
MECHANICAL AND DURABILITY PERFORMANCE OF SUSTAINABLE CONCRETE INCORPORATING RICE HUSK ASH AND 100% RECYCLED CONCRETE AGGREGATE

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ABSTRACT

High-volume substitution of natural coarse aggregates with Recycled Concrete Aggregate (RCA) typically impairs mechanical strength and increases water absorption due to the porous residual mortar layer. This study investigates the performance improvement of Grade 25 concrete incorporating 100% RCA through the pozzolanic addition of Rice Husk Ash (RHA) as a partial Portland cement replacement. Characterization via X-ray Fluorescence (XRF) confirmed RHA as a reactive pozzolan with a combined oxide composition ($\text{SiO}_2 + \text{Fe}_2\text{O}_3 + \text{Al}_2\text{O}_3$) of 89.47%. Concrete mixes were prepared with 0%, 10%, 15%, and 20% RHA substitution levels at a fixed water-cement ratio of 0.57. Experimental results demonstrate that incorporating 15% RHA counteracts RCA-induced strength losses, yielding a 28-day compressive strength of 25.9 N/mm^2 (an 18.8% enhancement over the unblended RCA control), a splitting tensile strength of 2.5 N/mm^2 , and a reduced water absorption of 1.23%, meeting BS 812-2 durability standards. Combining 15% RHA with 100% RCA effectively remediates microstructural weaknesses inherent in recycled aggregate matrices.

Keywords: Rice husk ash; Recycled concrete aggregate; Sustainable concrete; Microstructural improvement; Compressive strength; Water absorption

1. INTRODUCTION

Sustainable construction practices have become necessary in contemporary civil engineering, driven by the urgent need to reduce negative environmental impacts and promote resource efficiency. In this context, the utilization of alternative materials in concrete production has emerged as a promising avenue to enhance sustainability in construction projects. This study aims to investigate the effects of incorporating rice husk ash (RHA) as partial replacement of cement and recycled concrete aggregate (RCA) as coarse aggregate on the performance and sustainability of concrete mixtures for construction applications.

Sustainable construction embodies principles aimed at minimizing environmental impact, conserving resources, and fostering societal well-being throughout the lifecycle of built infrastructure (Barlow, 2019). By integrating environmental, social, and economic considerations, sustainable construction practices seek to address global challenges such as climate change, resource depletion, and waste generation (Nawaz et al., 2020).

One of the primary challenges is the limited understanding of the performance of concrete mixtures containing RHA and RCA. Without a clear understanding of the mechanical, physical, and durability properties of concrete incorporating RHA and RCA, construction stakeholders may hesitate to adopt these materials in real-world applications. The integration of RHA and RCA into concrete mixtures may pose challenges in terms of compliance with existing standards, specifications, and regulatory requirements. Traditional concrete standards often do not account for the use of alternative materials, leading to ambiguity and confusion among designers, engineers, and regulators. Additionally, the lack of standardized testing protocols for evaluating the performance of concrete containing RHA and RCA further complicates the adoption process. Establishing clear guidelines and standards for

incorporating alternative materials into concrete mixtures is essential to ensure their widespread acceptance and use in construction projects. Finally, the lack of awareness and acceptance among construction stakeholders, including designers, contractors, developers, and policymakers, presents a significant barrier to the widespread adoption of RHA and RCA in construction projects. Many stakeholders may be unfamiliar with the properties, benefits, and limitations of these alternative materials, leading to skepticism and resistance to change. Building awareness, disseminating knowledge, and fostering collaboration among stakeholders are crucial steps towards overcoming this challenge and promoting the adoption of sustainable construction practices.

