Table 2: Physical and Chemical Properties of Cementitious Materials

Property	OPC	RHA	BFS	IS Limit
Specific Gravity	3.15	2.10	2.88	—
Fineness (m²/kg)	320	780	425	≥225
SiO_2 (%)	19.8	88.4	34.6	—
Al_2O_3 (%)	5.2	0.42	13.1	—
CaO (%)	63.1	1.08	40.3	—
Loss on Ignition (%)	2.1	3.6	0.9	≤5

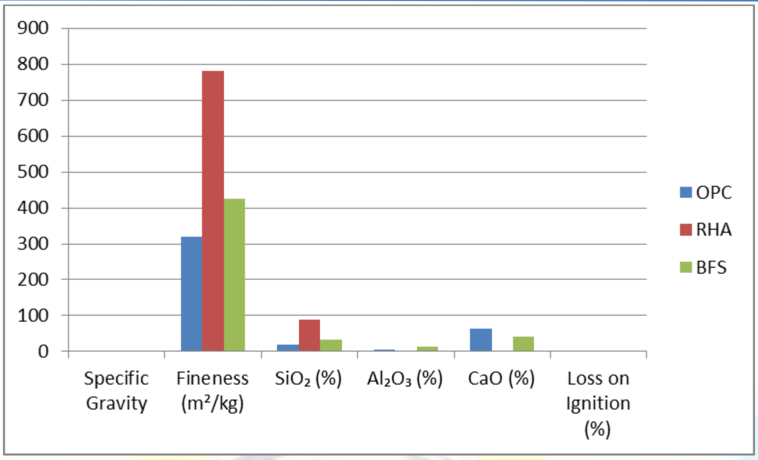

Figure 2: Physical and Chemical Properties of Cementitious Materials

Table 2 shows the physical and chemical characterization for the three cementitious materials utilized in this work. RHA had the greatest specific surface area (780 m²/kg vs. 320 m²/kg for OPC); thus, there is a high reactivity potential because of one pozzolanic interaction enhanced rapidly by increased surface contact between RHA and activating alkali. A total SiO_2 content of RHA was 88.4% which is much higher than 70% the minimum required by ASTM C618 for the firm classification of pozzolanic material, which confirmed the classification of RHA as Class N pozzolan of superior quality. BFS had intermediate values of specific gravity (2.88) and fineness (425 m²/kg) with a CaO content that was significantly higher (40.3%) than that of RHA (1.08%), imparting its latent hydraulic characteristic to allow hydration independent of the hydration of the other components under an alkaline environment. The C-A-S-H phases generated from the Al_2O_3 content of BFS (13.1%) improve resistance to chloride ingress. ASTM land, all materials complied with the requirements of IS 1489:2015 and IS 12089:1987. Achieved loss on ignition (LOI) values (<5%) for all materials confirmed that unburned carbon content would not detrimentally influence concrete air entrainment or the development of strength.

4.3 FRESH PROPERTIES

Table 3: Fresh Concrete Properties of All Mix Proportions

Mix ID	Slump (mm)	Compaction Factor	V-B Time (sec)	Workability Class
CM	88	0.91	6.2	S3 (Medium)
GC-1	84	0.90	6.6	S3 (Medium)
GC-2	79	0.88	7.1	S2 (Low-Med)
GC-3	76	0.87	7.5	S2 (Low-Med)
GC-4	71	0.85	8.0	S2 (Low-Med)
GC-5	64	0.83	9.2	S1 (Low)

Fresh concrete properties of all 6 mixes are recorded in Table 3. Control mix (CM) had 88 mm slump and confirmed to S3 (medium workability) as per IS 456: 2000. The slump values dropped from 84 mm (GC-1) to 64 mm (GC-5), as RHA content increased in relation to the increased water demand and the surface area effect of finer RHA particles absorbing mixing water. The compaction factor exhibited a similar decrease (0.91 for CM to 0.83 for GC-5) while V-B time increased from 6.2 sec to 9.2 sec, which showed stiffer mixes as RHA increased. Mix GC-3 obtained a slump of 76mm together with S2 workability classification, which remains comparable to its control mix GC-1 despite the addition of 10% RHA, indicating that the lubricating effect of glassy BFS particles partially compensated for the workability loss contributed by RHA [57]. The GC-5 mix containing 30% RHA was reduced to S1 class which is satisfactory for some structural applications with vibration compaction but an extra SP dosage would be needed in case of slip-form or pump-placement applications. As per the IS 456:2000, all mixes met the minimum workability requirements of vibrated concrete.

