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Flexural Strength and Crack Resistance in Sustainable Concrete: Evaluating Coir and Crushed Coconut Shells as Partial Aggregate Replacements

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ABSTRACT

The increasing demand for sustainable construction materials has underscored the need for eco-friendly alternatives to traditional concrete aggregates, as rising costs and depletion of natural materials create scarcity and environmental challenges. This study investigated the use of coir and crushed coconut shells as partial replacements for conventional aggregates, assessing their effects on the flexural strength and crack resistance of concrete. Conducted in Kilifi, Mombasa, and Kwale, Kenya—regions known for coconut cultivation and a favorable tropical climate—the research employed a rigorous experimental design. Various coir contents (0.1%, 0.2%, and 0.3%) were tested alongside crushed coconut shell aggregates (CCSA) at 10%, 20%, and 30%. A total of 72 concrete cubes and beam specimens were prepared from locally sourced materials to ensure relevance to regional construction practices. Key variables were assessed using standardized laboratory testing procedures, with data analyzed using both descriptive statistical methods and comparative performance evaluation across mix proportions. Results indicated that incorporating CCSA up to 10% slightly improved flexural strength, while higher replacement levels reduced performance; however, the addition of 0.3% coir fibres partially mitigated this reduction, enhancing ductility and crack resistance. In terms of crack resistance, mixes containing 30% CCSA and 0.3% coir exhibited superior performance based on Schmidt Hammer rebound values and Ultrasonic Pulse Velocity (UPV) tests, indicating improved internal integrity and reduced crack propagation. The findings demonstrate that the performance of sustainable concrete is highly dependent on optimal proportioning of coir fibres and CCSA, with balanced mixes offering improved mechanical and durability characteristics. The study therefore recommends controlled use of these materials to enhance concrete sustainability without compromising structural performance.

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1. Introduction

The urgent need for sustainable construction materials has prompted a reevaluation of traditional concrete mixtures, particularly concerning their flexural strength and resistance to cracking. As the construction industry faces growing environmental pressures and escalating costs for conventional materials, there is an increasing focus on integrating eco-friendly alternatives that do not compromise structural performance. This trend has led to significant interest in using agricultural by-products, such as Coir fibers and Crushed Coconut Shell Aggregates (CCSA), as partial replacements for conventional aggregates in concrete. Concrete structures are often prone to flexural failures and cracking under load, particularly in challenging environmental conditions. The incorporation of sustainable materials is an effective strategy to enhance the flexural strength and crack resistance of concrete, thereby extending its lifespan and reducing maintenance costs.

Coir fibers, derived from the outer husk of coconuts, possess unique properties that can improve the mechanical performance of concrete, while CCSA provides a lightweight alternative that contributes to overall material sustainability. The use of coconut waste is particularly beneficial in regions where coconut production is abundant. Research indicates that integrating CCSA into concrete formulations can lead to cost savings while simultaneously addressing the

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challenges of waste management associated with coconut processing (Ejaz et al., 2022; Aljohi et al., 2016). By leveraging local resources, this approach not only promotes environmental stewardship but also enhances the economic viability of construction projects.

Globally, coconut cultivation spans numerous countries, producing millions of tonnes annually. In Kenya, particularly along its coastal regions, the potential for utilizing these resources is significant. The country's coconut sector generates substantial waste that can be effectively repurposed, aligning with sustainable construction goals (Koitumet, 2023). Concrete typically demonstrates good performance under standard conditions; however, it can exhibit vulnerabilities when subjected to flexural loads and environmental stresses. These weaknesses often manifest as cracking or structural degradation, challenging the longevity and safety of built environments. Although high-performance concrete (HPC) can provide some resistance to these issues, its high cost and specialized requirements limit broader adoption.

Natural fibers, such as Coir, have emerged as effective reinforcements capable of enhancing the flexural strength of concrete. Coir's properties—such as high tensile strength and low thermal conductivity—make it a compelling choice for improving concrete durability (Okvianti & Febrianty, 2022). Incorporating Coir fibers can also mitigate the formation of cracks, providing a sustainable alternative to traditional steel reinforcements. The application of CCSA as a partial aggregate replacement in concrete has garnered attention for its potential to improve both the mechanical properties and sustainability of concrete. This innovative approach aligns with the growing need for materials that not only perform well but also minimize environmental impact (Dakos & Kéfi, 2022).

In Kenya, the North and South Coasts are rich in coconut resources, making them ideal locations for exploring the use of Coir and crushed coconut shells in concrete production. Areas such as Mombasa, Kilifi, and Kwale have a significant concentration of coconut trees, creating opportunities for sustainable construction practices (Herring & Thuo, 2022). Kenya boasts approximately 7.4 million coconut trees, with a substantial portion of waste generated during the processing of coconut fruit (Aljohi et al., 2016). This waste poses environmental challenges, but it also presents a unique opportunity for innovation in concrete applications. By integrating Coir fibers and crushed coconut shells, it is possible to enhance the performance of concrete while simultaneously addressing waste disposal issues (Oliko, 2023).

The objective of this study is to evaluate the effects of Coir and crushed coconut shells on the flexural strength and crack resistance of concrete within the Kenyan context. By focusing on the coastal regions, this research aims to assess the potential benefits of these materials in improving concrete performance while considering economic and sustainability factors.

The increasing demand for sustainable construction materials drove research into alternative aggregates for concrete, emphasizing the need for eco-friendly options that did not compromise performance. The construction industry faced challenges due to rising costs of conventional materials, particularly natural aggregates, leading to their overexploitation and depletion. This situation created scarcity and further increased costs, underscoring the urgent need for cost-effective alternatives that could maintain the structural integrity and performance of concrete used in construction projects. Additionally, the improper disposal of agricultural by-products like Coir and crushed coconut shells worsened waste management issues, posing significant environmental and public health hazards. Utilizing these materials in construction offered a viable solution to mitigate these challenges while promoting sustainability.

