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Coconut Coir Fiber and Coconut Shell as Substitute to Fine Aggregates in Concrete Mortar Cubes

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Abstract: *Traditional building materials often rely on non-renewable resources, raising environmental concerns. This study assesses the compressive strength of concrete mortar cubes through fine aggregate replacement with 20%, 40%, 60%, and 80% of coconut coir fiber (CCF) and coconut shell (CS). CCF replacements were viable up to 40% with 1768.88 psi but showed a decline thereafter. CS and combined coconut shell and coir fiber (CSCF) replacements consistently resulted in decreased compressive strength up to the 28th day of curing, specifically at the 20% replacement level with a result of 1695.29 psi* and *1,817 psi, respectively. However, all replacement types generally resulted in reduced strength compared to the control specimen but has shown potential in further concrete applications.*

Keywords: Building Material; Concrete technology; Coconut Fiber; Coconut Shell

1. INTRODUCTION

The most widely used construction material all over the world is concrete. This is composed of cement, fine aggregates and coarse aggregates mixed with water that cures and hardens with time [1]. The increasing need for sand in construction has turned it into a rare resource. While it was a common material used in building, the current availability of sand has not been able to match the rapid pace of urbanization worldwide [2]. With the diminishing supply of construction sand, it was anticipated that the cost of sand would rise, creating opportunities for alternative materials to emerge [3,4].

Concrete reinforcement often utilizes natural fibers derived from plants, including jute, bamboo, and brown coconut, among others [1]. In the Philippines, the coconut tree held the title of "tree of life" due to its immense significance. It played a crucial role in the country's agriculture, contributing significantly to its gross value-added (GVA) with a 3.6% share. The Philippines maintained its status as a leading global producer and exporter of coconuts [5]. In fact, an average of 14.77 million metric tons of coconut were produced in the last 11 years [6]. The beneficial use of coconut timber waste as a sustainable building material has been explored even in earthquake resistance [7]. However, farmers mainly involved themselves in the production of copra, which was the dried coconut meat used in making coconut oil, while coconut shells were generally disposed of as waste. In fact, the major coconut wastes included coconut shell, coconut husks, and coconut coir dust. Annually, an estimated 4.1 million tons of husks and 1.8 million tons of shells were discarded [8].

Given that the construction industry is one of the most common practices that utilizes sand and coconut as resources, adjustments in this field must be made to help address the problem at hand. Sand, as stated, is a key component for producing concrete, which is a key material in most building projects. Alternatives, especially those that are readily available and under-utilized, for this resource in producing concrete could contribute to and help solve its projected scarcity and depletion.

This paper aims to address the scarcity of construction-grade sand by partially replacing conventional fine aggregates in concrete mortar cubes with Crushed Coconut Shell (CS) and Coconut Coir Fiber (CCF). Specifically, it investigates the 7, 14, 21, and 28-day compressive strength of concrete mortar cubes where fine aggregates have been partially substituted with CS and CCF. The study differentiates the results by analyzing concrete mortar cubes containing 0%, 20%, 40%, 60%, and 80% CCF and CS by volume, providing a comprehensive comparison of how varying levels of these alternative materials affect the strength and performance of the mortars over time.

2. METHODOLOGY

The experimental method was used to conduct a series of compressive strength tests on concrete mortar cubes. This was carried out over a curing period of 28 days. Descriptive methods were employed to systematically record and present the data generated from these tests.

2.1 Materials

The materials used in the study included 12 mm (CCF), and coconut shell (CS) as shown in Fig. 1, Portland cement, water, and aggregates. The cement material, Portland cement, was locally sourced, adhering to the specifications outlined for Portland Cement (ASTM Designation: C 150). The fine and coarse aggregates were locally obtained and conformed to the requirements of the specifications for Portland Cement (ASTM Designation: C 33). The organic crushed coconut shell was locally obtained, and the 12 mm organic CCF derived from discarded coconut husks were locally sourced.

