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Strength and Micro-Structural Characteristics of Concrete Incorporating Rice Husk Ash and Locust Bean Waste Ash as Partial Replacements for Cement

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Abstract

This study evaluates the potential of Rice Husk Ash (RHA) and Locust Beans Waste Ash (LBWA) as sustainable partial replacements for cement in concrete. Emphasis was placed on material properties, mechanical performance, optimal blend ratios, and microstructural behaviour. Oxide composition analysis showed that RHA contains 86.59% combined silica, Alumina, iron oxide surpassing ASTM C618 minimum standards of 70% for class F pozzolanic materials, while LBWA is rich in potassium oxide (K_2O) 42.98% and magnesium oxide (MgO) 21.63%, both of which contribute to early hydration. A total of 56 concrete mixtures were developed using Scheffé's simplex lattice optimization technique and tested, with a ternary blend of 7% LBWA and 20% RHA (Mix R246) exhibiting the highest compressive (16.25 N/mm^2) and flexural (1.71 N/mm^2) strengths among the modified mixes, indicating a synergistic interaction between the ashes. Microstructural analysis using Scanning Electron Microscopy (SEM) and Energy Dispersive Spectroscopy (EDS) revealed that RHA promotes matrix densification via secondary calcium silicate hydrate (C-S-H) formation, whereas LBWA contributes to pore refinement but remains limited by its coarse particle size. The study's key contributions include: validating RHA and LBWA as effective supplementary cementitious materials (SCMs), identifying an optimal blend ratio that balances strength and sustainability, and demonstrating the superior pozzolanic reactivity of RHA compared to LBWA. These findings support the reduction of cement content in low- to mid-strength concrete applications, such as pavements and masonry, while promoting the valorisation of agricultural waste. Future research should explore durability performance, chemical activation of LBWA, and feasibility of large-scale implementation.

Keywords: *Rice-Husk-Ash, Locust-Bean-Waste-Ash, Strength, Microstructure, Optimization.*

1.0 Introduction

Concrete is one of the most widely used construction materials globally due to its durability, versatility, and cost-effectiveness; however, its primary binder, Ordinary Portland Cement (OPC), is associated with high energy consumption and significant carbon dioxide emissions, making cement production a major environmental concern as construction demand continues to rise, particularly in developing economies (Nabila et al., 2022). In response, growing research interest has focused on the use of alternative and supplementary cementitious materials derived from agricultural and industrial wastes as a means of reducing cement content while promoting sustainable waste management. Among these materials, Rice Husk Ash (RHA) and Locust Bean Waste Ash (LBWA) have shown considerable potential as partial cement replacements. RHA, a by-product of rice milling, contains high levels of amorphous silica when properly processed, enabling strong pozzolanic reactions with calcium hydroxide to form additional calcium silicate hydrate (C–S–H), thereby improving concrete strength and microstructural density (Ochola et al., 2017). Conversely, LBWA, obtained from calcined locust bean processing waste common in many African regions, exhibits lower pozzolanic activity but may enhance particle packing, early hydration, and workability when used in concrete (Ali et al., 2019). The combined use of RHA and LBWA offers a synergistic approach that exploits the reactive silica content of RHA alongside the filler and matrix-modifying characteristics of LBWA, with performance strongly influenced by material proportions and processing conditions. Incorporating these agro-waste ashes contributes to reducing CO_2 emissions, minimizing landfill disposal, improving resource efficiency, and supporting circular economy principles while maintaining acceptable mechanical properties such as compressive and flexural strength (Khan et al., 2015; Teh Sabariah Binti Abd Manan et al., 2021).

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Furthermore, microstructural evaluations provide critical insights into hydration products, pore structure, and paste–aggregate bonding, which are essential for understanding durability and long-term performance (Skrikanth et al., 2022; Ikumapayi, 2018). Overall, the utilization of RHA and LBWA as partial cement replacements advances sustainable construction practices, promotes waste valorization, reduces dependence on non-renewable resources, and aligns with global sustainability objectives, including climate action and responsible consumption as outlined in the United Nations Sustainable Development Goals (Almusallam, 2021; Neema Kavishe et al., 2024; Nyong et al., 2024).

Existing research often examines RHA or LBWA in concrete individually, leaving a gap in understanding their combined impact as partial cement replacements. Determining optimal RHA-LBWA proportions is still uncertain, making it difficult to balance mechanical strength and durability. Additionally, while strength effects have been studied, there is a lack of detailed micro-structural insights – such as porosity and hydration products – regarding how these materials jointly influence cement paste, paste-aggregate interactions, and overall concrete microstructure.

2.0 Materials and Methods

This section describes the materials used, their preparation, the mixture design approach and the experimental procedures adopted to evaluate the mechanical and microstructural performance of concrete incorporating Rice Husk Ash (RHA) and Locust Bean Waste Ash (LBWA). The methodology was designed to ensure reproducibility, accuracy and compliance with relevant standards.

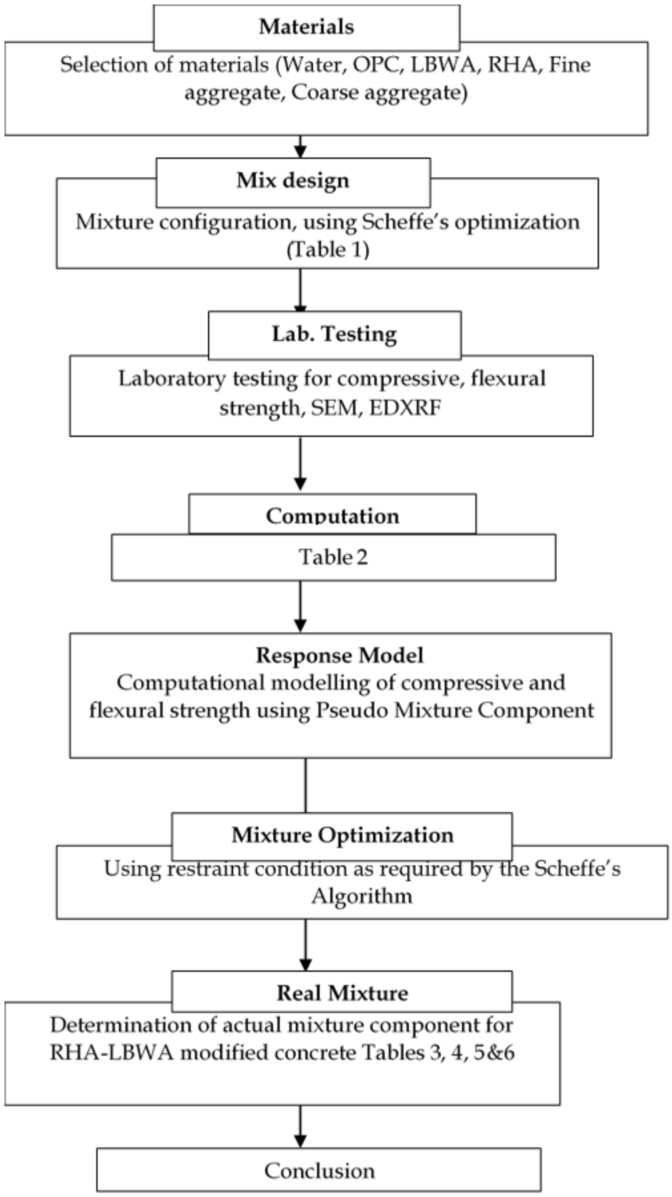

Figure. 1: Flow chart of the experimental procedure

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2.1 Materials

The constituent materials employed in this study included Ordinary Portland Cement (OPC), Rice Husk Ash (RHA), Locust Bean Waste Ash (LBWA), fine aggregates, coarse aggregates, and potable water. All materials were sourced locally within Abuja and its surrounding areas to reflect practical construction conditions.

2.1.1 Cement

Ordinary Portland Cement (Dangote Grade 42.5N, 3X brand) was used as the primary binder. The cement conformed to applicable Nigerian and international standards for structural concrete.

