Performance Evaluation of Coconut Shell as Partial Aggregate Replacement in Concrete: Compressive Strength, Sorptivity, and Sustainability Perspectives

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Performance Evaluation of Coconut Shell as Partial Aggregate Replacement in Concrete: Compressive Strength, Sorptivity, and Sustainability Perspectives

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Abstract: *The growing demand for construction materials, coupled with resource scarcity and environmental challenges, has driven interest in sustainable alternatives for conventional concrete aggregates. This study investigates the feasibility of using crushed coconut shells as a partial replacement for natural coarse aggregates. Concrete specimens incorporating 0%, 10%, 20%, and 30% coconut shell by volume were evaluated for compressive strength and sorptivity, in accordance with ASTM standards. Results indicate that a 10% replacement level yielded the highest compressive strength among the modified mixtures (19.58 MPa at 14 days), with diminishing strength at higher substitution levels. Interestingly, sorptivity tests revealed that increasing coconut shell content enhances resistance to water absorption, with 20% and 30% replacements exhibiting lower sorptivity than the control. These findings suggest that coconut shell aggregates, while less ideal for structural strength beyond 10% replacement, offer advantages for moisture-resistant applications and sustainable construction in low-cost settings.*

Keywords: Coconut shell aggregate; concrete; compressive strength; sorptivity; sustainable materials

1. INTRODUCTION

Concrete is the cornerstone of modern construction, used extensively in buildings, roads, and infrastructure due to its strength, availability, and adaptability. However, the environmental cost of sourcing its key ingredients, particularly natural coarse aggregates like gravel and crushed stone, is increasingly concerning[1]. In fast-developing countries such as the Philippines, the demand for construction materials is surging alongside economic growth. These puts added pressure on non-renewable resources, drive up material costs, and contributes to environmental degradation through unsustainable mining and quarrying practices [2].

At the same time, the Philippines generates significant agricultural waste, particularly from coconut production. As one of the world's largest coconut producers, the country sees thousands of tons of coconut shells discarded annually, with little to no commercial use. These shells are often burned or dumped in landfills, posing both environmental and logistical challenges [3]. However, their abundance, relatively low weight, and natural durability suggest a potential alternative use: as partial replacement for coarse aggregates in concrete [1].

Repurposing coconut shells in concrete not only address waste management issues but also supports the move toward greener and more sustainable construction practices. Several studies have investigated the feasibility of using coconut shell as an aggregate material [4].While results generally show promise, particularly in reducing the overall weight of concrete and improving water resistance, there are still concerns about strength performance, especially at higher replacement levels. Furthermore, more empirical evidence is needed to determine how coconut shell concrete behaves in terms of water absorption or sorptivity, an important indicator of long-term durability [5].

Despite the increasing emphasis on sustainable construction practices, the use of agricultural waste materials such as coconut shell as an alternative aggregate in concrete remains underexplored, especially in terms of performance trade-offs between strength and durability. Coconut shells are readily available in coconut-producing countries like the Philippines and repurposing them can help address both environmental waste and the depletion of natural aggregates [2]. However, the mechanical behavior and long-term durability of concrete containing coconut shell aggregates are not yet well established [6].

While some studies have indicated that limited amounts of coconut shell may be used without severely affecting strength, there is still insufficient evidence on how different replacement levels affect compressive strength and water absorption behavior, particularly under controlled testing conditions [7]. This study aims to evaluate concrete mixtures with 0%, 10%, 20%, and 30% coconut shell replacement to determine how these affects compressive strength and sorptivity. Specifically, it seeks to identify the most appropriate substitution level that offers a practical balance between structural performance and resistance to water ingress.

The research is significant as it promotes low-cost, sustainable building materials, particularly for rural communities and resource-constrained construction sectors. It also contributes to ongoing efforts to reduce construction's environmental footprint by integrating agricultural waste into structural materials[8]. The scope of the study is limited to laboratory-scale testing using a fixed concrete mix design, constant water-cement ratio, and a single type of cement and sand. Compressive strength was assessed at 14 and 28 days, while sorptivity was evaluated through short-term water absorption tests. Other factors such as chemical resistance, freeze-thaw behavior, and the use of admixtures or alternative curing methods were beyond the scope but are recommended for future research.

