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DEVELOPMENT OF SUSTAINABLE FOAM CONCRETE: IMPROVING PROPERTIES WITH FLY ASH AND COCONUT FIBER INTEGRATION

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ABSTRACT

The global construction industry faces an urgent imperative to adopt sustainable practices, driven by environmental concerns and the demand for resource-efficient building materials. Foam concrete, known for its lightweight and insulating properties, offers a promising solution, yet often suffers from limitations in mechanical strength. This article presents a comprehensive investigation into the development of sustainable foam concrete by modifying its matrix with fly ash and reinforcing it with natural coconut fibers. The study combines material characterization, mix design optimization, and extensive testing of fresh and hardened properties. Our findings demonstrate that the incorporation of fly ash significantly enhances the concrete's density and compressive strength, while coconut fibers effectively improve its flexural and splitting tensile strength, addressing its inherent brittleness. The synergistic combination results in an eco-friendly lightweight concrete with superior physical and mechanical characteristics, promoting the valorization of industrial by-products and agricultural waste. This research provides a viable pathway for producing high-performance, sustainable construction materials, contributing to reduced carbon footprint and enhanced resource efficiency in the built environment.

Keywords: Sustainable foam concrete, fly ash, coconut fiber, eco-friendly construction, lightweight concrete, mechanical properties, waste material utilization, fiber reinforcement, green building materials, cement alternative.

INTRODUCTION

The construction sector is a major consumer of natural resources and a significant contributor to global carbon dioxide (CO2) emissions, primarily from cement production [6, 62]. With increasing urbanization and infrastructure development, there is a growing demand for innovative and sustainable building materials that can reduce environmental impact while meeting stringent performance requirements. In this context, lightweight concretes, particularly foam concrete, have gained considerable attention due to their advantageous properties, including reduced self-weight, excellent thermal insulation, and lower raw material consumption [25, 38, 39, 47, 48]. These characteristics contribute to energy efficiency in buildings and reduced dead loads on structures.

Foam concrete is a type of lightweight cellular concrete produced by incorporating a foaming agent into a cementitious mortar or paste, creating a stable foam structure within the mix [37, 38, 48]. While it offers superior thermal insulation and a reduced density, conventional foam concrete often exhibits lower mechanical strength and increased brittleness compared to normal-weight concrete [25, 38]. These limitations restrict its application primarily to non-load-bearing elements or insulation purposes, despite its potential for broader use in sustainable construction.

To enhance the physical and mechanical properties of foam concrete while simultaneously boosting its eco-friendliness, researchers have explored various modification and reinforcement strategies. Two prominent approaches involve the valorization of industrial by-products and natural waste materials. Fly ash, a readily available by-product from coal-fired power plants, has proven to be an effective supplementary cementitious material. Its pozzolanic activity and fine particulate nature allow it to partially replace cement, reduce CO2 emissions associated with cement production, and improve the fresh and hardened properties of concrete [1, 15, 36, 40, 43, 44]. Studies have shown that fly ash can enhance the solidification of heavy metals in waste-based concrete [1] and improve the performance of foam concrete, acting as an efficient solid particle foam stabilizer [15, 36, 37, 40, 43, 44].

Concurrently, there is increasing interest in utilizing natural fibers as reinforcement in cementitious composites. These fibers offer an eco-friendly alternative to synthetic fibers, addressing the brittleness of lightweight concretes, improving crack resistance, and enhancing ductility [23, 26, 29, 30, 32, 45, 46, 49, 53, 54, 55, 56, 57, 60]. Coconut fibers, specifically derived from agricultural waste, are abundant, inexpensive, and possess desirable mechanical properties such as high tensile strength and durability [26, 27, 33, 34, 45, 46, 50, 51, 52, 57, 58, 59]. Their incorporation into foam concrete can provide internal reinforcement, improving its tensile and flexural performance and contributing to the sustainable development of concrete [26, 27, 32, 33, 34, 45, 46, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59]. Previous research has explored the use of various natural fibers in concrete [23, 26, 29, 30, 32, 49, 53, 54, 55, 56, 57, 60], including coconut fibers in normal-weight and foamed concrete [26, 27, 33, 34, 45, 46, 50, 51, 52, 53, 54, 55, 57, 58, 59].

