Multidisciplinary Journal of TUM 4(2) 2025: 74-87 https://doi.org/10.48039/mjtum.v4i2.99 **Research Article**

Sustainable Concrete with Coir and Crushed Coconut Shells: Workability and Strength Performance

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Abstract

The increasing demand for sustainable materials within the construction industry has heightened interest in alternative aggregates for concrete, motivated by escalating costs and environmental concerns associated with conventional natural aggregates. The overexploitation of these resources has led to scarcity and increased expenses, underscoring the necessity for cost-effective solutions that maintain concrete's performance and structural integrity. Furthermore, the improper disposal of agricultural by-products, such as coir and crushed coconut shells, exacerbates waste management challenges and poses environmental risks. This paper aimed to evaluate the workability and compressive strength of concrete incorporating coir fibers and crushed coconut shells as aggregate replacements. The study was conducted in the counties of Kilifi, Mombasa, and Kwale in Kenya, with a focus on the utilization of coir and crushed coconut shells in concrete mixtures. The experimental design involved the preparation of concrete mixtures with coir percentages of 0.1%, 0.2%, and 0.3%, along with crushed coconut shell aggregates at 10%, 20%, and 30% by volume. Key variables assessed included workability—measured through the Slump Test, Flow Table Test, and Vebe Consistometer. The mechanical properties, were evaluated via compressive strength and durability tests. A total of 72 concrete cubes and 72 short beams were prepared using locally sourced materials to ensure relevance to regional practices. Data collection adhered to standardized protocols, and the validity and reliability of measurement instruments were established through expert reviews and consistency checks. The study demonstrates that incorporating crushed coconut shell aggregates (CCSA) into concrete significantly reduces workability due to increased water demand and lower density. Conversely, adding coir fibers enhances workability, although excessive coir can negatively affect it. Compressive strength reduces making CCSA up to 20%, the minimum structurally usable mix, with, but further additions produces compression strength only suitable for non-structural use. The inclusion of 0.3% coir fibers further boosts compressive strength, especially with CCSA. This study recommends limiting coir to 0.3% for optimal workability and promoting CCSA use up to 20%, along with further research on their microstructural impacts.

Key Words: Workability, Compressive Strength, Sustainable Concrete, Coir, Crushed Coconut Shells, Partial Aggregate Replacements

Introduction

The construction industry is one of the largest consumers of natural resources globally and a significant contributor to environmental degradation. Traditional concrete production depends heavily on natural aggregates such as sand, gravel, and crushed stone, whose extraction has caused serious ecological problems including habitat destruction, groundwater depletion, soil erosion, and substantial carbon emissions (Cruz et al., 2020). With global urbanization and infrastructure development accelerating, the demand for these resources continues to rise, exacerbating environmental challenges and increasing the costs of construction materials. Consequently, there is an urgent imperative to identify and adopt more sustainable alternatives that can reduce the environmental footprint of concrete

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production without compromising its mechanical performance or durability.

In response to these challenges, research has increasingly focused on the use of agricultural and industrial by-products as partial or full replacements for natural aggregates in concrete. Utilizing waste materials not only addresses the problem of resource depletion but also provides a solution to waste management issues, turning otherwise discarded materials into valuable construction inputs (Mishra & Basu, 2020). Among the most promising of these alternatives are coir fibers and crushed coconut shells (CCSA), which originate from the abundant coconut industry, especially prevalent in tropical regions. Coir fibers, extracted from the fibrous husk of coconuts, possess desirable mechanical properties such as high tensile strength, flexibility, and resistance to environmental degradation. Their incorporation into concrete has shown potential to enhance tensile strength, reduce crack propagation, and improve impact resistance (Jeevana et al., 2023; Okvianti & Febrianty, 2022). This makes coir a natural reinforcement material capable of substituting or supplementing synthetic fibers and steel reinforcements, thereby offering a more environmentally friendly and cost-effective alternative (Hayes et al., 2019). Furthermore, coir fibers have low thermal conductivity, which could contribute positively to the thermal insulation properties of concrete. Similarly, crushed coconut shells have been investigated as lightweight aggregate replacements. Their use offers the benefit of reducing the overall density of concrete, which is advantageous for structures where weight reduction is critical, such as high-rise buildings or long-span bridges (Karugu, 2019). Beyond structural benefits, the utilization of crushed coconut shells addresses the environmental problem posed by coconut shell waste, which decomposes slowly and accumulates in large quantities in coconut-producing regions (Mbachu, 2023). Recycling these shells into concrete promotes the principles of circular economy, reducing waste and conserving natural aggregate resources. Despite these benefits, existing literature highlights several critical issues and challenges that require further exploration and resolution.