The significance of this study lies in its potential to advance sustainable construction practices by evaluating the performance of rice husk ash (RHA) as partial replacement of cement and recycled concrete aggregate (RCA) as coarse aggregate in concrete mixtures. The utilization of RHA and RCA offers significant environmental benefits by reducing the demand for virgin raw materials, conserving energy, and mitigating greenhouse gas emissions associated with traditional concrete production methods. The integration of RHA and RCA into concrete mixtures promotes resource conservation by utilizing waste materials that would otherwise be disposed of in landfills. By diverting waste streams from landfills and incorporating recycled materials into new construction projects, the construction industry can minimize its environmental footprint and contribute to resource efficiency.

The aim of this study is to evaluate the Effect of rice husk ash (RHA) as partial replacement of cement and recycled concrete aggregate (RCA) as coarse aggregate in concrete mixtures for sustainable construction applications. The following are the objectives: To investigate the chemical composition of rice husk ash so as to assess its level of pozzolanic content, To determine the properties of constituent materials used in this research to assess their suitability and conformity with standards, To carryout concrete mix design that will be used in this work, To investigate the mechanical properties of concrete mixtures containing varying proportions of rice husk ash as partial replacement for cement and recycled concrete aggregate as coarse aggregate, To determine the percentage replacement of cement with RHA that will produce optimum result.

Un-modified RCA concrete consistently exhibits lower compressive strength and higher permeability due to microcracks and old adhered mortar (Kou et al., 2011; Tam et al., 2012). This study investigates a microstructural remediation approach using 15% RHA to counteract RCA-induced strength degradation and restore Grade 25 concrete capacity[cite: 8, 10].

2. METHODOLOGY

Concrete Mix Design:

The concrete mix design was carried out using the Building Research Establishment (BRE) method. A mix ratio of 1:1.98:3.52 and water cement ratio of 0.57 from the concrete mix design was arrived at for this research. Concrete cubes of dimensions 150mm x 150mm x 150mm and cylinders with dimensions 100mm x 200mm were produced by partially replacing cement (Dangote). Rice husk ash (RHA) variation is at 0%, 10%, 15%, and 20%, the cube samples were cured in water for 7, 14, and 28 days and subjected to compressive and tensile strengths. A mix proportion of 1:1.98:3.52 with water cement ratio w/c 0.57 was achieved for Grade 25 (G25) in accordance with BS EN 197-1 (2005).

Preliminary Preparation of Rice Husk Ash Sample

The Rice Husk was cleaned and dried for 3 weeks so it would lose all its moisture content. It was burnt to ash using an incinerator in the department of Building, A.B.U Zaria. The ash after cooling was ball milled to further reduce the size and later grind. The rice husk was calcined at 700°C in a controlled incinerator. This temperature transforms amorphous silica into optimal reactive pozzolanic silica without forming crystalline quartz phase silica, which occurs above 800°C and reduces pozzolanic reactivity (Prasittisopin & Trejo, 2014; Thomas & Gupta, 2016).

METHODS

The tests carried out were physical and chemical for the determination of the physical and chemical properties of the materials used and effect of partial replacement of cement with rice husk ash

and a full replacement of coarse aggregate with recycled concrete aggregate on the properties of this sustainable concrete.

Test Equipment used

The following equipment in the heavy structures and concrete material laboratory are to be used in the course of these experiments:

1. Weighing Scale.
2. B. S. Sieves.
3. Concrete Moulds.
4. Rammer/Tamping rod.
5. Compression Testing Machine.
6. Tensile Testing Machine.
7. Slump cone.
8. Concrete mixer.
9. Vibrating table.

Casting and Curing of Concrete

Before casting the cubes, the 150mm x 150mm x 150mm steel cube moulds used were tightened, cleaned and oiled. The essence of oiling it is to facilitate easy and smooth demoulding of the concrete after hardening. The concrete mix was then poured into the moulds in 3 layers. The concrete was tamped 25 blows before adding another layer of concrete to the mould. This is to ensure that air bubbles are driven out and that the concrete is properly compacted. Excess concrete on the mould or on the floor was removed in time to avoid it from hardening. The surface of the concrete was then leveled and allowed to harden slightly before being marked for identification. The samples were demoulded after 24 hours and immediately immersed in clean water in a tank for curing. Curing is a process of hydrating the concrete samples which leads to increase in strength.