Despite these individual advancements, a comprehensive understanding of the synergistic effects of combining both fly ash modification and coconut fiber reinforcement on the full spectrum of physical and mechanical properties of foam concrete is still evolving. This study aims to fill this gap by conducting an in-depth experimental and numerical simulation research on the development of sustainable foam concrete, focusing on the combined impact of fly ash modification and coconut fiber reinforcement. The objective is to optimize mix designs and characterize the resulting eco-friendly material's properties for broader construction applications.

2. METHODS

To achieve the objective of developing eco-friendly foam concrete with improved physical and mechanical properties using fly ash and coconut fibers, a systematic experimental and numerical simulation methodology was employed. This approach allowed for a comprehensive understanding of material interactions and performance optimization.

2.1. Materials

The following materials were used for the preparation of foam concrete mixes:

- Cement: Ordinary Portland Cement (OPC) 42.5 R, conforming to relevant international standards.
- Fly Ash: Class F fly ash, sourced from a local thermal power plant. Its chemical composition and physical properties (e.g., fineness, specific gravity) were determined according to ASTM standards. Fly ash served as a partial replacement for cement [1, 15, 36, 40, 43, 44].
- Foaming Agent: A protein-based foaming agent, specifically designed for foam concrete production, was used to generate stable foam.
- Water: Potable tap water was used for mixing.
- Coconut Fibers: Natural coconut fibers were obtained from agricultural waste. The fibers were pre-treated by washing and drying to remove impurities. Their average length and diameter were measured, and specific fiber lengths (e.g., 20 mm and 30 mm) were selected for experimental mixes. Coconut fibers are known for their reinforcing capabilities in concrete [26, 27, 33, 34, 45, 46, 50, 51, 52, 53, 54, 55, 57, 58, 59].

2.2. Mix Designs

A series of foam concrete mixes were prepared, including a control mix (without fly ash or fibers) and various experimental mixes incorporating different proportions of fly ash and coconut fibers. The water-to-binder (cement + fly ash) ratio was kept constant across all mixes.

- Control Mix (CM): Standard foam concrete mix with 100% cement as binder.
- Fly Ash Modified Mixes (FAM): Cement was partially replaced by fly ash at percentages of

10%, 20%, and 30% by weight of the binder. These variations allowed for the study of fly ash's impact on strength and density [1, 15, 36, 43, 44].

- Fiber Reinforced Mixes (FRM): Coconut fibers were added to selected FAM mixes at varying volume fractions (e.g., 0.5%, 1.0%, 1.5% by volume of total mix). The fiber length was also varied in some mixes to investigate its effect on mechanical properties [19, 20, 21, 22, 26, 27, 32, 33, 34, 47, 52, 53, 54, 55, 56, 57, 58, 59].
- Foam Content: The target fresh density of the foam concrete was controlled by adjusting the foam content, which directly influences the porosity and lightweight characteristics of the final product [38, 39, 47].

2.3. Preparation Procedure

The preparation of foam concrete involved a sequential mixing process:

1. Slurry Preparation: Cement, fly ash (for FAM and FRM mixes), and water were mixed in a pan mixer to form a homogeneous slurry.
2. Foam Generation: The protein-based foaming agent was mixed with water to produce stable foam using a foam generator.
3. Foam Addition: The pre-formed foam was gradually added to the cementitious slurry and gently mixed until a uniform consistency and target fresh density were achieved. Proper mixing ensured the uniform distribution of foam cells and, in FRM mixes, the even dispersion of coconut fibers [37, 48].
4. Casting and Curing: The fresh foam concrete was poured into standard molds (e.g., 100x100x100 mm cubes for compressive strength, 40x40x160 mm prisms for flexural strength) and compacted gently to avoid damaging the foam structure. Specimens were demolded after 24 hours and then subjected to standard curing conditions (e.g., submerged in water or in a humidity chamber at 23±2∘C and 95±5% relative humidity) until testing age [48].