Fig. 1. Processed Coconut Fiber and Coconut Shell.

2.2 Pre-treatment of Coconut Coir Fiber

Alkali treatment, commonly referred to as mercerization, involves treating natural fibers like coconut coir with an alkali solution, usually sodium hydroxide (NaOH) [9]. Alkali treatment is a crucial process for enhancing the properties of coconut coir fibers, making them more effective and durable for different applications. In preparing coconut coir fiber for alkali treatment, the process is initiated with an initial cleaning phase to eradicate any dirt or debris from the fiber. This involved washing the fiber with water and subsequently air drying until dried. An alkali solution was then prepared by dissolving NaOH in water, with the concentration adjusted based on the intended properties of the treated coconut coir fiber. As shown in Fig. 2, the fiber was then immersed in the alkali solution for two hours, to not damage the desired properties. After the soaking period, the fiber was rinsed with water to remove any remaining alkali solution. To neutralize the fiber and ensure safe handling, it was soaked in a mild acid solution such as acetic acid or citric acid, preventing potential damage from the alkali solution. Finally, the treated coconut coir fiber was air dried for two weeks. Alkali-treated coconut coir fiber was expected to exhibit improved durability and increased resistance to biodegradation, making it a promising material for this study.

Fig. 2. Coconut Fiber soaked in NaOH Solution

2.3 Pre-treatment of Coconut Shell

CS were soaked in a solution of sodium hydroxide (NaOH) with a pH level of 10-12 for two hours to achieve the desired strength of the cellulose fibers. The alkali solution broke down the lignin and hemicellulose in the coconut shells, leaving behind the cellulose fibers. The coconut shell was then rinsed with warm water to remove leftover coconut meat. Afterwards, it was air-dried for 2 weeks as shown in Fig. 3. From this, it was crushed into 4.75 mm and smaller diameter particles.

Fig. 3. Air drying of treated Coconut Shells

2.4 Sieving

To ensure that the particles sizes are classified as fine aggregates, a #4 (4.75 millimeter) sieve with specific sieve openings were used. The fine aggregates passed through this sieve to ensure the removal of any oversized particles or impurities exceeding the predetermined size limit, maintaining the quality and uniformity of the aggregates for subsequent use in the concrete mixture.

2.5 Unit Weights

The bulk density of fine aggregates used was found in accordance with the standards set by ASTM C129. According to Kosmatka and Wilson [10], the unit weight of both coarse and fine aggregates specified within the grading limits set by ASTM, typically falls between the values of 1200 to 1750 kg/m^3. Meanwhile, the specific gravity of the sample (Type I) hydraulic cement using the Le Chatelier flask method in accordance with ASTM C188-18. This test will yield valuable information regarding the quality and suitability of the cement sample for the application in the study. One important component influencing the strength, durability, and other properties of concrete building materials is the cement's specific gravity [11]. Therefore, it is crucial to accurately determine the specific gravity of cement to guarantee that the cement used in the study conforms to the necessary specifications and standards. Table 1 shows the average of three tests conducted per material. Conventional fine aggregates, CS, CCF, and Cement had an average unit weight of 1641.9 kg/m^3, 698.86 kg/m^3, 213.28 kg/m^3, and 1489.09 kg/m^3 respectively.

Table 1. Unit Weight of Fine Aggregates and Cement

Material	Average Unit Weight (kg/m^3)
Fine Aggregates	1,641.9
Coconut Shell	698.86
Coconut Fiber	213.28
Cement	1,489.09

It can be seen in Table 1 that the unit weight determined for sand is 1641.85 kg/m^3 which falls between the range of typical values for unit weight of ASTM standardized graded sand. The unit weight found for sand was essential in computing for the quantities needed in the mix design of both the mortar and concrete hollow block specimens. The table also shows the different obtained values needed in the determination for the unit weight of combined coconut shell and coir fiber (CSCF). It was found that the unit weight of the coconut shell utilized for the study had an average unit weight of 698.86 kg/m^3 on three trials. This result is close to the unit weight obtained by a study conducted by [12] with regards to the effect of coconut shell and fiber on the strength of concrete. It was found that the coconut shell utilized in their study had a unit weight of 702.1 kg/m^3 which exhibits a low percentage discrepancy of 0.5% in contrast to the obtained unit weight of this study.