2. RELATED WORK

The pursuit of sustainable materials in concrete production has led to growing interest in using agricultural by-products like coconut shell as partial replacements for conventional aggregates. This section reviews key studies aligned with the four objectives of the present research: assessing compressive strength, evaluating water absorption behavior (sorptivity), determining the optimum coconut shell replacement level, and comparing results with global findings in the context of sustainable development.

2.1. Compressive Strength of Coconut Shell Aggregate Concrete

Several researchers have investigated the compressive strength of concrete incorporating coconut shell as a coarse aggregate substitute. In a widely cited study [9], it was reported that up to 15% replacement of natural aggregates with coconut shell did not significantly compromise compressive strength for non-structural applications. The study highlighted the rough texture and porous structure of coconut shells, which contributed to good bonding within the cement matrix, particularly when proper compaction and mix design were used.

A study [10] also examined the mechanical performance at different replacement levels. Their findings showed that a 10% replacement yielded compressive strength values comparable to the control, but strength declined sharply at 25% and beyond. This was attributed to the lower density and higher porosity of coconut shell compared to gravel, which affects load transfer mechanisms in hardened concrete.

Stel'makh et al. [11] performed structural and microstructural testing and confirmed that a limited replacement of aggregates with coconut shell can meet standard strength requirements for light-duty construction. However, performance heavily depends on proper grading and mixing techniques to minimize voids and achieve uniform distribution.

2.2. Sorptivity and Durability Performance

Beyond strength, the durability of coconut shell aggregate concrete, especially its resistance to moisture ingress, is crucial for long-term serviceability. Sorptivity, a measure of the rate of capillary water absorption, has been used as an indicator of concrete's durability under exposure to wet environments.

Sekar and Kandasamy [9] studied the effect of coconut shell combined with coconut fiber on sorptivity and reported a significant reduction in water uptake for mixes containing 10–15% coconut shell. The lower sorptivity values were linked to the shell's internal structure, which, despite being porous, reduces continuous capillary pathways in the concrete matrix.

Supporting this, it was found that coconut shell concrete had lower permeability and better resistance to chloride ingress compared to control samples, especially when proper curing was applied. This was a promising indicator for long-term durability in humid tropical environments [9].

2.3. Optimal Replacement Levels for Practical Use

Determining the optimal percentage of coconut shell replacement is key for balancing strength and durability. Most studies converge on 10% - 15% as the most effective range. Beyond this, the mechanical integrity tends to decline, while sorptivity may improve, but not enough to compensate for strength loss.

For example, [12] tested 0%, 10%, 20%, and 30% replacement levels and concluded that the 10% mix showed the best balance in terms of strength, workability, and water absorption. They noted that while 20% and 30% replacements reduced water ingress, the compressive strength dropped below acceptable thresholds for structural use.

This trade-off emphasizes the need to carefully define target applications. In cases where low weight and moisture resistance are more critical than structural strength, such as in non-load-bearing walls or rural low-cost housing, the higher replacement ratios may still be viable.

2.4. Comparative Studies and Relevance to Sustainability

Globally, the integration of coconut shell in concrete aligns with broader sustainability goals. The UN Sustainable Development Goals (SDGs), particularly SDG 11 (Sustainable Cities and Communities) and SDG 12 (Responsible Consumption and Production), support innovations that reduce environmental impact in the construction sector.

A review by [3] emphasized the dual environmental and economic benefits of coconut shell concrete, especially in regions with high coconut production and limited access to traditional aggregates. Their study noted the reduction of construction costs by up to 15% when coconut shell is used, without significantly affecting structural performance at lower substitution levels.

Moreover, [11] highlighted the life cycle benefits of using coconut shell as a renewable, low-carbon alternative. Their sustainability analysis found that using agricultural waste in concrete could reduce embodied energy and CO_2 emissions associated with natural aggregate mining.

3. MATERIALS AND METHODS

The experimental procedure followed a structured sequence, as illustrated in Figure 1. The process began with the selection of materials, including ordinary Portland cement, Ottawa sand, potable water, and coconut shells, which were pre-processed by drying, crushing, and sieving to a uniform particle size. After material preparation, four concrete mixes were designed with 0%, 10%, 20%, and 30% coconut shell (CS) replacement by volume of coarse aggregate, using a constant water-to-cement ratio to ensure uniformity across treatments.

