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Evaluation of the Compressive Strength of Concrete made using Recycled Concrete and Waste Ceramics as Aggregates

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Abstract
The rising demand for natural granite aggregates in concrete production, combined with environmental concerns, calls for sustainable alternatives. This study explores the potential use of waste ceramic tiles (WC) and recycled concrete aggregates (RCA) as substitutes for granite in concrete. Mechanical properties, specifically compressive strength, were evaluated and compared against granite-based concrete, serving as the control. RCA and WC, sourced from construction and demolition waste, were combined in ratios of 1:0, 3:1, 1:3, and 0:1 (WC). These aggregates were incorporated into concrete mixes with varying proportions of 1:1:2, 1:2:4, 1:3:6, and 1:4:8 (cement: fine aggregate: coarse aggregate), targeting nominal C30 concrete. A total of 384 concrete cubes (150 mm × 150 mm × 150 mm) were cast and cured for 7, 14, 21, and 28 days for compressive strength testing. Density and water absorption were also assessed to determine durability. Results reveal that both RCA and WC can effectively replace granite in non-structural or lower-strength applications. RCA exhibited superior compressive strength and lower water absorption than WC, attributed to its greater structural integrity. These findings highlight RCA's suitability for sustainable construction, offering a practical means of reducing dependence on natural aggregates and minimizing the environmental impact of concrete production by reusing construction waste.

Keywords: *Recycled concrete aggregate (RCA), waste ceramic tiles (WC), sustainable construction, concrete compressive strength, recycled aggregates, durability, environmental sustainability, construction waste recycling.*

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I. INTRODUCTION

Concrete plays a crucial role in modern construction due to its versatility and ability to provide structural integrity (Fapohunda & Oyedepo, 2014). Traditional concrete production involves a mixture of cement, water, fine aggregates (sand), and coarse aggregates, such as granite or gravel. However, the rising cost of raw materials, particularly in developing nations like Nigeria, has driven up construction costs, creating the need for affordable alternatives. In addition, rapid urbanization and high construction demand have led to a scarcity of natural aggregates, posing significant challenges to sustainable construction (Pacheco-Torgal et al., 2021).
Simultaneously, sustainable development goals in construction emphasize reducing environmental degradation through the adoption of eco-friendly materials. "Green concrete," which incorporates alternative or recycled materials, addresses both resource depletion and waste management challenges (Kang et al., 2019). Two promising materials derived from construction and demolition waste—recycled concrete aggregate (RCA) and waste ceramic tiles (WC)—offer solutions by repurposing waste and minimizing landfill use (Gholampour & Ozbakkaloglu, 2018).

The scarcity of natural aggregates and the rising cost of conventional materials have increased the financial and environmental burden of construction. There is an urgent need to explore sustainable, cost-effective alternatives that ensure comparable structural performance without compromising concrete's durability or strength.

This study investigated RCA and WC as potential replacements for granite aggregates in concrete. These recycled materials not only address the shortage of natural aggregates but also contribute to environmental sustainability by reducing construction waste.

Research indicates that RCA can be a viable alternative to natural aggregates, often achieving comparable mechanical properties when properly incorporated (Thomas et al., 2020). Similarly, ceramic waste has demonstrated potential in improving the durability and mechanical properties of concrete, though performance may vary based on the mix proportions and quality of recycled materials used (Gholampour et al., 2019). However, further studies are required to identify optimal design mixes using both RCA and WC to achieve desired structural and durability outcomes.

This research explored the feasibility of using RCA and WC as full replacements for granite aggregates, focusing on their effects on compressive strength, flexural strength, density, and water absorption. Concrete cubes with different RCA-WC mix ratios will be tested to determine the most effective design. By validating these recycled materials as viable alternatives, this study contributes to sustainable construction practices, reducing dependence on natural resources and promoting eco-friendly material reuse in construction projects. The findings will offer practical insights for developers, supporting cost-efficient construction while minimizing environmental impact.

II. Material and methods

Standard methods were followed, and any modifications are described to ensure reproducibility.

RCA and WC were sourced from local demolition and construction sites. They were cleaned to remove impurities, such as plaster and mortar, and crushed into coarse aggregates.

