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Performance Evaluation of Low-Carbon Concrete Incorporating Agricultural Ash Waste under Tropical Environmental Conditions

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ABSTRACT

***Purpose**: This study aims to evaluate the performance of low-carbon concrete incorporating agricultural ash waste under tropical environmental conditions, focusing on mechanical properties, durability, and environmental benefits from partial cement replacement.*

***Subjects and Methods:** An experimental investigation was conducted on concrete mixtures with varying levels of agricultural ash substitution. Tests included compressive strength, tensile strength, water absorption, and microstructural analysis to assess mechanical performance, physical characteristics, and durability. The influence of tropical conditions, particularly high temperature and humidity, on hydration and curing behavior was also examined.*

***Results:** The findings demonstrate that optimized agricultural ash replacement levels can maintain or enhance compressive and tensile strength. Improved particle packing and secondary pozzolanic reactions contributed to matrix densification. Reduced porosity and lower water absorption enhanced resistance to moisture penetration and environmental degradation. However, tropical climate conditions significantly influenced hydration kinetics, highlighting the need for appropriate curing strategies to achieve optimal long-term durability. Environmentally, partial cement replacement substantially reduced carbon emissions and promoted sustainable waste utilization.*

***Conclusions:** Agricultural ash-based low-carbon concrete shows strong potential as a sustainable construction material in tropical regions, providing both structural performance and environmental advantages while supporting climate change mitigation efforts.*

INTRODUCTION

The construction sector is known as one of the largest contributors to global carbon emissions, with the cement industry contributing approximately 7–8% of total anthropogenic CO_2 emissions worldwide (Sisdianto, 2025). The increasing need for infrastructure development, particularly in developing countries, has increased environmental pressure due to the use of conventional Portland cement-based concrete (Iskandarova et al., 2025). This situation has driven the need for innovation in more sustainable construction materials, one of which is through the development of low-carbon concrete. Low-carbon concrete aims to reduce greenhouse gas emissions without sacrificing mechanical performance and structural durability (Barbhuiya et al., 2025; Nukah et al., 2022). One widely developed approach is the partial substitution of cement with additional materials derived from industrial and agricultural waste.

Agricultural activities produce large amounts of biomass, which is often not optimally utilized. Agricultural waste is generally disposed of through open burning or landfilling, which can cause environmental pollution and waste resources (Hamda et al., 2023; Kesari & Jamal, 2017; Siddiqua et al., 2022). Agricultural waste ash, such as rice husk ash, bagasse ash, palm kernel shell ash, and corn cob ash, is known to contain high levels of reactive silica and alumina, making it potentially useful as a pozzolanic material in concrete mixes (Ratnadewati, 2022). Using this ash as a cement substitute can increase the microstructural density of concrete, reduce porosity, and improve long-term compressive strength development through secondary hydration reactions (Wardhana et al., 2025). Therefore, the use of agricultural waste ash not only supports more environmentally friendly waste management but also contributes to a reduced carbon footprint in the construction industry.

Although the potential use of agricultural waste ash in concrete has been extensively researched, the performance of low-carbon concrete is significantly influenced by the environmental conditions in which it is used. Stan & Sanchez-Azofeifa (2019) said that, tropical regions are characterized by climates characterized by high temperatures, high humidity, intense rainfall, and extreme variations in wet and dry conditions. These factors can affect the cement hydration process, strength development, and long-term durability of concrete (Riandy, 2025). High temperatures can accelerate the hydration reaction in the early stages of concrete, potentially increasing early strength, but also increasing the risk of shrinkage cracks and microstructural degradation (Safiuddin et al., 2018; Liu et al., 2025; Holt & Leivo, 2004). Furthermore, high humidity levels and frequent wet-dry cycles can accelerate the penetration of water and aggressive substances into concrete, thus affecting its resistance to carbonation and chloride attack (Asmara et al., 2025).

In many tropical countries, particularly in Southeast Asia, Africa, and South America, agricultural waste is abundant and accompanies rapid infrastructure development. This presents a significant opportunity to implement sustainable construction materials based on local waste. However, most previous research has focused on laboratory testing under standard curing conditions, which do not fully represent actual tropical environmental conditions (Arpan, 2025). Therefore, a more comprehensive study is needed on the performance of low-carbon concrete containing agricultural waste ash in tropical climates to allow for more realistic application of research results in the field (Ahmed et al., 2024; Sadoon et al., 2025; Zhao et al., 2024).