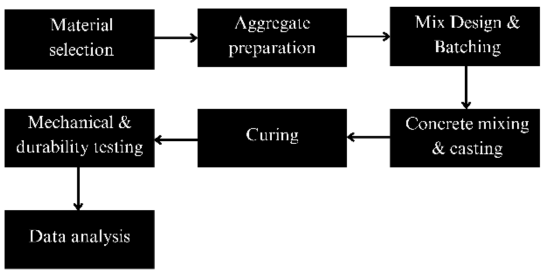

Fig. 1. General framework of the study

Concrete mixing and specimen casting were conducted following ASTM standards. Two specimen types were prepared: cubes for compressive strength testing and cylinders for sorptivity evaluation. After molding, the specimens were subjected to standard water curing for 14 and 28 days.

Upon reaching the designated curing ages, the specimens were tested for mechanical and durability performance. Compressive strength was measured using a universal testing machine, while water absorption behavior was evaluated through sorptivity testing [13]. The results were statistically analyzed using analysis of variance (ANOVA) to assess the significance of differences across treatments. This process allowed for the evaluation of both strength and durability characteristics, as well as the identification of the most suitable replacement level of coconut shell aggregate for sustainable concrete applications.

3.1 Material selection

The materials used in this study included Ordinary Portland Cement (Type I), Ottawa sand as fine aggregate, potable water, and coconut shells. The coconut shells were sourced locally and were air-dried, manually crushed, and sieved to a maximum size of 12 mm.

Fig. 2. Crushed coconut shell used in the study

All materials conformed to relevant ASTM standards.

- Cement: ASTM C150-compliant Ordinary Portland Cement (Type I)
- Fine Aggregate: Clean, dry Ottawa sand
- Coarse Aggregate: Crushed coconut shell (0%, 10%, 20%, 30% by volume)
- Water: Clean potable water

3.2 Preparation of Specimens

The coconut shells were pre-treated to remove dirt, crushed into irregular shapes, and passed through a 12 mm sieve to standardize size. Mix proportions were prepared by volume, replacing conventional coarse aggregates with coconut shells at 0%, 10%, 20%, and 30% levels. All mixes followed a consistent water-to-cement ratio of 0.55 to maintain comparability.

Specimens for compressive strength were cast into 50 mm × 50 mm × 50 mm cubes as per ASTM C109/C109M-95, while specimens for sorptivity testing were cylindrical (100 mm diameter × 50 mm height) based on ASTM C1585.

3.3 Mixing, Casting, and Curing

Concrete was mixed following ASTM C192 procedures. Each batch was hand-mixed in a clean mixing tray, ensuring uniform distribution of coconut shell in the matrix. After casting, specimens were covered with damp cloths for 24 hours before demolding. Curing was carried out by immersing specimens in water tanks maintained at 23 ± 2°C until the testing ages of 14 and 28 days.

3.4 Testing Procedures

Compressive strength was determined using a universal testing machine at a loading rate of 0.6 ± 0.2 MPa/s until failure. The compressive strength (f_s) was calculated using:

$$f_c = \frac{P}{A}$$

Where:

- Fc = compressive strength (MPa)
- P = maximum load at failure (kN)
- A = cross-sectional area (mm²)

Sorptivity testing followed ASTM C1585. The sides of the cylindrical specimens were sealed to ensure unidirectional water ingress from the base. Specimens were partially submerged in water, and mass was recorded at regular intervals (5 to 60 minutes) to calculate the sorptivity coefficient SSS using:

$$i = S\ (t^{0.5})$$

Where:

- i = cumulative absorption per area (mm³/mm²)
- S = sorptivity coefficient (mm/min$^{0.5}$)
- t = elapsed time (min)

3.5 Data Analysis

The average of three replicates per treatment was used for each test. Statistical analysis was conducted using ANOVA to determine the significance of variation between treatments [2]. Results were interpreted with reference to related literature to identify the optimal replacement level for coconut shell aggregate and assess its viability in sustainable concrete applications.

4. RESULTS AND DISCUSSIONS

This section presents the results of compressive strength and sorptivity tests for concrete mixtures incorporating different percentages of coconut shell (CS) as partial coarse aggregate replacement. The findings are discussed in relation to the study's objectives and supported by relevant literature.

4.1. Compressive Strength Performance

The compressive strength of concrete is a fundamental parameter for evaluating its structural performance. In this study, cube specimens were tested at 14 and 28 days to observe the influence of CS replacement levels (0%, 10%, 20%, and 30%) on strength development.