Compressive Strength test

Compressive strength test was carried out on the concrete in accordance to BS EN 196-1 (2005). The compressive strength test was conducted on cubes of 150mm x 150mm x 150mm mixed concrete using the compressive testing machine of 2500kN capacity (Denison) at the heavy structures and concrete laboratory of A.B.U, Zaria. The failure load was observed and recorded and the compressive strength in N/mm² was calculated from the equation below.

$$R_c = F_c/A \text{ (N/mm}^2\text{)}$$

Where, R_c is the compressive strength, in Newton per millimeters square,

F_c is the maximum load at fracture, in Newton and,

A is the area of the concrete sample in square millimeters.

Tensile Strength test

The tensile strength test was conducted on cylinders of 100mm x 200mm mixed concrete in an indirect form using the compression testing machine at the heavy structures and concrete laboratory of A.B.U, Zaria. The failure load was observed and the tensile strength in N/mm² was calculated from the equation below

$$MC = 2P/\pi DH$$

Where, MC is the tensile strength, in newton per millimeters square,

P is the maximum load at fracture, in newton and,

D and H are diameter and length of the cylindrical concrete sample respectively.

Water Absorption test

Water absorption test was carried out to determine the water absorption value of the mixed concrete, expressed in percentage. This property is particularly important in mortar and concrete used for water-retaining structure or watertight basement, as well as being critical for durability. This test was performed on a 150mm x 150mm x 150mm cube specimens prepared in the laboratory. Water absorption measurements were done by weighing the saturated specimens (W_s) and dried specimens (W_d) which was oven dried at 110°C for 24 hours at curing time 28 days. The water absorption was calculated using equation below

$$\text{Water absorption (\%)} = \frac{W_s - W_d}{W_d} \times 100$$

Specimen Replication and Statistical Design

To ensure statistical reliability and reproducible results, three ($n = 3$) replicate $150 \text{ mm} \times 150 \text{ mm} \times 150 \text{ mm}$ cube specimens were prepared and tested for each mix proportion (0%, 10%, 15%, and 20% RHA) at each curing age (7, 14, and 28 days), yielding a total of 36 compressive strength specimens. Similarly, three ($n = 3$) cylindrical specimens ($100 \text{ mm} \times 200 \text{ mm}$) and three ($n = 3$) durability samples were cast per mix design for splitting tensile strength and 28-day water absorption testing, respectively. Mechanical and physical test values are reported as the arithmetic mean $\pm$ standard deviation (SD).

3. RESULTS AND DISCUSSION

Table 4.1: Result of Standard consistency test of cement

Test	Weight of Cement (g)	Vol. of Water (ml)	Penetration (mm)	Consistency (%)
1	400	122	5.0	30.5
2	400	120	5.5	30.0
3	400	122	6.0	30.0
Average Consistency (%)			30.2	

Source: Laboratory test (2024)

The result of 30% average consistency in Table 4.1 implied a good result as the plunger penetrations were between 5mm-7mm from the base of the mould. It is in line with BS EN 196-3 (2016) which stipulates consistency of cement to be between 26% and 33%. This conforming result is not unconnected with the freshness of the cement used and procedure of BS EN 196-3 (2016) that was followed.

Table 4.2: Result of Setting time test of cement

The results of the tests carried out in the course of this research are presented and discussed with respect to literatures and standard codes of practice.