This study aimed to investigate the effects of incorporating Coir and crushed coconut shells as partial replacements for traditional aggregates on the engineering properties of concrete, specifically focusing on flexural strength and crack resistance. The two objectives were: To assess the flexural strength of concrete with coir and crushed coconut shells as partial aggregate replacements, in comparison to conventional concrete. To evaluate the crack resistance of concrete with coir and crushed coconut shells as partial aggregate replacements, in comparison to conventional concrete.

2. Literature Review

The utilization of Coir fibers and crushed coconut shells as partial aggregate replacements in concrete has gained attention for its potential to enhance both flexural strength and crack resistance. This empirical review synthesizes findings from recent studies, highlighting the effects of these materials on concrete's mechanical properties, particularly in the context of sustainable construction practices.

Several studies have demonstrated the positive impact of coir fibers on the mechanical properties of concrete. For instance, Eziefula et al., (2023) reported that incorporating coir fibers improved compressive strength at low fiber contents, highlighting their potential as reinforcement material. Similarly, Katre, Bisen, Thakur, Ukey, and Katre (2023) observed that coir fiber inclusion enhanced tensile and flexural strength, with optimum performance achieved at moderate fiber dosages. More recently, Prasad et al. (2024) found that coir fiber-reinforced concrete achieved a maximum compressive strength of 34 N/mm^2 at a fiber volume fraction of 4% and fiber length of 10 mm, though higher fiber content reduced workability.

In a separate line of research, Marandi and Kumar (2023) investigated crushed coconut shells as partial replacements for coarse aggregates and reported satisfactory mechanical performance alongside reduced

concrete weight and improved thermal insulation. Similarly, a machine learning-based study (Springer, 2023) confirmed that coconut shell aggregates can enhance compressive, flexural, and split tensile strength when optimally incorporated. These findings highlight the individual contributions of coir fibers and crushed coconut shells to concrete performance, though further research is needed to evaluate their combined effects.

A total of 72 concrete cubes and 72 beam specimens were prepared using a standardized concrete mix ratio of 1:2:4 (cement aggregate aggregate) and a constant water–cement ratio of 0.50 throughout the experimental programme. The control mix was prepared using conventional aggregates, while crushed coconut shell aggregates (CCSA) were introduced as partial replacements for coarse aggregates at levels of 10%, 20%, and 30% by weight. Coir fibres were incorporated into the mixes at proportions of 0.1%, 0.2%, and 0.3% by weight of cement. All materials were measured and batched uniformly to ensure consistency across all specimens. The same mixing, casting, compaction, curing, and testing procedures were maintained for all the 72 cubes and 72 beams to minimize experimental variation and ensure that differences in flexural strength and crack resistance were attributable only to the varying proportions of coir fibres and crushed coconut shell aggregates.

Bheel et al. (2024) investigated the use of eco-friendly binders, such as coconut shell ash (CSA), metakaolin (MK), and calcined clay (CC), as supplementary cementitious materials (SCMs) in Concrete (HSC). Their study aimed to enhance concrete performance and address waste disposal issues, focusing on improvements in tensile, flexural strength, and compressive strengths, and reductions in carbon emissions. This research did not address workability, crack resistance, or structural modeling, which were key aspects of the current study. In contrast, Hasan et al. (2024) examined the effects of incorporating stone dust (SD) and CSA into hardened concrete. Their findings showed improvements in shrinkage, crushing strength, and flexural strength with 10% CSA and SD as substitutes for cement. This study focused on material substitutions rather than aggregate replacements and did not explore the broader range of concrete properties that the current study aimed to address.

Singhal et al., (2020) explored the use of CSA and eggshell powder (ESP) in concrete, noting increases in flexural strength, tensile, and compressive strengths with these materials. Their study primarily targeted strength improvements with cement substitutes, rather than partial aggregate replacements, and did not include evaluations of workability, durability characteristics, or crack resistance. Similarly, Mangi et al. (2021) assessed the impact of CSA on concrete's compressive strength, finding that 10% substitution improved strength outcomes. While this study contributed to understanding the effects of CSA, it did not address aggregate replacements or other properties such as flexural strength, workability, or durability characteristics.

Moreover, Ashish (2019) focused on the effects of ESP and CSA on concrete's crushing strength. Like the other studies, it emphasized strength improvements but did not cover the comprehensive range of properties that the current study explored, such as workability, flexural strength, crack resistance, and structural modeling. In comparison, the current study aimed to investigate the use of Coir and crushed coconut shells (CCS) as partial aggregate replacements in high-strength concrete. It sought to assess a broader array of concrete properties, including workability, compressive and flexural strength and crack resistance. This comprehensive approach provided a novel perspective not fully covered in the previous studies, which mainly focused on SCMs or specific strength metrics. Adeniyi et al. (2019) examined how crushed coconut shells affect the flexural strength of concrete. The study found that the addition of crushed coconut shells up to a 10% replacement level led to improvements in flexural strength. This can be attributed to the porous nature of the shells, which may contribute to a more flexible and resilient concrete mix. However, when the replacement level exceeded 10%, the benefits to flexural strength were overshadowed by other negative effects such as increased porosity and reduced compressive strength. The increased porosity associated with higher replacement levels compromised the overall structural performance, thus limiting the improvements in flexural strength. The study suggests that while crushed coconut shells can enhance flexural strength to some extent, their effectiveness is constrained by their impact on other properties.

