Evaluating the Effectiveness of Using Coconut Shell as Coarse Aggregate for Self-compacting Lightweight Concrete

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Abstract
This study investigates the structural properties of concrete when coconut shell is used as a partial replacement for coarse aggregate. The objective is to evaluate the effect of this replacement on workability, compressive strength, and flexural strength of concrete. Mix designs were prepared by replacing conventional coarse aggregate with coconut shell at varying percentages of 0%, 10%, 20%, and 30% by weight. Standard concrete tests were conducted, including slump tests for workability, compressive strength tests at 7, 14, and 28 days, and flexural strength tests at 28 days. The results revealed that slump values decreased with an increase in coconut shell content, indicating reduced workability. Compressive and flexural strengths also decreased with higher percentages of coconut shell; however, concrete with a 10% replacement showed acceptable strength for light structural applications. The study concludes that coconut shells can be used effectively as a partial replacement for coarse aggregate in concrete for non-load-bearing and low-cost construction, contributing to sustainable waste management and reduction of construction costs.

Keywords: Self-compacting lightweight concrete, coconut shell, strength properties, environmental impact.

INTRODUCTION

The drive for environmentally sustainable construction has intensified interest in alternative cementitious materials and industrial by-products in concrete production. Calcium carbide residue (CCR), a waste from acetylene gas manufacturing, has attracted attention for its pozzolanic properties and potential as a partial cement replacement (Wang *et al*., 2024). Reusing CCR addresses disposal issues while reducing the carbon footprint of Portland cement production, a major contributor to global CO_2 emissions (Kaptan *et al*., 2024). Ordinary Portland cement (OPC), although essential to modern construction, is energy-intensive and environmentally taxing (Akintayo *et al*., 2023). Consequently, partial replacement of OPC with supplementary cementitious materials (SCMs) such as fly ash, silica fume, and CCR is being actively investigated to improve sustainability without compromising performance (Aryal and Ghimire, 2023).

CCR is rich in calcium hydroxide ($Ca(OH)_2$), enabling it to react with siliceous materials in concrete to produce additional calcium silicate hydrate (C–S–H), the primary strength-giving phase in cement paste. Studies have reported that moderate CCR use can enhance compressive strength, reduce permeability, and improve long-term performance (Wang *et al*., 2024; Ammar *et al*., 2024), although excessive replacement may weaken the matrix through dilution and incomplete hydration.

In parallel, attention has turned to agricultural by-products as sustainable aggregate alternatives. Coconut shell, a waste product from coconut processing, offers low density, high porosity, and acceptable mechanical strength, making it suitable as a lightweight aggregate (Safiuddin *et al*., 2023; Balaji *et al*., 2022).

Its use reduces environmental waste and construction costs (Mannan and Ganapathy, 2004). When incorporated into self-compacting concrete (SCC), coconut shell yields self-compacting lightweight concrete (SCLWC), which combines reduced structural weight with high flowability. However, its high-water absorption can compromise workability, necessitating admixtures such as superplasticisers and viscosity modifiers (Singh *et al*., 2023; Natarajan *et al*., 2024).

Fig. 1: Different stages of coconut shell extraction.

Mix design strategies, including combining coconut shell with fine materials like manufactured sand, have been shown to improve cohesiveness and stability (Pathak and Patel, 2023). Pre-soaking shells helps mitigate absorption issues, preserving hydration and workability (Ranjith *et al*., 2022; Usman *et al*., 2021). Although compressive strength typically declines with higher coconut shell content, acceptable values exceeding 20 MPa at 28 days can be achieved at up to 30% replacement (Ali *et al*., 2024). Strength performance can be further enhanced through fibre reinforcement, such as polypropylene or basalt, which improves tensile and flexural strength by bridging micro-cracks (Ramachandran and Sekar, 2021). Bonding between shell and cement paste is generally adequate, but pre-treatment and pozzolanic additives can strengthen the interfacial transition zone (Elangovan *et al*., 2024).

Durability concerns, such as increased porosity and water absorption, can be addressed with SCMs like fly ash and silica fume (Ogunyemi and Aliyu, 2023). Freeze–thaw performance improves with air-entraining agents and reduced water–binder ratios (Chinonso *et al*., 2022), while blended cements enhance resistance to chemical attack (Kabir *et al*., 2023). Environmentally, coconut shell use supports sustainable waste management, lowers the carbon footprint, and demonstrates favourable life cycle assessment outcomes (Mahmoud *et al*., 2024; Ibrahim *et al*., 2023; Nwachukwu *et al*., 2022).