Granite aggregates were obtained from a quarry, while fine aggregates (sharp river sand), Portland limestone cement (CEM II), and clean tap water were procured locally.

All aggregates were sieved and graded to conform to standard specifications for coarse and fine aggregates (BS EN 12620:2013; ASTM C136:2014). These standards ensure consistency in particle size distribution for optimal mixing and compaction.

Sieve Analysis was conducted on the aggregates to determine particle size distribution.

Specific Gravity was measured using a pycnometer to assess the density of the aggregates.

Water Absorption Test was conducted to evaluate the porosity and absorption potential of aggregates.

These tests ensured the materials met the required properties for concrete production (ASTM C127-15, 2015).

Concrete mixes were prepared with varying proportions of RCA and WC as replacements for granite. Replacement ratios were 1:0, 3:1, 1:3, and 0:1 (WC to RCA). Four different mix designs were employed:

Mix Ratios: 1:1:2, 1:2:4, 1:3:6, and 1:4:8 (cement: fine aggregate: coarse aggregate).

Target Strength: C30 nominal strength to evaluate structural performance under varying mix designs.

Each mix was tested for both mechanical properties (compressive strength) and durability (density and water absorption).

A total of 384 concrete cubes (150 mm × 150 mm × 150 mm) were cast for testing. Each cube was compacted to remove air voids, ensuring uniform density. Standard methods (BS EN 12390-2, 2019) were followed for casting and curing. Concrete was poured into molds and compacted using vibration to remove air pockets. Cubes were removed from the molds 24 hours after casting. The cubes were submerged in water baths at room temperature for 7, 14, 21, and 28 days to promote hydration. Compressive strength tests were performed using a compression testing machine in accordance with BS EN 12390-3 (2019). Cubes were tested at intervals of 7, 14, 21, and 28 days, with three specimens per mix tested at each interval. The results were averaged to identify trends in strength development over time.

Density and water absorption tests were carried out on selected samples using the procedures outlined in BS EN 12390-7 (2019). These tests provided insights into the compactness and porosity of the concrete. The mass of each cube was recorded, and the density was calculated by dividing the mass by the volume of the cube.

Samples were oven-dried, weighed, immersed in water, and re-weighed to calculate water absorption as a percentage of the dry weight.

The compressive strength, density, and water absorption data were statistically analyzed to identify trends. Mean values and standard deviations were calculated for each test batch. Graphs were generated to illustrate the relationship between aggregate replacement ratios and mechanical performance over time.

III. RESULTS AND DISCUSSION

3.1 Compressive strength test

Table 1 presents a summary of the compressive strength results, water absorption and density for each curing interval and mix design for granite concrete.

Table 2 presents a summary of the compressive strength results, water absorption and density for each curing interval and mix design for WC+RCA Concrete.

Table 1: Compressive Strength Results (MPa) For Granite Concrete

Mix Ratio	W/C Ratio	Compressive Strength (N/mm2)				Density (kg/m^3)
		7 Days	14 Days	21Days	28 Days	
1:1:2	0.50	19.83	27.56	28.72	30.49	2450
1:2:4	0.55	14.77	20.41	21.36	22.75	2400
1:3:6	0.65	12.82	17.46	18.26	19.56	2400
1:4:8	0.70	10.38	14.00	15.30	16.01	2400

Table 2: Compressive Strength Results (MPa) For WC+RCA concrete cubes

Mix Ratio	W/C Ratio	WC	RCA	Compressive Strength (N/mm2)				Density (kg/m^3)	Water Absorption
				7 Days	14 Days	21 Days	28 Days		
1:1:2	0.50	1	0	12.04	16.34	17.61	18.23	2350	6.5
		0.75	0.25	12.05	16.34	17.76	18.32		5.8
		0.25	0.75	13.23	18.40	19.17	20.03		5.3
		0	1	14.09	20.13	20.77	21.51		4.0
1:2:4	0.55	1	0	10.02	13.29	14.56	15.38	2300	7.9
		0.75	0.25	10.19	13.92	14.93	15.60		7.1
		0.25	0.75	10.83	14.75	15.78	16.33		6.5
		0	1	11.82	16.21	17.14	17.99		5.5
1:3:6	0.65	1	0	8.38	11.72	12.06	12.71	2250	8.4
		0.75	0.25	8.61	11.86	12.58	13.10		8.0
		0.25	0.75	9.13	12.39	13.18	13.91		7.6
		0	1	9.81	13.34	14.31	15.11		6.9
1:4:8	0.70	1	0	6.85	9.01	9.82	10.32	2200	9.2
		0.75	0.25	6.98	9.61	10.50	11.08		8.8
		0.25	0.75	7.11	10.05	10.80	11.15		8.0
		0	1	7.54	10.32	11.08	11.53		7.4

