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Optimizing Compressive Strength and Sustainability in Concrete: A Statistical and Experimental Analysis of Rice Husk Ash (RHA) as a Partial Cement Replacement

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Abstract

This study explores the impact of partially replacing cement with Rice Husk Ash (RHA) on the compressive strength of concrete, using both experimental and statistical approaches. The goal is to assess how RHA affects the properties of concrete, from material characteristics to strength performance, while also analyzing the consistency of the results through statistical methods.

To achieve this, tests were conducted on the materials used, including cement, fine and coarse aggregates, and RHA. The sieve analysis showed a fineness modulus of 2.95 and a coefficient of uniformity of 3.035, while the specific gravity test gave a value of 2.49. Concrete mixes were prepared using water-to-cement (w/c) ratios of 0.45, 0.50, and 0.55, corresponding to 0%, 10%, and 20% RHA replacement. As the RHA content increased, workability decreased, as observed in the slump test. Compressive strength tests were carried out to understand how RHA replacement affects concrete strength, and statistical methods including revised mean and covariance, experimental mean and covariance, and within-test data analysis—were used to interpret the variations in results.

This study evaluates the effect of a 10% replacement of cement with Rice Husk Ash (RHA) on the revised compressive strength variability of concrete at different water-cement (w/c) ratios. The analysis considers the mean compressive strength, revised Coefficient of Variation (COV), and standard deviation for w/c ratios of 0.45, 0.50, and 0.55. The results indicate that the highest mean strength (28 MPa) and lowest variability (COV = 0.14, SD = 3.87 MPa) were observed at a w/c ratio of 0.45, suggesting better consistency and strength performance. Conversely, an increase in w/c ratio to 0.50 and 0.55 led to a decrease in mean strength (25.3 MPa and 24 MPa, respectively) and higher variability, highlighting the sensitivity of RHA-modified concrete to water content.

Keywords: Rice Husk Ash (RHA), Sustainable concrete, Compressive strength, Cement replacement, Statistical variability, Water-cement ratio (w/c), Pozzolanic materials, green construction, Material characterization, Structural integrity

INTRODUCTION

The use of concrete and cement, two of the most popular man-made materials, is being examined. Because of its widespread use, the manufacturing of cement and concrete strains the supply of natural resources like water and contributes significantly to greenhouse gas emissions. The demand for cement and concrete will consequently continue to rise due to projected urbanization over the next 50–100 years, requiring measures to reduce their environmental impact. (Habert and others, 2020). Clay, limestone, and other materials are fired in a kiln to create cement. The energy required to burn the material and the chemical reaction that results from the combination when it is heated both release carbon dioxide (2020, Ramsden). The National Ready Mixed Concrete Association states that 0.93 pounds of carbon dioxide are released for every pound of concrete. The amount of CO2 released in the concrete industry is increasing because it is such a common product. (Mohamad et al., 2021) The use of aggregate, particularly limestone, which is crucial to the production of Portland cement, is increasing as a result of the continuously rising demand for cement supplies. Because of the sharp rise in energy use in the twenty-first century, the depletion of the planet's non-renewable resources is becoming an increasingly pressing issue. Due to the extensive mining and quarrying industry, non-renewable resource reserves will eventually be depleted as they are taken out of the environment. The number of non-renewable resources is limited, and once they are mined, their stocks do not replenish. Permanent economic decline, including biodiversity loss, global warming, climate change, vegetation degradation, ecosystem devastation, river damage, and dust contamination, is a result of ongoing natural resource harvesting. (Rodrigues et al,2010), A common agricultural by-product that is widely accessible is rice husk. This biomass source is appropriate for producing energy. The burned rice husk yields a large amount of ash (about 20%) compared to other agricultural by-products. This ash is primarily made up of silica, which will be primarily amorphous when properly incinerated. The introduction of rice husk ash (RHA) as an additional raw material in cement-based products has been made possible by extensive study over the past three decades. This has helped to meet ecological criteria while also achieving notable gains in strength and durability. (Muthadhi et al, 2007), The result of the rapidly polluted environment is the growing need for the production of long-lasting building materials. The majority of the requirements for durable concrete can be effectively met by supplemental cementitious ingredients such as Fly ash, silica fume, slag, and other supplemental materials are shown to be inferior to rice husk ash. Concrete's strength and durability are enhanced by its high pozzolanic activity. Rice husk ash must be made from the raw agricultural waste, husk, in contrast to other industrial by-products. The process used to produce ash has a big impact on its quality.