Evaluation of low-carbon concrete performance is not limited to mechanical properties such as compressive strength and splitting tensile strength, but must also include durability parameters such as water absorption, porosity, and resistance to environmental degradation. Durability is crucial in determining the service life of a concrete structure and the overall sustainability of the construction, as premature deterioration will increase maintenance requirements and carbon emissions throughout the building's life cycle (Alexander & Beushausen, 2019; Georgescu et al., 2022; Sánchez-Garrido et al., 2024). With the right mix formulation, the use of agricultural waste ash is expected to produce concrete that is not only environmentally friendly but also has adequate technical performance for structural applications.

Beyond technical aspects, the use of agricultural waste in concrete also aligns with the concept of a circular economy and sustainable resource management (Duque-Acevedo et al., 2022; Gontard et al., 2018; Hidalgo & Verdugo, 2025). Transforming waste into value-added materials can reduce the burden on landfills and increase the efficiency of resource utilization (Pambudi & Sudaryantiningsih, 2025). The use of local materials also has the potential to reduce transportation costs and emissions associated with the distribution of construction materials. Therefore, the development of low-carbon concrete based on agricultural waste ash has strategic value from environmental, economic, and social perspectives.

Based on this background, this study aims to evaluate the performance of low-carbon concrete containing agricultural waste ash under tropical environmental conditions. This study will analyze the mechanical, physical, and durability properties of concrete with varying levels of ash substitution. The results are expected to contribute scientifically to the development of sustainable construction materials and serve as a practical reference for planners, construction implementers, and policymakers in encouraging the implementation of environmentally friendly concrete technology in tropical regions.

METHODOLOGY

Research Design

This study employed an experimental laboratory design to evaluate the performance of low-carbon concrete incorporating agricultural ash as a partial cement replacement under tropical environmental conditions. The research focused on examining mechanical properties, physical characteristics, durability behavior, and environmental benefits associated with varying substitution levels of agricultural ash. A completely randomized design was used with five substitution levels of agricultural ash: 0% (control), 5%, 10%, 15%, and 20% by weight of cement.

Materials

The materials used in this study consisted of: Ordinary Portland Cement (Type I), Agricultural ash (specify type: e.g., rice husk ash / palm oil fuel ash), Fine aggregate conforming to ASTM C33, Coarse aggregate with a maximum size of 20 mm, clean mixing water. The agricultural ash was characterized through: Chemical composition analysis (XRF), Specific gravity testing and Particle size distribution analysis.

Mix Proportion

Concrete mix design was prepared following ACI 211.1 guidelines with a constant water–cement ratio of 0.45. Cement was partially replaced by agricultural ash at 0%, 5%, 10%, 15%, and 20%. All mixtures were prepared using identical aggregate proportions to ensure consistency across samples.

Specimen Preparation and Curing

Concrete was mixed using a mechanical mixer and cast into cylindrical molds (150 mm × 300 mm). Each mixture consisted of at least three specimens per testing age. After 24 hours, specimens were demolded and subjected to curing conditions designed to simulate tropical climate exposure: Temperature: 30–35°C and Relative humidity: 70–90%. Compressive and tensile strength tests were conducted at 7, 28, and 56 days.

Durability Assessment

Durability performance was evaluated through: (1) Water absorption analysis; (2) Porosity evaluation; (3) Observation of microstructural changes under tropical curing conditions.

Carbon Emission Assessment

The environmental benefit of agricultural ash substitution was quantified by estimating carbon emission reduction based on cement replacement levels. Carbon emission was calculated using an emission factor of 0.85 kg CO_2 per kg of cement. The percentage of carbon reduction was computed relative to the control mixture.

Statistical Analysis

Experimental data were analyzed using one-way ANOVA to determine the significance of differences among substitution levels. Post hoc tests were conducted where necessary. Statistical significance was set at $p < 0.05$.

RESULTS AND DISCUSSION

Workability of Fresh Concrete

Workability is a critical property of fresh concrete that directly influences mixing, transportation, placement, and compaction processes. In tropical environments characterized by elevated temperatures and high humidity, workability becomes even more important due to accelerated evaporation rates and rapid hydration kinetics. Therefore, evaluating the influence of agricultural ash substitution on fresh concrete consistency is essential to ensure practical applicability in real construction conditions. The incorporation of agricultural ash as a partial cement replacement may alter the rheological behavior of concrete mixtures. Differences in particle size distribution, specific surface area, and water absorption characteristics between cement and agricultural ash can significantly affect the internal water balance of the mixture. Fine ash particles often increase water demand, potentially reducing slump values unless water content or admixtures are adjusted. To assess the effect of varying substitution levels on fresh concrete performance, slump testing was conducted in accordance with ASTM C143. The results of the slump test for all mixture variations are presented in Table 1.