3.2 Specific gravity tests

The specific gravity test evaluated the particle size range and suitability of the aggregates for concrete production. Results show that the specific gravity of the fine aggregate was 2.656, well within the British Standard (BS 812:107, 1995) range of 2.6–2.7, confirming its appropriateness. For coarse aggregates, values were:

Granite: 2.717; RCA: 2.776; WC: 1.912

While granite and RCA align with the acceptable range of 2.5–3.0, WC fell below the threshold, likely due to its non-granite composition (Figure 1.0). However, the inclusion of WC aligns with sustainable construction goals by reducing reliance on virgin aggregates and waste disposal, fig 1.0 shows the trend of the different specific gravity of each aggregate.

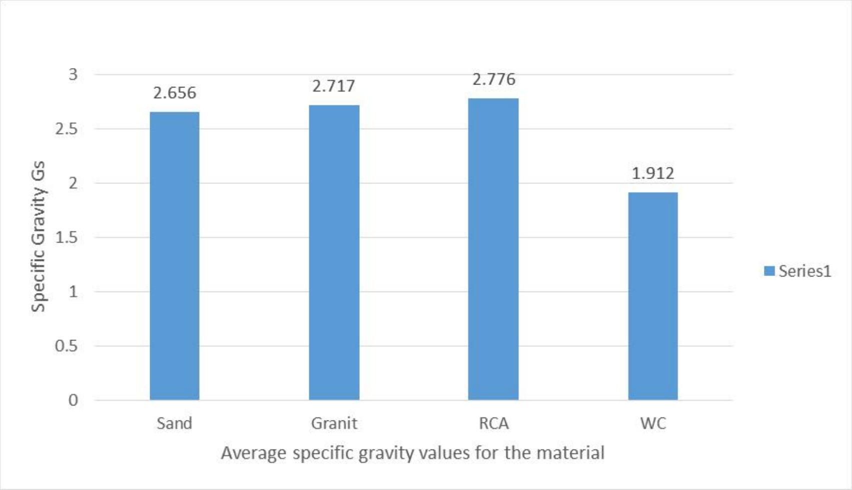

Fig.1.0: Average Specific Gravity Values of the Aggregates

3.3 Water absorption test

The Water absorption test determined the porosity and void content of the aggregates. Results are as follows (Figure 2):
Granite: 1.45%; WC: 2.47%;; RCA: 2.22%; Sand: 2.65%
All materials complied with BS EN 12620:2002 standards, with absorption rates below the 5% limit for coarse aggregates and 3% limit for fine aggregates. WC and RCA exhibited slightly higher absorption, indicating increased porosity. To maintain workability with these materials, mix designs must be adjusted to account for their water retention properties.