The incorporation of coir fibers and crushed coconut shells in concrete offers promising enhancements, yet the mechanical performance reported in the literature shows notable variability. This inconsistency is a critical issue that complicates the material's acceptance in mainstream construction. For example, Main et al. (2015) found that moderate coir fiber additions, up to 10% by volume, improved tensile strength and workability, primarily by reinforcing the matrix and mitigating crack propagation. However, when fiber content exceeded this threshold, a decline in compressive strength was observed. This reduction is often attributed to fiber clustering and inadequate bonding with the cement paste, which compromises the concrete's structural integrity. The hydrophobic nature of untreated coir fibers further exacerbates this issue by weakening the fiber-matrix interface, leading to reduced load transfer efficiency. Similarly, Mishra and Basu, (2020) examined the effects of replacing fine aggregates with crushed coconut shells and reported that up to 10% replacement caused no significant loss in compressive strength. This finding highlights the potential of coconut shells as lightweight, eco-friendly aggregate substitutes that can reduce the density of concrete while maintaining performance. However, increasing the replacement beyond 10% resulted in a marked increase in porosity and a consequent drop in strength. The porous and absorptive characteristics of coconut shells lead to higher void content and a less dense microstructure, which undermines load-bearing capacity and durability. These divergent outcomes emphasize the necessity of meticulous mix design and material processing techniques to harness the benefits of natural fibers and aggregates without compromising essential mechanical properties.

Durability remains a cornerstone of concrete performance, especially for infrastructure subjected to aggressive environmental conditions such as chemical exposure, freeze-thaw cycles, and mechanical abrasion. Coir fibers have been reported to enhance durability by reducing permeability and improving crack resistance, as noted by Jeevana et al. (2023). This enhancement is critical in mitigating ingress of deleterious agents like chlorides and sulfates, which accelerate corrosion of reinforcement and concrete deterioration. However, the existing literature reveals a significant gap in long-term empirical studies evaluating the environmental resilience of coir- and coconut shell-modified concretes under real-world exposure scenarios. Herring and Thuo, (2022) contributed valuable insights regarding the use of coconut shell ash, highlighting its potential to improve resistance against sulphuric acid attack and elevated temperature conditions. Despite this, their work—and others like it—has not comprehensively addressed other durability factors such as freeze-thaw resistance, carbonation rates, and chloride penetration, which are critical for reinforced concrete structures. The lack of data on these fronts limits the understanding of how these bio-based modifications influence the lifespan and maintenance needs of concrete infrastructure, presenting a barrier to their widespread adoption. The integration of natural fibers and lightweight agricultural aggregates into concrete introduces substantial challenges in achieving consistent and workable mixes. The fibrous, entangling nature of coir fibers tends to reduce the flowability of fresh concrete, as fibers can cluster or ball together if not properly dispersed. Koku-Ojumu et al. (2022) observed that increased content of coconut shell ash similarly reduced workability, complicating the mixing and casting process. These challenges necessitate precise adjustments in mix design, including the use of chemical admixtures such as superplasticizers, and modifications to water content to maintain adequate slump and ensure uniform compaction (Figure 1).

Figure 1. Appearance of CS and conventional aggregate particles (Source: Gómez-Hernández et al., 2023)

Without such adjustments, concrete mixes incorporating these materials risk poor homogeneity, leading to voids and weak zones that compromise structural integrity. Ru et al. (2022) emphasized that tailored mix designs and pretreatment of fibers—such as chemical surface modification to improve dispersion - are crucial for balancing the mechanical benefits with practical constructability. Consequently, addressing these workability issues is essential not only for ensuring performance but also for minimizing labor costs and preventing defects during construction. Another significant research gap is the limited investigation into the effects of coir fibers and coconut shell aggregates on high-strength concrete (HSC). HSC, typically characterized by compressive strengths exceeding 40 MPa, is essential for demanding applications such as high-rise buildings, bridges, and critical infrastructure where superior mechanical performance and durability are imperative. Most extant studies have focused predominantly on normal or low-strength concretes, leaving a critical void in knowledge regarding how these natural materials behave within the dense microstructure and stringent performance requirements of HSC.

Katte et al., (2022) underscores the importance of this knowledge gap, noting that without comprehensive studies, the structural integrity and longevity of HSC modified with coir and coconut shells remain uncertain. The unique challenges posed by HSC—such as lower water-to-cement ratios, higher cement content, and denser matrices—may interact differently with natural fibers and aggregates compared to conventional concrete (Figure 1). Bridging this gap is crucial to expanding the sustainable use of agricultural waste products in high-performance, safety-critical construction environments. The feasibility and impact of utilizing coir fibers and crushed coconut shells in concrete are heavily influenced by regional factors, particularly the geographic distribution of coconut cultivation. For instance, Kenya's coastal counties—including Mombasa, Malindi, Lamu, and Kwale—are abundant in coconut trees, producing millions of tons of husk and shell waste annually (Nuts and Oil Crops Directorate, 2022). Despite this substantial resource availability, local construction industries have yet to fully capitalize on these materials as cost-effective, sustainable alternatives to conventional aggregates.

Utilizing locally sourced coir and coconut shells offers multifaceted benefits: it reduces dependency on imported construction materials, mitigates environmental pollution from agricultural waste disposal, and stimulates local economies by creating new value chains (Herring & Thuo, 2022). However, successful application depends on region-specific research that addresses the unique properties of local coconut materials, their processing techniques, and environmental factors affecting performance. Tailored studies could unlock optimized concrete formulations that are economically viable and environmentally sustainable for local infrastructure development. This study focused on evaluating the workability and compressive strength of concrete when coir fibers and crushed coconut shells were used as partial replacements for traditional aggregates. The investigation was guided by two main objectives: first, to assess the workability of concrete incorporating coir and crushed coconut shells, and compare it to that of conventional concrete; and second, to determine the compressive strength of the modified concrete relative to standard concrete mixes. These objectives aimed to explore the feasibility of using agricultural waste materials in concrete without compromising performance, thereby promoting sustainable construction practices.