MATERIALS AND METHOD

A. Material Selection

The materials to be used in this work are Rice Husk Ash, Ordinary Portland Cement (OPC), aggregates (fine and coarse) using BS EN12620: (2002) and water using BS EN 1008:(2002)

B. Preparation of RHA

Rice husk ash is an agricultural by product with potential to be a sustainable alternative in concrete production. RHA utilizes waste material from rice production, reducing landfill burden and promoting resource efficiency. It was sourced from a Warake rice farm, Owan East Local Government Area of Edo State, Nigeria. Where was dried in order to eliminate moisture, grinded and then burnt up 600^0c in a controlled setting (University of Benin Structural Lab).

C. Ordinary Portland Cement

The cement used was gotten from Dangote cement depot at Oluku. **Dangote 3X, cement type CEMII 42.5N (A-L)** is a general-purpose cement that is used to produce all kinds of products including C8/10-C35/45 class of concrete. It is a high-strength product packaged in a 50kg bag for customer convenience.

D. Aggregate

Aggregates can be categorized into two main types:

i. **Fine Aggregates**: it was sourced from Okhuaihe is located in the Uhunmwode Local Government Area (LGA) of Edo State, Nigeria. Fine aggregates are necessary for construction and are granular materials that may be sieved through a 4.75 mm screen.

ii. **Coarse aggregates**: it was sourced from Ulouke Quarry, Auchi, Edo State,Nigeria. Coarse aggregate, which usually comprises crushed stone and gravel, is made up of bigger granular components that stay on a 4.75 mm filter. The size of coarse aggregate used is 14mm (Medium coarse aggregate.

E. Water

Clean water from University of Benin Structural Laboratory was used for the mixture of the concrete.

F. Proportioning

Table 1: Proportioning of concrete constituents

Cement replacement	**Rice husk (kg)**	**Cement (kg)**	**Sand (kg)**	**Granite (kg)**	**Water (kg) 0.45**	**Water (kg) 0.5**	**Water (kg) 0.55**
0%	-	28.35	28.35	56.7	12.75	14,18	15.59
10%	2.83	25.53	28.35	56.7	12.75	14.18	15.59
20%	5.67	22.68	28.35	56.7	12.75	14.18	15.59

RESULTS

A. SIEVE ANALYSIS OF THE RIVER SAND (FINE AGGREGATE)

Sand used in concrete mixing was analyzed using sieve analysis, adhering to the standards outlined in ISO – 14688. The detailed results of this analysis are provided in Table 2. Additionally, the gradation curve is shown below in fig 1.

Table 2: Sieve Analysis

Sieve size (mm)	Mass of empty sieve	Mass of sieve + soil (g)	Mass of soil retained (g)	Cumulative mass of soil retained (g)	Percent retained %	Cumulative percent retained	Percent passing %
2.000	523	650	118	118	9.966	9.966	90.034
1.180	484	564	80	198	6.757	16.723	83.277
0.600	480	784	04	502	25.676	42.399	57.601
0.425	452	734	282	784	23.818	66.217	33.783
0.300	426	634	208	992	17.565	83.784	16.216
0.212	424	522	98	1090	8.277	92.061	9.739
0.150	444	498	54	1144	4.561	96.622	3.378
0.075	404	430	26	1170	2.196	98.818	1.182
0.063	390	396	6	1176	0.506	99.324	0.676
Pan	376	384	8	1184	0.676		
Pan + fine aggregate			1184		100		295
Fineness modulus =295/ 100 = 2.95							