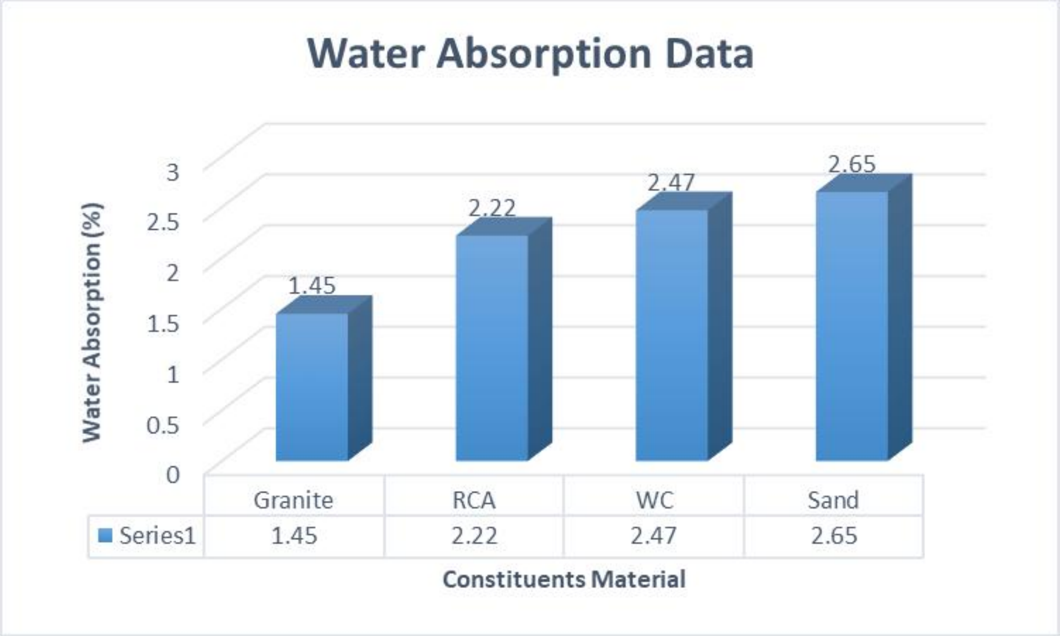

Fig. 2: Water Absorption of Aggregates' chart

3.4 Particle size distribution analysis

According to Fig.3 and Table 3, the sand exhibited a well-graded distribution with:
Coefficient of Uniformity (Cu): 2.653
Coefficient of Curvature (Cc): 1.067
These values fell within the acceptable range of 1–3 as specified by ASTM (2017), indicating stability and minimal erosion risks. Well-graded aggregates ensure better interlocking and reduced settlement, contributing to the concrete's strength and durability.

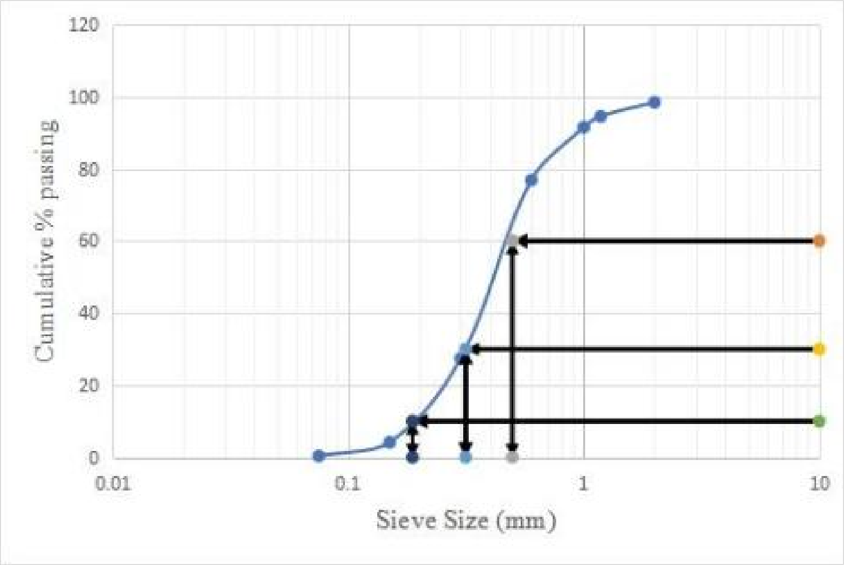

Fig. 3: Particle Size Distribution Curve for sand with representation of D10, D30, D60

Table 3: Deductions and Interpretations from the Sieve Analysis curve

% gravel	0.00	D60 (mm)	0.49747		$Cu = \frac{D60}{D10}$	2.65296
% sand	99.64	D30 (mm)	0.31547		$Cc = \frac{D30^2}{D60XD10}$	1.06686
% fine	0.36	D10 (mm)	0.18752			

The Aggregates Crushing Value measures the resistance of aggregates to crushing. Results (Figure 4): Granite: 25.42%; WC: 34.50%; RCA: 28.97%

According to BS 812-110:1990, acceptable ACV limits are ≤30% for heavy-duty concrete and ≤40% for low-load applications. Granite and WC met the required standard for light-duty concrete, while RCA's 28.97% value indicates marginal suitability, suggesting further modifications might be needed for structural applications.