Materials and Methods

Study Area

The present study was conducted in the coastal towns of Kilifi, Mombasa, and Kwale in Kenya, in a coastal region known for its significant coconut cultivation (Figure 2). Each location's tropical climate supports the growth of coconut palms, making them integral to the local economies. Kilifi Town, situated approximately 60 km north of Mombasa, enjoys a humid, rainy season ideal for coconuts. Mombasa, as Kenya's bustling port city, has a long history of coconut agriculture, with palms deeply embedded in local agricultural practices. Kwale Town, located southwest of Mombasa, shares similar climatic conditions, promoting coconut farming.

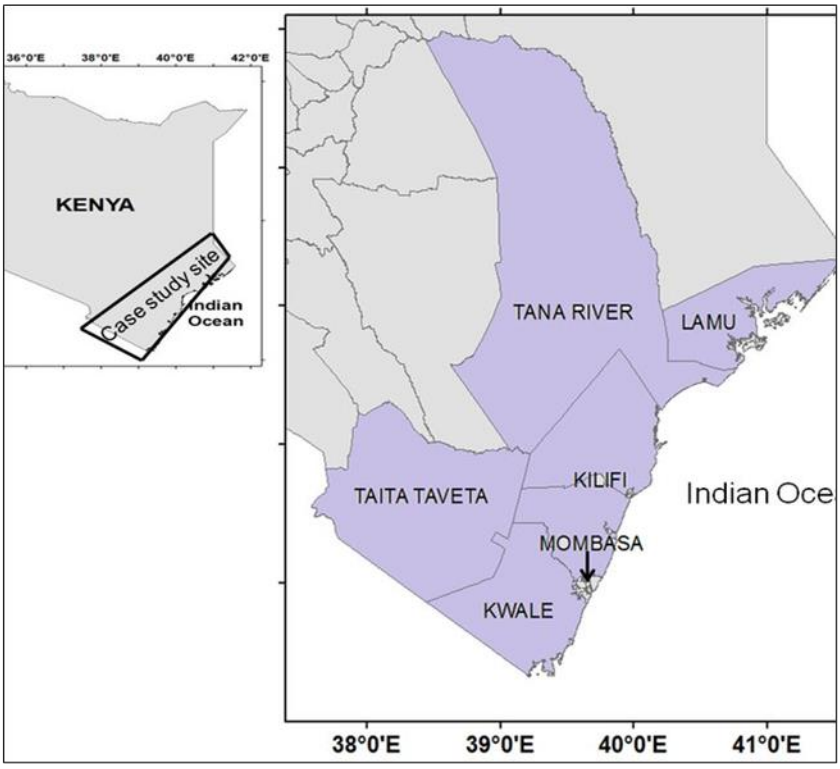

Figure 2. A map of the study area showing the study sites of Kilifi, Mombasa and Kwale in coastal Kenya

Research Design

A comprehensive experimental research design was employed to evaluate concrete with coir and crushed coconut shells as partial aggregate

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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 was capable of analyzing causal relationships effectively.

Description of Study Variables

The present study focused on several critical variables. Workability was assessed through the Slump Test, Flow Table Test, and Vebe Consistometer, which measure the consistency and ease of handling of the concrete mix. Mechanical properties were evaluated through tests for Compressive Strength, Tensile Strength, Modulus of Elasticity, and Shear Strength, providing insights into the concrete's structural performance. Durability characteristics were examined via Water Absorption, Freeze-Thaw Resistance, Chemical Resistance, and Corrosion Resistance tests, reflecting the concrete's ability to withstand environmental conditions over time.

Target Group

The target population comprised concrete mixtures typically incorporating traditional aggregates, with a focus on assessing the impact of replacing these aggregates with coir and crushed coconut shells. This approach aimed to understand how the inclusion of alternative materials affects the overall performance and sustainability of concrete in structural applications.

Sample Size and Sampling Procedure

To ensure sufficient data for statistical analysis, a total of 72 concrete cubes and 72 short beams were prepared. Local materials were sourced to reflect regional practices, including river sand, coarse aggregates, Ordinary Portland cement, coir fibers, and crushed coconut shell aggregates. These materials were proportioned according to experimental requirements, ensuring relevance to local construction methods.

Data Collection Instruments

Key instruments for data collection included the slump cone, flow table, and Vebe consistometer for assessing workability. The concrete compression testing machine was used to measure the compressive strength of the concrete samples, allowing for accurate evaluation of the material's load-bearing capacity.

Validity and Reliability of Instruments

Validity was addressed through expert reviews, pilot tests, and comparisons with established benchmarks to ensure that the measurement methods adequately covered relevant aspects of concrete properties. Reliability was maintained through internal consistency checks, where multiple technicians conducted tests to confirm that results remained consistent across different evaluations.

Data Collection Procedure

The data collection process involved standardized preparation of concrete mixes, followed by immediate workability tests and controlled curing of samples. Mechanical properties, such as compressive strength, were assessed at specified curing intervals, ensuring comprehensive data collection relevant to the research objectives.

Data Analysis and Presentation

Data were cleaned and organized for analysis using descriptive statistics for initial assessments. Inferential statistics, including ANOVA, t-tests, and regression analysis, were applied to evaluate relationships between variables. Results were descriptively analysis and presented in tables and graphical representations, highlighting key findings and their implications for concrete properties.