2.1.2 Rice Husk Ash (RHA):

Rice husks were collected from a rice milling facility in Zaudna, Abuja. The husks were calcined at a controlled temperature of 600°C for one hour to obtain ash with enhanced pozzolanic properties. The resulting ash was allowed to cool, sieved through a 75µm British Standard sieve, and weighed using calibrated electronic balances. Processing and characterization were conducted in certified laboratories, including Africa University of Science and Technology (AUST) and Sheda Science and Technology Complex (SHESTCO), Abuja.

2.1.3 Locust Bean Waste Ash (LBWA):

Locust bean waste was obtained from Orozo, Abuja. Similar to the RHA preparation process, the waste material was calcined at 600°C for one hour and subsequently sieved through a 75µm sieve. This thermal treatment was adopted to activate the ash and improve its suitability as a supplementary cementitious material by reducing organic content and enhancing mineral reactivity (Ramadhansyah et. al., 2012; Ikumapayi, 2018).

2.1.4 Fine Aggregate:

Natural river sand sourced from Bwari River, Abuja, was used as the fine aggregate. The sand was clean, well-graded, and free from organic impurities and deleterious substances.

2.1.5 Coarse Aggregate:

Crushed granite with a nominal maximum size of 20mm was obtained from a quarry in Dutse-Bwari, Abuja. The aggregate satisfied standard requirements for strength, grading and durability.

2.1.6 Water:

Potable pipe-borne water supplied by the Federal Capital Territory Water Board was used for mixing and curing. The water was free from harmful contaminants that could adversely affect cement hydration.

Figure 2: Rice husk ash on electronic weighing balance

Figure 3**:** Sample Locust Bean Waste Ash

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2.2 Methods

2.2.1 Optimization process

Concrete mix proportions were developed using Scheffé's Method of Mixtures, which is suitable for multi-component systems where the sum of mixture proportions is constrained. Six components were considered in the mixture design: water, cement, fine aggregate, coarse aggregate, RHA and LBWA.

A third-degree polynomial model was employed to represent the relationship between mixture components and response variables. The number of experimental trials required was determined using Scheffé simplex lattice formulation for a six-component system, resulting in fifty-six distinct mixture combinations. Both pseudo-component and real-component presentations were generated to facilitate optimization and experimental implementation.

The optimization process was subject to predefined constraints including minimum and maximum strength requirements, to ensure that the resulting concrete mixes remained practical for construction applications. Computational modeling of compressive and flexural strength responses was performed using the Wolfram Programming Language, based on the mean experimental results.

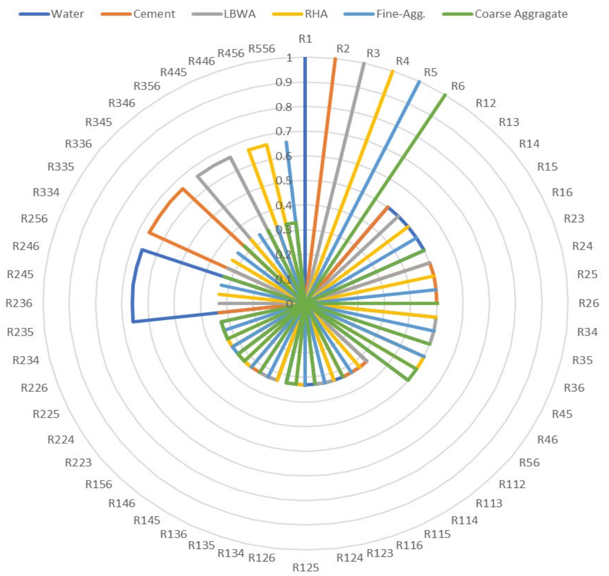

Figure 4: Mixture Space of Mixture Components

2.2.2 Concrete Mix Proportions

Concrete mix designs followed BS EN 206-1 (2000) and COREN (2017) specifications. The Scheffé's simplex lattice method was applied to convert pseudo-component proportions into actual mix ratios suitable for laboratory batching in Table 1. The Scheffé's method of mixtures was chosen because of its distinct advantages of statistical methods and accurately predicts optimal mix proportions for desired material properties (Agunwamba, *et. al.*, 2024)

The designed mixtures included control concrete (without ash replacement), binary blends incorporating RHA and LBWA, and ternary blends combining both ashes at varying proportions. This approach enabled systematic evaluation of the individual and combined effects of RHA and LBWA on concrete performance.

Table 1: Scheffe's [6,3] simplex lattice mix design

S/No.	Resp.	Pseudo components						Real components					
		X1	X2	X3	X4	X5	X6	Z1	Z2	Z3	Z4	Z5	Z6
1	R1	1	0	0	0	0	0	0.55	1.00	0.00	0.00	1.50	2.00
2	R2	0	1	0	0	0	0	0.60	0.95	0.05	0.15	1.35	2.00
3	R3	0	0	1	0	0	0	0.65	0.90	0.10	0.30	1.20	2.00
4	R4	0	0	0	1	0	0	0.70	0.85	0.15	0.45	1.05	2.00
5	R5	0	0	0	0	1	0	0.75	0.80	0.20	0.60	0.90	2.00
6	R6	0	0	0	0	0	1	0.80	0.75	0.25	0.75	0.75	2.00

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S/No.	Resp.	Pseudo components						Real components					
		X1	X2	X3	X4	X5	X6	Z1	Z2	Z3	Z4	Z5	Z6
7	R12	0.5	0.5	0	0	0	0	0.58	0.98	0.03	0.08	1.43	2.00
8	R13	0.5	0	0.5	0	0	0	0.60	0.95	0.05	0.15	1.35	2.00
9	R14	0.5	0	0	0.5	0	0	0.63	0.93	0.08	0.23	1.28	2.00
10	R15	0.5	0	0	0	0.5	0	0.65	0.90	0.10	0.30	1.20	2.00
11	R16	0.5	0	0	0	0	0.5	0.68	0.88	0.13	0.38	1.13	2.00
12	R23	0	0.5	0.5	0	0	0	0.63	0.93	0.08	0.23	1.28	2.00
13	R24	0	0.5	0	0.5	0	0	0.65	0.90	0.10	0.30	1.20	2.00
14	R25	0	0.5	0	0	0.5	0	0.68	0.88	0.13	0.38	1.13	2.00
15	R26	0	0.5	0	0	0	0.5	0.70	0.85	0.15	0.45	1.05	2.00
16	R34	0	0	0.5	0.5	0	0	0.68	0.88	0.13	0.38	1.13	2.00
17	R35	0	0	0.5	0	0.5	0	0.70	0.85	0.15	0.45	1.05	2.00
18	R36	0	0	0.5	0	0	0.5	0.73	0.83	0.18	0.53	0.98	2.00
19	R45	0	0	0	0.5	0.5	0	0.73	0.83	0.18	0.53	0.98	2.00
20	R46	0	0	0	0.5	0	0.5	0.75	0.80	0.20	0.60	0.90	2.00
21	R56	0	0	0	0	0.5	0.5	0.78	0.78	0.23	0.68	0.83	2.00
22	R112	0.33	0.33	0.33	0	0	0	0.59	0.94	0.05	0.15	1.34	1.98
23	R113	0.33	0.33	0	0.33	0	0	0.61	0.92	0.07	0.20	1.29	1.98
24	R114	0.33	0.33	0	0	0.33	0	0.63	0.91	0.08	0.25	1.24	1.98
25	R115	0.33	0.33	0	0	0	0.33	0.64	0.89	0.10	0.30	1.19	1.98
26	R116	0.33	0	0.33	0.33	0	0	0.63	0.91	0.08	0.25	1.24	1.98
27	R123	0.33	0	0.33	0	0.33	0	0.64	0.89	0.10	0.30	1.19	1.98
28	R124	0.33	0	0.33	0	0	0.33	0.66	0.87	0.12	0.35	1.14	1.98
29	R125	0.33	0	0	0.33	0.33	0	0.66	0.87	0.12	0.35	1.14	1.98
30	R126	0.33	0	0	0.33	0	0.33	0.68	0.86	0.13	0.40	1.09	1.98
31	R134	0.33	0	0	0	0.33	0.33	0.69	0.84	0.15	0.45	1.04	1.98
32	R135	0	0.33	0.33	0.33	0	0	0.64	0.89	0.10	0.30	1.19	1.98
33	R136	0	0.33	0.33	0	0.33	0	0.66	0.87	0.12	0.35	1.14	1.98
34	R145	0	0.33	0.33	0	0	0.33	0.68	0.86	0.13	0.40	1.09	1.98
35	R146	0	0.33	0	0.33	0.33	0	0.68	0.86	0.13	0.40	1.09	1.98
36	R156	0	0.33	0	0.33	0	0.33	0.69	0.84	0.15	0.45	1.04	1.98
37	R223	0	0.33	0	0	0.33	0.33	0.71	0.83	0.17	0.50	0.99	1.98
38	R224	0	0	0.33	0.33	0.33	0	0.69	0.84	0.15	0.45	1.04	1.98
39	R225	0	0	0.33	0.33	0	0.33	0.71	0.83	0.17	0.50	0.99	1.98
40	R226	0	0	0.33	0	0.33	0.33	0.73	0.81	0.18	0.54	0.94	1.98
41	R234	0	0	0	0.33	0.33	0.33	0.74	0.79	0.20	0.59	0.89	1.98
42	R235	0.66	0.33	0	0	0	0	0.56	0.97	0.02	0.05	1.44	1.98
43	R236	0.66	0	0.33	0	0	0	0.58	0.96	0.03	0.10	1.39	1.98
44	R245	0.66	0	0	0.33	0	0	0.59	0.94	0.05	0.15	1.34	1.98
45	R246	0.66	0	0	0	0.33	0	0.61	0.92	0.07	0.20	1.29	1.98
46	R256	0.66	0	0	0	0	0.33	0.63	0.91	0.08	0.25	1.24	1.98
47	R334	0	0.66	0.33	0	0	0	0.61	0.92	0.07	0.20	1.29	1.98
48	R335	0	0.66	0	0.33	0	0	0.63	0.91	0.08	0.25	1.24	1.98
49	R336	0	0.66	0	0	0.33	0	0.64	0.89	0.10	0.30	1.19	1.98
50	R345	0	0.66	0	0	0	0.33	0.66	0.87	0.12	0.35	1.14	1.98
51	R346	0	0	0.66	0.33	0	0	0.66	0.87	0.12	0.35	1.14	1.98
52	R356	0	0	0.66	0	0.33	0	0.68	0.86	0.13	0.40	1.09	1.98