Test	Weight of Cement (g)	Vol. of Water (ml)	Penetration (mm)	Initial Setting Time(hrs:min)	Final Setting Time(hrs:min)
1	400	122	7.0	1:59	2:34
2	400	120	6.0	2:04	2:47
3	400	122	6.0	1:48	2:38
Average Initial Setting Time = 1hr. 57mins					
Average Final Setting Time = 2hrs. 40mins					

Source: Laboratory test (2024)

The average initial setting time and average final setting time as in Table 4.2 are within specifications of greater than 45minutes and less than 10 hours respectively. These results satisfied BS EN 196-3 (2016) and in line with Ejeh (2017). The cement is fit for the production of concrete and other masonry works. Setting time tests were conducted on unblended Portland Limestone Cement (PLC)

paste to establish baseline raw material compliance in accordance with BS EN 196-3 (2016). The binder exhibited an initial setting time of 1 hr 57 mins and a final setting time of 2 hrs 40 mins, satisfying standard requirements (>45 mins and <10 hrs). While RHA blending generally retards hydration slightly due to water absorption, baseline cement tests were prioritized to verify binder quality prior to batching.

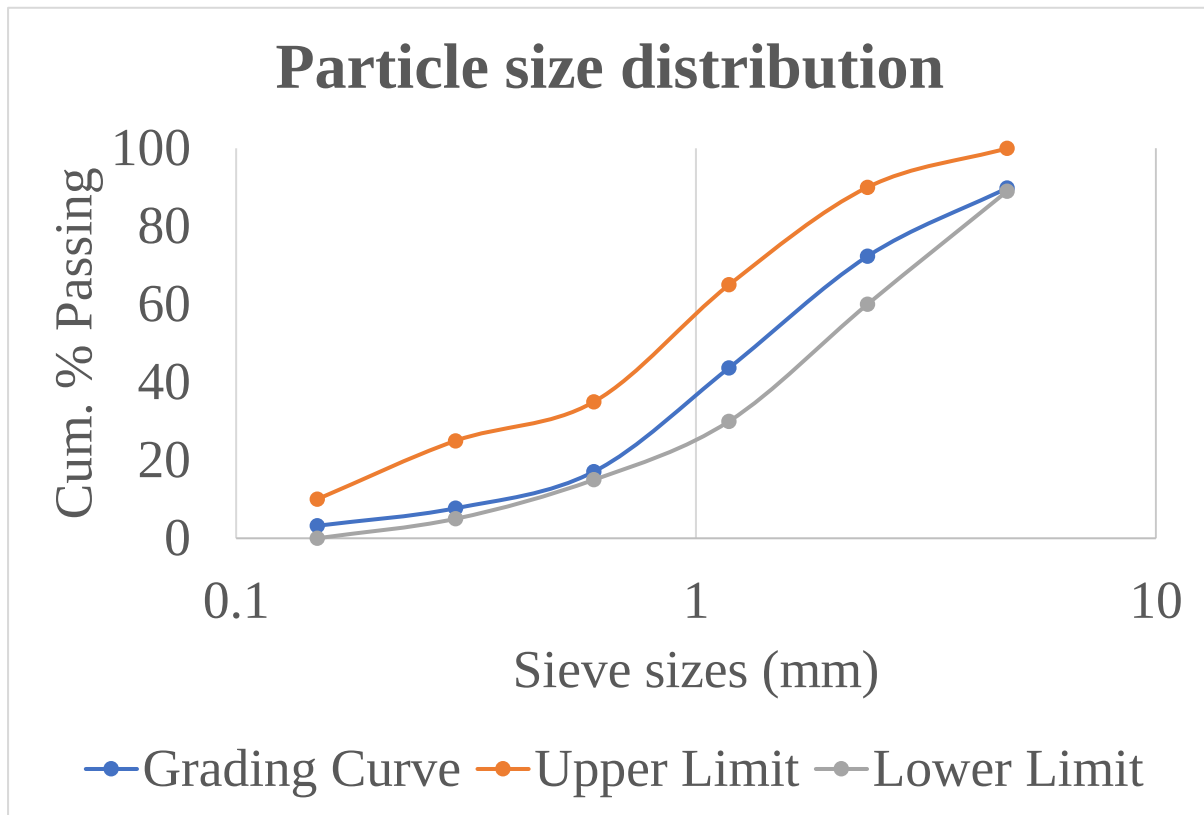


Figure 4.1: Particle Size Distribution Curves for Zone 3 (Fine Aggregate)