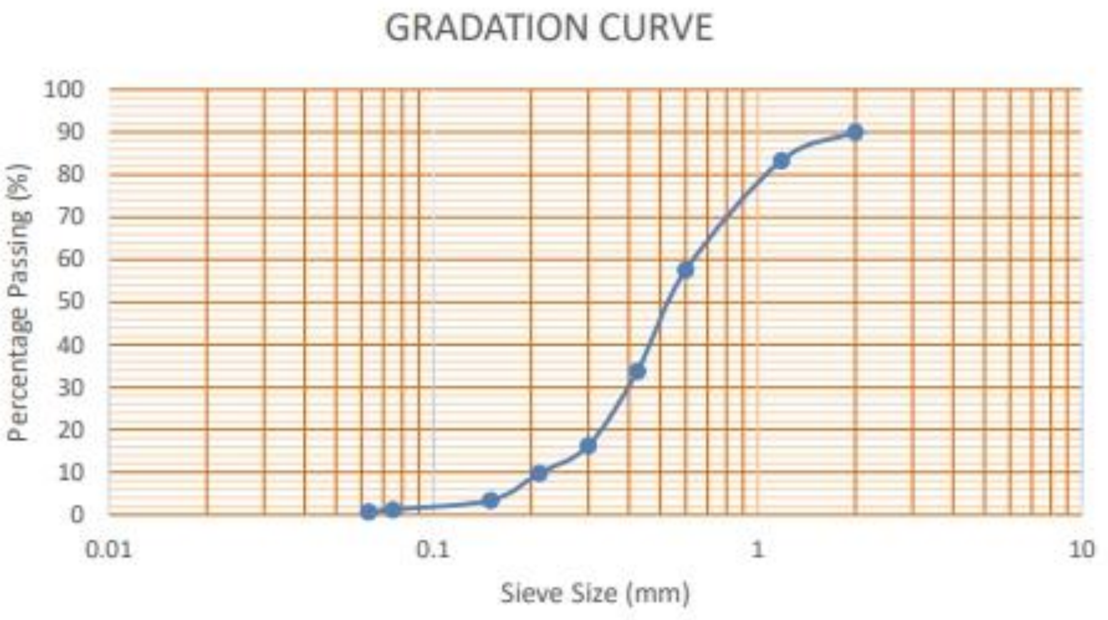

Figure 1; shows the sieve analysis curve for the sand used

The sieve analysis curve generated from the result of the sieve analysis test taken exhibits gradual sloping curve which indicates a good distribution of particle sizes. This is essential for optimal workability, strength and durability of the concrete. The coefficient of uniformity and coefficient of curvature for the fine aggregates is 3.035 and 1.24 respectively. If the coefficient of uniformity is less than 4, then the soil is uniformly graded. Hence the fine aggregates can be said to be uniformly graded and the coefficient of curvature further confirms the fine aggregate to be well graded having a value of 1.24 (If coefficient of curvature is between 1-3, the aggregate is said to be well graded). The fine aggregate is classified under zone 3 since the fineness modulus is 2.95 and a maximum particle size of 2.36mm.

B. SPECIFIC GRAVITY TEST

Specific gravity test was carried out on the sand following the specified guidelines in ASTM C128. Table below shows the results of the tests carried out to determine the specific gravity of the sand used for this project work.

Table 3: Results of Specific Gravity Test for sand

Description	Test
Weight of pycnometer W_1 (g)	10.5
Weight of pycnometer + sample, W_2 (g)	24.2
Weight of pycnometer + sample + water, W_3 (g)	46.9
Weight of empty pycnometer + water W_4 (g)	38.7
Specific Gravity	2.49

Table 4: Results of Specific Gravity Test for rice husk ash

For Rice Husk Ash	A	B	C
Weight of the bottle W_1 (g)	260.82	263.51	257.8
Weight of bottle + water +ash W_2 (g)	336.68	335.86	336.68
Weight of evaporator dish + dry ash, W_3 (g)	178	178	178
Weight of dish W_4 (g)	135.12	135.15	135.13
Weight of ash W_5 (g)	42.88	42.85	44.88
Specific gravity of ash	2.3	2.45	2.32

Table 4, gives the specific gravity value of Sand to be 2.49. This shows that the sand sample used is within the range of standard specific gravity value (2.4 – 3.0) (ATSM C128,2021) which means it fits the requirement to be classified as fine aggregate. It indicates that the aggregate is dense and of good quality. The mean specific gravity for RHA is 2.36 (table 6), According to literature and standards, the specific gravity of RHA typically ranges between 2.0 to 2.6 depending on the source, burning conditions, and purity. ASTM C618 (Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete) does not directly specify SG for RHA but requires consistency with pozzolanic materials. High carbon RHA has an SG of 2.3 -2.6.

Slump Test

A higher slump indicates that the concrete is more workable, while lower slump indicates that the concrete is less workable and it may be necessary to add more water to the mix to make it more workable.