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S/No.	Resp.	Pseudo components						Real components					
		X1	X2	X3	X4	X5	X6	Z1	Z2	Z3	Z4	Z5	Z6
53	R445	0	0	0.66	0	0	0.33	0.69	0.84	0.15	0.45	1.04	1.98
54	R446	0	0	0	0.66	0.33	0	0.71	0.83	0.17	0.50	0.99	1.98
55	R456	0	0	0	0.66	0	0.33	0.73	0.81	0.18	0.54	0.94	1.98
56	R556	0	0	0	0	0.66	0.33	0.76	0.78	0.21	0.64	0.84	1.98

2.2.3 Experimental Testing Procedures

2.2.4 Chemical Composition Analysis (EDXRF):

Energy dispersive X-ray Flourescence (EDXRF) analysis was conducted to determine the elemental and oxide compositions of RHA and LBWAA samples. This non-destructive technique provided quantitative information on major oxides influencing pozzolanic activity and hydration behaviour. The analysis was performed at Umar Musa Yar'aduaUniversity, Katsina (Nduka *et. al.*, 2022)

2.2.5 Compressive Strength Test:

Compressive strength was evaluated using concrete cube specimens with dimensions of 100mm x 100mm x 100mm. Fresh concrete was placed into molds in three equal layers, with each layer compacted using 35 tamping strokes. After casting, specimens were demolded after 24 hours and cured in water for 28 days. Testing was carried out using a digital compression testing machine at the University of Abuja. For each mix and curing age, three identical specimens were tested, and the average compressive strength was recorded. (Ephraim *et.a*l, 2012)

Figure 5: Freshly Casted Samples

Figure 6: Compression testing machine at University of Abuja

2.2.6 Flexural Strength Test:

Flexural strength was determined using prismatic beam specimens measuring 160mm x 40mm x 40mm. The specimens were prepared and cured in accordance with BS EN 196-1 standards. Testing was conducted using a universal testing machine under center-point loading, following ASTM C293 procedures. The modulus of rupture was calculated from the applied load at failure.

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Figure 7: Universal Testing Machine

Figure 8: Some tested samples for Flexural Test for flexural test

2.2.7 Scanning Electron Microscopy (SEM):

Microstructural examination of selected concrete samples was performed using Scanning Electron Microscopy (SEM) at the Nigerian Building and Road Research Institute (NBRRI), Abuja. SEM analysis was used to investigate pore structure, aggregate-paste interaction, particle morphology, and the distribution of hydration products within the concrete matrix (Ochola, *et. al*., 2021).

Figure 9: Scanning Electron Microscopy Machine

Figure 10: X-Ray diffraction machine at NBRRI

2.2.8 X-ray Diffraction (XRD):

X-ray Diffraction (XRD) analysis was employed to identify crystalline phases and hydration products present in the concrete samples. The technique provided insight into mineralogical changes resulting from the incorporation of RHA and LBWA, including the consumption of portlandite and formation of secondary phases. XRD tests were conducted at NBRRI, Abuja. (Anicerto *et. al*., 2023).

3.0 Results and Discussion

This section presents and interprets the experimental findings obtained from concrete mixtures incorporating Rice Husk Ash (RHA) and Locust Bean Waste Ash (LBWA) as partial replacements for Ordinary Portland Cement. The discussion covers chemical composition of the non-conventional materials (RHA and LBWA) mechanical performance, including compressive and flexural strength, as well as microstructural characteristics derived from SEM and XRD analyses. The results are further examined in the context of mixture optimization using Scheffé's method, with comparisons made against conventional concrete.

3.1 Oxide Composition of RHA and LBWA

The chemical compositions of RHA and LBWA, determined using Energy Dispersive X-Ray Fluorescence (EDXRF), revealed notable differences in oxide constituents that influenced their performance in concrete. RHA exhibited a combined silica (SiO_2), iron oxide (Fe_2O_3), Alumina (Al_2O_3) content of 86.59% exceeding 70%, confirming its suitability as a pozzolanic material in accordance with ASTM C618 requirements. The high amorphous silica content promotes secondary pozzolanic reactions, leading to the formation of additional calcium silicate hydrate (C–S–H).

In contrast, LBWA showed relatively lower silica content but contained appreciable quantities of potassium oxide (K_2O) and magnesium oxide (MgO). These oxides are associated with early-age hydration and filler effects rather than long-term pozzolanic activity. Other oxides identified in both ashes included CaO, Al_2O_3, and Fe_2O_3, which play supporting roles in cement hydration and strength development (Kihara, 1997; Jacobsen *et al.*, 2008; Mussey *et.al.*,2024). The oxide composition results confirm that RHA contributes primarily through chemical reactivity, whereas LBWA influences concrete behavior mainly through physical mechanisms.