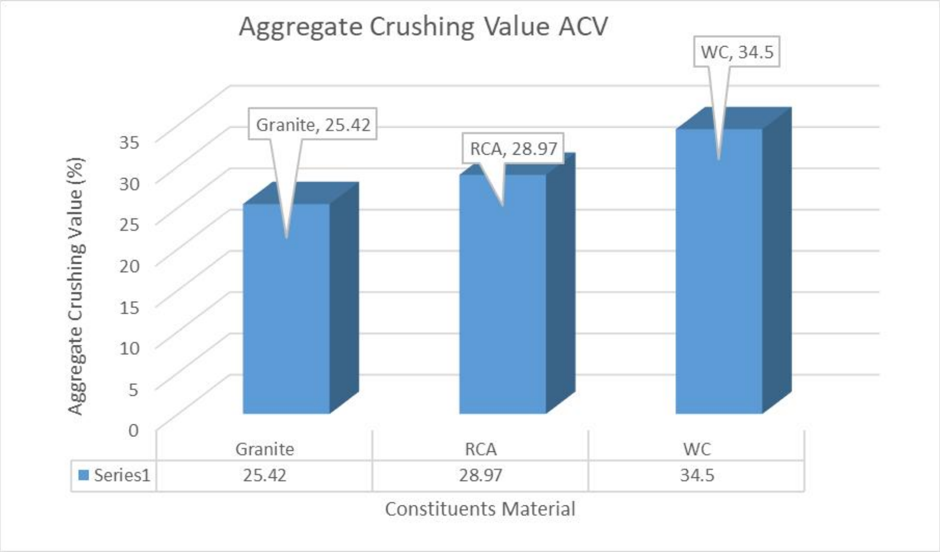

Fig. 4: Aggregate Crushing Value for Coarse Aggregates

3.5 The Slump Test

Results indicate that RCA-enhanced mixes showed increased fluidity, whereas WC inclusion led to reduced slump due to its higher water absorption. All mixes demonstrated a true slump between 30–170 mm, meeting standards for adequate workability (BS EN 12350-2).

Mix Ratio 1:1:2 (w/c = 0.50): Increased RCA content improved fluidity; WC reduced slump.

Mix Ratios 1:2:4, 1:3:6, 1:4:8 (w/c = 0.60–0.85): Slump values decreased with increasing WC due to its high absorption. Adjustments, such as using plasticizers or modifying the water-cement ratio, are recommended for achieving optimal consistency when using WC aggregates.

3.6 The Compressive Test

In the 1:1:2 mix, granite concrete achieved a compressive strength of 30.49 N/mm^2, within the target range for high-strength applications (30–40 N/mm^2). In comparison, RCA concrete reached only 21.51 N/mm^2, indicating its unsuitability for high-strength concrete in this mix. For the 1:2:4 mix, granite achieved 22.75 N/mm^2, while RCA obtained 17.99 N/mm^2, further underscoring RCA's lower performance relative to granite in mid-range strength applications. In the 1:3:6 mix, RCA's strength of 15.11 N/mm^2 fell within the target range for low-strength applications (10–15 N/mm^2), making it viable for this purpose, while granite exceeded the required range, suggesting potential overdesign. In the 1:4:8 mix, both granite and RCA achieved strengths beyond the target range for low-strength concrete (7–10 N/mm^2), indicating RCA's suitability for low-strength applications, with granite offering an excessive margin. These are presented in Figures 5a and 5b.