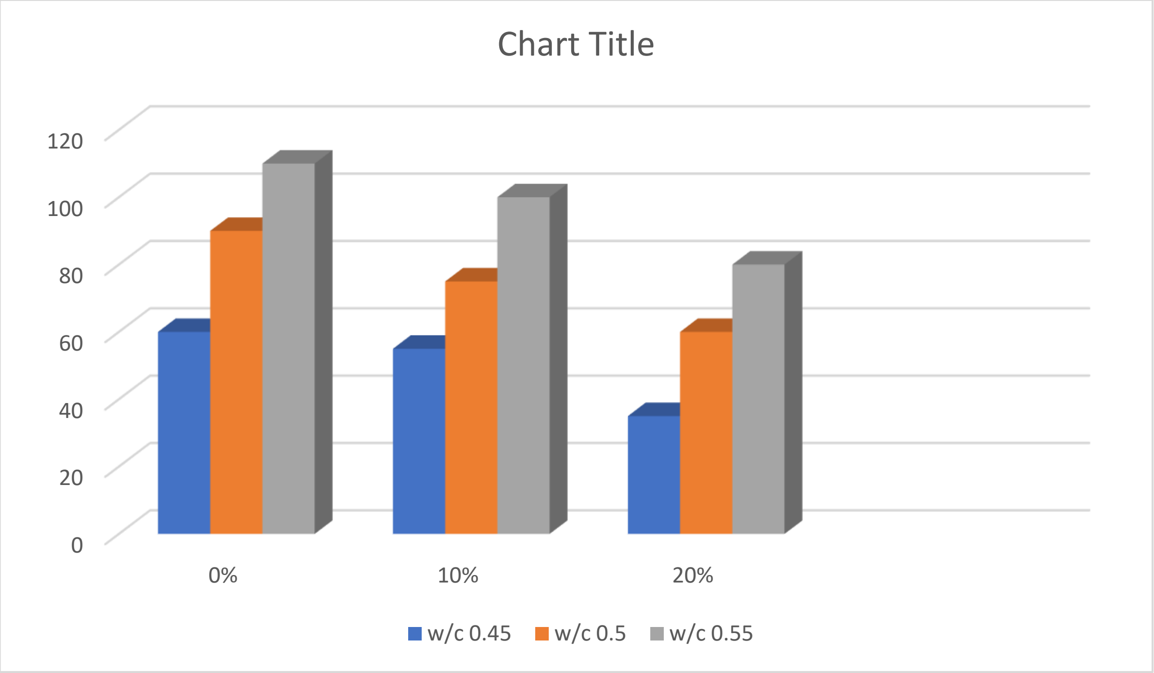

Figure 2 :Bar Chart for Slump Test

The slump value for the concrete containing 0% was found to be 101mm indicating high workability which falls under the range of 10mm -210mm as stated in BS (2009). A drop in slump value was observed as the percentage of the ash increases for the same water cement ratio. This shows that as the percentage of RHA increases, concrete becomes less workable and will suggest the incorporation of superplasticizer.

C. WATER ABSORPTION TEST

Table 5: Water Absorption Test

w/c ratio	**Control (%)**	**10 % (%)**	**20% (%)**
0.45	0.175	0.135	0.275
0.5	0.31	0.21	0.28
0.55	0.38	0.385	0.395

According to the results of the water absorption test, the addition of RHA at a 10% replacement level resulted in a lower water absorption rate (0.135%) than that of the control mix (0.175%). The pozzolanic reaction of RHA, in which silica and calcium hydroxide combine to generate more C-S-H gel, is responsible for this improvement. This process refines the pore structure and lowers permeability. (Amran and others, 2021). Nevertheless, the water absorption dramatically rose to 0.275% when the RHA replacement was raised to 20%. This implies that the excess RHA may not completely react at higher replacement levels, which could result in an imbalance in the mix design or increased porosity because of the high surface area of the unreacted RHA particles (Kumar and Kumar, 2008). The water absorption increased slightly from 0.38% (control) to 0.385% for w/c 0.55, suggesting that RHA had little influence on permeability at a 10% replacement level. This implies that the RHA has reacted well in the mixture without appreciably raising porosity. (Jing and others, 2024) influence on 20%, A slight but discernible increase in water absorption was seen, reaching 0.395%. This would suggest that there are some unreacted RHA particles present at greater replacement levels, which could result in modest increases in porosity. The fact that the increase is not significant, nevertheless, suggests that the mix design is still mostly balanced. (Endale et al., 2022).

D. COMPRESSIVE STRENGTH TEST

The area of each of the cubes cast and crushed was 10000mm^2 (100mm x 100mm) and this was used in the computation of the compressive strengths.