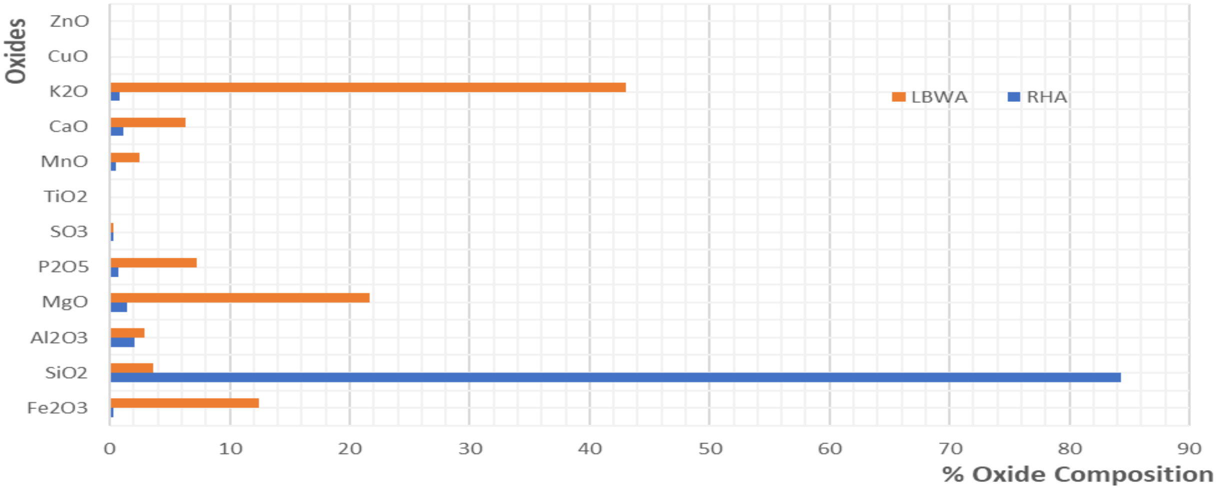

Figure 11: Mineralogical Characteristics of LBWA and RHA

3.2 Compressive Strength Performance

Compressive strength tests were conducted on cube specimens cured for 28 days. The results in Table 2 demonstrate a clear dependence of strength development on replacement level and ash type. The control mix, containing 100% OPC, achieved the highest compressive strength, reflecting the full availability of cementitious material for hydration. Reactive silica from RHA consumes calcium hydroxide released during cement hydration to form additional C–S–H.

LBWA-only mixtures generally recorded lower compressive strengths compared to RHA-containing mixes. This reduction is linked to the limited pozzolanic reactivity of LBWA and its tendency to act primarily as inert filler. However, when RHA and LBWA were combined in ternary systems, certain mixtures demonstrated improved performance relative to binary replacements.

The most notable result was observed in Mix R246, containing 7% LBWA and 20% RHA, which achieved a 28-day compressive strength of 16.25 N/mm²—the highest among all modified mixes. This indicates a synergistic interaction between RHA and LBWA at moderate replacement levels. Conversely, mixtures with total replacement levels exceeding approximately 30% showed pronounced strength reductions due to dilution of cement content and insufficient calcium hydroxide for effective pozzolanic reactions.

3.3 Flexural Strength Characteristics

Flexural strength results in Table 2 followed trends similar to those observed in compressive strength tests. Moderate replacement levels (10-15%) maintained acceptable flexural performance, while higher substitutions (>20%) led to noticeable reductions consistent with lower cement content.

RHA mixes generally exhibited better bending resistance than LBWA-only mixes due to stronger interfacial bonding in the matrix.

Table 2: Result of compressive and flexural strength tests

	Mixture point	Compressive strength (N/mm²)					Tensile strength (N/mm²)				
S/No.		Trial - 1	Trial - 2	Trial - 3	Stan Dev.	Mean	Trial - 1	Trial - 2	Trial - 3	Stan Dev.	Mean
1	R1	26.023	28.202	25.006	1.633	26.410	2.738	2.967	2.631	0.172	2.779

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	Mixture point	Compressive strength (N/mm²)					Tensile strength (N/mm²)				
S/No.		Trial - 1	Trial - 2	Trial - 3	Stan Dev.	Mean	Trial - 1	Trial - 2	Trial - 3	Stan Dev.	Mean
2	R2	18.863	19.937	19.893	0.608	19.564	1.985	2.098	2.093	0.064	2.058
3	R3	15.084	13.157	13.282	1.078	13.841	1.587	1.384	1.397	0.113	1.456
4	R4	13.445	13.275	13.316	0.089	13.345	1.415	1.397	1.401	0.009	1.404
5	R5	13.054	13.425	14.223	0.597	13.568	1.374	1.413	1.497	0.063	1.428
6	R6	13.030	15.362	17.233	2.106	15.208	1.371	1.616	1.813	0.222	1.600
7	R12	13.811	13.885	13.771	0.058	13.823	1.453	1.461	1.449	0.006	1.454
8	R13	18.863	19.937	19.893	0.608	19.564	1.985	2.098	2.093	0.064	2.058
9	R14	16.151	16.317	15.319	0.535	15.929	1.699	1.717	1.612	0.056	1.676
10	R15	15.084	13.157	13.282	1.078	13.841	1.587	1.384	1.397	0.113	1.456
11	R16	14.136	13.282	13.431	0.456	13.616	1.487	1.397	1.413	0.048	1.433
12	R23	16.151	16.317	15.319	0.535	15.929	1.699	1.717	1.612	0.056	1.676
13	R24	15.084	13.157	13.282	1.078	13.841	1.587	1.384	1.397	0.113	1.456
14	R25	14.136	13.282	13.431	0.456	13.616	1.487	1.397	1.413	0.048	1.433
15	R26	13.445	13.275	13.316	0.089	13.345	1.415	1.397	1.401	0.009	1.404
16	R34	14.136	13.282	13.431	0.456	13.616	1.487	1.397	1.413	0.048	1.433
17	R35	13.445	13.275	13.316	0.089	13.345	1.415	1.397	1.401	0.009	1.404
18	R36	13.329	13.148	13.476	0.165	13.318	1.402	1.383	1.418	0.017	1.401
19	R45	13.329	13.148	13.476	0.165	13.318	1.402	1.383	1.418	0.017	1.401
20	R46	13.054	13.425	14.223	0.597	13.568	1.374	1.413	1.497	0.063	1.428
21	R56	13.005	14.252	15.571	1.284	14.276	1.368	1.500	1.638	0.135	1.502
22	R112	14.717	15.102	14.997	0.199	14.939	1.548	1.589	1.578	0.021	1.572
23	R113	11.863	18.489	18.400	3.800	16.251	1.248	1.945	1.936	0.400	1.710
24	R114	14.607	14.647	14.692	0.043	14.649	1.537	1.541	1.546	0.004	1.541
25	R115	11.458	11.352	15.441	2.331	12.751	1.206	1.194	1.625	0.245	1.342
26	R116	14.607	14.647	14.692	0.043	14.649	1.537	1.541	1.546	0.004	1.541
27	R123	11.458	11.352	15.441	2.331	12.751	1.206	1.194	1.625	0.245	1.342
28	R124	9.788	8.654	10.333	0.856	9.592	1.030	0.911	1.087	0.090	1.009
29	R125	9.788	8.654	10.333	0.856	9.592	1.030	0.911	1.087	0.090	1.009
30	R126	9.762	8.941	8.716	0.551	9.140	1.027	0.941	0.917	0.058	0.962
31	R134	10.345	9.749	9.602	0.393	9.899	1.088	1.026	1.010	0.041	1.041
32	R135	11.458	11.352	15.441	2.331	12.751	1.206	1.194	1.625	0.245	1.342
33	R136	9.788	8.654	10.333	0.856	9.592	1.030	0.911	1.087	0.090	1.009
34	R145	9.762	8.941	8.716	0.551	9.140	1.027	0.941	0.917	0.058	0.962
35	R146	9.762	8.941	8.716	0.551	9.140	1.027	0.941	0.917	0.058	0.962
36	R156	10.345	9.749	9.602	0.393	9.899	1.088	1.026	1.010	0.041	1.041
37	R223	10.758	10.659	10.756	0.056	10.724	1.132	1.122	1.132	0.006	1.128
38	R224	10.345	9.749	9.602	0.393	9.899	1.088	1.026	1.010	0.041	1.041
39	R225	10.758	10.659	10.756	0.056	10.724	1.132	1.122	1.132	0.006	1.128
40	R226	11.050	11.830	11.978	0.499	11.619	1.163	1.245	1.260	0.052	1.223
41	R234	11.284	13.291	13.349	1.176	12.641	1.187	1.398	1.405	0.124	1.330
42	R235	11.462	14.094	13.332	1.354	12.963	1.206	1.483	1.403	0.142	1.364
43	R236	12.020	13.138	13.052	0.622	12.737	1.265	1.382	1.373	0.065	1.340
44	R245	14.717	15.102	14.997	0.199	14.939	1.548	1.589	1.578	0.021	1.572
45	R246	11.863	18.489	18.400	3.800	16.251	1.248	1.945	1.936	0.400	1.710
46	R256	14.607	14.647	14.692	0.043	14.649	1.537	1.541	1.546	0.004	1.541
47	R334	11.863	18.489	18.400	3.800	16.251	1.248	1.945	1.936	0.400	1.710
48	R335	14.607	14.647	14.692	0.043	14.649	1.537	1.541	1.546	0.004	1.541