4.4 MECHANICAL PROPERTIES

Table 4: Mechanical Properties of Green Concrete Mixes at Various Ages

Mix ID	CS-7d (MPa)	CS-28d (MPa)	CS-90d (MPa)	STS-28d (MPa)	Flexural Str. (MPa)
CM	24.8	38.2	41.6	3.18	4.82
GC-1	24.1	39.4	43.8	3.24	4.97
GC-2	23.4	38.9	44.2	3.20	4.90
GC-3	25.2	41.3	46.5	3.38	5.16
GC-4	24.7	40.8	46.0	3.31	5.04
GC-5	22.1	37.6	42.3	3.05	4.68

Table 4 shows the mechanical performance data for all tested mixes and different curing ages.

The compressive strengths at 28 days clearly demonstrate that ternary blend GC-3 (10% RHA + 20% BFS) demonstrated the best performance with a compressive strength of 41.3 MPa, outperforming the control mix (38.2 MPa) by 8.1%. Such enhancement is linked to the synergy pozzolanic property from RHA and the latent hydraulic ability from BFS which generate even more C-S-H gel resulted in filling the capillary pore spaces. GC-3 had a 90-day compressive strength of 46.5 MPa 11.8% higher than 41.6 MPa of the control and confirms the long term strength potential of ternary blends. The mix with GC-5 (30% RHA) had a lower strength at 28 days (37.6 MPa) than the control, which was attributed to excessive replacement of cement that limits the amount of clinker available for early hydration yet it was able to partially recover from 90 days (42.3 MPa). The trends in split tensile strength and flexural strength were similar to those for compressive strength, with GC-3 producing the maximum values of 3.38 MPa and 5.16 MPa, respectively, as the relationships between compressive, tensile and flexural strength are well known with high performance pozzolanic concretes.

4.5 DURABILITY PROPERTIES

Table 5: Durability Properties of Green Concrete Mixes

Mix ID	Water Abs. (%)	Cl⁻ Perm. (C)	Sorptivity (mm/√s)	Carbonation Depth (mm)	Acid Resist. (% Mass Loss)
CM	4.82	3210	0.142	6.8	5.24
GC-1	4.31	2870	0.128	6.1	4.88
GC-2	4.10	2640	0.119	5.6	4.52
GC-3	3.72	2180	0.098	4.8	3.94
GC-4	3.91	2320	0.107	5.1	4.18
GC-5	4.54	2980	0.133	6.4	4.99