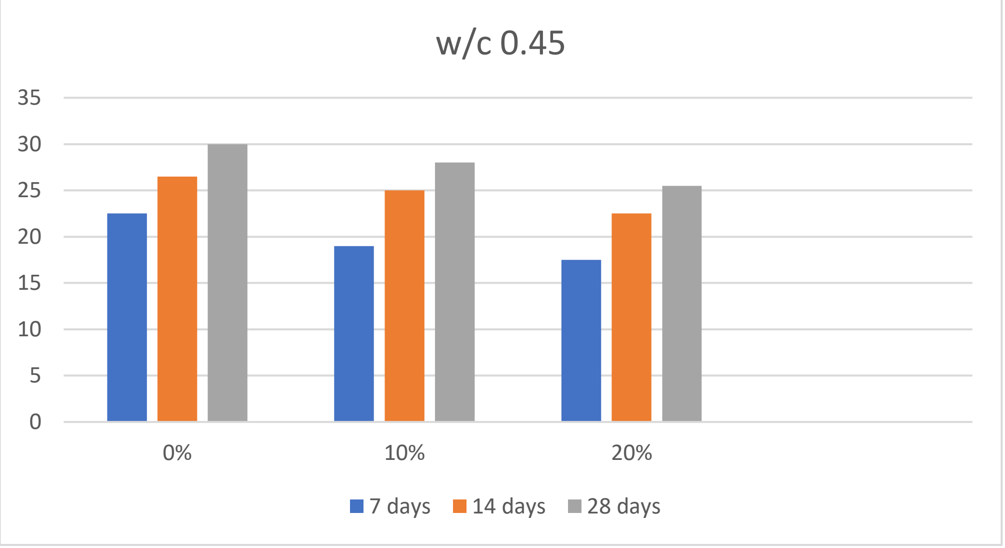

Figure 3:Bar Chart for Compressive Strength Test (w/c 0.45)

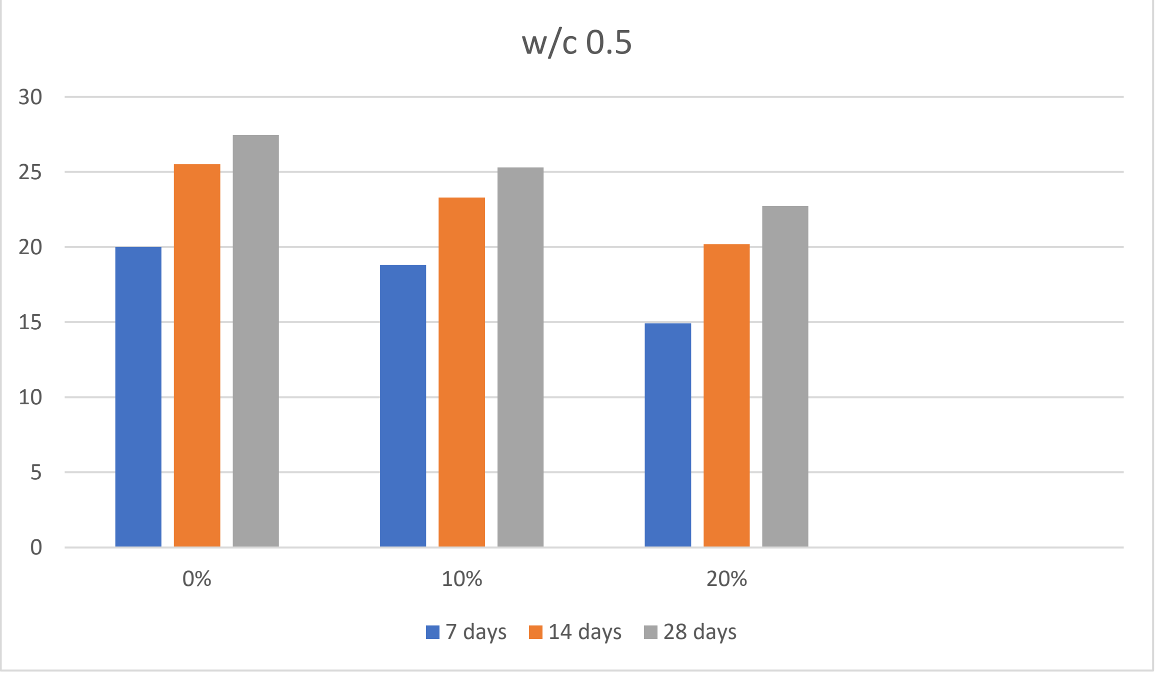

Fig. 4:Bar Chart for Compressive Strength Test (w/c 0.5)