Despite the well-documented benefits of CCR as a cement replacement and coconut shell as a lightweight aggregate, research on their combined use in SCLWC is scarce. Given the potential for CCR to enhance hydration and strength, and for coconut shell to deliver weight reduction and resource conservation, their integration could produce concrete with improved environmental and structural performance. This study investigates the effects of varying CCR replacement levels on the compressive strength of SCLWC made with coconut shell aggregates at different curing ages, alongside assessments of aggregate characteristics, workability, and durability, to establish an optimal mix design that meets both sustainability and structural requirements.

Unlike previous studies that have investigated CCR or coconut shell individually, this work explores their *synergistic integration* within self-compacting lightweight concrete. It evaluates how CCR's pozzolanic reactivity interacts with the unique physical characteristics of coconut shell aggregates to influence hydration, strength development, and durability over extended curing periods. By addressing both cement and aggregate substitution within a single sustainable mix design, this research provides new insight into optimising low-density, eco-friendly concrete for structural applications while maximising industrial and agricultural waste utilisation.

METHODOLOGY

Research Design

This study adopted an experimental research design. The design was chosen to enable the manipulation of variables, particularly the replacement levels of coarse aggregate with coconut shell, to examine their effects on the mechanical properties of concrete. Experimental research is appropriate for this study as it allows for the establishment of cause-and-effect relationships between the independent variable (coconut shell content) and the dependent variables (compressive strength, flexural strength, and density).

Materials

The materials used in this study include cement, sand, coconut shell aggregates, water, and a superplasticiser. The coconut shells were obtained from local coconut processing plants and processed to obtain appropriate aggregate sizes. They were sorted, washed, and sun-dried before being crushed by a mechanical crusher to a maximum size of 18 mm. Dangote Ordinary Portland Cement (OPC) was used for this study, and the properties of the cement conformed to BS EN 12390 (2000). The coarse aggregates used were normal-weight dry aggregates from an igneous rock source with a maximum size of 20 mm. The fine aggregates (sharp sand) were obtained from a stream at Ikole Local Government Area, Ekiti State, Nigeria, and tested in accordance with BS 882: (1992) specifications. The water used for the study was sourced from a tap and was free from impurities and suitable for drinking.