Table 1. Analysis of variance (ANOVA) for 14-day compressive strength results

Source	DF	Sum of Square	Mean Square	F Value	Pr (>F)
Treatment	2	21.33	10.67	2.74	0.1430^{ns}
Error	6	23.3779	3.8963		
Total	8	44.71			

The ANOVA results in Table 1 show that the differences in compressive strength between the treatment groups were not statistically significant at the 0.05 level of probability. Specifically, the p-value was 0.1430, which is greater than 0.05, indicating that there was no significant variation in compressive strength among the different CS replacement levels at 14 days of curing. The F-value of 2.74 further supports this conclusion, as it falls below the critical threshold for statistical significance.

These results suggest that within the early curing stage, the variation introduced by replacing natural coarse aggregates with coconut shells did not drastically affect the strength performance of the concrete. This lack of significant difference could be attributed to several factors, including the compaction process and the uneven distribution of coconut shell within the concrete mix, especially considering the manual preparation methods used in the study.

Moreover, the inherent inconsistencies in the physical properties of coconut shell, such as shape, texture, and density, may lead to slight fluctuations in specimen strength, which, when averaged, reduce the apparent differences between treatment groups. It's also worth noting that mechanical testing equipment sensitivity or minor variations in curing conditions may contribute to the observed discrepancies.

Although no statistical significance was observed at this stage, a clear trend in decreasing compressive strength with increasing coconut shell content was still evident from the raw values, which becomes more pronounced in the 28-day results discussed in the succeeding section.

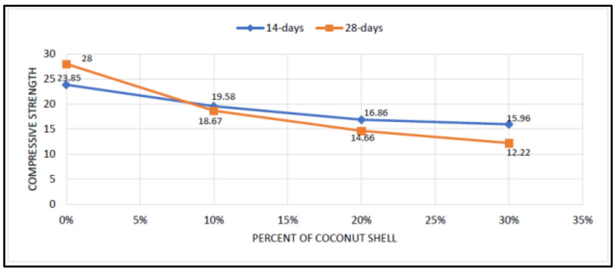

Fig.3. Maximum compressive strength versus amount of coconut shell

Figure 2 illustrates the relationship between compressive strength and the percentage of coconut shell (CS) used as a partial coarse aggregate replacement at two curing ages: 14 days and 28 days. The results indicate a clear, inverse correlation between CS replacement level and compressive strength, with both 14-day and 28-day data exhibiting a consistent downward trend.

At 0% replacement (control), the concrete achieved its highest strength, with values of 23.85 MPa at 14 days and 28.00 MPa at 28 days. This reflects the expected strength gain associated with hydration and continued curing. When 10% of the natural aggregate was replaced with CS, the compressive strength slightly decreased to 19.58 MPa and 18.67 MPa at 14 and 28 days, respectively. Despite the reduction, these values remain within acceptable ranges for structural applications, particularly for lightweight or low-load-bearing structures.

Further increasing the CS content to 20% and 30% led to a more pronounced decrease in compressive strength. At 30% replacement, the concrete recorded values of only 15.96 MPa at 14 days and 12.22 MPa at 28 days, which are below the 17 MPa minimum requirement for structural lightweight concrete as per ASTM C330. This suggests that the mechanical integrity of concrete is significantly compromised at higher CS levels.

The sharper decline in 28-day strength values compared to the 14-day trend may be attributed to the inconsistent compaction and distribution of CS particles within the mix. The porous and lightweight nature of coconut shells may result in weak interfacial bonding zones, which deteriorate over time, especially under prolonged curing. Additionally, the higher organic content and lower density of CS aggregates reduce the concrete's overall stiffness and hinder effective stress transfer, contributing to lower strength development.

These observations are consistent with previous findings by Kanojia and Jain [10] and Sekar and Kandasamy [9], who similarly reported diminishing returns in mechanical strength beyond 10% - 15% CS replacement. The results affirm the importance of optimizing CS content to maintain both strength and sustainability, with 10% emerging as the most practical substitution level for applications requiring moderate load-bearing capacity.

4.2. Sorptivity and Water Absorption Behavior

Sorptivity provides insight into a material's resistance to moisture ingress, which is vital for long-term durability. In this study, cylindrical specimens were partially submerged in water and tested for mass gain over time. Sorptivity coefficients were calculated for each mix.

To assess the effect of coconut shell (CS) content on the water absorption behavior of concrete, a sorptivity test was conducted, and the results were statistically analyzed using a two-way Analysis of Variance (ANOVA).