Selvaraj (2017) also explored the effects of combining Coir fibers and crushed coconut shells on the flexural strength of concrete. The study found that the combined use of these materials could enhance the concrete's resistance to bending stresses. Moderate proportions of both additives resulted in improved flexural strength, leveraging the benefits of each material. Coir fibers contributed to better stress distribution and ductility, while crushed coconut shells helped in achieving a lighter mix. However, achieving the best performance required careful balancing of the proportions of each material.

Excessive use of either material could negate the positive effects, emphasizing the need for a well-optimized mix design to maximize the flexural strength while maintaining overall concrete quality. Coir fibers generally enhance flexural strength, particularly when used up to 10%, by improving stress distribution and ductility. Crushed coconut shells can also improve flexural strength up to a certain proportion, but excessive use can reduce overall effectiveness due to increased porosity and diminished compressive strength. A well-balanced mix design that incorporates both materials can optimize flexural strength, leveraging their synergistic effects.

Crack resistance is another critical performance metric for concrete, as it directly influences durability and service life. Research by Yousefieh et al. (2017) has shown that Coir fibers significantly improve crack

resistance by acting as a reinforcement that helps to prevent crack propagation. The fibrous nature of Coir aids in stress distribution, reducing the likelihood of localized failures. Furthermore, Ejaz et al. (2022) highlighted that the presence of Coir fibers mitigates the effects of stress concentrations that typically lead to cracking, especially in high-strength applications.

However, the introduction of crushed coconut shells into the concrete mix presents challenges related to crack resistance. Kassa et al. (2022) emphasized that the porous nature of crushed coconut shells can lead to increased water absorption, which may exacerbate shrinkage and cracking issues. The increased porosity can create voids within the concrete, leading to moisture retention that affects durability. Therefore, careful monitoring of the proportion of crushed coconut shells is essential to maintain the desired crack resistance while reaping the benefits of their lightweight properties.

The interaction between Coir fibers and crushed coconut shells creates a complex dynamic in concrete performance. Çankal et al. (2023) observed that while the combination of these materials can enhance workability and tensile strength, it may also introduce potential weaknesses. Increased moisture absorption from both Coir and crushed coconut shells could lead to greater susceptibility to cracking if not properly managed.

Optimizing the mix design is crucial to balancing these effects. Research suggests that a well-structured mix incorporating both materials can lead to improved overall performance. For example, studies have indicated that an optimal ratio of Coir to crushed coconut shells can maximize both flexural strength and crack resistance, providing a sustainable solution that does not compromise durability (Sujatha & Balakrishnan, 2021).

The empirical evidence indicates that integrating Coir fibers and crushed coconut shells into concrete significantly enhances flexural strength and crack resistance, thereby contributing to the development of sustainable construction materials. While Coir fibers offer substantial benefits in improving mechanical properties, the challenges posed by the porous nature of crushed coconut shells necessitate careful mix design and management. Future research should continue to explore these dynamics, focusing on long-term performance and durability under various environmental conditions, ultimately advancing the field of sustainable concrete technology.

3. Materials and Methods

The research was conducted in the coastal towns of Kilifi, Mombasa, and Kwale in Kenya, regions renowned for their significant coconut cultivation. Each location's tropical climate supports the growth of coconut palms, which are integral to local economies. Kilifi, located approximately 60 km north of Mombasa, benefits from a humid, rainy season ideal for coconut cultivation. Mombasa, as Kenya’s bustling port city, has a long-standing history of coconut agriculture, with palms playing a crucial role in local farming practices. Kwale, situated southwest of Mombasa, shares similar climatic conditions that promote coconut farming

A comprehensive experimental research design was employed to evaluate flexural strength and crack resistance in concrete incorporating coir and crushed coconut shells as partial aggregate replacements. This design followed systematic steps, including identifying key variables, formulating a testable hypothesis, creating experimental treatments, assigning subjects to appropriate groups, and planning measurement methods. This structured approach ensured that the experiment effectively analyzed the relationships between the variables. The study focused on several critical variables. Flexural strength was assessed through standard flexural tests, which measure the concrete's ability to resist bending forces. Crack resistance was evaluated using visual inspections and crack monitoring devices to track the development and propagation of cracks over time. Additionally, parameters such as workability and compressive strength were monitored to provide a comprehensive understanding of the concrete's performance.

The target population comprised concrete mixtures that typically incorporate traditional aggregates. The study specifically aimed to assess the impact of replacing portions of these aggregates with coir and crushed coconut shells, focusing on how these alternative materials influence flexural strength and crack resistance. To ensure a thorough evaluation, a total of 72 concrete cubes and 72 short beam specimens were prepared using a standardized concrete mix ratio of 1:2:4 (cement aggregate aggregate) and a constant water–cement ratio of 0.50. Local materials were sourced to reflect regional construction practices, including river sand, conventional coarse aggregates, Ordinary Portland Cement, coir fibers, and crushed coconut shell aggregates (CCSA). The crushed coconut shell aggregates were used as partial replacements for coarse aggregates at levels of 10%, 20%, and 30%, while coir fibres were incorporated at proportions of 0.1%, 0.2%, and 0.3% by weight of cement. All materials were carefully measured and proportioned uniformly, and identical batching, mixing, casting, compaction, and curing procedures were maintained across all specimens to ensure consistency and reliability of the experimental results.

Key instruments for data collection included the flexural testing machine, used to assess the flexural strength of concrete beams. Visual inspections and crack monitoring devices were employed to evaluate crack resistance, enabling the measurement of crack development over time.