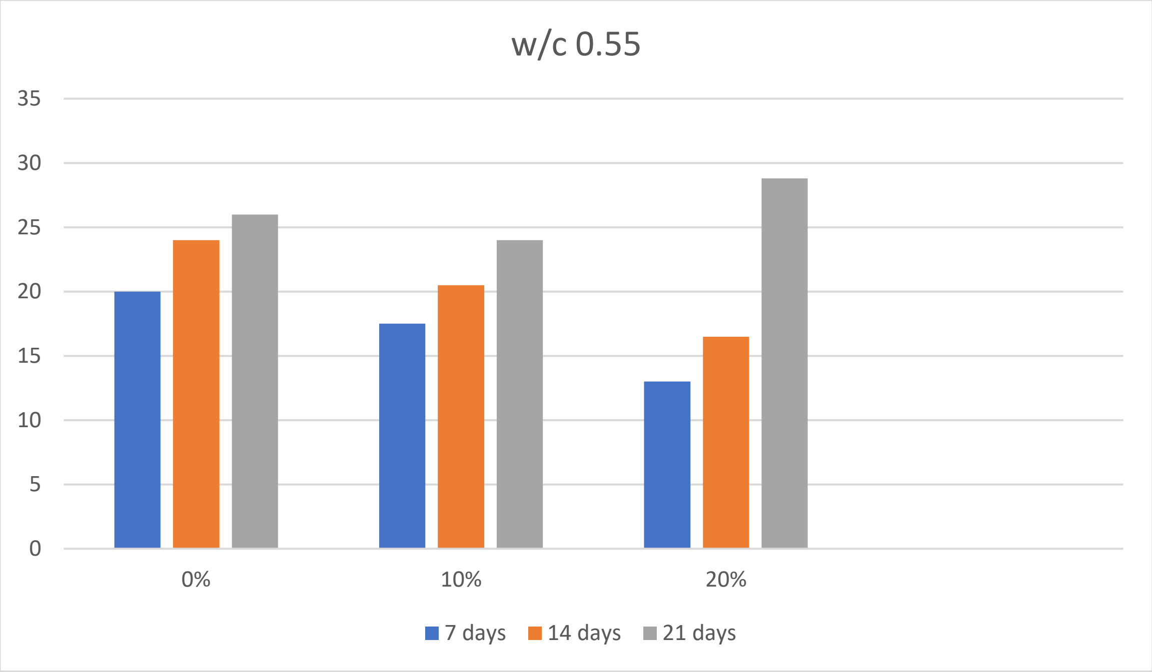

Figure 5: Bar Chart for Compressive Strength Test (w/c 0.55)

E. STATISTICAL ANALYSIS OF STRENGTH CONSISTENCY

Table 6: Within test variation for w/c 0.45

RHA Replacement (%)	Mean Strength (MPa)	Standard Deviation (MPa)	Within COV (%)
0% (Control)	29.5	1.22	**4.6%** (Most consistent)
10% RHA	28.0	1.3	**12.6%** (Moderate consistency)
20% RHA	25.5	1.45	**15 %** (Least consistent)

As the RHA replacement increases, the consistency of compressive strength decreases. At 0% RHA, the COV is 4.6%, indicating high consistency. However, at 10% and 20% RHA, the COV increases to 12.6% and 15.0%, respectively, showing greater variability in strength.
A COV below 10% is acceptable, while values above 12% indicate significant variation, which may affect concrete performance. To improve uniformity at higher RHA levels, mix design adjustments or additives may be necessary.

Table 7: Within test variation for w/c 0.5

RHA Replacement (%)	Mean Strength (MPa)	Standard Deviation (MPa)	COV (%)
0% (Control)	27.46	1.25	**4.55%** (Most consistent)
10% RHA	25.3	1.869	**7.39%** (Moderate consistency)
20% RHA	22.73	2.571	**12.51%** (least consistent)

The consistency of concrete strength decreases as the RHA replacement increases. The 0% RHA mix is the most consistent, with the lowest COV (4.55%), while the 20% RHA mix is the least consistent, with the highest COV (11.31%). The increasing standard deviation and decreasing mean strength indicate greater variability and reduced reliability in strength as RHA content rises. To maintain uniform performance, higher RHA replacements should be carefully controlled.