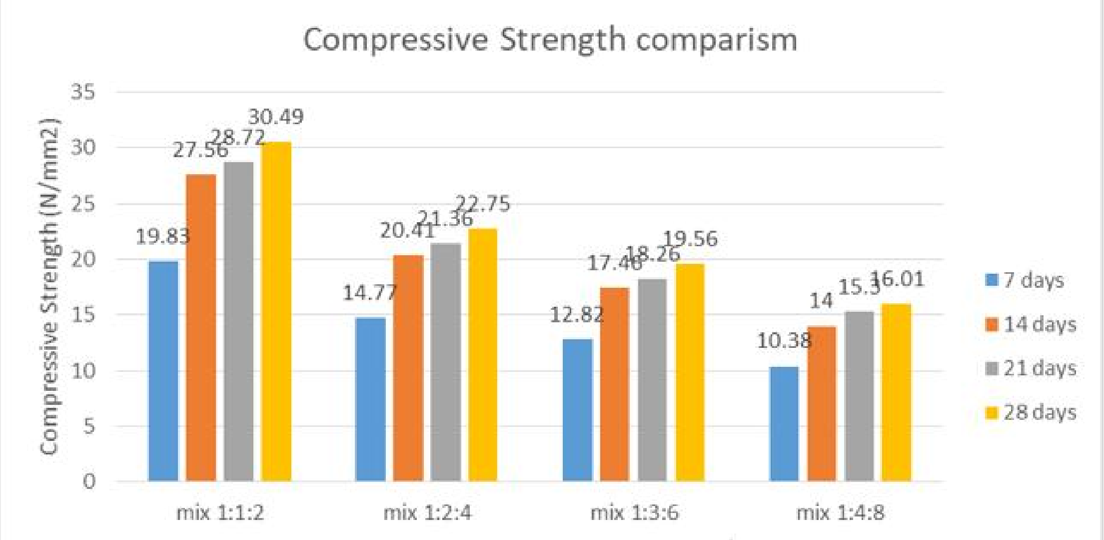

Fig 5a: Bar chart for compressive strength test for Granite Concrete Cubes (Control)

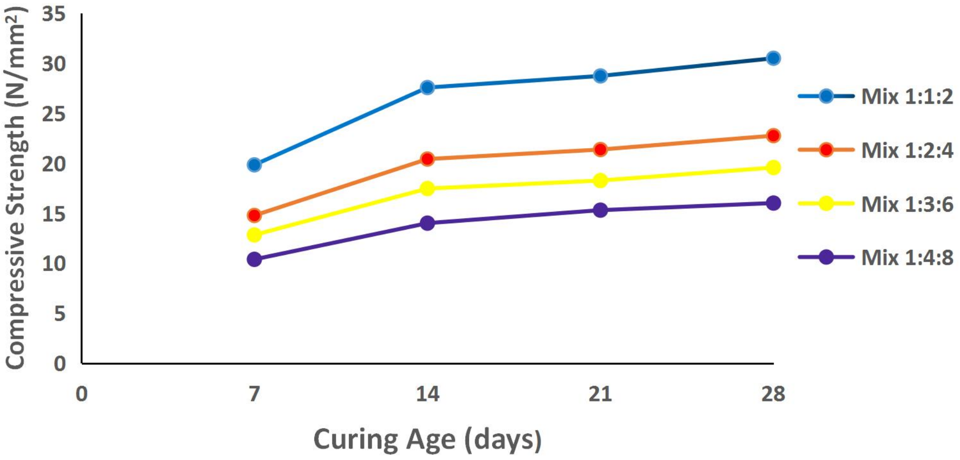

Fig.5b: a graph of compressive strength against curing days for granite concrete.

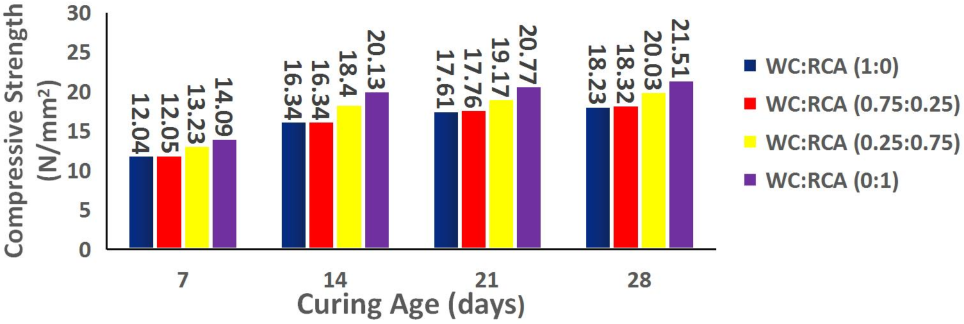

Fig.6: Compressive Strength against Curing days for WC + RCA (1:1:2)