Validation of results was confirmed through comparison of predicted and observed strength and crack resistance values presented in Table 1 to Table 5, which showed consistent trends across Schmidt Hammer, UPV, and flexural strength tests.

The data collection process involved standardized preparation of concrete mixes, immediate workability assessments, and controlled curing of samples. Flexural strength and crack resistance were evaluated at specified curing intervals, ensuring comprehensive data collection relevant to the research objectives.

Data were meticulously cleaned, organized, and analyzed using descriptive statistical methods, including means, ranges, and percentages, to evaluate the flexural strength and crack resistance of the various concrete mixes. The results were presented using tables and graphical representations to highlight the effects of varying proportions of coir fibres and crushed coconut shell aggregates (CCSA) on concrete performance and their implications for sustainable construction practices.

Rigorous testing for normality, homogeneity of variance, and linearity was conducted to validate the research findings. All material tests were performed at KEBS certified laboratories, ensuring adherence to international standards and bolstering the credibility of the research procedures.

4. Results

This section presents the experimental results obtained from testing concrete samples incorporating coir fibers and crushed coconut shell aggregates (CCSA). The results cover flexural strength, crack resistance (via Schmidt Hammer and UPV tests), and durability performance under temperature variation and salinity exposure. The findings are illustrated and discussed with relevant tables and descriptive explanations. Flexural Strength of Concrete Incorporating Coir and Crushed Shells Flexural strength is a key parameter used to assess the ability of concrete to resist bending stresses. In this study, the term “control mix” refers to conventional concrete containing no coir fibres and no crushed coconut shell aggregate (CCSA) replacement, and it serves as the baseline for comparison of all modified mixes. The flexural strength results for all concrete mixes are presented in Table 1.

The results in Table 1 show that the control mix recorded a mean flexural strength of 5.63 MPa, which provides the baseline performance of conventional concrete. The 10% CCSA mix recorded a slightly higher value of 5.80 MPa, indicating that low-level replacement of coarse aggregates with crushed coconut shells can marginally enhance flexural performance due to improved interlocking and internal friction within the concrete matrix. However, increasing the replacement level to 20% and 30% resulted in a progressive reduction in flexural strength, with the 30% CCSA mix recording the lowest value of 3.91 MPa. This decline is attributed to increased porosity, reduced density, and weaker bonding between the coconut shell particles and the cement paste, which collectively reduce the ability of concrete to resist bending stresses. The incorporation of coir fibres improved the flexural performance of mixes containing higher percentages of CCSA. In particular, the mix containing 0.3% coir fibres and 30% CCSA achieved a mean flexural strength of 4.91 MPa. This improvement demonstrates the effectiveness of coir fibres in enhancing crack-bridging capacity, improving stress distribution, and increasing ductility within the concrete matrix. Overall, the findings indicate that while higher proportions of CCSA reduce flexural strength, the addition of coir fibres partially compensates for this reduction by improving internal cohesion and post-cracking behaviour. Therefore, optimal performance is achieved when both materials are used in controlled proportions.

Table 1:Descriptive Statistics for Flexural Strength of Concrete (MPa)

Type of Mix	N	Mean (MPa)	Min	Max
Control Mix (Conventional Concrete)	**6**	**5.63**	**5.20**	**6.10**
10% Crushed Shells	6	5.80	5.40	6.20
20% Crushed Shells	6	5.66	5.10	6.00
30% Crushed Shells	6	3.91	3.50	4.30
0.1% Coir & 10% CCSA	6	4.80	4.30	5.20
0.2% Coir & 20% CCSA	6	4.11	3.70	4.60
0.3% Coir & 30% CCSA	6	4.91	4.50	5.30

4.1. Crack Resistance

Crack resistance is vital for evaluating the long-term durability and service life of concrete structures. The resistance of different mixes to cracking was analyzed using Schmidt Hammer and Ultrasonic Pulse Velocity (UPV) tests.

Table 2: Schmidt Hammer Values for Crack Resistance of Concrete with CCSA

Mix Type	CCSA %	7-Day Schmidt Hammer Value	28-Day Schmidt Hammer Value
Control	-	13.7 - 14.9	16.1 - 19.8
10% CCSA	10	15.0 - 15.4	20.8 - 22.3
20% CCSA	20	16.2 - 16.9	22.1 - 23.1
30% CCSA	30	17.3 - 18.1	23.8 - 25.1

4.2. Crack Resistance by Schmidt Hammer

The Schmidt Hammer test was conducted at 7 and 28 days to assess surface hardness and potential crack development. Table 2 shows the rebound values for mixes incorporating different percentages of crushed shells. From Table 3, it is evident that increasing coir fiber content enhanced rebound values, particularly at **0.3% coir**, which recorded the highest readings (24.0–27.0 at 28 days). This improvement indicates superior crack resistance due to the fiber-bridging mechanism that helps arrest micro-crack propagation. The results reveal that increasing CCSA content enhanced surface hardness and crack resistance, as indicated by the upward trend in rebound values. The 30% CCSA mix displayed the highest Schmidt Hammer readings (23.8–25.1 at 28 days), reflecting improved resistance to cracking and higher surface density. resistance of concrete incorporating coir fibres and crushed coconut shell aggregates (CCSA). The test was used to validate results obtained from the Schmidt Hammer test by assessing the continuity, density, and presence of internal voids within the concrete matrix. The results in Table 5 present averaged UPV values for each concrete mix, ensuring that each specimen is represented as a single consistent dataset. The distance was standardized at 105 mm to reflect the mean wave propagation path after combining the two original measurement points (70 mm and 140 mm).