Test for Assumptions

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.

Results and Discussion

Workability

The slump test for concrete made with partial replacement of concrete aggregates with

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crushed coconut shells were carried out with each mix having three samples and their mean was ascertained (Table 1).

Table 1. Results of concrete made with partial replacement of concrete aggregates with CCSA

	N	Mean	Min	Max
Mix design (control sample)	**3**	**57.95 ± 1.370**	**55.29**	**59.85**
Mix design+10%CCSA	3	33.88± 2.054	31.35	37.95
Mix design+ 20%CCSA	3	14.79 ± 0.673	13.86	16.10
Mix design+ 30%CCSA	3	11.58 ± 0.413	10.89	12.32

Results of Table 1 presents descriptive statistics for concrete mixes incorporating varying levels of crushed coconut shell aggregates (CCSA) as a partial replacement for natural aggregates. Specifically, the data highlights how the substitution of traditional aggregates with CCSA affects the slump of the concrete, which is a measure of workability. Initially, the control mix, which contains no CCSA, had a mean slump of 57.95 mm. This value serves as the baseline for assessing the impact of CCSA on concrete workability. When 10% of the natural aggregates were replaced with CCSA, the mean slump decreased significantly to 33.88 mm. This substantial reduction in slump indicates that even a modest inclusion of CCSA negatively impacts the workability of the concrete.

Increasing the proportion of CCSA to 20% led to a more pronounced drop in the mean slump, which fell to 14.79 mm. This indicates a further decrease in the concrete's workability as the percentage of CCSA increases. At 30% CCSA, the slump value was the lowest, at 11.59 mm, demonstrating the most significant reduction in workability compared to the control sample. The statistical analysis provided an $F = 270.828$ and $p < 0.001$. These results from the ANOVA test confirm that the differences in slump across the various mix designs are statistically significant. The high F-value and very low p-value indicate that the variations in CCSA content have a meaningful and significant impact on the slump of the concrete.

These findings are consistent with previous studies, such as those by Sabarish (2020), who noted that the non-uniform shapes and rough surfaces of coconut shells create gaps and voids in the concrete mix, making it challenging to achieve a homogeneous and cohesive mixture. Additionally, research by Leman et al. (2017) and Bheel et al. (2021, 2022) supports the observation that the irregular surface of CCSA does not interlock well with cement paste and other aggregate particles, thereby reducing the fluidity and flowability of the concrete. The presence of CCSA thus significantly impairs the workability of the mix, reinforcing the observed trend of decreased slump values with increased CCSA content. Results show a clear decreasing trend in slump values as the percentage of crushed coconut shell aggregate (CCSA) increases in the concrete mix (Figure 3). This trend signifies that higher replacement levels of conventional aggregates with CCSA result in reduced workability of the concrete, as indicated by the lower slump values.

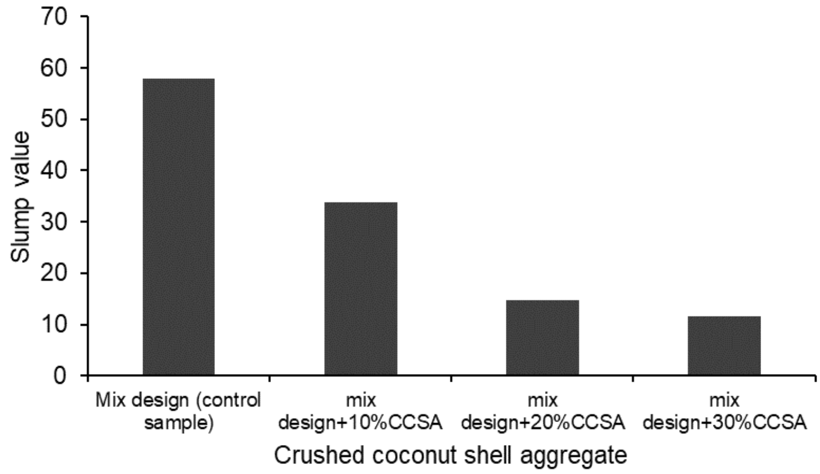

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Figure 3. Slump Mean for Concrete Aggregates with CCSA

Crushed coconut shells are lighter than traditional aggregates such as gravel or sand, which introduces air voids and decreases the overall density of the concrete mix. As the proportion of CCSA in the mix rises, the concrete's density diminishes, impacting its workability and leading to lower slump values. Additionally, higher CCSA content increases the surface area of the lightweight aggregate, which requires more water for adequate lubrication. This increased water demand further diminishes the workability and slump of the concrete. Therefore, the observed decrease in slump values with higher CCSA content indicates a reduction in the cohesion and flowability of the concrete mix. This suggests that the use of CCSA affects the concrete's consistency, making it more challenging to handle and shape as the percentage of replacement aggregate increases. Post-hoc tests were further conducted to examine this relationship (Table 2).