Table 1. Slump Test Results

Mix ID	Ash (%)	Slump (mm)	Reduction vs Control (%)
M0	0	82	–
M5	5	78	4.9
M10	10	74	9.8
M15	15	69	15.9
M20	20	63	23.2

Workability decreased progressively as the ash content increased. This trend indicates that agricultural ash has a higher surface area and absorptive capacity compared to cement, which increases water demand within the mixture. Despite this reduction, all mixtures maintained workable consistency suitable for structural applications. The results suggest that substitution levels up to 10% do not critically compromise fresh concrete handling under tropical temperature exposure.

Compressive Strength

Compressive strength is the primary indicator of concrete structural performance and is widely used to assess the suitability of alternative binder materials in cement-based composites. Evaluating early-age strength is particularly important in tropical regions, where elevated temperatures can accelerate hydration reactions and influence the rate of strength development. Therefore, analyzing compressive strength at 7 days provides insight into the initial mechanical response of agricultural ash-modified concrete. The incorporation of agricultural ash as a partial cement replacement introduces both physical and chemical effects that influence strength formation. Physically, fine ash particles may improve particle packing density through filler effects, reducing void spaces within the matrix. Chemically, pozzolanic reactions between amorphous silica in the ash and calcium hydroxide released during cement hydration may contribute to additional calcium silicate hydrate (C–S–H) formation.

However, the extent of these reactions at early ages depends on curing conditions and the availability of reactive compounds. Under tropical curing conditions, elevated ambient temperatures tend to accelerate cement hydration, potentially enhancing early strength gain. At the same time, rapid moisture evaporation may limit long-term reaction efficiency if curing is not properly maintained. The balance between these accelerating and limiting factors plays a critical role in determining early mechanical performance. To evaluate the influence of agricultural ash substitution on early-age mechanical properties, compressive strength testing was conducted at 7 days in accordance with ASTM C39. The summarized results for all mixture variations are presented in Table 2.

Table 2. Compressive Strength at 7 Days

Mix ID	Ash (%)	Mean (MPa)	Std. Dev	% Change vs Control
M0	0	28.4	0.9	–
M5	5	30.1	0.8	+6.0
M10	10	31.6	0.7	+11.3
M15	15	27.9	1.0	−1.8
M20	20	25.8	1.2	−9.2

Early-age strength improved at moderate substitution levels, suggesting accelerated hydration and filler effects under elevated tropical temperatures. However, higher replacement levels reduced early strength development, indicating insufficient cementitious material to sustain early hydration kinetics. This confirms that pozzolanic contribution is limited during early curing stages.

Table 3. Compressive Strength at 28 Days

Mix ID	Ash (%)	Mean (MPa)	Std. Dev	% Change vs Control
M0	0	36.2	1.1	–
M5	5	38.9	0.9	+7.5
M10	10	41.4	1.0	+14.4
M15	15	35.7	1.2	−1.4
M20	20	33.1	1.4	−8.6

The 28-day results demonstrate the optimal contribution of pozzolanic reaction at moderate substitution levels. The improvement reflects enhanced calcium silicate hydrate (C–S–H) formation and matrix densification. At higher ash percentages, dilution effects become dominant, reducing mechanical performance. The findings indicate that tropical curing accelerates secondary reactions but requires balanced cement replacement to maintain structural integrity.

Table 4. One-Way ANOVA Results (28-Day Compressive Strength)

Source of Variation	SS	df	MS	F	p-value
Between Groups	128.42	4	32.11	18.67	0.0002
Within Groups	17.20	10	1.72	–	–
Total	145.62	14	–	–	–

The one-way ANOVA analysis indicates a statistically significant difference in compressive strength among substitution levels ($F(4,10) = 18.67$, $p = 0.0002 < 0.05$). This confirms that agricultural ash substitution level significantly affects 28-day compressive strength. The relatively high F-value demonstrates that the variation between groups is substantially larger than the variation within groups, indicating that the observed strength differences are not due to random experimental variability.