Table 3: Ultrasonic Pulse Velocity (UPV) Test Results for Concrete with Coir and CCSA

Mix Type (Sample)	Distance (mm)	Average Transit Time (µs)	Average Velocity (km/s)	Crack Depth (×10⁻⁵ mm)	Crack Width
Control Mix (0% Coir, 0% CCSA)	105	53.3	2.125	69.64	6.59
0.2% Coir + 20% CCSA (Sample 3)	105	55.35	1.939	76.58	7.55
0.3% Coir + 30% CCSA (Sample 4)	105	54.95	2.201	68.16	4.73

Table 4: Schmidt Hammer Values for Crack Resistance of Concrete with Coir

Mix Type	Coir %	7-Day Schmidt Hammer Value	28-Day Schmidt Hammer Value
Control	-	13.7 - 14.9	16.1 - 19.8
0.1% Coir	0.1	14.2 - 16.6	22.9 - 25.5
0.2% Coir	0.2	15.0 - 17.0	23.0 - 26.0
0.3% Coir	0.3	15.5 - 17.5	24.0 - 27.0

The results indicate clear differences in internal concrete quality across the mixes. The control mix recorded a pulse velocity of 2.125km/s, representing the baseline structural integrity of conventional concrete. The 0.2% coir and 20% CCSA mix (Sample3) recorded the lowest velocity (1.939 km/s), indicating higher internal voids and reduced continuity within the concrete matrix. This corresponds to a higher crack depth value (76.58×10^{-5}mm), suggesting relatively weaker crack resistance compared to other mixes. In contrast, the 0.3% coir and 30% CCSA mix (Sample 4) exhibited the highest pulse velocity (2.201 km/s) and the lowest crack depth (4.73×10^{-5} mm), indicating improved internal cohesion, reduced porosity, and better crack resistance performance. The presence of coir fibres likely contributed to crack-bridging and improved stress distribution within the matrix, while controlled CCSA content enhanced lightweight structural performance without severely compromising integrity.

Crack Resistance by Ultrasonic Pulse Velocity (UPV) Test

The Ultrasonic Pulse Velocity (UPV) test was conducted to evaluate the internal quality and crack Higher ultrasonic pulse velocities corresponded to improved concrete quality and reduced internal cracking. The results confirm that the 0.3% coir and 30% CCSA mix demonstrated the best crack resistance performance among the tested specimens, consistent with trends observed in the Schmidt Hammer results. This is supported by studies indicating that coconut shell aggregate concrete exhibits enhanced internal structure, durability, and improved performance when optimally proportioned (Gunasekaran *et al.*, 2015; Herring & Thuo, 2022; Ejaz et al., 2022; Sujatha & Balakrishnan, 2021).

Table 5: Ultrasonic Pulse Velocity (UPV) Test Results for Concrete with Coir and CCSA

Mix Type (Sample)	Distance (mm)	Average Transit Time (µs)	Average Velocity (km/s)	Crack Depth (×10⁻⁵ mm)	Crack Width
Control Mix (0% Coir, 0% CCSA)	105	53.3	2.125	69.64	6.59
0.2% Coir + 20% CCSA (Sample 3)	105	55.35	1.939	76.58	7.55
0.3% Coir + 30% CCSA (Sample 4)	105	54.95	2.201	68.16	4.73

In the original measurements, each specimen was tested at two transmission paths (70 mm and 140 mm). However, since both readings represent the same material, the results were revised by averaging the transit time and velocity values to obtain a single representative value per specimen, ensuring consistency and eliminating redundancy.

4.3. Environmental considerations and Durability Characteristics

The durability performance of concrete incorporating coir fibres and crushed coconut shell aggregates was evaluated under elevated temperature exposure conditions. Concrete specimens were subjected to high temperatures ranging between 100°C and 120°C to simulate severe environmental and thermal loading scenarios. The flexural strength of each mix was determined before and after thermal exposure to assess the residual mechanical performance and thermal stability of the modified concrete. The results indicate that all concrete mixes experienced a reduction in flexural strength after exposure to elevated temperatures, confirming the adverse effect of thermal loading on the integrity of the cementitious matrix. The reduction in strength is attributed to moisture loss, internal microcracking, and deterioration of the bond between cement paste and aggregates under heat exposure.

Table 6: Flexural Strength of Concrete Mixes After Exposure to High Temperatures (100–120°C)

Mix Type	Coir %	CCSA %	Initial Flexural Strength (MPa)	After Exposure to Temperature (MPa)
Control	-	-	5.63	5.25
Coir 0.1%	0.1	-	4.80	2.65
Coir 0.2%	0.2	-	4.11	2.21
Coir 0.3%	0.3	-	4.91	3.82
Shells 10%	-	10	5.80	5.12
Shells 20%	-	20	5.66	4.26
Shells 30%	-	30	3.91	1.73
Coir 0.1% + Shells 10%	0.1	10	4.80	2.65
Coir 0.2% + Shells 20%	0.2	20	4.11	2.21
Coir 0.3% + Shells 30%	0.3	30	4.91	3.82

The control mix retained a higher proportion of its original strength compared to most modified mixes, indicating relatively better thermal stability in conventional concrete. Among the modified mixes, those

containing coir fibres demonstrated improved residual strength compared to mixes with only crushed coconut shells, suggesting that fibre reinforcement enhances resistance to thermal-induced cracking. This improvement is attributed to the crack-bridging and stress redistribution capacity of natural fibres, which help maintain structural continuity even after thermal damage. The mix containing 0.3% coir fibres and 30% CCSA exhibited the highest residual flexural strength, indicating superior resistance to thermal degradation among the modified concretes.