Table 2. Post Hoc Results of the Effect of Coconut Shells on Concrete Mixture

(I) type of mixture	(J) type of mixture	Mean Difference (I-J)	Sig.	95% Confidence Interval	
				Lower Bound	Upper Bound
Mix design (control sample)	mix design +10% CCSA	24.07*	0.000	19.8418	28.2982
	mix design +20% CCSA	43.15*	0.000	38.9285	47.3848
	mix design +30% CCSA	46.36*	0.000	42.1352	50.5915
mix design+10% CCSA	Mix design (control)	-24.07*	0.000	-28.2982	-19.8418
	mix design +20% CCSA	19.08*	0.000	14.8585	23.3148
	mix design +30% CCSA	22.29*	0.000	18.0652	26.5215
mix design+20% CCSA	Mix design (control)	-43.15*	0.000	-47.3848	-38.9285
	mix design +10% CCSA	-19.08667*	0.000	-23.3148	-14.8585
	mix design +30% CCSA	3.20667	0.118	-1.0215	7.4348
mix design+30% CCSA	Mix design (control)	-46.36333*	0.000	-50.5915	-42.1352
	mix design +10% CCSA	-22.29333*	0.000	-26.5215	-18.0652
	mix design +20% CCSA	-3.20667	0.118	-7.4348	1.0215

The post hoc results in Table 2 provide detailed comparisons between the different concrete mixtures, including the control sample and mixtures with varying percentages of crushed coconut shell aggregate (CCSA). These comparisons help elucidate how each mixture differs significantly from the others in terms of their slump values. From Table 4, we observe that the mean slump values are significantly lower in mixes with CCSA compared to the control sample. Specifically, the control mix shows a mean slump that is significantly higher than those of mixes with 10%, 20%, and 30% CCSA, with mean differences of 24.07 mm, 43.16 mm, and 46.36 mm respectively. These differences are statistically significant, as indicated by the p-values (Sig. = 0.000), which are well below the 0.05 threshold. The confidence intervals for these differences do not include zero, further confirming the statistical significance.

Comparing the 10% CCSA mix to the control sample, there is a significant mean difference of -24.07 mm, indicating a substantial decrease in slump value with the addition of 10% CCSA. This trend continues with the 20% and 30% CCSA mixes, which show mean differences of -19.09 mm and -22.29 mm respectively, all

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significant at the 0.05 level. This suggests that increasing CCSA content reduces workability, as reflected in the lower slump values. When examining the 20% CCSA mix, it shows a significant decrease in mean slump compared to the control mix with a difference of -43.16 mm, and also compared to the 10% CCSA mix with a difference of -19.09 mm. However, the difference between the 20% and 30% CCSA mixes is not statistically significant, with a p-value of 0.118, suggesting that the addition of an additional 10% CCSA beyond 20% does not produce a significant further decrease in slump. Lastly, for the 30% CCSA mix, significant decreases are observed compared to both the control mix and the 10% CCSA mix, with mean differences of -46.36 mm and -22.29 mm respectively. However, the difference between the 30% CCSA and 20% CCSA mixes is not statistically significant, indicating that beyond a certain level, the impact of increasing CCSA on slump values may plateau.

The post hoc analysis confirms that higher percentages of CCSA result in significantly lower slump values, highlighting a substantial reduction in workability as more CCSA is added to the concrete mix. These findings align with the understanding that CCSA, being a lightweight aggregate, introduces air voids into the mix and reduces overall density, which impacts workability. As the proportion of CCSA increases, the need for more water to maintain workability becomes apparent, contributing to the observed lower slump values. The results emphasize that higher levels of CCSA adversely affect the concrete's consistency and flowability, reinforcing the trend of decreased workability with increased CCSA content. Similarly, the slump test for concrete made with partial replacement of concrete aggregates with Coir were carried out with each mix having three samples and their mean was ascertained (Table 3).

Table 3. Descriptive Results for concrete made with partial replacement of concrete aggregates with coir

Type of mixture	N	Mean	Std. Error	Minimum	Maximum	F(P-Value)
Mix design (control sample)	3	57.9500	1.37011	55.29	59.85	249. 295
mix design+0.1% Coir	3	60.8000	0.56607	59.99	61.89	(<0.001)
mix design+0.2% Coir	3	79.4600	0.79793	78.22	80.95	
mix design+0.3% Coir	3	88.4600	0.79793	87.22	89.95	

Results in Table 3 provide a comprehensive overview of how different percentages of Coir fibers affect the slump values of concrete mixtures, shedding light on their impact on workability. The control mix, without coir fibers, had a mean slump of 57.95 mm, establishing the baseline for comparison. When 0.1% coir fibers were introduced, the mean slump increased slightly to 60.80 mm. This modest rise in slump indicates a minor improvement in workability compared to the control sample. Increasing the Coir content to 0.2% led to a more significant increase in mean slump to 79.46 mm. This substantial improvement in workability suggests that the addition of Coir fibers enhances the fluidity and ease of handling of the concrete. This aligns with findings by Solangi et al. (2021), who noted that the fibrous nature of Coir promotes better binding of concrete components, resulting in improved consistency and ease of placement. The Coir fibers likely help reduce the risk of segregation by ensuring a more uniform distribution of aggregates and cement paste.