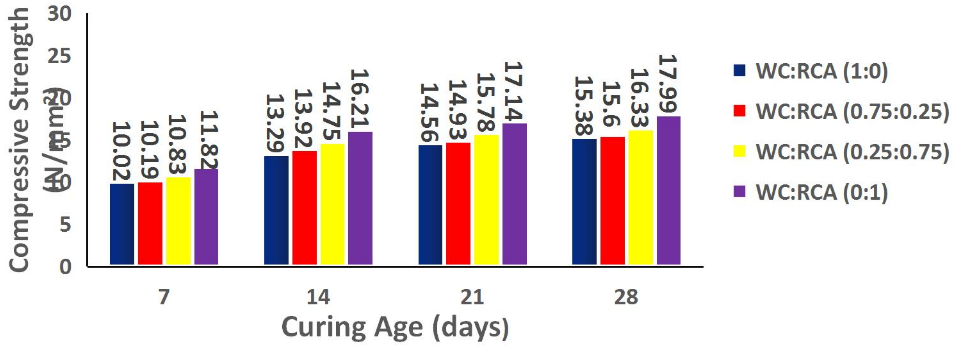

Fig.7: Compressive Strength against Curing days for WC + RCA (1:2:4)

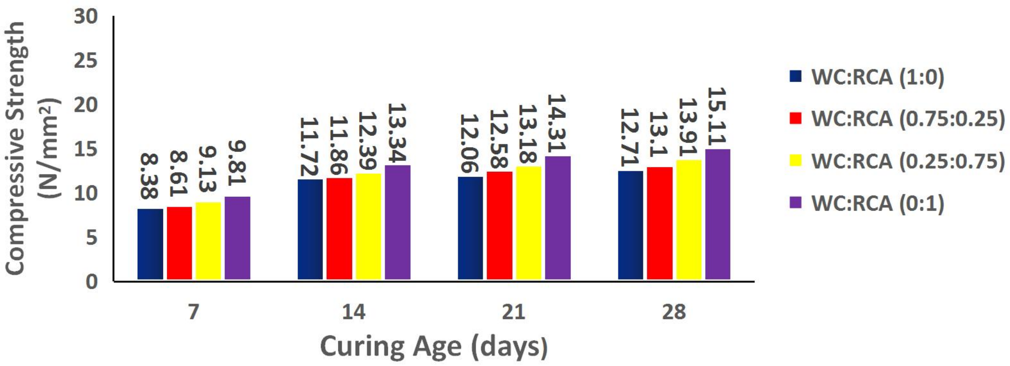

Fig.8: Compressive Strength against Curing days for WC + RCA (1:3:6)

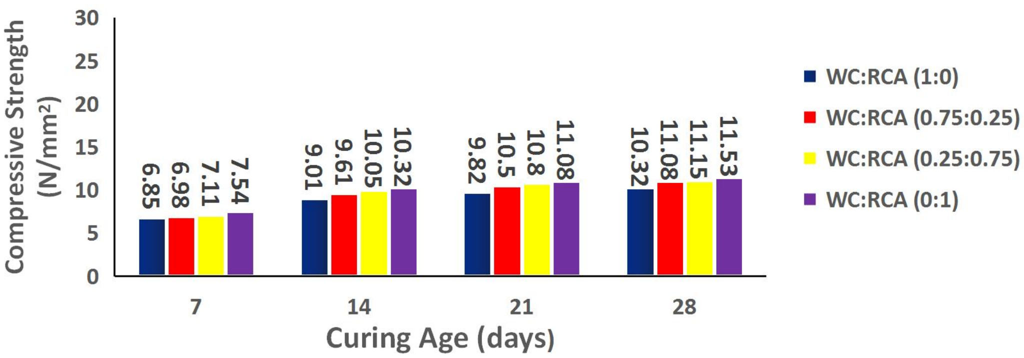

Fig.9: Compressive Strength against Curing days for WC + RCA (1:4:8)

The compressive strength of concrete mixes containing granite, RCA, and WC was measured over multiple curing periods. Results are summarized table 4 below:

Table 4: Summary of compressive strength of concrete mixes containing granite, RCA, and WC