Table 2 presents the outcome of this analysis, evaluating the influence of treatment (CS replacement level), time (water absorption intervals), and their interaction.

Table 2. Analysis of Variance (ANOVA) for sorptivity test result

Source	DF	Sum of Square	Mean Square	F Value	Pr (>F)
Treatment	3	203503.89	67834.63	174.95	0.00*
Time	8	56.18	7.02	0.02	1.0^{ns}
Treatment: Time	24	3.50	0.15	0.00	1.00^{ns}
Error	72	27916.67	387.73		
Total	107	231480.25			

The ANOVA results clearly show that Treatment (i.e., the percentage of coconut shell replacement) had a statistically significant effect on sorptivity at the 0.05 level of probability, with a p-value of 0.0000 and an F-value of 174.95. This indicates that variations in CS content affected how much water the concrete absorbed through capillary action.

In contrast, Time (with DF = 8, Pr = 1.0000) and the Treatment × Time interaction (DF = 24, Pr = 1.0000) were not statistically significant. This means the time intervals over which absorption was measured did not contribute significantly to differences in sorptivity among the mixes, and the absorption behavior over time was relatively consistent across treatments. This supports the conclusion that the type of aggregate, rather than duration of testing, was the primary driver of changes in water absorption.

Post-hoc comparisons using the Least Significant Difference (LSD) test further revealed that the control (0% CS) and T1 (10% CS) groups were not significantly different from one another, suggesting that a 10% replacement does not markedly alter the sorptivity behavior of concrete. However, both T2 (20% CS) and T3 (30% CS) exhibited significantly different (and lower) sorptivity values, confirming that higher CS content improves resistance to moisture ingress.

The improvement in sorptivity at 20% and 30% CS can be attributed to the disrupted capillary network in the concrete matrix caused by the irregular surface and internal structure of the coconut shells. These particles may block continuous pore paths, thereby reducing water uptake. This supports the findings of Sekar and Kandasamy [9], who observed improved durability in coconut shell concrete in terms of lower permeability and water absorption.

From a practical perspective, the data imply that coconut shell can be an effective material for enhancing the water-resisting properties of concrete, especially at 20% and 30% replacement levels. These mixes are potentially well-suited for non-structural applications where durability and water resistance are more critical than compressive strength, such as external paving, walkways, perimeter fencing, or masonry blocks in wet tropical environments.

However, while higher CS contents improve moisture resistance, this must be weighed against the corresponding loss in compressive strength (as discussed in Section 4.1). Therefore, the optimal mix must strike a balance, with 10% CS being most viable for general applications and 20 - 30% CS being more appropriate for moisture-prone but low-load-bearing structures.

Figure 3 illustrates the relationship between cumulative water absorption and elapsed time for concrete mixes with 0%, 10%, 20%, and 30% coconut shell (CS) replacement. The sorptivity uptake plot provides a visual understanding of how moisture penetrates the concrete matrix during the initial 30-minute exposure period, which is critical for assessing the early-age durability of cementitious materials.

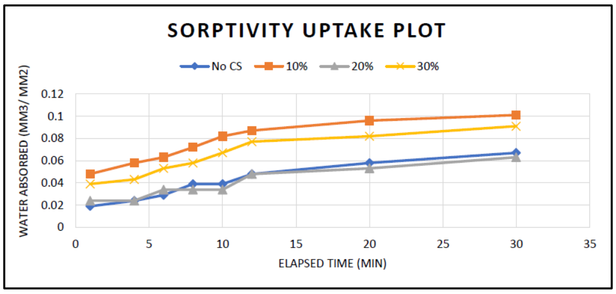

Fig.4. Sorptivity uptake plot - water absorbed vs. elapsed time

As presented in the figure, all treatments exhibit a progressive increase in water absorption with time. This is consistent with the capillary suction phenomenon, where unsaturated concrete draws in water until saturation limits are approached. However, the rate and extent of absorption vary significantly among the mixes, reflecting the influence of coconut shell content on the concrete's pore structure.

The control sample (0% CS) absorbed less water than the 10% CS mix throughout the testing period. This may initially appear counterintuitive, but it suggests that the introduction of a small amount of coconut shell, while not sufficient to create a tightly packed matrix, may increase the internal void content or microchannels, facilitating capillary flow.