At 0.3% Coir, the mean slump value rose to 88.46 mm, showing the highest workability among the tested mixtures. However, despite the increased slump, this result suggests that very high levels of Coir might lead to potential challenges in workability similar to those observed with high levels of crushed coconut shell aggregate (CCSA). The findings are supported by Vaishnavi et al. (2021), who indicated that Coir fibers provide internal reinforcement, enhancing the structural integrity of the concrete mix, which could contribute to increased slump values. Furthermore, Namandadin et al. (2020) found that the absorbent properties of Coir fibers help regulate water content, which prevents excessive bleeding and maintains optimal fluidity. The F-value of 249.295 with a $p < 0.001$ confirms that the differences in slump values among the various Coir content mixtures are statistically significant. This indicates that the addition of Coir fibers has a meaningful impact on improving the workability of the concrete. The results demonstrate that incorporating coir fibers improves the workability of concrete, with higher percentages leading to progressively greater slump values. However, very high levels of coir might introduce workability challenges similar to those seen with high levels of other aggregates, suggesting a need to balance Coir content for optimal performance. The resultant means for concrete made with partial replacement of concrete aggregates with coir are further illustrated (Figure 4).

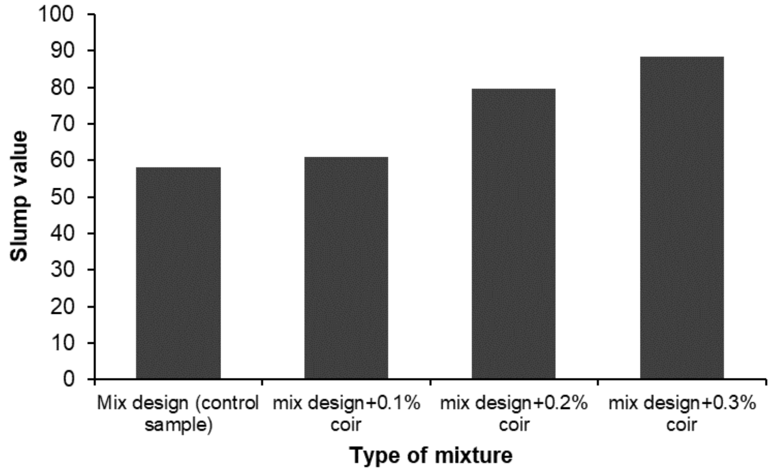

Figure 4. Slump Means for Concrete Aggregates with CCSA

Table 4 presents the post-hoc analysis results comparing the mechanical properties of concrete mixtures incorporating different percentages of coir. This table details the mean differences in performance between various coir-mixed concrete samples and the control mix. It includes standard errors, significance levels, and 95% confidence intervals for each comparison. Significant differences, indicated by an asterisk, highlight the statistical relevance of coir percentages on concrete's mechanical properties.

Table 4. Post-Hoc Results for Concrete Mixed with Coir. Asterisk means difference is significant at the 0.05 level.

(I) Type of mixture	(J) Type of mixture	Mean Difference (I-J)	Sig. p-value
Mix design (control sample)	Mix design +0.1% Coir	-2.85	0.062
	Mix design +0.2% Coir	-21.51*	0.000
	Mix design +0.3% Coir	-30.51*	0.000
mix design +0.1% Coir	Mix design (control)	2.85	0.062
	Mix design +0.2% Coir	-18.66*	0.000
	Mix design +0.3% Coir	-27.66*	0.000
mix design +0.2% Coir	Mix design (control)	21.51*	0.000
	Mix design +0.1% Coir	18.66*	0.000
	Mix design +0.3% Coir	-9.00*	0.000
mix design +0.3% Coir	Mix design (control)	30.51*	0.000
	Mix design +0.1% Coir	27.66000*	0.000
	Mix design +0.2% Coir	9.00000*	0.000

Table 4 outlines the post-hoc analysis comparing the mean slump values across various concrete mixtures containing different percentages of Coir fibers. The results reveal significant differences in workability between the different Coir content mixes. The control mix, which had no Coir, was compared with mixtures containing 0.1%, 0.2%, and 0.3% Coir. The comparison showed that the control mix had a significantly higher mean slump than the 0.2% and 0.3% Coir mixes, with mean differences of -21.51 mm and -30.51 mm, respectively. These differences are statistically significant (p-value < 0.001), indicating that the inclusion of 0.2% and 0.3% Coir fibers significantly reduced the slump value compared to the control mix. The confidence intervals for these differences do not include zero, confirming the robustness of these findings.

In the comparison between the control mix and the 0.1% Coir mix, the mean difference of -2.85 mm was not statistically significant (p-value = 0.062), suggesting that the addition of 0.1% Coir did not lead to a meaningful change in slump compared to the control mix. When analyzing the 0.1% Coir mix against the 0.2% and 0.3% Coir mixes, the results showed significant mean differences of -18.66 mm and -27.66 mm, respectively. These differences are statistically significant (p< 0.001), indicating that the addition of 0.2% and 0.3% Coir fibers resulted in a substantial reduction in slump compared to the 0.1% Coir mix. The confidence intervals for these differences confirm that the reductions are both substantial and statistically significant. Between the 0.2% and 0.3% Coir mixes, the mean difference of -9.00 mm is also statistically significant (p < 0.001). This indicates that while increasing the Coir content from 0.2% to 0.3% resulted in a significant decrease in slump, the effect was less pronounced compared to the reductions observed with lower percentages of Coir. This indicates that the addition of Coir generally improves the workability of concrete, making it less fluid (lower slump values). The negative mean differences across all comparisons between mixtures with Coir and the control sample confirm that Coir inclusion enhances the concrete's workability by reducing its fluidity. Therefore, the findings provide robust evidence supporting the use of Coir as a beneficial additive for enhancing the workability of concrete mixture. However, the results of the post-hoc analysis indicate that higher percentages of Coir fibers significantly reduce the workability of the concrete mix. Hence, the suggestion that while Coir fibers can improve certain aspects of concrete performance, excessive amounts may lead to challenges in handling and workability, similar to other aggregate additives (Figure 5).