Mix Ratio	Granite (N/mm²)	RCA (N/mm²)	Target Range (N/mm²)
1:1:2	30.49	21.51	30–40 (High-Strength)
1:2:4	22.75	17.99	15–25 (Medium-Strength)
1:3:6	15.11	13.15	10–15 (Low-Strength)
1:4:8	10.92	8.76	7–10 (Low-Strength)

Granite consistently achieved higher strengths across all mixes, particularly in high- and mid-range applications. RCA exhibited satisfactory performance in low-strength applications (1:3:6 and 1:4:8), supporting its use in non-structural elements, in line with sustainable construction practices.

3.7 Regression Statistical Analysis

Analysis of Variance (REGRESSION) was performed to determine the statistical significance of strength differences across the mixes. The results are presented below:
1:1:2 Mix: P-value = 0.00296
1:2:4 Mix: P-value = 0.026125
1:3:6 Mix: P-value = 0.017312
1:4:8 Mix: P-value = 0.017602
Furthermore, the F-crit value for all tests was 3.055568, confirming that the calculated F-values are sufficiently high to **reject the null hypothesis of equal means.**

Statistical analysis through REGRESSION ANOVA Single factor confirmed significant strength differences between the mixes, with P-values below 0.05, supporting RCA's role in lower-strength applications while highlighting granite's suitability for higher-strength concrete. These findings contribute to sustainable construction efforts by validating RCA's use in lower-strength concrete mixes, aligning with global trends in eco-friendly building practices.
Since all P-values are <0.05, significant differences exist between the compressive strengths of different mixes. The F-crit value of 3.055568 confirms the rejection of the null hypothesis, indicating the influence of aggregate type on concrete strength.
These results highlight the strengths and limitations of RCA and WC in comparison to granite. RCA performs well in low-strength applications, making it viable for eco-friendly construction. However, its reduced compressive strength in high-strength mixes suggests that it is best suited for non-structural elements or applications with reduced load-bearing requirements (Li et al., 2019). The higher water absorption of WC poses challenges for achieving adequate slump, necessitating additional water or admixtures (Shi & Zhang, 2021).
The study supports sustainable construction efforts by validating the use of RCA and WC for low-strength applications (1:4:8 and 1:3:6), reducing the environmental impact of virgin aggregate consumption. Future research may explore enhanced RCA treatments or modified mix designs to improve its suitability for structural applications (Gómez et al., 2018).

IV. Conclusion

Granite-based concrete consistently achieved the highest compressive strength, confirming its suitability for high-strength applications.
RCA demonstrated better mechanical performance than WC, making it a viable partial substitute in lower-strength mixes. Its structural properties resemble natural aggregates, explaining its superior performance relative to WC.
WC's high water absorption capacity negatively impacted strength, suggesting the need for mix design adjustments to maintain adequate performance.
ANOVA analysis confirmed statistically significant differences in compressive strength among the aggregate types, emphasizing that granite remains essential for applications requiring higher strength. RCA and WC, however, are viable for lower-strength applications, reducing dependency on natural aggregates.

4.2 Recommendation

Granite should be prioritized for high-strength structural elements where compressive strength is critical.

RCA can be implemented in non-structural or low-strength applications to promote sustainable construction. Further research on treatment methods for RCA may enhance its suitability for higher-strength concrete.

WC use requires water management strategies (e.g., plasticizers) to offset its high absorption. Studies on ceramic surface treatment or optimized mix designs are recommended to improve its performance.

The findings contribute to eco-friendly building practices by validating RCA and WC as partial substitutes for granite, aligning with global trends in sustainable construction (Li et al., 2019; Shi & Zhang, 2021).

Nomenclature

WC = Waste Ceramic
RCA = Recycled Concrete Aggregate
W/C = Water Cement Ratio
ACV = Aggregate Crushing Value
AIV = Aggregate Impact Value
BS = British Standard
PC= Portland Cement
OPC= Ordinary Portland Cement
Gs.= Specific Gravity
Cu = Coefficient of Uniformity
Cc = Coefficient of Curvature
ASTM = American Society of Testing and Materials
NIS = Nigeria Institute of Standardization
Mpa = Mega Pascal

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