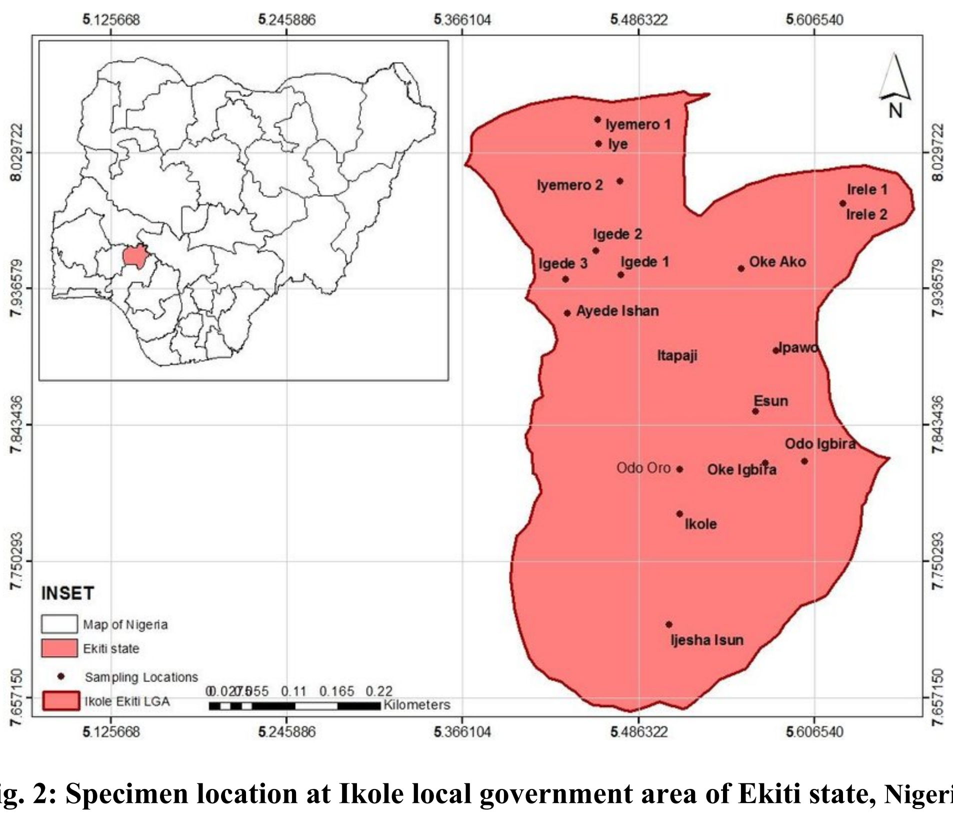

Fig. 2: Specimen location at Ikole local government area of Ekiti state, Nigeria

Mix Proportions: Mix proportions were prepared by replacing traditional coarse aggregates with coconut shell aggregates at varying percentages (0%, 20%, 40%, 60%, 80%, and 100%). A superplasticiser was used to maintain the required workability in self-compacting lightweight concrete mixes. A grade 20 concrete was designed using a mix proportion of 1:2:4 by weight of OPC, river sand, and coarse aggregate/coconut shell.

Sampling Techniques: The sampling technique employed was purposive sampling, specifically targeted to ensure that each replacement level (0-100%) was adequately represented. Concrete samples were prepared in replicates to ensure statistical reliability. A total of 54 cubes and 54 beams were cast, with three specimens for each mix ratio (0%, 20%, 40%, 60%, 80%, 100%) tested at 7, 14, and 28 days of curing.

Methods of Data Collection: The primary data collection involved laboratory testing of concrete specimens. The tests conducted include the slump test, compressive strength test, flexural strength test, and density test. All tests were conducted at the Structures Laboratory, Department of Civil Engineering, Federal University, Oye Ekiti.

Methods of Data Analysis: The data obtained from laboratory tests were subjected to descriptive and inferential statistical analysis. Descriptive statistics such as mean and standard deviation were used to summarise the test results. Inferential statistical tools, including Analysis of Variance (ANOVA), were used to assess the significance of the effects of coconut shell replacement on the mechanical properties of concrete. All statistical analyses were conducted using SPSS software version 25. Results were presented in tables and charts to facilitate interpretation.

Physical Properties of the Constituent Materials: The physical properties of Dangote cement, coconut shells, coarse aggregate, and fine aggregate were examined at the Structures Laboratory of the Department of Civil Engineering, Federal University, Oye Ekiti.

Slump Test: A slump test was conducted on the freshly prepared concrete to determine the effect of replacing coconut shell aggregate on its workability. This test was carried out in accordance with BS EN 12350: Part 2 (1999).

Compressive Strength Test: Concrete cubes of size 150 mm × 150 mm × 150 mm were produced to determine compressive strength. The samples were tested using a motorised compression machine in accordance with BS EN 12390, Part 4 (2000).

The compressive strength (N/mm^2) was calculated using Equation 1:

$$Compressive\ Strength = \frac{\text{Failure Load (kN)}}{\text{Area of Specimen (mm}^2\text{)}} \dots\dots\dots Eq. 1$$

Flexural Strength Test: Flexural strength tests were carried out on hardened concrete beams of 100 mm × 100 mm × 500 mm. The flexural strength was determined for each curing period according to BS EN 12390 Part 5: (2000). It was expressed as the modulus of rupture (MOR) (N/mm^2) using Equation 2:

$$MOR = \frac{PL}{bd^2} \dots\dots\dots\dots\dots\dots Eq. 2$$

where: P = Maximum load (kN), L = Span of the beam (mm), d = Depth of the beam (mm) and b = Breadth of the beam (mm)

Density Test: The density (kg/mm^3) of the hardened concrete samples was determined in accordance with BS EN 12390 Part 7: (2000). It was computed using Equation 3:

$$Density = \frac{m}{V} \dots\dots\dots\dots Eq. 3$$

where: m = Mass (kg) and v = Volume (mm^3)

RESULTS AND DISCUSSION

Overview

This chapter presents and discusses the results obtained from the experimental investigation on self-compacting lightweight concrete (SCLC) incorporating coconut shell (CS) as a partial replacement for coarse aggregate. The results are discussed under fresh and hardened concrete properties, including workability (slump), compressive strength, and flexural strength. Additionally, the physical characteristics of coconut shell were analysed to justify its suitability as a lightweight aggregate.