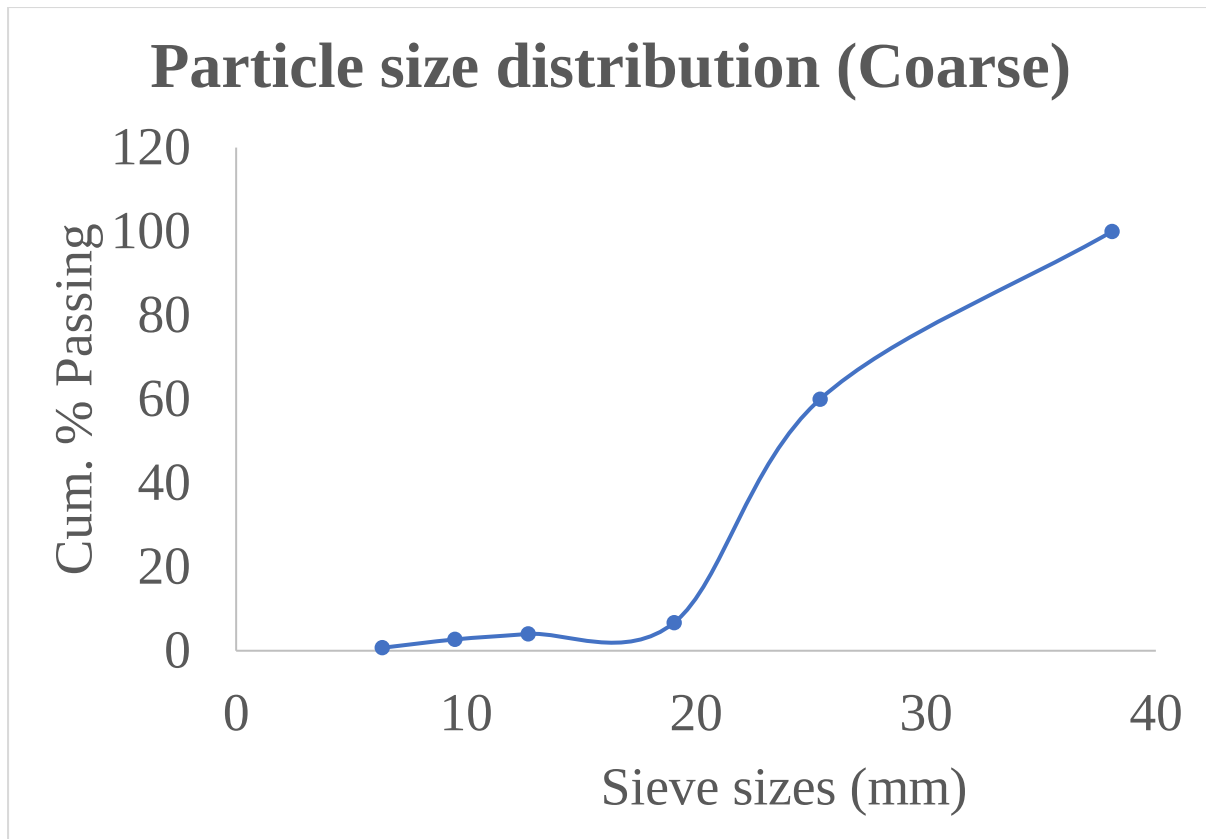


Figure 4: 2 Particle Size Distribution Curve for Coarse Aggregate

The result in Figure 4.1 conformed to BS EN 933-1 (2012) with a fineness modulus of 3.662. From the result of the sieve analysis, the sample is of zone 3 having a coarse grain size. From Figure 4.1 it can be seen that the sample falls within the standard upper and lower limits therefore good for the production of concrete.