Moreover, the average unit weight obtained for the CCF in the study was 213.28 kg/m^3. Similarly, the obtained value is similar to the literature study conducted by Albuja-Sánchez et al. [13] regarding CCF in Composite Concrete. The study found that coconut fiber had a unit weight of 237.04 kg/m^3 which only has a relatively low discrepancy of 10.5%.

2.6 Mix Design

The index properties of the aggregates and coconut elements were used in the mix design of the cubes. The batching phase strictly adhered to precise mix designs and measurements to accurately weigh and proportion essential materials like Portland cement, aggregates, and water, as shown in Tables 2, 3 and 4. The replacements were targeted based on a volume basis and were then converted into mass for a more precise substitution.

Table 2. Mix Design for Coconut Coir Fiber

Replacement (%)	Cement (g)	Sand (g)	Coconut Coir Fiber (g)
0	500	1375	0
20	500	1100	35.72
40	500	825	71.45
60	500	550	107.17
80	500	275	142.89

Table 3. Mix Design for Coconut Shell

Replacement (%)	Cement (g)	Sand (g)	Coconut Coir Fiber (g)
0	500	1375	0
20	500	1100	117.05
40	500	825	234.11
60	500	550	351.16
80	500	275	468.22

Table 4. Mix Design for Coconut Coir and Coconut Shell

Total Replacement (%)	Sand (g)	Coconut Coir Fiber (g)	Coconut Shell (g)
0	1375	0	0
20	1100	17.86	58.53
40	825	35.72	117.05
60	550	53.58	175.58
80	275	71.45	234.11

In Table 4, a constant mass of 500 grams was used in the preparation of the materials, and a fiber-to-shell ratio of 50:50 was used to calculate the total replacement.

For all the mix designs in Tables 2 through 4, the pre-mixed dry materials were combined with water to form the concrete mixture, guaranteeing a thorough and uniform integration of materials. Accurate proportions were ensured, dry ingredients were mixed thoroughly, water was gradually added while mixing, and mixing continued until a consistent, workable texture was achieved. This process was crucial in achieving the desired strength of the specimens.

The casting involved pouring the concrete mortar mixture into 2-inch concrete cube dimensions. A total of 156 specimens were cast with three specimens per mixture on the 7th, 14th, 21st, and 28th compressive strength. Additionally, 56 concrete cubes served as safeguards to account for potential breakage during the hydration process.

Fig. 4. Labeled and Casted Concrete Cubes

These were then allowed to air dry for 48 hours, demolded, then placed into a water bath.

2.7 Testing

The Uniaxial Compressive Strength Test was conducted for all 2-inch concrete cube specimens targeting the 7th, 14th, 21st, and 28th day compressive strength. This is to ensure that the strength development may be observed and recorded. Each block was placed in the compression testing machine and positioned so that the load was applied perpendicular to the top and bottom faces of the block. Compressive force was applied to the block at a constant rate of loading, and the force at which the block failed was recorded. Finally, the compressive strength was calculated using equation:

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

Where: f'c = compressive strength
F is force at failure
A is the cross-sectional area of the block

3. RESULTS AND DISCUSSION

This section presents the key findings regarding the control specimen samples and the partial replacement of conventional fine aggregates in mortar specimens with CCF and CS. Table 5, Figs. 5 through 13 present the average compressive strength for the Control, CSCF replacement, CF replacement, and CS replacement mortar specimens respectively. These tables and figures present the varying percent replacements of the mortar specimens and their corresponding 7th, 14th, 21st, and 28th day compressive strengths in psi. Moreover, data collected were subject to the Dixon-Q Test and potential outliers were filtered and removed, indicating that the data points are relatively close together and are consistent with the trend.