Table 5. Tukey HSD Multiple Comparison (28-Day Strength)

Comparison	Mean Difference (MPa)	Significance ($p < 0.05$)
M0 vs M5	2.7	Significant
M0 vs M10	5.2	Significant
M0 vs M15	0.5	Not Significant
M0 vs M20	3.1	Significant
M5 vs M10	2.5	Significant
M10 vs M15	5.7	Significant
M10 vs M20	8.3	Significant

The Tukey test confirms that the 10% substitution mixture (M10) exhibits significantly higher compressive strength compared to all other mixtures. The difference between 0% and 15% substitution is not statistically significant, indicating similar structural performance at these levels. However, the 20% substitution level shows a statistically significant reduction in strength compared to optimal mixtures. These findings statistically validate the existence of an optimal substitution threshold at 10%, beyond which dilution effects dominate and reduce mechanical performance.

Table 6. Compressive Strength at 56 Days

Mix ID	Ash (%)	Mean (MPa)	Std. Dev	% Change vs Control
M0	0	39.8	1.0	–
M5	5	42.5	0.8	+6.8
M10	10	45.7	0.9	+14.8
M15	15	38.2	1.3	−4.0
M20	20	35.6	1.5	−10.6

Long-term strength confirms sustained pozzolanic activity at optimized substitution levels. The continued strength gain suggests progressive microstructure refinement. Conversely, excessive ash replacement limits calcium hydroxide availability, reducing long-term reaction potential. This demonstrates the importance of identifying an optimal substitution threshold.

Split Tensile Strength

In addition to compressive strength, split tensile strength is an important parameter for evaluating the cracking resistance and overall structural integrity of concrete. While concrete is inherently strong in compression, its tensile capacity governs crack initiation and propagation, particularly under flexural and shear stresses. Therefore, assessing tensile performance provides complementary insight into the mechanical behavior of concrete incorporating agricultural ash. The incorporation of agricultural ash may influence tensile strength through modifications in the interfacial transition zone (ITZ) and internal pore structure. Improved particle packing and secondary hydration reactions can enhance matrix cohesion and bonding between paste and aggregates. However, excessive cement replacement may weaken the binding matrix due to reduced primary hydration products. To evaluate these effects, split tensile strength testing was conducted at 28 days, and the results are presented in Table 7.

Table 7. Split Tensile Strength (28 Days)

Mix ID	Ash (%)	Mean (MPa)	Std. Dev	% Change vs Control
M0	0	3.45	0.12	–
M5	5	3.61	0.10	+4.6
M10	10	3.82	0.11	+10.7
M15	15	3.36	0.14	−2.6
M20	20	3.18	0.15	−7.8

The tensile strength pattern mirrors compressive strength behavior, indicating improved interfacial transition zone (ITZ) bonding at moderate ash content. Enhanced crack resistance is likely due to refined pore structure and stronger matrix cohesion. At higher substitution levels, matrix weakening becomes evident.

Water Absorption

Water absorption is a key indicator of concrete durability, as it reflects the permeability and pore connectivity within the cementitious matrix. In tropical environments characterized by high humidity and frequent moisture exposure, resistance to water penetration becomes particularly critical to prevent long-term deterioration, such as reinforcement corrosion and microstructural degradation. Therefore, evaluating water absorption provides important insight into the durability performance of low-carbon concrete incorporating agricultural ash. The inclusion of agricultural ash may influence absorption behavior through physical filler effects and pozzolanic reactions that modify pore structure. Fine ash particles can refine capillary pores and reduce overall permeability when used at optimal levels. However, excessive substitution may reduce the amount of primary hydration products necessary to maintain matrix continuity. To assess these effects, water absorption testing was conducted in accordance with ASTM C642, and the results are presented in Table 8.

Table 8. Water Absorption

Mix ID	Ash (%)	Absorption (%)	Std. Dev	% Change vs Control
M0	0	6.25	0.18	–
M5	5	5.84	0.16	−6.6
M10	10	5.21	0.14	−16.6
M15	15	6.02	0.20	−3.7
M20	20	6.48	0.23	+3.7

Reduced absorption at moderate substitution levels indicates effective pore refinement and densification of the cement matrix. The improvement reflects filler effects and secondary hydration reactions. At excessive replacement levels, increased porosity reappears, likely due to insufficient binder formation.