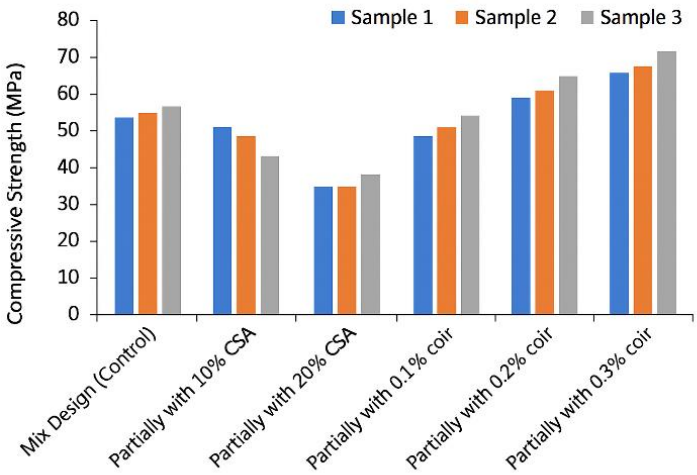

Figure 5. Comparison of slump results between Coir and CCSA

The mix design control samples consistently show moderate to high values of workability across all three samples, with Sample 3 having the highest value. Further increasing CCSA to 20% drastically reduces workability across all samples, with Sample 3 again exhibiting the highest workability. At 30% CCSA, workability continues to decrease, indicating that higher proportions of CCSA negatively impact workability. Sample 3 still shows the highest workability among the three samples. However, Introducing 0.1% Coir into the mix design results in improved workability compared to CCSA mixtures, with consistent and moderate workability values across all samples. Increasing Coir content to 0.2% further enhances workability significantly, with all samples showing higher workability values compared to CCSA mixtures. At 0.3% Coir, workability reaches its peak, demonstrating substantial improvement compared to other mixtures. All samples

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consistently exhibit very high workability values. Therefore, increasing the percentage of CCSA leads to a significant reduction in workability. In contrast, adding Coir into the mix design enhances workability, with higher percentages of Coir (0.2% and 0.3%) resulting in the highest workability values (Figure 6).

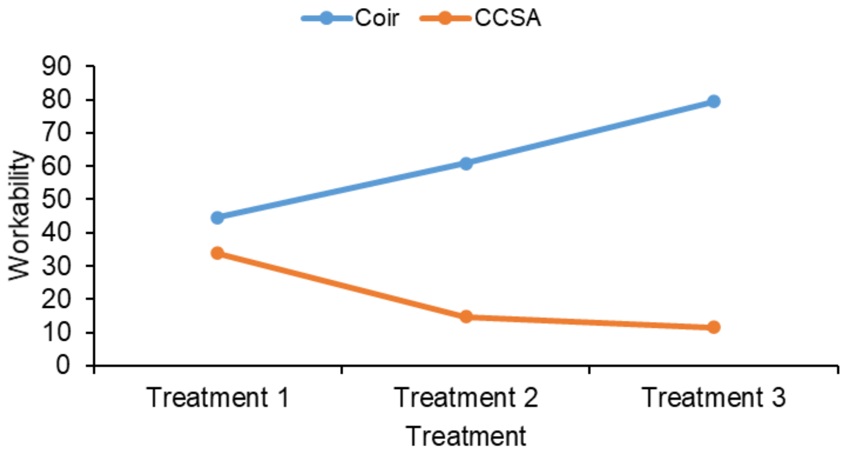

Figure 6. Workability Results for concrete made with partial replacement of CA with Coir and CCSA)

Compressive Strength

To assess the impact of CCSA on the compressive strength of concrete, various mixes were prepared with different percentages of CCSA replacement. The compressive strength was tested at 7 and 28 days. Table 5 summarizes the results, showing how different levels of CCSA replacement affect concrete strength. The results illustrate the effect of CCSA on the compressive strength of concrete. The data reveal that compressive strength increases with up to 20% CCSA replacement, with notable improvements at both 7 and 28 days. Specifically, the mean compressive strength at 10% CCSA replacement reached 15.44 MPa at 7 days and 23.51 MPa at 28 days. At 20% CCSA, the strength further increased to 16.76 MPa at 7 days and 24.88 MPa at 28 days. These findings align with Sujatha and Balakrishnan (2023), who also observed an increase in compressive strength with CCSA. However, a 30% replacement level led to a decrease in strength, consistent with Mbachu (2023).