3.1 Control Specimen

From the results shown in Table 5 and Fig. 5, The 7th day strength of the control specimen is at 3036.54 psi (20.94 MPa), which increased to 3410.60 (23.53 MPa) psi on the 14th day, This had a significant increase on the 21st day and then a minimal increase from the 21st day to the 28th day with values 4103.12 psi (28.29 MPa) and 4153.75 psi (28.64 MPa), respectively.

Table 5. Average Compressive Strength of the Control Mortar Specimens

Replacement (%)	Day	Compressive Strength (psi)	Compressive Strength (MPa)
0	7th	3036.54	20.94
	14th	3410.60	23.52
	21st	4103.12	28.29
	28th	4153.76	28.64

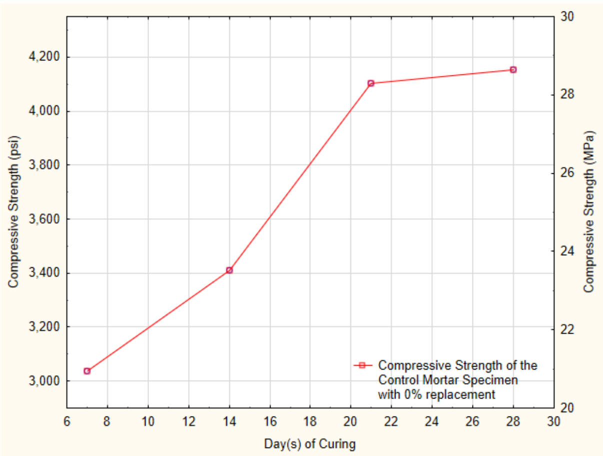

Fig. 5. Compressive Strength Test results of the Control Mortar Specimens with 0% replacement.

3.2 Coconut Fiber as Fine Aggregate Substitute

It can be observed in Fig. 6 that there is a significant reduction in strength against the control specimen. However, the strength development from the 20% up to 80% replacement of sand by CF was found optimum at 40% with a corresponding 1768.88 psi (12.20 MPa).

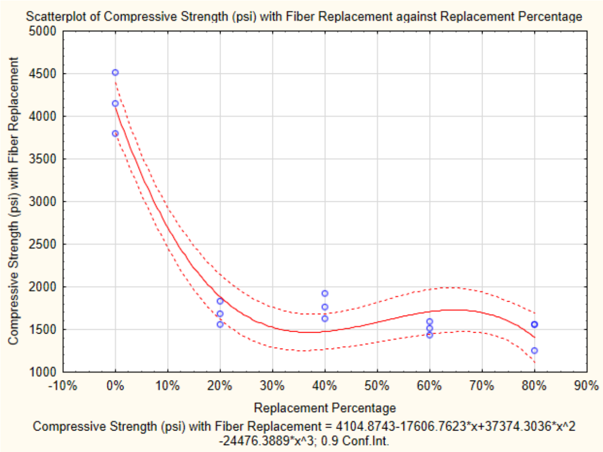

Fig. 6. Scatterplot of the Compressive Strength Test results of the Coconut Fiber Replacement

It may be attributed that the CF may act as *fiber* in the development of the cubes up to the 40% replacement. This trend can be observed closely in Fig. 7, the trend shows an increase in strength with time. On the 28th day, the results show a 1,687.14 psi (11.63 MPa) for the 20%, 1768.88 (12.20 MPa) for the 40%, 1513.12 psi (10.43 MPa) for the 60% and 1455.99 psi (10.04 MPa) for the 80% substitution of fiber to the fine aggregates.