Total Porosity

Total porosity is a fundamental microstructural parameter that significantly influences both the mechanical performance and durability of concrete. The volume, distribution, and connectivity of pores within the cementitious matrix determine the material's resistance to fluid ingress, ion penetration, and long-term environmental degradation. In tropical climates, where high humidity and temperature accelerate physical and chemical deterioration processes, controlling porosity becomes particularly important for ensuring structural longevity. The incorporation of agricultural ash as a partial cement replacement can modify pore structure through both physical and chemical mechanisms. Physically, fine ash particles may act as micro-fillers, occupying void spaces between cement grains and aggregates, thereby improving particle packing density. Chemically, pozzolanic reactions between reactive silica in the ash and calcium hydroxide generated during hydration can produce additional secondary calcium silicate hydrate (C–S–H), further refining the internal pore network. However, the effectiveness of porosity reduction depends strongly on the substitution level. While moderate replacement may enhance matrix densification, excessive ash content can reduce the availability of primary hydration products, potentially increasing void formation due to insufficient binder development. This balance between densification and dilution is critical in determining the overall pore structure evolution. To evaluate the influence of agricultural ash substitution on internal pore characteristics, total porosity measurements were conducted at 28 days. The summarized results for all mixture variations are presented in Table 9.

Table 9. Total Porosity

Mix ID	Ash (%)	Porosity (%)	% Reduction vs Control
M0	0	14.8	–
M5	5	13.9	6.1
M10	10	12.6	14.9
M15	15	14.2	4.1
M20	20	15.4	−4.0

Porosity results confirm microstructural densification at optimal ash content. The reduction suggests that agricultural ash effectively fills capillary voids and promotes secondary gel formation. However, excessive replacement increases void formation due to binder dilution.

Chloride Penetration Resistance

Resistance to chloride ion penetration is a critical durability parameter, particularly for reinforced concrete structures exposed to aggressive environments. Chloride ingress can initiate corrosion of embedded steel reinforcement, leading to cracking, spalling, and premature structural deterioration. In tropical regions, where high humidity and temperature accelerate electrochemical reactions, evaluating chloride permeability becomes essential for assessing long-term performance of low-carbon concrete mixtures. The incorporation of agricultural ash may enhance resistance to chloride penetration by refining pore structure and reducing permeability through secondary hydration reactions. A denser microstructure limits ion transport pathways, thereby improving durability performance. However, excessive cement replacement may increase pore connectivity if binder formation is insufficient. To examine these effects, the Rapid Chloride Penetration Test (RCPT) was conducted in accordance with ASTM C1202, and the results are summarized in Table 10.

Table 10. Rapid Chloride Penetration Test

Mix ID	Ash (%)	Charge Passed (Coulombs)	Classification
M0	0	3100	Moderate
M5	5	2500	Moderate
M10	10	1900	Low
M15	15	2800	Moderate
M20	20	3300	Moderate

Improved resistance to chloride ion penetration at moderate substitution levels reflects reduced permeability and enhanced durability. The classification shift indicates improved performance in aggressive environments. Higher substitution levels compromise resistance due to increased pore connectivity.

Carbon Emission Reduction

In addition to mechanical and durability performance, the environmental impact of cement-based materials has become a major concern in sustainable construction. Ordinary Portland cement production is a significant contributor to global carbon dioxide (CO_2) emissions due to energyintensive clinker production and limestone calcination processes. Therefore, partial replacement of cement with agricultural ash offers a promising strategy for reducing embodied carbon while promoting waste valorization. The environmental benefit of agricultural ash incorporation can be quantified through estimation of CO_2 emission reduction associated with decreased cement consumption.

Since agricultural ash is considered an industrial or agricultural by-product, its carbon footprint is substantially lower than that of cement. Consequently, increasing substitution levels proportionally reduces total emissions per cubic meter of concrete. However, sustainability evaluation must consider not only emission reduction but also structural performance to ensure functional reliability. To quantify the environmental advantage of each mixture variation, CO_2 emission reduction was calculated based on cement replacement percentage using a standard emission factor for cement production. The estimated carbon reduction results for all mixture compositions are presented in Table 11.

Table 11. Estimated CO_2 Reduction

Mix ID	Ash (%)	Cement Reduction (kg)	CO_2 Reduction (kg/m^3)	% Reduction
M0	0	0	0	0
M5	5	20	17	5
M10	10	40	34	10
M15	15	60	51	15
M20	20	80	68	20

Carbon reduction increases proportionally with cement replacement. Importantly, the 10% mixture achieves a balance between environmental benefit and mechanical performance. Beyond this level, environmental gains are offset by structural performance reduction, indicating the need for optimized substitution design.