Table 5. Compressive Strength of Concrete with Different Levels of CCSA Replacement

Type of Mix	7 Days Compressive Strength (MPa)	28 Days Compressive Strength (MPa)
	S1	S2
Control Mix	**12.8**	**16.26**
10% CCSA Replacement	14.02	17.01
20% CCSA Replacement	15.65	18.32
30% CCSA Replacement	9.33	9.76

Descriptive Statistics

To provide a deeper understanding of the variation in compressive strength across different mixes, Table 6 presents the descriptive statistics for the compressive strength data, including mean values, standard errors, and range of measurements. This is a summary of the descriptive statistics for the compressive strength measurements. It highlights that the mean compressive strength improves with increasing CCSA up to 20%, after which it decreases. The F-test shows a significant difference among the mix types ($p = 0.018$), indicating that the variations in compressive strength are statistically significant.

Table 6. Descriptive Statistics for Compressive Strength

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Type of Mix	N	Mean ± SE (MPa)	Minimum	Maximum
Control Mix	**6**	**17.6567±1.864**	**12.80**	**23.29**
10% CCSA	6	19.4717±1.860	14.02	24.52
20% CCSA	6	20.8200±1.856	15.65	25.52
30% CCSA	6	14.2933±1.876	9.33	19.41
Overall mean	**24**	**18.0604±1.008**	**9.33**	**25.52**

Post-Hoc Analysis

Table 7 presents the results of post-hoc analysis to compare the compressive strength between different mix types. This analysis helps in identifying which specific replacements significantly differ from one another. This table presents the post-hoc analysis of compressive strength differences among various mix types. Significant differences are noted between the control mix and the 30% CCSA mix (p = 0.017), as well as between 10% CCSA and 30% CCSA (p = 0.044). The analysis shows that higher CCSA percentages significantly reduce compressive strength compared to lower percentages.

Table 7. Post-Hoc Analysis for Compressive Strength

(I) Type of mix	(J) Type of mix	Mean Diff (I-J)	Sig. p-value
Control Mix	**10% CCSA**	**-1.815**	**0.499**
Control Mix	20% CCSA	-3.163	0.244
Control Mix	30% CCSA	3.363	0.217
10% CCSA	Control Mix	1.815	0.499
10% CCSA	20% CCSA	-1.348	0.615
10% CCSA	30% CCSA	5.178	0.044
20% CCSA	Control Mix	3.163	0.244
20% CCSA	10% CCSA	1.348	0.615
20% CCSA	30% CCSA	6.526*	0.022
30% CCSA	Control Mix	-3.363	0.017
30% CCSA	10% CCSA	-5.178	0.044
30% CCSA	20% CCSA	-6.52667*	0.022

Effect of Coir on Concrete Properties

Table 8 summarizes the compressive strength results for concrete mixes with varying percentages of coir fiber addition. This table demonstrates the effect of coir on the compressive strength at both 7 and 28 days. Results indicate that the inclusion of coir fibers enhances the compressive strength of concrete. The mean compressive strength with 0.1% coir was 15.67 MPa at 7 days and 23.35 MPa at 28 days, showing improvements over the control mix. The trend continues with higher coir percentages, with 0.3% coir yielding the highest mean strength of 16.59 MPa at 7 days and 24.61 MPa at 28 days. This supports the findings of Morris (2018), who reported that coir fibers positively affect concrete strength.

Table 8. Compressive Strength of Concrete with Coir Addition

Type of Mix	7 Days Compressive Strength (MPa)	28 Days Compressive Strength (MPa)
	S1	S2
Control Mix	**12.8**	**16.26**
0.1% Coir	13.66	17.56
0.2% Coir	15.30	17.55
0.3% Coir	15.53	17.12

Conclusions and Recommendations

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The study concludes that incorporating crushed coconut shell aggregates (CCSA) into concrete leads to a significant reduction in workability, particularly at higher replacement levels such as 20% and 30%. This decline is attributed to the lower density and higher water absorption capacity of CCSA, which introduces air voids and lowers the overall cohesiveness of the mix. In contrast, the addition of Coir fibers improves the workability of concrete, especially at a 0.3% content level. This improvement is due to enhanced internal cohesion and reduced segregation, although excessively high fiber content may counteract these benefits and hinder workability. In terms of compressive strength, the study found that concrete mixes incorporating CCSA up to a 20% replacement level exhibited increased strength at both 7-day and 28-day curing periods. This suggests that CCSA, within this optimal range, can contribute positively to concrete performance. However, exceeding 20% replacement leads to a decline in compressive strength, likely due to the porous nature of CCSA and its weaker structural properties. The inclusion of Coir fibers at 0.3% further enhances compressive strength by acting as micro-reinforcements that resist cracking and improve the integrity of the concrete matrix, especially when used alongside CCSA.

To enhance the workability of concrete, it is recommended to incorporate Coir fibers at controlled levels, ideally between 0.2% and 0.3% by weight of the total aggregate. This range has been shown to significantly improve the mix's fluidity without compromising consistency. Excessive Coir content should be avoided, as it may lead to handling difficulties and reduced workability. Clear guidelines should be developed to ensure optimal usage that maintains construction standards and performance. For improving compressive strength, the use of crushed coconut shell aggregates (CCSA) should be promoted at replacement levels of up to 20% by weight of total aggregates. At this level, CCSA contributes to both strength and sustainability without compromising the structural integrity of the concrete. Additionally, combining CCSA with 0.3% Coir fiber content can further enhance concrete strength and durability. It is also recommended that further research be conducted on the microstructural behavior of CCSA and Coir-reinforced concrete, particularly their effects on the bond between the cement matrix and aggregates, to optimize material performance in structural applications.

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