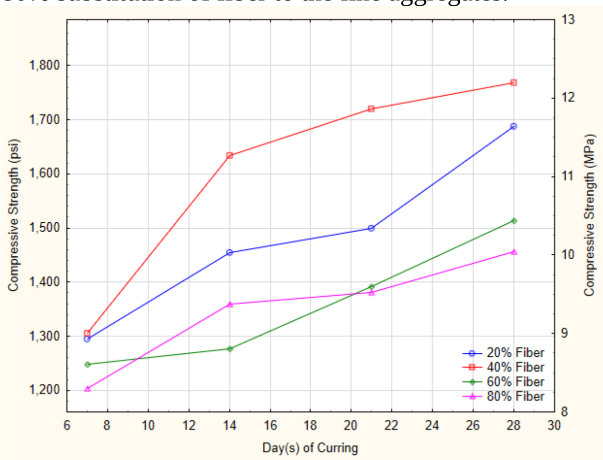

Fig. 7. Compressive Strength Test results of the Fine Aggregate Replacement with 20% to 80% Fiber.

3.3 Coconut Shell as Fine Aggregate Substitute

A similar trend is observed in Fig. 8 where a significant reduction in strength against the control specimen is observed. The maximum strength developed was from the 20% replacement of sand by CS with a corresponding value 1695.29 psi (11.69MPa).

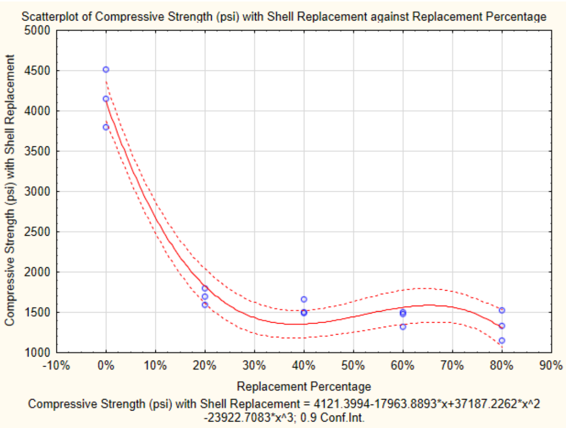

Fig. 8. Scatterplot of the Compressive Strength Test results of the Coconut Shell Replacement

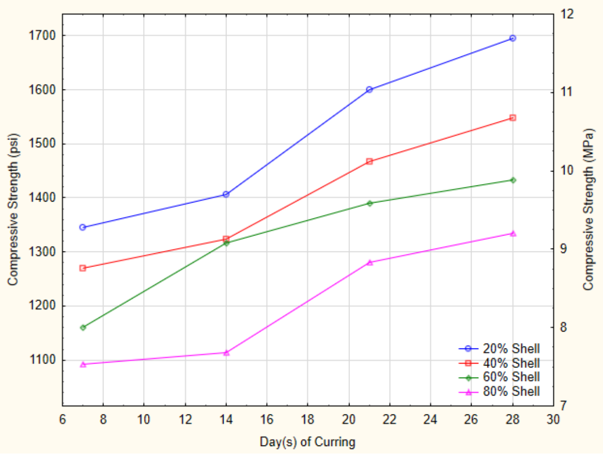

Fig. 9. Compressive Strength Test results of the Fine Aggregate Replacement with 20% to 80% Shell.

On the 28th day, the results show a 1,695.29 psi for the 20%, 1548.91 for the 40%, 1433.72 psi for the 60% and 1334.04 psi for the 80% substitution of CS to the fine aggregates. It can be attributed that the CS only act as a *filler* in the development of the concrete cubes, as observed in the actual specimens.

3.2 Coconut Fiber and Coconut Shell as Fine Aggregate Substitutes

To maintain the percentage replacements, a fiber to shell ratio of 50:50 was used to calculate the total replacement of 20 to 80 percent, in the same increments of 20. Fig. 10 presents the results of the simultaneous replacement of the fine aggregates.