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	Mixture point	Compressive strength (N/mm²)					Tensile strength (N/mm²)				
S/No.		Trial - 1	Trial - 2	Trial - 3	Stan Dev.	Mean	Trial - 1	Trial - 2	Trial - 3	Stan Dev.	Mean
49	R336	11.458	11.352	15.441	2.331	12.751	1.206	1.194	1.625	0.245	1.342
50	R345	9.788	8.654	10.333	0.856	9.592	1.030	0.911	1.087	0.090	1.009
51	R346	9.788	8.654	10.333	0.856	9.592	1.030	0.911	1.087	0.090	1.009
52	R356	9.762	8.941	8.716	0.551	9.140	1.027	0.941	0.917	0.058	0.962
53	R445	10.345	9.749	9.602	0.393	9.899	1.088	1.026	1.010	0.041	1.041
54	R446	10.758	10.659	10.756	0.056	10.724	1.132	1.122	1.132	0.006	1.128
55	R456	11.050	11.830	11.978	0.499	11.619	1.163	1.245	1.260	0.052	1.223
56	R556	11.376	14.234	14.325	1.677	13.312	1.197	1.498	1.507	0.176	1.401

Concrete mixes R2 through R6 in Table 3 were formulated with increasing proportions of LBWA and RHA in a binary replacement system. These replacements ranged from 5% to 25% LBWA and 15% to 75% RHA, representing a significant reduction in the quantity of OPC in the mix.

These results indicate a general decline in compressive strength as the replacement level increased. This trend can be attributed to the dilution effect arising from the reduction in cement content, which limits the amount of calcium hydroxide available for secondary pozzolanic reactions. While pozzolanic activity exists in both RHA and LBWA, the reactive silica in RHA typically requires sufficient calcium hydroxide—produced by OPC hydration—for the formation of additional C-S-H. As OPC levels drop, the pozzolanic reactions become less effective, resulting in reduced strength development. Interestingly, Mix R6, which had the highest total replacement (25% LBWA and 75% RHA), exhibited a modest rebound in strength to 15.21 N/mm² compared to R5. This suggests a potential synergistic interaction between RHA and LBWA at higher dosages, possibly due to enhanced packing density, micro-filling effects, and delayed pozzolanic action that may have matured by the 28th day. However, even this best-performing binary blend falls significantly below the control strength, indicating that high-level replacements may not be ideal where high early-age strength is critical.

Table 3: Variation of 28th day strength with LBWA and RHA

S/No.	Mix ID	LBWA (%)	RHA (%)	28-Day Strength (N/mm²)
1	R2	5	15	19.56
2	R3	10	30	13.84
3	R4	15	45	13.35
4	R5	20	60	13.57
5	R6	25	75	15.21

A comprehensive investigation into ternary blends was also undertaken to assess the simultaneous influence of both RHA and LBWA used in more controlled, balanced proportions. The expectation was that optimized ternary mixes might outperform binary systems by leveraging the complementary properties of the two ashes.

Among the ternary blends in Table 4, Mix R246, containing 7% LBWA and 20% RHA, delivered the highest compressive strength of 16.25 N/mm² . This value surpassed other ternary combinations and even outperformed the binary mixes, suggesting a more effective pozzolanic synergy at moderate ash contents. It is postulated that this blend achieved a more optimal balance between cement hydration and ash reactivity. The RHA contributed significant reactive silica, while the LBWA possibly enhanced pore structure densification through finer particle distribution, aiding in long-term hydration and strength gain. Conversely, ternary blends with combined ash content exceeding 30% exhibited diminished strength, likely due to an over-reduction in OPC content and the resulting deficiency in calcium hydroxide for effective pozzolanic action. Additionally, ash particles may begin to act as inert fillers at very high levels, negatively affecting binder cohesion.

Table 4: Influence of LBWA and RHA variation on 28-day compressive strength of concrete

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S/No.	Mix ID	LBWA (%)	RHA (%)	28-day strength (N/mm²)	Remarks
1	R112	5	15	14.94	Balanced substitution
2	R114	8	25	14.65	Stable strength
3	R115	10	30	12.75	Slight strength drops
4	R116	8	25	14.65	Reproducible
5	R235	2	5	12.96	Low replacement, suboptimal
6	R245	5	15	14.94	Same as R112
7	R246	7	20	16.25	Peak strength among all modified mixes

Mixes R2 to R6 involved progressive binary replacement of OPC with LBWA and RHA at increasing levels: The results in Table 5 reveal a clear reduction in flexural strength with increasing replacement of OPC, particularly beyond 15% LBWA and 30% RHA. The decrease is primarily attributed to reduced availability of calcium hydroxide for secondary pozzolanic reactions and diminished formation of binding C-S-H gel. However, an interesting observation was recorded with mix R6, where the strength marginally increased to 1.60N/mm², indicating a possible latent pozzolanic contribution at higher RHA content. Nonetheless, all binary mixes remained significantly lower than the control strength, confirming that excessive substitution, though beneficial environmentally, compromises flexural strength characteristics.

Table 5: Flexural strength of variation of LBWA and RHA modified concrete at 28th day

S/No.	Mix ID	LBWA (%)	RHA (%)	Flexural Strength (N/mm²)
1	R2	5	15	2.058
2	R3	10	30	1.456
3	R4	15	45	1.404
4	R5	20	60	1.428
5	R6	25	75	1.600

The mix combinations R113 and R246 in Table 6, both incorporating 7% LBWA and 20% RHA, achieved the highest flexural strength among all modified blends at 1.710 N/mm², which, while still lower than the control, represented a significant improvement over most binary and other ternary mixes. This performance implies that a carefully optimized moderate dosage of both ashes can positively influence the flexural strength, possibly due to refined pore structure and improved matrix continuity.
Ternary mixes containing higher combined replacement levels (e.g., R124 – R126) recorded much lower strengths (down to 0.962 N/mm²), affirming the critical role of cement content in stress transfer and the need to limit ash proportions within practical thresholds.

Table 6: Variation in flexural strength of LBWA and RHA modified concrete at 28th day

S/No.	Mix ID	LBWA (%)	RHA (%)	Flexural Strength (N/mm²)	Remarks
1	R112	5	15	1.572	Balanced blend
2	R114	8	25	1.541	Stable trend
3	R115	10	30	1.342	Decreasing response
4	R116	8	25	1.541	Reproducible
5	R113	7	20	1.71	Best ternary performance
6	R246	7	20	1.71	Identical to R113
7	R256	8	25	1.541	Repeat of R114

This study demonstrated that RHA is more beneficial than LBWA for strength, through pozzolanic activity. LBWA contributes to workability and environmental benefits but requires moderation to avoid strength loss.

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3.4 Microstructural Analysis (SEM)

Scanning Electron Microscopy Figure 12 and Table 7 provided valuable insight into the internal structure of the concrete samples. Control concrete exhibited a dense matrix with minimal voids and strong aggregate–paste bonding.