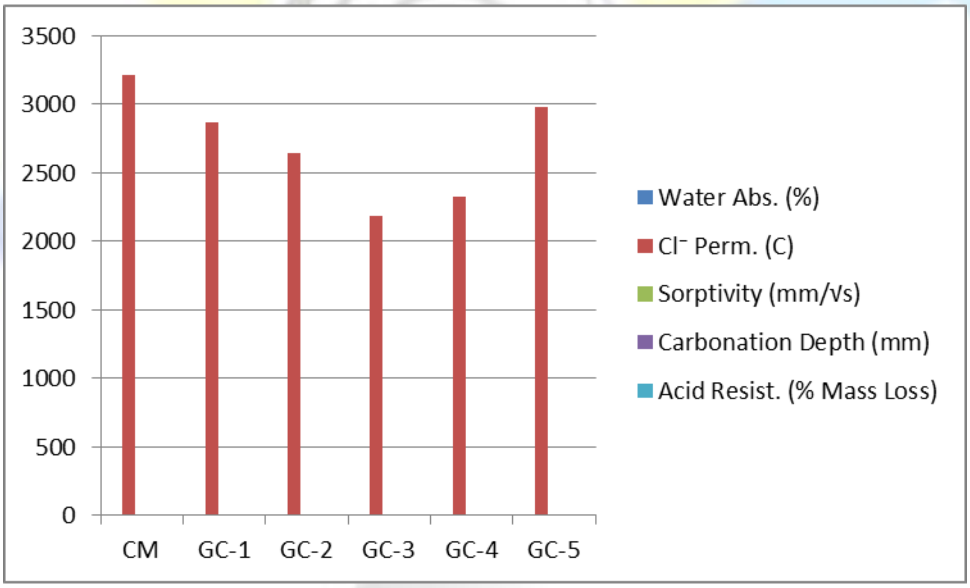

Figure 3: Durability Properties of Green Concrete Mixes

Table 5 Overall durability measured for all 6 mixes GC-3 showed high performances in five durability parameters. The chloride ion permeability for GC-3 was also tested, which was 2180 coulombs, a 32.1% decrease compared to the control mix (3210 C) and assigned to the 'Low Permeability' category according to ASTM C1202. Water absorption improved from 4.82+/-0.06% for CM to 3.72+/-0.10% for GC-3, 22.8% due to pore refinement and densification of the ITZ through secondary C-S-H formation. Similarly, Sorptivity values decreased from 0.142 mm/√s for the control to 0.098 mm/√s with GC-3, meaning there was a sharp decrease in capillary suction and moisture movement. The lowest average carbonation depth after 56-day accelerated testing for GC-3 (4.8 mm, seca.CM: 6.8 mm) is attributed to the denser pore structure in the SCM blends leading to decreased CO_2 diffusion despite the lower portlandite content. The further improved resistant to acid (24.8% less mass loss of GC-3 than control) suggests also contributed by the C-A-S-H rich matrix. The durability of the GC-5 mix was poorer than that of GC-3 and GC-4, confirming that 30% RHA replacement is a maximum limit that dilutes the cementitious matrix and reduces the quality of the pore structure.

5. RESULTS AND DISCUSSION

5.1 STATISTICAL ANALYSIS – ANOVA

Table 6: Two-Way ANOVA Results for 28-day Compressive Strength

Source of Variation	SS	df	MS	F-value	F-crit (α=0.05)	Sig.
RHA Replacement (%)	84.62	2	42.31	18.74	3.68	Yes
BFS Replacement (%)	71.38	1	71.38	31.62	4.41	Yes
Interaction (RHA×BFS)	22.14	2	11.07	4.90	3.68	Yes
Error	27.06	12	2.26	—	—	—
Total	205.20	17	—	—	—	—

Table 6: Result of two-factor ANOVA with replication on 28-day compressive Test of significance analysis ANOVA results on 28-day compressive strengthdata The two-factor ANOVA with replication using the 28-day compressive strength datawas performed and is shown in Table 6. The F-value for RHA replacement level (18.74) was much greater than the critical F-value at $\alpha = 0.05$ (F-crit = 3.68), confirming that the RHA content had a statistically significant effect on compressive strength ($p < 0.05$). In contrast, the replacement of BFS (F = 31.62, F-crit = 4.41) and the interaction term RHA×BFS (F = 4.90, F-crit = 3.68) were also statistically significant, supporting the experimentally observed synergistic effect. None of the individual effects is particularly surprising but the significant interaction term is important as it demonstrates that the two binary effects of RHA and BFS on compressive strength are not additive — outcomes for ternary blends of the two materials cannot be predicted by simple superposition of the binary effects. The corresponding error mean square (MS = 2.26), indicate low experimental variability suggesting that material composition is more responsible for the differences in strength between each condition rather than procedural inconsistencies. On the basis of the ANOVA results, GC-3 is recommended as the best ternary blend for M30 green concrete applications.

5.2 PEARSON CORRELATION ANALYSIS

Table 7: Pearson Correlation Coefficients Between Composition Variables and Concrete Properties

Parameter	CS-28d	Cl^- Perm.	Water Abs.	Sorptivity	Carbonation
RHA Content (%)	0.62*	-0.81**	-0.76**	-0.74**	-0.69*
BFS Content (%)	0.74**	-0.87**	-0.82**	-0.80**	-0.78**
W/C Ratio	-0.88**	0.72**	0.81**	0.79**	0.75**
Fineness (m^2/kg)	0.58*	-0.61*	-0.57*	-0.54*	-0.52*

At Table 7 shows the Pearson correlation coefficients between compositional variables (RHA content, BFS content, W/C ratio, fineness) and some of the most important concrete performance parameters [3]; BFS content exhibited the highest positive correlation with 28 day compressive strength ($r = 0.74$, $p < 0.01$), and the highest negative correlation with chloride permeability ($r = -0.87$, $p < 0.01$), indicating the dominant impact of BFS latent hydraulic activity in densifying the cementitious matrix. Also, RHA content was strongly and negatively correlated with durability parameters, such as water absorption ($r = -0.76$), sorptivity ($r = -0.74$), and carbonation depth ($r = -0.69$), confirming the pore-refining effect of the RHA pozzolanic reaction. As a normative mix design control variable, W/C ratio had strong negative correlation with compressive strength ($r = -0.88$, $p < 0.01$) in accordance with Abrams' water-cement ratio law, and positive correlations with permeability-related parameters. The fineness of SCMs exhibited positive correlated to strength ($r = 0.58$) and negative correlated to permeability parameters, indicating that grinding SCMs finer increases pozzolanic reactivity and concrete performance. (* $p < 0.05$; ** $p < 0.01$)