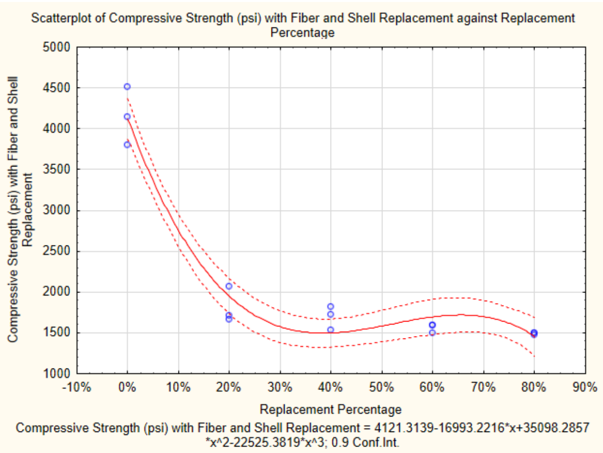

Fig. 10. Scatterplot of the Compressive Strength Test results of the Coconut Fiber and Shell Replacement

Fig. 11 shows that the maximum compressive strength was attained at the 20% combination with strengths of 1,322.45 psi (9.12 MPa) on the 7th day, 1,371.62 psi (9.46 MPa) on the 14th day, 1,556.83 psi (10.73 MPa) on the 21st day and a result of 1,816.62 psi (12.53 MPa) for the 28th day compressive strength test result.

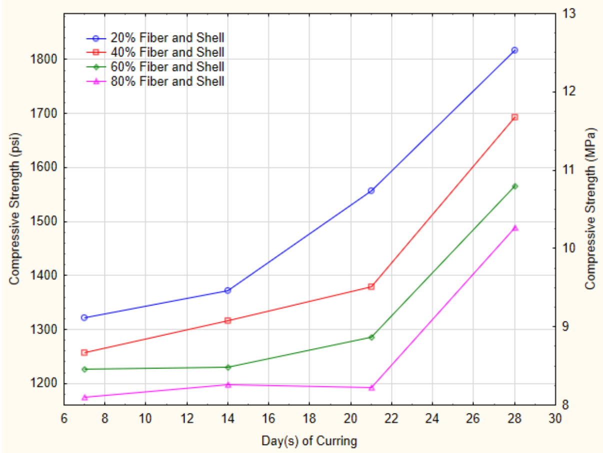

Fig. 11. Compressive Strength Test results of the Fine Aggregate Replacement with 20% to 80% Shell.

The relationship between CS and CCF replacements on compressive strength was further analyzed through Response Surface Methodology (RSM).

Fig. 12 shows the relationship between CCF and CS replacements and compressive strength using a color gradient. Red areas indicate higher compressive strength, while green areas indicate lower strength. The axes, from 0 to 20, correspond to 0% to 20% replacement levels for both materials. The gradient transitions from green (1800-2600 psi) to yellow (2600-3000 psi), and then to orange and red (3000-3800 psi). The contour lines show significant interaction between the two variables, with moderate replacements leading to lower compressive strength and optimal combinations resulting in higher strength.

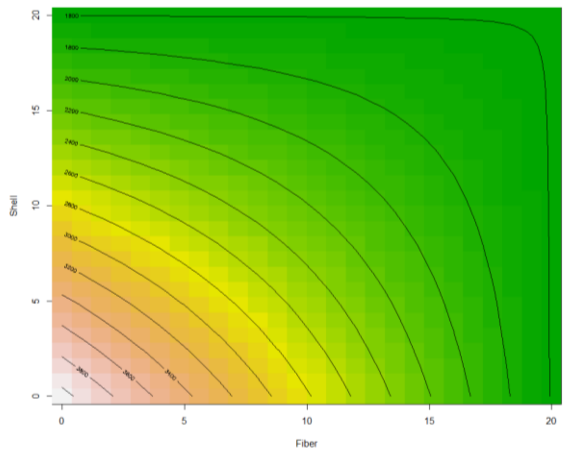

Fig. 12. Contour Graph of the Relationship between Coconut Coir Fiber and Coconut Shell Replacement Parameters and Compressive Strength.