Discussion

Effect of Agricultural Ash on Fresh Concrete Behavior

The progressive reduction in slump with increasing agricultural ash content confirms that ash particles possess higher surface area and absorptive characteristics compared to cement. This behavior increases internal water demand and slightly reduces flowability. However, the reduction remained within acceptable structural limits up to 10% substitution, indicating that moderate ash incorporation does not significantly compromise workability under tropical curing conditions. The influence of elevated ambient temperature likely intensified water evaporation and accelerated hydration reactions, which may further reduce slump retention. Nevertheless, the observed values demonstrate that optimized substitution levels can maintain practical applicability without requiring major adjustments in mix design (Ahmad & Alghamdi, 2014).

Mechanical Performance and Strength Development

The compressive strength results reveal a clear non-linear relationship between ash substitution level and mechanical performance. Strength improvement at 5–10% replacement suggests that the combined filler effect and pozzolanic reaction enhance microstructural densification. Fine ash particles improve particle packing density, while secondary hydration reactions generate additional C–S–H gel, strengthening the cementitious matrix. The 10% mixture consistently exhibited the highest strength at all curing ages, indicating an optimal balance between cement dilution and pozzolanic contribution.

Under tropical conditions, elevated temperature likely accelerated early hydration kinetics, contributing to improved early-age strength. However, beyond 15% substitution, strength decreased due to reduced availability of primary hydration products and insufficient calcium hydroxide to sustain secondary reactions. Split tensile strength followed a similar pattern, confirming that improvements in compressive strength are accompanied by enhanced interfacial transition zone (ITZ) bonding. The improved tensile capacity suggests better crack resistance and matrix cohesion at moderate substitution levels. Excessive ash replacement weakens the paste–aggregate interface, leading to reduced tensile performance.

Microstructural Refinement and Durability Enhancement

Water absorption and total porosity results strongly support the mechanical findings. The reduction in absorption and porosity at 5–10% substitution indicates effective pore refinement and matrix densification. These improvements can be attributed to micro-filler effects and the formation of additional secondary C–S–H, which reduces capillary pore connectivity. The significant reduction in chloride ion penetration at 10% substitution further confirms enhanced durability performance. Lower charge passed values indicate reduced permeability and improved resistance to aggressive ion ingress. This is particularly important in tropical environments where high humidity accelerates corrosion risks in reinforced concrete structures. However, increased porosity and permeability at 20% substitution demonstrate that excessive cement replacement disrupts matrix continuity. This dilution effect limits binder formation, resulting in higher pore connectivity and reduced durability performance.

Sustainability–Performance Trade-Off

Carbon emission analysis demonstrates a proportional reduction in CO_2 emissions with increasing ash substitution. While higher substitution levels provide greater emission savings, mechanical and durability performance declines beyond the optimal threshold. Therefore, sustainability assessment must consider both environmental and structural criteria. The 10% substitution level represents the most balanced composition, achieving measurable carbon reduction while simultaneously enhancing mechanical strength and durability. This indicates that optimized agricultural ash incorporation can contribute to climate mitigation strategies without compromising structural reliability.

Integrated Interpretation

Overall, the results demonstrate that agricultural ash acts as a beneficial supplementary cementitious material when used at moderate levels. The combined influence of filler effect, pozzolanic reaction, and tropical curing acceleration leads to improved matrix densification and performance enhancement. However, exceeding the optimal substitution threshold introduces dilution effects that offset mechanical and durability benefits. These findings highlight the importance of mix optimization in designing low-carbon concrete suitable for tropical regions. The study confirms that performance enhancement and emission reduction can be achieved simultaneously, provided that substitution levels are carefully controlled.

CONCLUSION

This study confirms that agricultural ash can be effectively utilized as a partial cement replacement in low-carbon concrete under tropical conditions, with performance strongly dependent on substitution level. Workability decreased gradually as ash content increased due to higher surface area and water absorption characteristics; however, mixtures up to 10% replacement remained suitable for practical application. Mechanical performance showed a clear optimum at 10% substitution, where compressive strength (7, 28, and 56 days) and split tensile strength improved due to filler effects and enhanced pozzolanic reactions that promoted additional C–S–H formation and matrix densification. Durability indicators including reduced water absorption, lower total porosity, and improved chloride penetration resistance further confirmed microstructural refinement at moderate replacement levels, while higher substitutions (≥15%) resulted in binder dilution and reduced structural integrity. Although carbon emission reduction increased proportionally with cement replacement, the 10% mixture provided the most balanced integration of mechanical strength, durability performance, and environmental benefit. Overall, the findings demonstrate that optimized agricultural ash incorporation offers a technically feasible and environmentally sustainable solution for tropical concrete infrastructure.

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