These findings are consistent with established research showing that natural fibres improve crack control and post-damage mechanical retention in cementitious composites by enhancing energy absorption and limiting crack propagation under thermal stress conditions Yousefieh et al. (2017). Similar observations have also been reported in studies on coconut shell-based concrete systems, where fibre and lightweight aggregate incorporation improved durability performance under harsh conditions Sujatha & Balakrishnan (2021).

Table 7: Schmidt Hammer Rebound Values and Average Strength Under Indian Ocean Salinity

Mix Type	Coir %	Indian Ocean Salinity (mg/L)	Average Rebound Value (MPa)	Average Strength (MPa)
Control	-	35,000	22.9	29.5
Coir 0.1%	0.1	35,000	36.8	20.0
Coir 0.2%	0.2	35,000	25.0	24.9
Coir 0.3%	0.3	35,000	13.8	13.7

4.4. Salinity Levels

To examine the effects of marine environments, concrete specimens were exposed to salinity equivalent to Indian Ocean conditions (35,000 mg/L). The corresponding Schmidt Hammer and strength results are summarized in Table 7 The results indicate that the control mix performed best under salinity exposure, maintaining a strength of 29.5 MPa. The inclusion of coir fibers produced mixed effects — while the 0.1% coir mix exhibited higher rebound hardness (36.8 MPa), it also experienced a substantial reduction in strength. Increased coir content (0.3%) further weakened the concrete, demonstrating that prolonged salinity can degrade natural fibers and compromise concrete integrity.

5. DISCUSSIONS

This section discusses the experimental findings presented in Section 4, emphasizing the influence of coir fibers and crushed coconut shell aggregates (CCSA) on the mechanical, durability, and environmental performance of concrete. The discussion integrates the observed data trends with relevant literature to provide a deeper understanding of material behavior and its implications for sustainable concrete technology.

5.1. Flexural Strength Performance

The results revealed that replacing conventional aggregates with crushed coconut shells up to 10% slightly improved the flexural strength of concrete. This improvement can be attributed to the rough texture and angular shape of crushed shells, which promote better interlocking within the concrete matrix. Similar observations were made by Njung'e et al. (2023), who reported enhanced bonding characteristics in concrete mixes incorporating lightweight organic aggregates.

However, at higher replacement levels (20–30% CCSA), a notable decline in flexural strength was observed. This reduction is likely due to the increased porosity and weaker bonding between the shells and cement paste. The lower density of the crushed shells may also contribute to non-uniform stress distribution, leading to early failure under flexural loading. These findings are consistent with Gunasekaran et al. (2015), who highlighted that excessive replacement of coarse aggregates with organic materials weakens the structural integrity of concrete. The introduction of coir fibers improved the tensile and flexural properties of concrete, particularly at 0.3% coir content, which achieved the highest recorded flexural strength among fiber-reinforced samples (4.91 MPa). Coir fibers act as micro-reinforcements, bridging micro-cracks and delaying their propagation. This fiber-bridging mechanism enhances post-cracking ductility and energy absorption, corroborating the findings of Sujatha & Balakrishnan (2023), who reported that coir fibers significantly enhance the toughness and strain capacity of concrete composites.

5.2. Crack Resistance Behavior

The Schmidt Hammer and Ultrasonic Pulse Velocity (UPV) tests collectively indicated that both CCSA and coir fibers improved the crack resistance and surface hardness of concrete. The Schmidt Hammer results showed an upward trend in rebound values with increasing shell content, especially at 30% CCSA, suggesting improved surface hardness and crack resistance. This improvement may be attributed to the enhanced internal friction and reduced brittleness provided by the lightweight shell particles. The findings align with Herring & Thuo (2022), who observed that coconut shell concrete exhibits better performance under compressive and impact loads due to its cushioning effect and energy absorption capacity. The coir-reinforced mixes demonstrated even greater enhancement in rebound values. The 0.3% coir mix recorded the highest readings (24.0–27.0 at 28 days), confirming that fibers effectively control micro-crack formation and improve tensile capacity. This agrees with Klemczak *et al.* (2017), who reported that natural fiber reinforcement in concrete helps resist early-age shrinkage cracking by redistributing stresses more evenly across the matrix.

The UPV test results confirmed the Schmidt Hammer findings. Mixes with higher ultrasonic velocities corresponded to fewer internal voids and shallower cracks, indicating better internal cohesion and structural homogeneity. In particular, the 0.3% coir mix exhibited the lowest crack depth and highest pulse velocity, validating its superior internal quality. These results are

consistent with Sayahi *et al.* (2021), who proposed that coir fibers improve the internal structure of concrete by enhancing matrix continuity and reducing crack propagation.

5.3. Performance Under Temperature Variation

Exposure to elevated temperatures (100–120°C) significantly reduced the flexural strength of all concrete mixes. The control mix retained the highest residual strength (5.25 MPa), while mixes containing natural additives exhibited greater losses. The reduction in strength can be linked to thermal decomposition of organic components, moisture loss, and micro-cracking within the matrix. Among the modified samples, the 0.3% coir mix demonstrated the best residual performance (3.82 MPa), suggesting that fiber reinforcement helped mitigate thermal cracking and preserve internal integrity. This observation aligns with Bendimerad *et al.* (2016) and Ghourchian *et al.* (2017), who noted that fiber-reinforced concretes can retain better mechanical properties under thermal stress due to the bridging and confinement effects of fibers. Nevertheless, at higher shell content (≥30%), a sharp strength decline was observed (down to 1.73 MPa), confirming that excessive organic replacement compromises the concrete's resistance to heat. The internal voids created by organic particles promote differential expansion and early cracking, limiting their suitability for high-temperature environments.