Physical Properties of Materials

The physical properties of the materials used, particularly coconut shell, cement, fine aggregate, and coarse aggregate, are summarised in Table 1. The specific gravity of the coconut shell (1.51) is significantly lower than that of conventional coarse aggregate (2.70), confirming its potential for producing lightweight concrete. Similarly, the bulk density of CS (648 kg/m^3) is much lower than that of coarse aggregate (1437 kg/m^3), further validating its lightweight nature.

The aggregate crushing value (ACV) of CS was 3.34%, which is considerably less than that of the coarse aggregate (22.33%). This lower ACV indicates better resistance to crushing under a gradually applied compressive load, which is advantageous for concrete durability.

Table 1: Physical Properties of Cement, Coconut Shell (CS), Fine and Coarse Aggregates

Property	Cement	Coconut Shell (CS)	Fine Aggregate	Coarse Aggregate
Specific Gravity	3.15	1.51	2.62	2.70
Bulk Density (kg/m³)	-	648	1588	1437
Loss on Ignition (%)	1.0	-	-	-
Blaines Fineness (m²/kg)	370	-	-	-
Aggregate Crushing Value (%)	-	3.34	-	22.33

Workability of Fresh Concrete

The slump test was conducted to evaluate the workability of the fresh concrete mixtures. The results presented in Table 2 show a decreasing trend in slump values as the percentage of CS increased. This behaviour is attributed to the higher water absorption capacity and irregular surface texture of CS, which reduces the effective water content available for lubrication.

Table 2: Slump Test Results for Coconut Shell Concrete

Mix ID	Coconut Shell (%)	Slump (mm)
CS-00	0	26
CS-10	10	21
CS-20	20	17
CS-40	40	14
CS-60	60	12
CS-80	80	10
CS-100	100	6

At 10% and 20% replacement levels, the reduction in slump was manageable; however, further increases led to pronounced reductions in workability. At 100% replacement, the slump dropped to 6 mm, falling below the range specified for Class S1 slump (10–40 mm) according to BS EN 206-1 (2000), thus rendering it unsuitable for most construction applications without admixtures or modifications.

Compressive Strength of Concrete

The compressive strength results of coconut shell (CS) concrete presented in Fig. 4 reveal a progressive decline in strength with increasing replacement of conventional coarse aggregate by coconut shell. The control mix (CS-00), with no CS substitution, achieved the highest compressive strength across all curing periods, ranging from 15.24 MPa at 7 days to 23.95 MPa at 90 days. This increase over time is consistent with the hydration and microstructural densification of cementitious materials, a behaviour that is well documented in concrete technology (Neville, 2011).