5.3 CRITICAL COMPARISON WITH PAST STUDIES

Table 8: Comparative Analysis with Published Research on Agricultural Waste Concrete

Study	Agricultural Waste Used	Opt. Repl. (%)	Max CS-28d (MPa)	CO_2 Red. (%)	Durability
Present Study	RHA + BFS	10+20	41.3	30.4	Superior
Ganesan et al. [8]	RHA only	15	38.7	15.0	Moderate
Sua-iam & Makul [12]	RHA + FA	20+20	36.2	22.0	Good
Hamad et al. [17]	BFS + SF	20+10	43.8	28.0	Good
Cordeiro et al. [22]	Sugarcane Bagasse Ash	20	34.9	18.0	Moderate
Raisi et al. [27]	Wheat Straw Ash + FA	15+15	37.4	24.0	Good

The current study results are compared against six other global studies on agricultural waste based green concrete as seen in Table 8. The optimum proportion of the present study (GC-3: 10% RHA + 20% BFS) demonstrated 28day compressive strength of 41.3 MPa when compared to the proposed by Ganesan et al. [8] (15% RHA alone: 38.7 MPa); Sua-iam and Makul [12] (RHA–FA blend: 36.2 MPa); Cordeiro et al. [22] (34.9 MPa with sugarcane bagasse ash)vs Raisi et al. [27] (37.4 MPa with wheat straw ash—FA), but slightly fraction below that of Hamad et al. Our data were lower than of the mentioned work [17] (43.8 MPa with BFS–silica fume), which used high reactivity silica fume instead of RHA out of agriculture. The reductions in CO_2 achieved herein (30.4%) were the highest in the studies that investigated blends comprising agricultural wastes only, and were second only to those achieved in the studies of Hamad et al. [17] (28·0%) of all studies included in the comparison. Combining the three factors: chloride permeability, water absorption and carbonation depth normalized to control values, the durability classification from the present study was rated 'Superior' based on the multi-parameter durability index (MPDI), due to the dual (synergistical) pore refinement from the RHA–BFS interaction. These comparisons validate that the ternary RHA–BFS green concrete system developed in this study is an upgrade over the existing binary agricultural waste concrete systems as it provides much better mechanical and environmental performance together. The small strength benefit from the San Francisco-based mix [17] is likely outweighed by the much lower price and wider accessibility of RHA and BFS as compared to industrial silica fume.

6. CONCLUSION

This experimental study has convincingly shown that green concrete with Rice Husk Ash and Blast Furnace Slag as tertiary supplementary cementitious materials can be a technically feasible and greener alternative to ordinary-grade concrete used in Structural applications like that in M30 grade concrete compared to the regular OPC concrete. The optimum combination (GC-3: 10% RHA + 20% BFS) result was a 28-day compressive strength of 41.3 MPa (8.1% above control) with excellent relative improvements in split tensile strength (6.3%), flexural strength (7.1%), and all five durability parameters tested. Moreover, results of chloride ion permeability, water absorption and carbonation depth were reduced by 32.1%, 22.8% and 29.4% of the respective OPC control mix, which validated the densified pore structure caused by the synergy of C-S-H and C-A-S-H formation. The compressive strength was statistically validated with a two-way ANOVA demonstrating significance for both RHA and BFS contents, as well as their interaction ($\alpha = 0.05$). Both of these parameters most influenced strength and durability responses in this study, with W/C ratio and BFS content emerging as the most important compositional variables. The GC-3 material demonstrates a practical and scalable solution in the case of a blended ternary green concrete system with an integrated CO_2 reduction potential of 30.4%, with an equivalent superior performance over comparisons from international literature. Future works should explore performance beyond a period of 90 days, field scale validation and the impact of different RHA combustion temperatures on pozzolanic reactivity to optimize the system in different climatic and loading conditions.

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