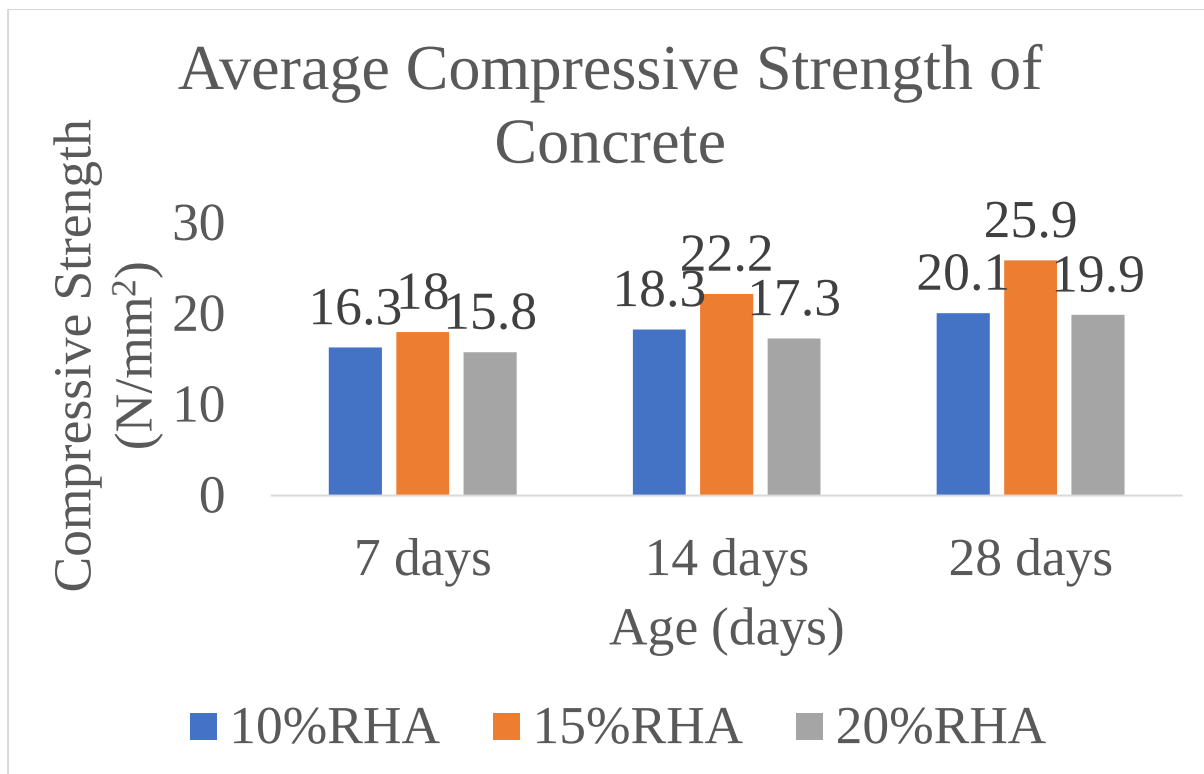
The result in Figure 4.2 with Fineness modulus of 4.259 indicates a coarser aggregate. This is also supported by BS EN 933-1 (2012).

Table 4.3: Result of Chemical composition of Rice Husk Ash

CHEMICAL COMPOSITION	RICE HUSK ASH (%)
SiO₂	87
Fe₂O₃	1.29
Al₂O₃	1.18
C	17.24
CaO	1
K₂O	1.32
SiO₂ + FeO₃ + Al₂O₃ = 89.47 %	
Carbon / Loss on Ignition	(LOI)17.24%
Calcium Oxide (CaO)	1.00%
Potassium Oxide	(K₂O)1.32%

Source: Laboratory test (2024)

Table 4.3 presents the sum of pozzolanic oxides (89.47%) exceeds the 70% minimum threshold specified by ASTM C618 for Class F/N pozzolans, confirming high pozzolanic reactivity. The LOI value reflects residual unburnt carbon from controlled incineration.