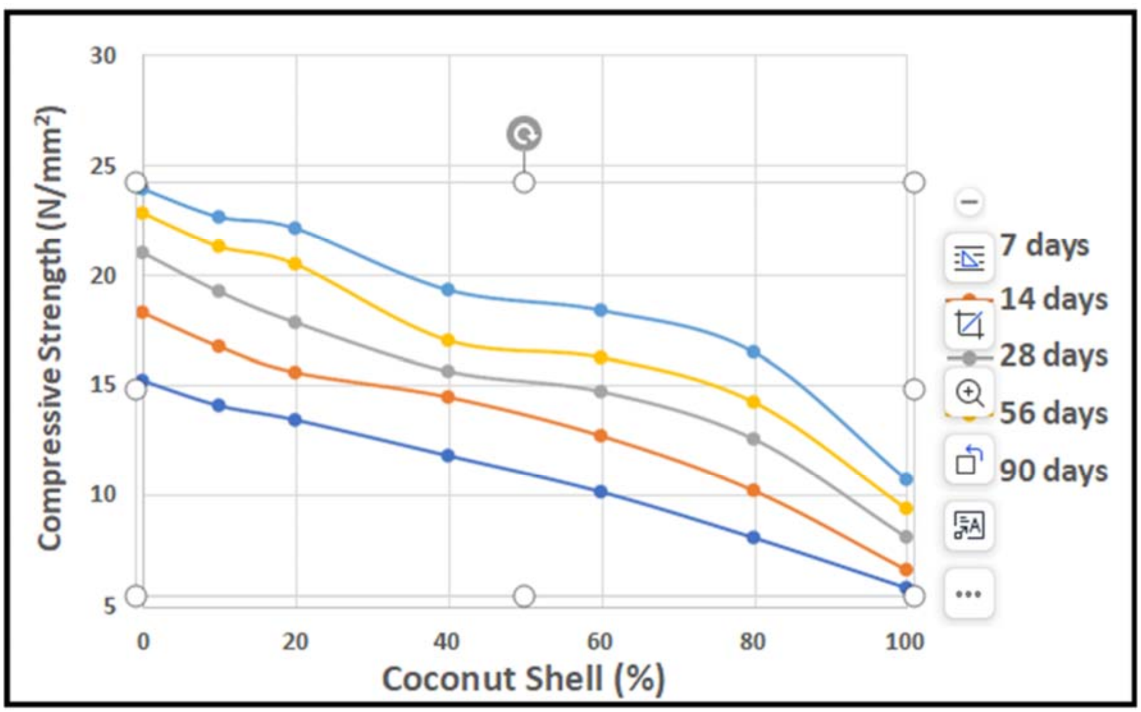

Figure 4: Variation of Compressive Strength with Coconut Shell Content

At lower levels of replacement, specifically 10% (CS-10) and 20% (CS-20), compressive strengths remained relatively close to the control values. For instance, at 90 days, CS-10 reached 22.67 MPa, while CS-20 recorded 22.15 MPa, representing reductions of only 5.3% and 7.5%, respectively, compared to the control. This suggests that limited substitution of natural aggregates with coconut shell does not severely compromise the compressive performance of concrete, corroborating earlier findings that sustainable agricultural waste materials can be used up to certain thresholds without detrimental effects (Gunasekaran, Annadurai, & Kumar, 2011).

However, at higher replacement levels, the strength reduction became pronounced. CS-40 attained only 19.35 MPa at 90 days, reflecting a 19% reduction relative to the control, while CS-60, CS-80, and CS-100 recorded further decreases to 18.42, 16.53, and 10.75 MPa, respectively. The reduction in compressive strength with increasing CS content can be attributed to the lower density, higher water absorption capacity, and weaker bond strength of coconut shell compared with conventional aggregates (Olanipekun, Olusola, & Ata, 2006). These properties contribute to increased porosity, reduced matrix integrity, and ultimately lower load-bearing capacity.

It is nevertheless noteworthy that all mixes demonstrated strength gain with curing age, including the 100% replacement (CS-100), which improved from 5.81 MPa at 7 days to 10.75 MPa at 90 days. This continuous increase highlights the role of cement hydration in strength development, irrespective of aggregate type (Shetty, 2013). However, the magnitude of the gain was much smaller compared to the control, reflecting the limited structural contribution of coconut shell when used as the sole coarse aggregate.

These results suggest that coconut shell can effectively replace natural coarse aggregate up to 20% without substantial compromise in compressive strength, making it suitable for applications where moderate strength is acceptable. Beyond this threshold, the decline becomes significant, limiting the use of high CS-content mixes to non-structural or lightweight applications such as partition blocks, paving units, and filler materials. These findings are consistent with sustainable construction goals, where agricultural waste materials are increasingly promoted as partial substitutes in concrete to reduce environmental impact and promote circular economy practices (Mannan & Ganapathy, 2004).

Flexural Strength of Concrete

The flexural strength results presented in Fig. 5 indicate a clear trend in the performance of coconut shell (CS) concrete across different replacement levels and curing ages. At 0% CS replacement (CS-00), the control mix recorded the highest strengths, achieving 3.29 MPa at 7 days and increasing steadily to 6.07 MPa at 90 days. This behaviour aligns with the expected hydration process of cementitious materials, where strength gain continues over time due to ongoing hydration and pozzolanic activity (Neville, 2011).