Conversely, the 20% and 30% CS mixes displayed significantly lower water absorption, especially after the 10-minute mark. This trend indicates enhanced resistance to moisture ingress, consistent with the earlier statistical findings (Section 4.2). The drop in water uptake at higher CS content is likely due to the disruption of capillary continuity within the concrete matrix, as coconut shell particles, being more irregular and less permeable, introduce barriers that slow down fluid migration.

The 30% CS mix showed the lowest water absorption, suggesting it has the most moisture-resistant matrix among the treatments. However, this improved durability comes at the cost of a significant reduction in compressive strength, indicating a performance trade-off between strength and durability.

The implications of these results are significant for practical applications. In structures where water resistance is critical, such as drainage channels, pavement layers, boundary walls, or exposure zones in tropical climates, higher CS contents (20% - 30%) can be strategically employed to improve service life by minimizing water-induced deterioration like cracking, scaling, or corrosion initiation in reinforcement.

However, for structural members requiring high load-bearing capacity, a compromise must be made. The 10% CS mix provides a practical middle ground, offering modest improvements in water absorption while retaining acceptable compressive strength for non-critical structural applications.

4.4. Comparison with Existing Literature and Implications

The trends observed in this study agree with international research. Sekar and Kandasamy [9] observed strength reductions at higher CS replacement levels but noted improvements in durability characteristics such as lower water permeability. Similarly, Stel'makh et al. [11] emphasized that coconut shell can be integrated into concrete up to a certain limit, beyond which mechanical integrity is compromised.

These findings support the idea that coconut shell concrete can contribute meaningfully to sustainable construction, particularly in resource-constrained regions. The material's light weight, moisture resistance, and cost-effectiveness make it suitable for specific applications such as masonry blocks, non-structural elements, pavement layers, and other environments where water resistance is critical but high strength is not the priority.

5. CONCLUSIONS AND RECOMMENDATIONS

This study evaluated the performance of concrete incorporating crushed coconut shell (CS) as a partial replacement for conventional coarse aggregates at varying levels of 0%, 10%, 20%, and 30%. The investigation focused on two key performance indicators: compressive strength and sorptivity.

The results revealed that coconut shell significantly influences both the mechanical and durability characteristics of concrete. At 10% replacement, the mix maintained relatively high compressive strength, achieving 19.58 MPa at 14 days and 18.67 MPa at 28 days, which are acceptable for certain structural applications. However, as the percentage of CS increased to 20% and 30%, a clear decline in strength was observed, with the 30% mix falling below the minimum strength requirement for structural lightweight concrete as specified in ASTM C330. This indicates that while coconut shell can be used as an aggregate, its proportion must be carefully controlled to preserve structural performance.

In contrast, the sorptivity results showed a different trend. Higher CS content corresponded to significantly reduced water absorption, with the 20% and 30% mixes demonstrating strong resistance to moisture ingress. Statistical analysis confirmed that the treatment (i.e., coconut shell percentage) had a significant effect on sorptivity ($p < 0.05$), whereas time and the interaction between treatment and time were not statistically significant. This suggests that the material composition, rather than the duration of exposure, predominantly influences water absorption behavior [14]. The 10% CS mix displayed moderate water absorption, while the 20% and 30% mixes exhibited lower sorptivity values, which can be advantageous for applications where durability in wet environments is prioritized.

The findings indicate that a 10% coconut shell replacement level offers the most practical balance between maintaining compressive strength and improving water resistance. For applications where strength is less critical, and water resistance is essential, such as pavements, low-load-bearing blocks, or boundary walls, higher replacement levels of 20% to 30% may be beneficial. The study reinforces the potential of coconut shell as a sustainable construction material, contributing to waste reduction and the conservation of natural aggregates [15].

Based on these findings, it is recommended to limit the use of coconut shell to a maximum of 10% replacement for structural concrete applications that require moderate load-bearing capacity. For non-structural and durability-focused applications, particularly in humid or water-exposed environments, 20% to 30% replacement can be adopted to capitalize on improved sorptivity performance.

Future studies are encouraged to explore long-term durability characteristics of CS concrete under real-world exposure conditions, including chemical attack, freeze-thaw cycles, and carbonation. Additional investigations may also examine the effects of pre-treating coconut shells, combining them with other supplementary materials, or incorporating fibers and admixtures to offset strength reductions at higher replacement levels.

Moreover, life cycle assessments and economic analyses should be conducted to evaluate the scalability and sustainability benefits of coconut shell concrete in regional construction practices.

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