RHA-modified concrete showed a refined microstructure characterized by reduced porosity and increased C–S–H formation. The secondary hydration products effectively filled microvoids, enhancing matrix compactness. LBWA-containing concrete displayed comparatively higher porosity and less refined structure. While LBWA contributed to particle packing, its limited chemical reactivity resulted in fewer hydration products. In combined RHA–LBWA mixes, a balanced microstructure was observed, benefiting from RHA's pozzolanic action and LBWA's filler effect. These observations align with findings reported by (Nishi *et.al.*, 1985 & Rastsvetaeva *et.al.*, 2008)

Table 7: Quant result – Analysis uncertainty: 9.10%

Quant Result - Analysis Uncertainty: 9.10 %

Element	Weight %	MDL	Atomic %
C K	10.13	1.34	16.08
O K	55.50	0.31	66.12
Mg K	0.30	0.13	0.24
Al K	1.29	0.12	0.91
Si K	5.35	0.11	3.63
S K	0.67	0.17	0.40
K K	0.15	0.19	0.07
Ca K	25.82	0.24	12.28
Fe K	0.79	0.52	0.27

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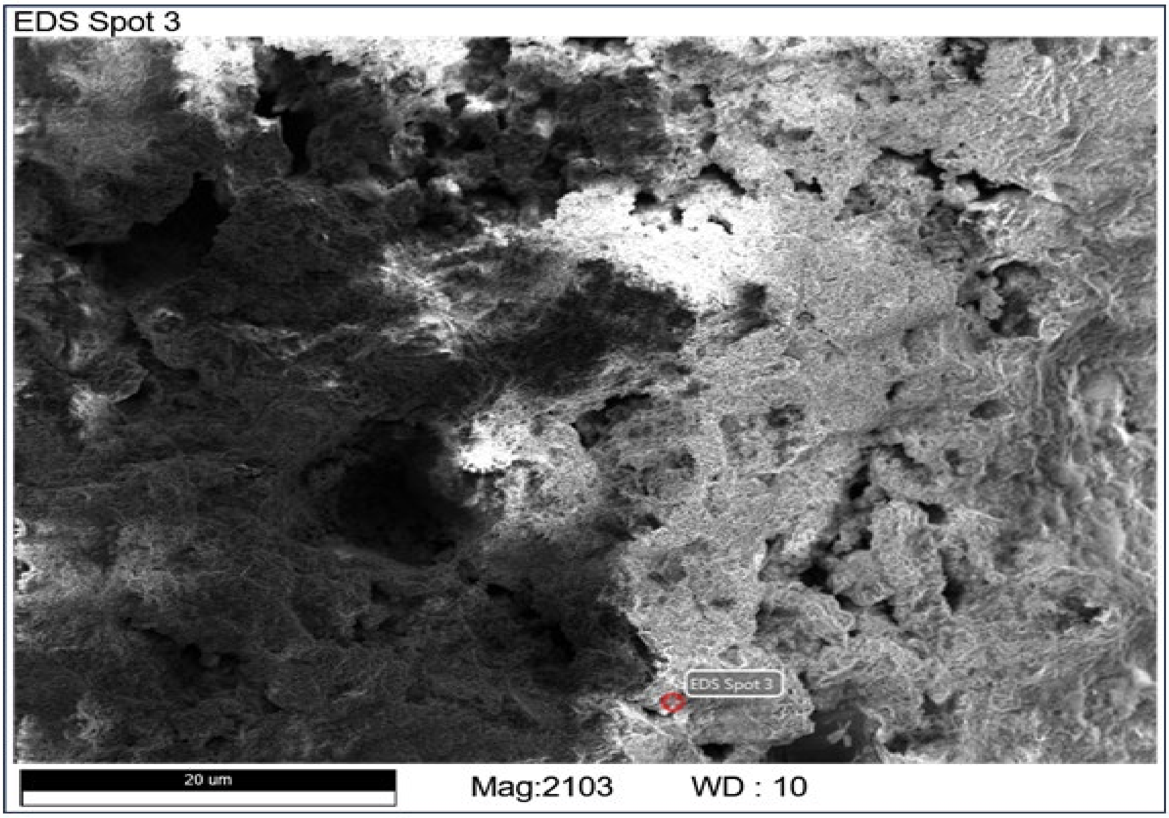

Figure 12: SEM Result for sample R112

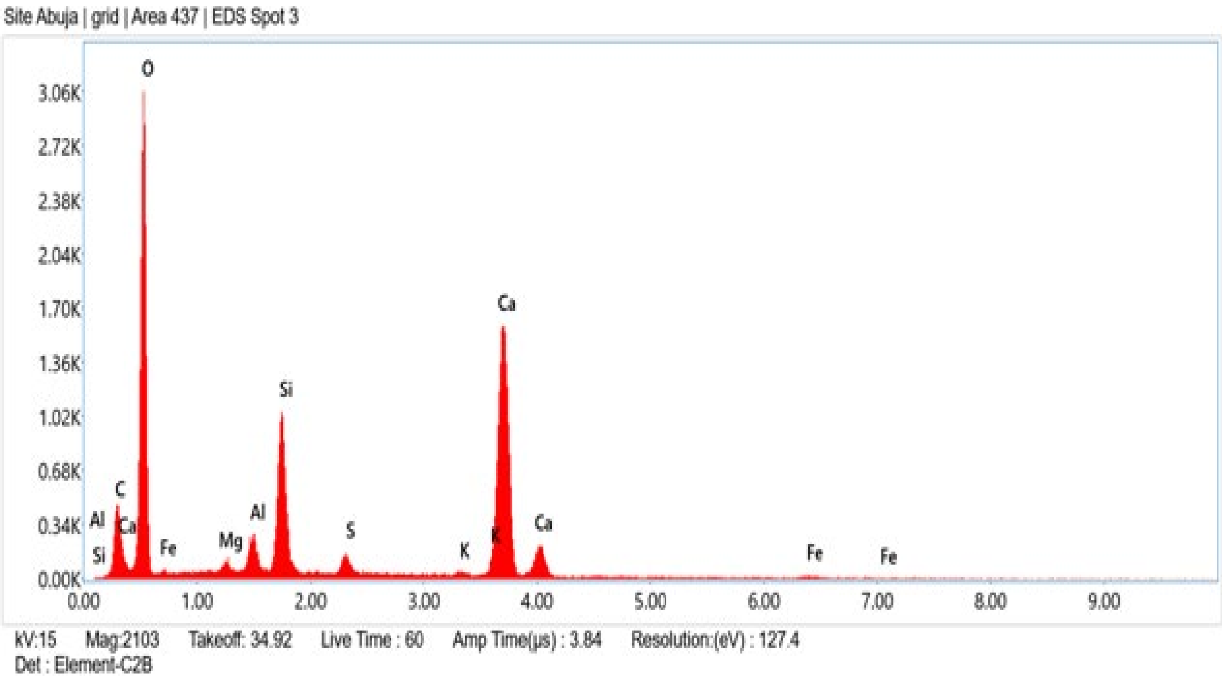

Figure 13: XRD Result for Sample R112

3.5 Phase Identification (XRD Analysis)

X-ray Diffraction analysis in Figure 13 confirmed the presence of major crystalline phases such as quartz, calcite, and portlandite across all concrete samples. RHA-modified mixes exhibited reduced portlandite peak intensities, indicating active consumption of calcium hydroxide during pozzolanic reactions.

LBWA-containing samples showed mineralogical patterns similar to the control mix, with minor variations in peak intensity attributable to dilution effects rather than chemical transformation. The XRD results support the SEM findings and further confirm the superior pozzolanic contribution of RHA relative to LBWA.

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Microstructural evidence supports the mechanical results, with RHA densifying the matrix and LBWA acting mainly as inert filler. SEM and XRD confirmed chemical and physical mechanism underlying strength development.

3.6 Optimization Results

Scheffé's mixture optimization technique was applied to model compressive and flexural strength responses (Ogbo *et al.*,2023) The developed polynomial models demonstrated excellent predictive capability, with coefficients of determination (R^2) exceeding 99% for both strength parameters.