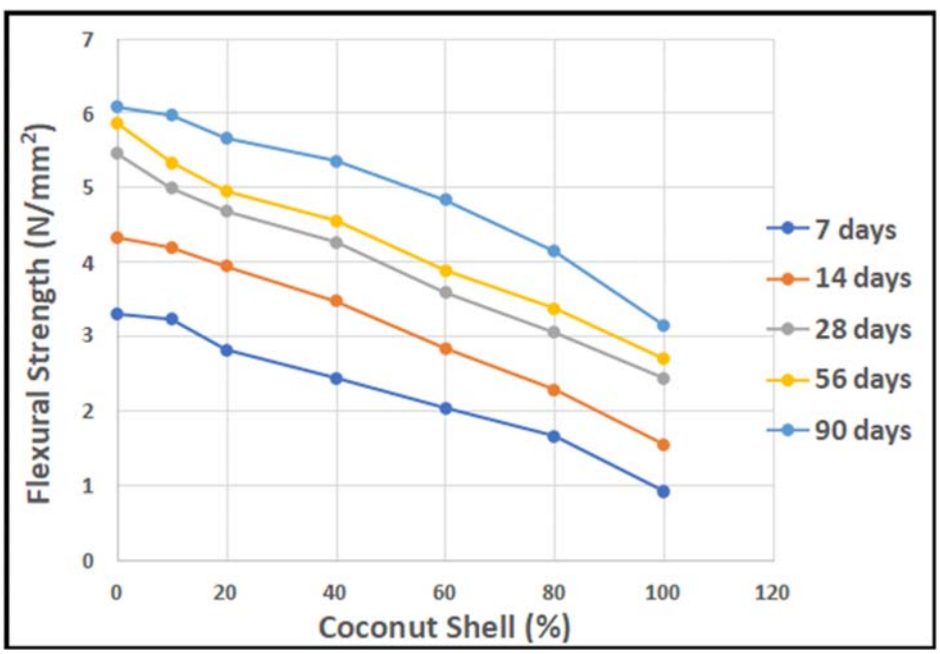

Figure 5: Variation of Flexural Strength with Coconut Shell Content

When the coconut shell was introduced as a partial replacement, a gradual reduction in flexural strength was observed. At 10% CS replacement (CS-10), the strength remained relatively close to the control values, reaching 5.96 MPa at 90 days compared to 6.07 MPa for the control, suggesting that low-level incorporation of coconut shell has a marginal effect on strength. This finding corroborates earlier studies, which reported that moderate substitution of conventional aggregates with lightweight agricultural wastes can yield comparable strengths while enhancing sustainability (Gunasekaran, Annadurai, & Kumar, 2011).

As the replacement level increased beyond 20%, however, there was a pronounced decline in strength. For instance, CS-40 attained only 5.35 MPa at 90 days, while CS-60 and CS-100 recorded significantly lower values of 4.82 MPa and 3.14 MPa, respectively. The reduction in flexural strength at higher replacement levels can be attributed to the lower density, higher porosity, and weaker bonding characteristics of coconut shell compared with conventional aggregates (Olanipekun, Olusola, & Ata, 2006). This weakening effect becomes more significant with increasing coconut shell content, reflecting a compromise in structural integrity.

Nevertheless, it is noteworthy that strength gain was evident across all mixes with age, even at high replacement levels. For example, CS-100 improved from 0.91 MPa at 7 days to 3.14 MPa at 90 days. Although the ultimate strength remained lower than that of the control, the continuous gain highlights the pozzolanic contribution and cementitious hydration processes that persist irrespective of the aggregate type (Shetty & Nayak, 2023).

These results suggest that coconut shell can be utilised as a partial replacement for coarse aggregate up to about 20% without substantial compromise in flexural strength. Beyond this threshold, the reduction becomes significant, potentially limiting the structural applications of such mixes. However, the observed trends also underscore the potential of coconut shell as a sustainable material for non-load-bearing and lightweight construction purposes, consistent with global efforts to incorporate agro-waste in green construction practices.

CONCLUSION

This study investigated the compressive strength performance of cement-calcium carbide residue (CCR) modified concrete using a range of CCR contents (0%, 5%, 10%, and 15%) and curing durations (7, 14, and 28 days). It also involved laboratory characterisation of fine and coarse aggregates through sieve analysis and specific gravity determination, a slump test for workability, and compressive strength tests on hardened concrete. The results indicate that incorporating CCR as a partial cement replacement affects both the fresh and hardened properties of concrete. Slump test results showed a gradual reduction in workability with increasing CCR content, likely due to the higher water demand and fineness of CCR particles. Compressive strength results revealed that concrete samples with 5% CCR replacement achieved comparable strength to the control at all curing ages, especially at 28 days, where 5% CCR-modified concrete reached peak strength. However, higher replacement levels (10% and 15%) led to significant strength reductions, suggesting that excessive CCR substitution negatively affects the cement hydration process and bonding. Aggregate tests confirmed that both fine and coarse aggregates used fall within acceptable grading limits and possess suitable specific gravities, affirming their adequacy for structural concrete applications. These foundational materials supported the reliable interpretation of the concrete's performance. The study concludes that CCR can be effectively used as a partial cement substitute up to 5% without compromising concrete strength or workability. This demonstrates a sustainable approach to managing calcium carbide waste while reducing the environmental footprint of cement production.

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