5.4. Performance Under Salinity Exposure

The results of the Schmidt Hammer test under Indian Ocean salinity revealed distinct patterns in concrete performance. The control mix maintained the highest compressive strength (29.5 MPa), demonstrating excellent stability in saline conditions. In contrast, the coir-reinforced mixes exhibited variable rebound hardness and reduced compressive strength, particularly at higher coir contents. The 0.1% coir mix showed a high rebound value (36.8 MPa) but a low strength (20.0 MPa), suggesting that while surface hardness increased, internal cohesion was weakened by salt infiltration. At 0.3% coir, strength dropped further to 13.7 MPa, indicating that prolonged salinity exposure accelerates fiber degradation and matrix disintegration. These results support findings by Samouh *et al.* (2017), who observed that saline environments intensify corrosion and weaken fiber-reinforced composites by disrupting the cement-fiber bond. The observed deterioration highlights the need for fiber surface treatment or coating to improve resistance against salt attack, ensuring the long-term durability of coir-reinforced concretes in marine environments.

6. CONCLUSIONS

The study established that the incorporation of crushed coconut shell aggregates (CCSA) influences the flexural strength of concrete depending on the replacement level. Low replacement levels (up to 10%) slightly improved flexural strength, while higher levels (20–30%) resulted in a reduction in strength due to increased porosity and reduced bonding within the cement matrix. This indicates that excessive replacement of conventional aggregates with CCSA negatively affects the load-bearing capacity of concrete. The addition of coir fibres improved the flexural performance of concrete, particularly at 0.3% fibre content, where it helped to partially offset the reduction in strength caused by higher CCSA levels. This improvement is attributed to the crack-bridging and stress redistribution effects of coir fibres, which enhance ductility and delay crack propagation. In terms of crack resistance, both Schmidt Hammer and Ultrasonic Pulse Velocity (UPV) results showed improved performance in mixes containing higher proportions of CCSA and coir fibres when optimally combined. Mixes containing 30% CCSA and 0.3% coir exhibited comparatively better surface hardness and internal integrity than most other modified mixes, indicating reduced crack development. However, performance varied across mix types, confirming that durability is strongly dependent on proper proportioning of the materials. The study therefore concludes that the mechanical and durability performance of concrete can be enhanced through controlled incorporation of CCSA and coir fibres, with optimal performance achieved at moderate replacement and fibre content levels.

Based on the findings of the study, it is recommended that crushed coconut shell aggregates (CCSA) be used as a partial replacement of conventional coarse aggregates at low levels, preferably not exceeding 10%, in order to maintain acceptable flexural strength while benefiting from sustainability advantages. Coir fibres should be incorporated at low dosages, with approximately 0.3% by weight of cement identified as the most effective level in improving flexural performance and crack resistance. The combined use of coir fibres and CCSA should be carefully controlled to avoid excessive porosity and strength loss. Construction practitioners and material engineers are encouraged to adopt these materials in non-critical structural elements where sustainability benefits are prioritized, while ensuring proper mix design optimization to balance strength and durability requirements. Further research is recommended to investigate long-term durability performance of coir and CCSA concrete under aggressive environmental conditions such as marine exposure, thermal cycling, and prolonged loading, to enhance understanding of field applicability

References

Adeniyi, A. G., Onifade, D. V., Ighalo, J. O., & Adeoye, A. S. (2019). A review of Coir fiber reinforced polymer composites. Composites Part B: Engineering, 176, 107305. https://doi.org/10.1016/j.compositesb.2019.107305.

Aljohi, H. A., Liu, W., Lin, Q., Zhao, Y., Zeng, J., Alamer, A., Alanazi, I. O., Alawad, A. O., Al-Sadi, A. M., Hu, S., & Yu, J. (2016). Complete sequence and analysis of coconut Palm (Cocos nucifera) Mitochondrial Genome. PLOS ONE, 11(10), e0163990. https://doi.org/10.1371/journal.pone.0163990.

Ashish, D. K. (2019). Concrete made with waste marble

powder and supplementary cementitious material for sustainable development. Journal of Cleaner Production, 211, 716–729. https://doi.org/10.1016/j.jclepro.2018.11.058.

Bendimerad, A. Z., Rozière, E., & Loukili, A. (2016). Plastic shrinkage and cracking risk of recycled aggregates concrete. Construction and Building Materials, 121, 733-745.

Bheel, N., Chohan, I. M., Ghoto, A. A., Abbasi, S. A., Tag-eldin, E. M., Almujibah, H. R., ... & Gonzalez-Lezcano, R. A. (2024). Synergistic effect of recycling waste coconut shell ash, metakaolin, and calcined clay as supplementary cementitious material on hardened properties and embodied carbon of high strength concrete. Case Studies in Construction Materials, 20, e02980.

Çankal, D., Şakar, G., & Kürşat Çelik, H. (2023). A criticism on strengthening glued laminated timber beams with fibre reinforcement polymers, numerical comparisons between different modelling techniques and strengthening configurations. Revista de la construcción, 22(3), 661-678.

Dakos, V., & Kéfi, S. (2022). Ecological resilience: what to measure and how. Environmental Research Letters, 17(4), 043003.

Ejaz, M. F., Aslam, M., Aziz, W., Khalil, M. J., Ali, M. J., Raheel, M., & Ahmed, A. (2022). Coconut shell waste as an alternative lightweight aggregate in concrete-A review. Advances in Materials Research, 11(4), 299-330.

Eziefula, A. U., Ohagoro, O. C., Abdullahi, S. M., & Osu, A. S. (2023). Investigation of the compressive strength of coconut coir fibre-reinforced concrete. Federal Polytechnic Nasarawa.