Optimization results identified an optimal replacement level of approximately 12% RHA and 3% LBWA. This blend achieved mechanical performance close to that of the control mix while significantly reducing cement content. Replacement levels beyond 20% RHA or 15% LBWA resulted in substantial performance loss, highlighting the importance of controlled substitution. The Scheffe's homogenous model of the compressive and flexural strength of RHA and LBWA Modified Concrete at the 28th day of testing is given in the general form in Eqn.(3.7.1) and (3.7.2) respectively. The model was developed from a [6,3] mixture space requiring 56 distinct mix ratio samples

$$\begin{aligned} X_i(f_c) = {} & 26.4694X_1 + 19.6077X_2 + 3.4184X_1X_2 - 81.6802X_1^2X_2 \\ & + 13.8765X_3 + 121.7516X_1X_3 - 249.4720X_3 + 1.7706X_2X_3 \\ & - 171.8905X_1X_2X_3 - 11.5782X_2^2X_3 + 13.3821X_4 \\ & + 31.9179X_1X_4 - 96.9089X_1^2X_4 - 7.9529X_2X_4 \\ & + 13.5680X_1X_2X_4 - 6.8558X_2^2X_4 + 53.3764X_3X_4 \\ & - 252.7967X_1X_3X_4 - 84.0164X_2X_3X_4 - 108.5520X_3^2X_4 \\ & + 13.6095X_5 - 22.2761X_1X_5 - 6.1456X_1^2X_5 + 14.6295X_2X_5 \\ & + 19.5738X_1X_2X_5 - 54.7462X_2^2X_5 + 54.4440X_3X_5 \\ & - 232.5233X_1X_3X_5 - 192.9469X_2X_3X_5 - 113.7830X_3^2X_5 \\ & + 30.6365X_4X_5 - 173.4485X_1X_4X_5 - 153.4513X_2X_4X_5 \\ & - 224.6962X_3X_4X_5 - 64.4150X_4^2X_5 + 15.2543X_6 \\ & - 8.8980X_1X_6 - 41.2841X_1^2X_6 + 49.5775X_2X_6 \\ & - 81.3042X_1X_2X_6 - 133.3949X_2^2X_6 + 37.1853X_3X_6 \\ & - 316.6817X_1X_3X_6 - 223.7557X_2X_3X_6 - 86.0736X_3^2X_6 \\ & + 16.0116X_4X_6 - 187.2093X_1X_4X_6 - 155.5020X_2X_4X_6 \\ & - 173.0965X_3X_4X_6 - 39.7504X_4^2X_6 + 3.9862X_5X_6 \\ & - 87.4179X_1X_5X_6 - 147.9539X_2X_5X_6 - 141.1215X_3X_5X_6 \\ & - 67.5110X_4X_5X_6 - 10.8548X_5^2X_6 \end{aligned} \qquad \textbf{(3.7.1)}$$

And;

$$\begin{aligned} X_i(f_f) = {} & 2.7850X_1 + 2.0630X_2 + 0.3596X_1X_2 - 8.5941X_1^2X_2 + 1.4600X_3 \\ & + 12.8102X_1X_3 - 26.2485X_1^2X_3 + 0.1863X_2X_3 - 18.0857X_1X_2X_3 \\ & - 1.2182X_2^2X_3 + 1.4080X_4 + 3.3583X_1X_4 - 10.1964X_1^2X_4 \\ & - 0.8367X_2X_4 + 1.4275X_1X_2X_4 - 0.7213X_2^2X_4 + 5.6160X_3X_4 \\ & - 26.5984X_1X_3X_4 - 8.8399X_2X_3X_4 - 11.4214X_3^2X_4 + 1.4319X_5 \\ & - 2.3438X_1X_5 - 0.6466X_1^2X_5 + 1.5392X_2X_5 + 2.0594X_1X_2X_5 \\ & - 5.7602X_2^2X_5 + 5.7284X_3X_5 - 24.4653X_1X_3X_5 \\ & - 20.3012X_2X_3X_5 - 11.9718X_3^2X_5 + 3.2234X_4X_5 \\ & - 18.2496X_1X_4X_5 - 16.1456X_2X_4X_5 - 23.6417X_3X_4X_5 \\ & - 6.7775X_4^2X_5 + 1.6050X_6 - 0.9362X_1X_6 - 4.3437X_1^2X_6 \\ & + 5.2163X_2X_6 - 8.5545X_1X_2X_6 - 14.0353X_2^2X_6 + 3.9125X_3X_6 \\ & - 33.3201X_1X_3X_6 - 23.5428X_2X_3X_6 - 9.05637X_3^2X_6 \\ & + 1.6846X_4X_6 - 19.6975X_1X_4X_6 - 16.3613X_2X_4X_6 \\ & - 18.2126X_3X_4X_6 - 4.1824X_4^2X_6 + 0.4194X_5X_6 - 9.1978X_1X_5X_6 \\ & - 15.5672X_2X_5X_6 - 14.8483X_3X_5X_6 - 7.1032X_4X_5X_6 \\ & - 1.1421X_5^2X_6 \end{aligned} \qquad \textbf{(3.7.2)}$$

The average value of the coefficient of determination value R^2 of 99. 62% and 99.16% were indicated for compressive and flexural medicating the fitness of the model for modeling both compressive and flexural characteristics of RHA and LBWA Modified Concrete and thus suitable for use in optimization computations.

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Optimization enables balancing environmental and mechanical performance by identifying ideal mix proportions. Scheffe's optimization validated the experimental observations, highlighting feasible sustainable mix designs

3.7 Optimal Mixture Compositions and Corresponding Compressive Strengths

Table 8 presents the pseudo-component ratios for nine optimized concrete mixtures and their respective compressive strengths. The mixture compositions were formulated to investigate the influence of agro-waste ashes—namely Rice Husk Ash (RHA) and Locust Beans Waste Ash (LBWA)—on the mechanical performance of concrete, particularly its compressive strength.

Each mix was designed using a unique combination of six primary components: water, Ordinary Portland Cement (OPC), LBWA, RHA, fine aggregate, and coarse aggregate. The pseudo-component approach facilitated normalization and ensured the total proportions of the mixtures adhered to the unity constraint, which is critical in mixture experiment design.

The water content across the mixes ranged from 0.5509 (Mix-2) to 0.99485 (Mix-1), while cement content varied between 0.8251 (Mix-8) and 0.9991 (Mix-2). The incorporation of LBWA and RHA was purposefully limited to smaller proportions, reflecting their role as partial cement replacements. Notably, RHA content peaked in Mix-7 at 0.4947, and LBWA was highest in Mix-7 as well, at 0.1649—indicating this mixture had the most aggressive substitution level. Fine aggregate and coarse aggregate were also varied slightly but generally remained around similar values across the mixes, maintaining structural consistency.

In terms of mechanical performance, compressive strength varied significantly across the mixtures, with values ranging from 20.096 MPa (Mix-5) to 32.548 MPa (Mix-7). This highlights the sensitivity of strength development to changes in mixture proportions. Mix-7, which exhibited the highest compressive strength, also had relatively elevated contents of both LBWA and RHA, suggesting a synergistic effect of these supplementary cementitious materials when used in optimal balance.

Conversely, Mix-5, despite having a moderate RHA content (0.2977) and low LBWA (0.0991), recorded the lowest compressive strength. This may be attributed to a suboptimal water-to-cement ratio or inadequate pozzolanic reactivity at the specific blend proportions.

Overall, the results underscore the potential of RH and LBW ashes as effective partial replacements for cement, capable of enhancing compressive strength when appropriately proportioned. These findings support ongoing efforts toward sustainable concrete production through the valorization of agricultural waste materials.

Table 8: Optimal mixture composition and compressive strengths values

S/No.	Mixture Items	Pseudo Component	Mixture Label								
			Mix -1	Mix -2	Mix -3	Mix -4	Mix -5	Mix -6	Mix -7	Mix -8	Mix -9
1	Water	0.99485	0.5509	0.5754	0.6502	0.7246	0.6436	0.6929	0.7094	0.5777	0.6437
2	Cement	0.00070	0.9991	0.9746	0.8998	0.8254	0.8909	0.8416	0.8251	0.9568	0.8908
3	LBWA	0.00037	0.0009	0.0254	0.1002	0.1746	0.0991	0.1484	0.1649	0.0332	0.0992
4	RHA	0.00078	0.0027	0.0761	0.3007	0.5238	0.2972	0.4452	0.4947	0.0996	0.2977
5	Fine-Agg.	0.00218	1.4973	1.4239	1.1993	0.9761	1.1878	1.0398	0.9903	1.3854	1.1873
(6	Coarse Aggregate	0.00111	2.0000	2.0000	2.0000	1.9999	1.9800	1.9800	1.9800	1.9800	1.9800
	Compressive Strength	1.00000	22.237	26.398	25.123	25.665	20.096	21.245	32.548	21.024	21.903

3.8 Optimal Mixture Compositions and Corresponding Flexural Strength

The influence of mixture compositions on the flexural strength of concrete, based on nine optimized blend configurations. Each mixture was prepared using varying proportions of key constituents in Table 9: water, Ordinary Portland Cement (OPC), Locust Beans Waste Ash (LBWA), Rice Husk Ash (RHA), fine aggregate, and coarse aggregate. The pseudo-component approach was employed to normalize component ratios such that the sum of all constituent proportions equaled unity, facilitating the application of mixture experiment methodologies.