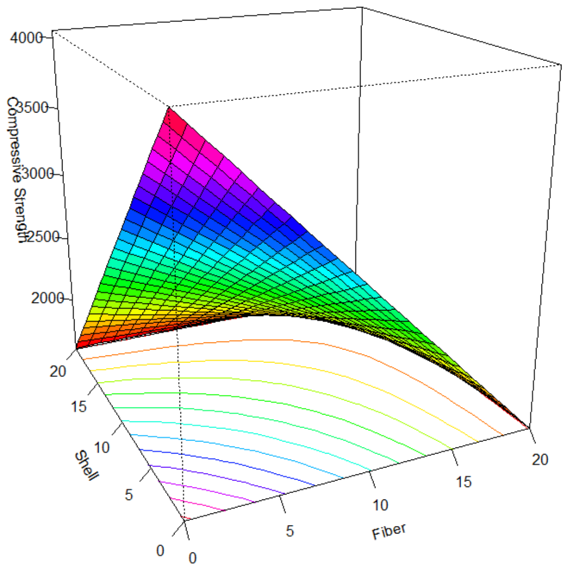

Fig. 13. 3D Surface Graph of the Relationship between Coconut Coir Fiber and Coconut Shell Replacement Parameters and Compressive Strength.

Figure 13 shows a three-dimensional perspective of the relationship between CCF, CS replacements, and compressive strength. It highlighted peaks and valleys, with peaks corresponding to areas of high compressive strength, aligned with the red regions in Fig. 5.12, and valleys indicating low compressive strength. The surface plot revealed a pronounced interaction effect between CCF and CS replacements. The curvature of the surface plot showed that a specific combination of these replacements could mitigate the negative impact on compressive strength. The highest point on the surface marked the optimal combination of approximately 1% replacement, for maximizing compressive strength. This is because the highest compressive strength was achieved in concrete without these replacements. Although using CS and CCF still results in compressive strength, it is lower than the maximum achieved without replacements.

The relationship between the compressive strength of CCF and CS suggests that when shell and fiber replacements are combined, their negative impact on compressive strength is lessened. From this, the individual effect of shell and fiber replacement significantly decreases compressive strength, while there is a significant positive interaction effect when combined.

The correlation between pore volume and mortar performance underscores the economic and structural viability of using recycled materials like CCF and CS. Increased pore volume, associated with higher replacement levels, generally leads to reduced compressive strength [15]. However, up to 40% replacement with CCF, 20% with CS, and 20% with combined CFCS still retained significant strength, suggesting a limit beyond which these materials negatively impact performance. Using CCF, CS, and combined CFCS not only cuts down on the need for traditional aggregates but also aids in waste reduction and supports sustainable building practices.

4. CONCLUSION

The study evaluated varying CCF and CS replacements in 2-inch concrete mortar cube mixes over curing periods of 7, 14, 21, and 28 days, which addresses the scarcity of construction-grade sand. The key findings revealed that while both CCF and CS replacements led to a reduction in compressive strength compared to the control specimens, there were optimal replacement levels where strength was maximized. Optimal replacement percentages for achieving the highest compressive strengths were identified as 20% for combined CSCF, 20% for CS, and 40% for CCF among the levels tested (20%, 40%, 60%, and 80%). These results demonstrate that coconut waste materials can replace fine aggregates in concrete. As replacements increase, compressive strength decreases, emphasizing the need to optimize the mix for both strength and sustainability. Using coconut coir fiber and shell helps tackle sand scarcity, reduces waste, and supports the circular economy in construction. Future research should explore the use of CS, CF, and combined CFCS as fine aggregate replacements in other concrete applications, such as concrete hollow blocks and similar products. This would help assess their effectiveness and performance across different types of concrete structures.

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