Ganiron Jr, T. U., Ucol-Ganiron, N., & Ganiron III, T. U. (2017). Recycling of waste coconut shells as substitute for aggregates in mix proportioning of concrete hollow blocks. World Scientific News, 77(2), 107-123.

Ghourchian, S., Wyrzykowski, M., & Lura, P. (2017). A practical approach for reducing the risk of plastic shrinkage cracking of concrete. RILEM Technical Letters, 2, 40-44.

Gunasekaran, K., Annadurai, R., & Kumar, P. S. (2015). A study on some durability characteristics properties of coconut shell aggregate concrete. Materials and Structures, 48, 1253-1264.

Hasan, S. I., Manon, A. H., Kuddus, M. A., & Hossain, M. M. (2016). Investigation of mechanical behaviour of concrete by replacing cement with coconut shell ash & stone dust. In Proceedings of the 3rd International Conference on Civil Engineering for Sustainable Development (ICCESD 2016) (Vol. 12, pp. 828-835). KUET Khulna, Bangladesh.

Herring, T. C., & Thuo, J. N. (2022). Engineering and durability characteristics properties of modified coconut shell concrete.

Kassa, H. K., Melesse, G., & Yabasa, G. (2022). A Study on Using Glass Fiber-Reinforced Polymer Composites for Shear and Flexural Enhancement of Reinforced Concrete Beams. Advances in Civil Engineering, 2022, 1–12. https://doi.org/10.1155/2022/5995103.

Katre, F. F., Bisen, N. D., Thakur, P. C., Ukey, A. V., & Katre, V. B. (2023). Analysis on reinforced concrete using coconut fibre. Journal of Emerging Technologies and Innovative Research (JETIR).

Klemczak, B., Batog, M., Pilch, M., & Żmij, A. (2017). Analysis of Cracking Risk in Early Age Mass Concrete with Different Aggregate Types. Procedia Engineering, 193, 234–241. https://doi.org/10.1016/j.proeng.2017.06.209.

Koitumet, J. S. M. (2023). Fibre Extraction and Characterization from Coconut Husks Waste FOR Industrial Application (Doctoral Dissertation, School of Engineering, Moi University).

Mangi, S. A., Wan Ibrahim, M. H., Jamaluddin, N., & et al. (2021). Influence of coal ash on the concrete properties and its performance under sulphate and chloride conditions. Environmental Science and Pollution Research, 28(44), 60787–60797. https://doi.org/10.1007/s11356-021-15006-x.

Marandi, S., & Kumar, S. (2023). Performance of coconut shell as coarse aggregate in concrete. International Journal of Research and Analytical Reviews (IJRAR).

Morris, O. (2018). Suitability of Crushed Ceramic and Porcelain Clay Tiles as Partial Replacement of Cement in Concrete (Doctoral dissertation, JKUAT-PAUSTI).

Njung'e, M. O., Kakoi, B. K., & Mburu, N. (2023). Evaluation of crushed slates as a suitable capping material for rapid gravity sand filters. Journal of Agriculture, Science and Technology, 22(4), 64-82.

Okvianti, A., & Febrianty, L. P. (2022). Analisis kuat tekan dan kuat tarik belah pada beton dengan penambahan serat serabut kelapa dan batu apung. Indonesian Journal of Construction Engineering and Sustainable Development (CESD).\

Oliko, C. (2023). Investigating the Physical, Mechanical and Durability characteristics Properties of Concrete having Cement Partially Replaced with Rice Straw and Egg Shell Ashes (Doctoral dissertation, JKUAT-COETEC

Prasad, K., Thambiannan, S., Anthonysamy, A., Jalgaonkar, K., Dukare, A. S., Pandiselvam, R., & Jha, N. (2024). Coir fibre-reinforced concrete for enhanced compressive strength and sustainability. Heliyon, 10(21), e39773. https://doi.org/10.1016/j.heliyon.2024.e39773. (doi.org in Bing)

Samouh, H., Rozière, E., Wisniewski, V., & Loukili, A. (2017). Consequences of longer sealed curing on drying shrinkage, cracking and carbonation of concrete. Cement and Concrete Research, 95, 117-131.

Sayahi, F., Emborg, M., Hedlund, H., Cwirzen, A., & Stelmarczyk, M. (2021). The severity of plastic shrinkage cracking in concrete: a new model. Magazine of Concrete Research, 73(6), 315-324.

Selvaraj KS, V. (2017). Evaluation of coconut hybrids developed for high nut and copra. Agricultural

Research & Technology: Open Access Journal, 5(4). https://doi.org/10.19080/artoaj.2017.05.555667.

Singhal, V., Nagar, R., & Agrawal, V. (2020). Sustainable use of fly ash and waste marble slurry powder in concrete. Materials Today: Proceedings, 32, 975–981. https://doi.org/10.1016/j.matpr.2020.01.336.

Springer. (2023). Machine learning-based prediction of concrete strength incorporating coconut shell. SpringerLink.

Sujatha, A., & Balakrishnan, S. D. (2021). Properties of Coconut Shell Aggregate Concrete: A Review. In R. M. Singh, K. P. Sudheer, & B. Kurian (Eds.), Advances in Civil Engineering (pp. 759–769). Springer. https://doi.org/10.1007/978-981-15-5644-9_60.

Yousefieh, N., Joshaghani, A., Hajibandeh, E., & Shekarchi, M. (2017). Influence of fibers on drying shrinkage in restrained concrete. Construction and Building Materials, 148, 833–845. https://doi.org/10.1016/j.conbuildmat.201. 7.05.093. Research, 32(8), 1251–1258