Water content ranged from 0.23524 (Mix-1) to 0.7604 (Mix-4), while cement proportions varied between 0.7894 (Mix-4) and 0.9366 (Mix-2), suggesting a relatively high cement content across most mixes. LBWA

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content was highest in Mix-1 (0.73854) and generally lower in the other mixes, indicating its dominant presence in that particular configuration. RHA content varied notably, reaching a peak of 0.6314 in Mix-4, with the lowest proportion observed in Mix-1 (0.00566).

The observed flexural strength results reveal a wide performance range, spanning from 0.168 MPa (Mix-5) to 3.488 MPa (Mix-7). Mix-7, which recorded the highest flexural strength, was characterized by relatively balanced proportions of LBWA (0.1644) and RHA (0.4932), alongside moderate cement and water contents. This mixture suggests an optimal synergy between the pozzolanic reactions of the agro-waste ashes and the hydration process of the cement matrix, resulting in improved tensile resistance.

In contrast, Mix-5 showed the lowest flexural strength despite containing appreciable quantities of RHA (0.2975) and cement (0.8908), indicating that the interaction between constituents at this proportioning may have led to poor microstructural integrity or inadequate bonding within the matrix. The significantly higher water content in Mix-4 (0.7604), which still achieved a moderate flexural strength (1.964 MPa), further demonstrates the complex interplay between water demand, binder efficiency, and aggregate packing.

The trends in the table suggest that neither LBWA nor RHA alone dictates performance; rather, their relative proportions in combination with other constituents govern the flexural behavior. Mixes such as Mix-8 (2.174 MPa) and Mix-3 (2.024 MPa) also displayed superior strength compared to Mixes 1, 2, and 5, reinforcing the importance of a balanced mixture design.

The results validate the potential of LBWA and RHA as viable supplementary cementitious materials (SCMs) that can enhance the flexural strength of concrete when proportioned optimally. This supports the broader objective of sustainable concrete development through the utilization of agro-waste byproducts while maintaining mechanical performance standards required for structural applications.

Table 9: Optimal mixture composition and flexural strengths values

S/No.	Mixture Items	Pseudo component	Mixture label								
			Mix -1	Mix -2	Mix -3	Mix -4	Mix -5	Mix -6	Mix -7	Mix -8	Mix -9
1	Water	0.23524	0.6274	0.6134	0.6879	0.7604	0.6437	0.6679	0.7089	0.6027	0.6566
2	Cement	0.01067	0.9226	0.9366	0.8621	0.7894	0.8908	0.8666	0.8256	0.9318	0.8779
3	LBWA	0.73854	0.0774	0.0634	0.1379	0.2105	0.0992	0.1234	0.1644	0.0582	0.1121
4	RHA	0.00566	0.2323	0.1901	0.4138	0.6314	0.2975	0.3703	0.4932	0.1747	0.3363
5	Fine-Agg.	0.00521	1.2677	1.3099	1.0862	0.8683	1.1875	1.1147	0.9918	1.3103	1.1487
6	Coarse Aggregate	0.00468	2.0000	2.0000	2.0000	1.9997	1.9800	1.9800	1.9800	1.9800	1.9800
	Flexural Stght	1.00000	1.203	1.953	2.024	1.964	0.168	1.302	3.488	2.174	1.699

Optimal mechanical and microstructural performance achieved with low to moderate replacement levels. The implication of practice is that sustainable cement reduction is achievable without significant performance loss using agricultural waste materials. Mixes with ≤15% replacement can meet structural requirements while lowering carbon footprint. Industrial adoption will require field trials and economic assessments to confirm laboratory findings.

4.0 Conclusion

This study examined the feasibility of utilizing Rice Husk Ash (RHA) and Locust Bean Waste Ash (LBWA) as partial replacements for Ordinary Portland Cement in concrete, with emphasis on chemical composition, mechanical performance, mixture optimization, and microstructural behavior.

The findings demonstrate that both agricultural waste ashes can be effectively incorporated into concrete when used in controlled proportions, contributing to more sustainable construction practices. Oxide composition analysis confirmed the pozzolanic suitability of RHA, which exhibited a high silica content exceeding the ASTM C618 minimum requirement for Class F materials. This high reactive silica content enabled RHA to actively participate in secondary pozzolanic reactions, leading to improved matrix densification and long-term strength development. In contrast, LBWA contained relatively lower silica but higher concentrations of potassium oxide and magnesium oxide, which influenced early hydration behavior and contributed primarily through physical filler effects rather than strong chemical reactivity.

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Mechanical testing revealed that partial replacement of cement with RHA and LBWA is feasible without excessive loss of strength, provided that substitution levels remain moderate. While the control concrete achieved the highest compressive and flexural strengths, several modified mixtures demonstrated acceptable performance for practical applications. Among these, the ternary blend containing 7% LBWA and 20% RHA (Mix R246) recorded the highest compressive strength (16.25 N/mm²) and flexural strength (1.71 N/mm²) among all modified mixes, indicating a synergistic interaction between the two ashes. However, replacement levels exceedingly approximately 30% resulted in significant reductions in strength due to dilution of cement content and limited availability of calcium hydroxide for effective pozzolanic reactions.

Microstructural investigations using Scanning Electron Microscopy and X-ray Diffraction provided further insight into the observed mechanical behavior. RHA-modified concrete exhibited a denser and more refined microstructure characterized by increased formation of secondary calcium silicate hydrate and reduced porosity. LBWA-rich mixes showed comparatively higher porosity and less pronounced hydration products, suggesting the need for finer grinding or chemical activation to enhance its reactivity. These microstructural observations were consistent with the strength performance trends.

Optimization using Scheffé's mixture design technique successfully identified optimal replacement proportions that balance mechanical performance and sustainability. The developed predictive models demonstrated high accuracy and reliability, confirming their suitability for optimizing agro-waste-based concrete mixtures.

Overall, the study confirms that RHA is a more effective supplementary cementitious material than LBWA due to its superior pozzolanic activity, while LBWA can serve as a complementary filler material when used sparingly. The combined use of both ashes offers a viable pathway for reducing cement consumption, lowering environmental impact, and promoting the valorization of agricultural waste.

This research contribution to knowledge validates rice husk ash (RHA) as a high –silica pozzolan and locust bean waste ash(LBWA) as a hydration–enchancing complement, identifying an optimal 7% LBWA-20% RHA blend with superior strength. SEM/EDS and scheffe's-ANOVA modeling linked microstructure to performance, providing limits and a replicable framework for sustainable, low-carbon concrete.

4.1 Recommendations

Adopt a ternary blend of 7% LBWA and 20% RHA for non-structural, low-to-mid-strength applications such as pavement blocks, masonry units and rural infrastructure.

Enhance LBWA reactivity through finer grinding, chemical activation, nano-modification, or hybrid blends with SCMs like fly ash or slag to improve performance.

Assess alkali-silica reaction risks associated with LBWA's high potassium content, particularly when used with reactive aggregates in concrete.

Investigate fiber reinforcement nano-silica addition, durability properties, and life-cycle cost analyses to address strength limitations and evaluate sustainability benefits.

Promote agro-waste-based concrete through standards, incentives, and pilot projects in resource-rich regions to encourage sustainable construction and carbon reduction.

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