Table 8: Within test variation for w/c 0.55

RHA Replacement (%)	Mean Strength (MPa)	Standard Deviation (MPa)	COV (%)
0% (Control)	26.0	0.913	3.51% (Most consistent)
10% RHA	24.0	1.225	5.10% (Higher variability)
20% RHA	22.8	2.571	12.50% (least consistent)

As RHA replacement increases, concrete strength becomes less consistent. The 0% RHA mix is the most reliable (COV 3.51%), while the 20% RHA mix is the least consistent (COV 11.31%). Increasing RHA leads to higher variability (standard deviation increases) and strength reduction. To maintain uniform performance, higher RHA replacements should be carefully controlled.

F. SUMMARY OF STATISTICAL DATA

Table 9: Summary of Statistical Data

CONTROL MIX			
W/c ratio	Exp. Mean	Revised Cov.	Within Cov.
0.45	29.5	0.08	4.00
0.50	27.17	0.14	5.70
0.55	26	0.45	13.5
10% REPLACEMENT WITH RHA			
0.45	28	0.14	5.10
0.50	25.30	0.16	7.39
0.55	24	0.19	12.60
20% REPLACEMENT WITH RHA			
0.45	25.5	0.05	6.55
0.50	22.73	0.07	8,35
0.55	20.25	0.45	16.50

Increasing the water-cement (w/c) ratio leads to greater variability in mix performance, as evidenced by the significant increase in the Coefficient of Variation (Cov). Higher water content results in greater inconsistency, making the mix less predictable. Among the tested mixes, the 0.45 w/c ratio proves to be the most stable, with a Cov of just 8%, indicating well-controlled composition and reliable strength. In contrast, the 0.55 w/c mix exhibits high inconsistency, with a Cov of 45%, suggesting poor mix control, potential segregation, and bleeding issues. Notably, the jump in Cov from 0.50 (14%) to 0.55 (45%) is substantial, highlighting that beyond a certain threshold, approximately 0.50 w/c, the mix becomes highly unpredictable and difficult to control.

With 10% Rice Husk Ash (RHA), higher w/c ratios still increase variability, but the rise in CoV is more gradual than in the control mix. While RHA improves durability, it slightly increases variability due to higher water demand. However, it helps control extreme fluctuations at higher w/c ratios. Overall, the mix remains stable, with all Cov values below 20%, though workability adjustments may be needed.

CONCLUSION

This study presents a detailed experimental and statistical investigation into the effects of partially replacing cement with Rice Husk Ash (RHA) on the compressive strength and workability of concrete. The research demonstrates that RHA, an agricultural byproduct, can serve as a sustainable supplementary cementitious material, contributing to both environmental conservation and structural performance. The findings reveal that a 10% replacement of cement with RHA at a water-cement (w/c) ratio of 0.45 yields the optimal balance between strength and consistency, achieving a mean compressive strength of 28 MPa with the lowest variability (COV = 0.14, SD = 3.87 MPa). This suggests that moderate RHA incorporation enhances concrete durability while maintaining structural reliability. Higher replacement levels (20%) were found to reduce workability and increase water absorption, indicating the need for careful mix design adjustments or chemical admixtures to mitigate these effects. From an environmental perspective, the use of RHA in concrete aligns with global sustainability goals by reducing cement consumption—a significant source of CO_2 emissions—and repurposing agricultural waste. However, the economic analysis highlights a cost increase due to the current pricing and processing of RHA, emphasizing the need for improved supply chains and large-scale adoption to make RHA-based concrete economically competitive.

Statistical analyses, including revised covariance and within-test variability assessments, confirmed that lower w/c ratios (0.45–0.50) produce more stable and predictable concrete performance, whereas higher ratios (0.55) introduce significant inconsistency. These insights are critical for quality control in practical applications. For future research, extended curing periods, advanced material treatments (e.g., nano-silica modification), and industrial-scale trials are recommended to further optimize RHA-concrete properties. Additionally, policy incentives and industry collaboration will be essential to promote the widespread adoption of RHA in construction, ensuring both ecological and structural benefits. In conclusion, this study validates RHA as a viable partial cement substitute, offering a pathway toward greener concrete without compromising performance. The integration of RHA into construction practices can contribute to a more sustainable built environment, provided that economic and logistical challenges are addressed through further innovation and stakeholder engagement.

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