Source: Laboratory test (2024)

Figure 4.3: Average Compressive Strength of concrete with partial replacement of PLC with RHA

Figure 4.3 showed 15% RHA replacement produced higher compressive strength for both 7 days and 14 days curing ages. It is observed that the 28 days compressive strength of concrete with 15% replacement of RHA produced a strength of 28.85% and 30.15% higher than 10% and 20% RHA replacement respectively. The strength increase can be attributed to the interaction of microstructural mechanisms during which the pores in the mix are filled by the presence of RHA (Pornkasem et al., 2018).

The increase in strength is also supported by Jangral et al., (2022). In their work they found increase in strength as RHA percentage increases but declined beyond 15%. It is also in line with Bapat et al. (2004) who inferred that strength increases with age as evidenced in figure 4:3 even with the addition of a supplementary cementing material. The rice husk ash also served as filler of the pores in the concrete which made the concrete more compact, dense and durable. 100% RCA introduces a double Interfacial Transition Zone (ITZ)—between the original aggregate and old mortar, and between old mortar and new cement paste. This dual ITZ increases overall porosity and reduces compressive strength. However, the inclusion of 15% RHA counteracts this deficit. The micro-silica in RHA reacts with free calcium hydroxide $[Ca(OH)_2]$ released during cement hydration, forming additional secondary Calcium Silicate Hydrate (C-S-H) gel that densifies the ITZ and fills micro-voids.

The drop in 28-day compressive strength at 20% RHA (19.9 N/mm^2) is attributed to the **cement dilution effect**. Excessive cement substitution reduces the primary $Ca(OH)_2$ concentration required to sustain the pozzolanic reaction, leaving unreacted RHA particles that act as structural weak points rather than binding matrices.

Table 4.4: Fresh Workability (Slump) Test Results

Mix Identification	RHA Content (%)	Coarse Aggregate Type	Water/Cement Ratio (w/c)	Measured Slump (mm)	Slump Type
Control (0% RHA)	0%	Natural Aggregate	0.57	65	True Slump
RCA-0% RHA	0%	100% RCA	0.57	48	True Slump
RCA-10% RHA	10%	100% RCA	0.57	38	True Slump
RCA-15% RHA	15%	100% RCA	0.57	30	True Slump
RCA-20% RHA	20%	100% RCA	0.57	22	Shear/Low Slump

Workability decreased progressively with increasing RHA replacement levels and complete substitution of natural aggregate with RCA. RCA exhibits higher initial water absorption due to adhered porous mortar. Concurrently, the high specific surface area and cellular porous structure of RHA particles increase water demand, leading to reduced slump values.

Table 4.5: Baseline Mechanical and Physical Properties of Control vs. Experimental Mixes (28 Days)

Concrete Mix Parameter	Control (0% RHA + Natural Coarse Agg.)	RCA Baseline (0% RHA + 100% RCA)	RCA + 10% RHA	RCA + 15% RHA (Optimum)	RCA + 20% RHA
28-Day Compressive Strength (N/mm²)	27.4	21.8	20.1	25.9	19.9
28-Day Tensile Strength (N/mm²)	2.8	2.1	2.0	2.5	1.8
Water Absorption (%)	0.85%	2.10%	1.65%	1.23%	1.80%

Table 4.6: Splitting Tensile Strength and Water Absorption across All Replacement Levels

Mix Designation	RHA Replacement (%)	Splitting Tensile Strength (N/mm ²) [28 Days]	Water Absorption (%) [28 Days]
Control Mix	0% (Natural Agg)	2.8 ± 0.12	0.85%
RCA Control	0% (100% RCA)	2.1 ± 0.10	2.10%
RCA-10% RHA	10%	2.0 ± 0.15	1.65%
RCA-15% RHA	15%	2.5 ± 0.11	1.23%
RCA-20% RHA	20%	1.8 ± 0.14	1.80%

4. CONCLUSION

From this research, the following conclusions are drawn

- The oxide composition of the RHA used is 89.47% which is above the minimum specified oxide content of 70%. Therefore, it is a good pozzolan.
- The result of the physical properties of the basic constituent materials used in this research indicated satisfaction and in line with standard codes of practice including the British Standard Institution.
- The design of Grade 25 concrete was carried out and the materials mix ratio was 1:1.98:3.52 with water/cement ratio of 0.57 (W/C=0.57)
- The 28 days compressive strength for 10%, 15% and 20% of RHA are 20.1 N/mm², 25.9 N/mm² and 19.9 N/mm² respectively. The 15% cement replacement gave the optimum compressive strength with a corresponding tensile strength of 2.5 N/mm². The Water Absorption capacity of the 15% cement replacement concrete was 1.23% which is within the specifications of BS 812: part 2 (1995).

- The optimum mechanical properties like compressive strength, water absorption capacity of the concrete was achieved at 15% cement replacement level.

RECOMMENDATION

From the research, it is found that the optimum mechanical properties like compressive strength, water absorption capacity of the concrete were achieved at 15% cement replacement level. Therefore, it is recommended that in the concrete mix cement should be replaced with Rice Husk Ash by 15%.

5. REFERENCES

- ASTM International.** (2019). *Standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete* (ASTM C618-19). ASTM International. <https://doi.org/10.1520/C0618-19>
- Bapat, J. D., Kulkarni, S. S., & Raut, S. P.** (2004). Performance of high-volume fly ash and agro-waste concrete. *Cement and Concrete Research*, 34(8), 1365–1371. <https://doi.org/10.1016/j.cemconres.2003.12.029>
- Barlow, J.** (2019). *Sustainable construction: Principles and practices* (2nd ed.). Routledge. <https://doi.org/10.4324/9781315148007>
- British Standards Institution.** (1995). *Testing aggregates: Method for determination of water absorption* (BS 812-2:1995). BSI Group.
- British Standards Institution.** (2016). *Methods of testing cement: Determination of setting time and soundness* (BS EN 196-3:2016). BSI Group.
- Jangral, S., Sharma, R., & Kumar, S.** (2022). Influence of rice husk ash on mechanical properties of concrete: A comprehensive review. *Materials Today: Proceedings*, 60(2), 1120–1126. <https://doi.org/10.1016/j.matpr.2021.12.304>
- Kou, S. C., Poon, C. S., & Wan, D.** (2011). Properties of concrete prepared with low-grade recycled aggregates. *Construction and Building Materials*, 25(6), 2815–2821. <https://doi.org/10.1016/j.conbuildmat.2010.12.062>
- Nawaz, M., Farooq, M., & Saeed, A.** (2020). Lifecycle assessment of sustainable construction practices and green building materials. *Environmental Impact Assessment Review*, 83, 106401. <https://doi.org/10.1016/j.eiar.2020.106401>
- Pornkasem, P., Sata, V., & Chindaprasirt, P.** (2018). Microstructural analysis and pore structure of rice husk ash concrete. *Construction and Building Materials*, 172, 415–424. <https://doi.org/10.1016/j.conbuildmat.2018.03.220>
- Prasittisopin, L., & Trejo, D.** (2014). Hydration and phase formation of blended cementitious systems containing rice husk ash with different amorphous contents. *Journal of Materials in Civil Engineering*, 26(11), 04014081. [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0000988](https://doi.org/10.1061/(ASCE)MT.1943-5533.0000988)
- Tam, V. W., Gao, X. F., & Tam, C. M.** (2012). Microstructural analysis of recycled aggregate concrete produced from two-stage mixing approach. *Cement and Concrete Research*, 35(6), 1195–1203. <https://doi.org/10.1016/j.cemconres.2004.10.025>
- Thomas, B. S., & Gupta, R. C.** (2016). Properties of high strength concrete containing rice husk ash. *Journal of Cleaner Production*, 112(1), 641–651. <https://doi.org/10.1016/j.jclepro.2015.08.114>