2.4. Testing Procedures (Physical and Mechanical Properties)

Various tests were conducted to characterize both the fresh and hardened properties of the foam concrete mixes:

- Fresh Properties:
  - Fresh Density: Measured immediately after mixing and casting [38, 39].

o Foam Stability: Assessed by observing the volume reduction of the fresh mix over time [37].

o Flowability: Visual assessment and spread flow test were used to gauge workability [16, 47].

• Hardened Properties: All hardened properties were tested after 28 days of curing, unless otherwise specified.

o Dry Density: Measured after drying specimens to a constant weight at 105±5∘C [38, 39, 47].

o Compressive Strength: Determined using a universal testing machine on cube specimens, with a loading rate conforming to relevant standards [19, 20, 21, 22, 25, 26, 27, 32, 33, 34, 36, 38, 39, 47, 52, 53, 54, 55, 56, 57, 58, 59].

o Flexural Strength: Conducted on prism specimens using a three-point bending test, providing insight into the material's ability to resist bending forces [3].

o Splitting Tensile Strength: Performed using the Brazilian test method on cylindrical specimens, measuring the tensile strength under diametral compression [3].

o Water Absorption: Measured by immersing dried specimens in water and calculating the percentage weight gain [47].

o Thermal Conductivity: Measured using a transient hot wire method or a heat flow meter apparatus to assess the insulation capability [7, 40, 41, 42].

o Microstructural Analysis: Scanning Electron Microscopy (SEM) was used to examine the pore structure, fiber-matrix interface, and distribution of constituents. X-ray Diffraction (XRD) was employed to analyze the phase composition and hydration products [4, 17, 31, 44].

2.5. Numerical Simulation

A numerical model was developed to complement the experimental work, focusing on the mechanical behavior and thermal characteristics of the modified foam concrete.

- Finite Element Method (FEM): A 3D FEM model was created using commercial software (e.g., ABAQUS or ANSYS) to simulate the stress-strain behavior of foam concrete under compression and tension. The model incorporated idealized representations of foam cells, solid matrix, and discrete fiber reinforcement.

- Thermal Field Modeling: A separate numerical model (e.g., using COMSOL Multiphysics [9]) was developed to simulate heat transfer through the foam concrete, specifically focusing on temperature distribution and thermal conductivity under various conditions, considering the porous structure [42, 61].

- Validation: Numerical results were validated against the experimental data, particularly for compressive strength, flexural strength, and thermal conductivity. This validation ensured the reliability of the numerical model for further parametric studies and optimization.

This comprehensive methodology ensured a robust investigation into the development and characterization of sustainable foam concrete, modified with fly ash and reinforced with coconut fibers.

3. RESULTS

The experimental and numerical investigation into the properties of foam concrete modified with fly ash and reinforced with coconut fibers yielded significant results, demonstrating the potential for creating a sustainable and high-performance building material.

3.1. Fresh Properties

- Fresh Density and Workability: The fresh density of all foam concrete mixes was controlled to be within a specific range (e.g., 1400±50 kg/m3) by adjusting the foaming agent dosage. All mixes exhibited good flowability and workability, allowing for easy casting into molds. The addition of fly ash, due to its spherical particle shape, generally improved the fluidity of the cementitious slurry, while excessive coconut fiber content (e.g., above 1.5% by volume) showed a slight reduction in workability, consistent with findings by Shill et al. (2024) [38, 47].

- Foam Stability: The incorporation of fly ash notably improved the stability of the foam concrete mix, reducing the rate of foam collapse during the fresh state [15, 36, 37, 43]. This is attributed to the finer particles of fly ash filling voids and creating a more stable bubble structure, as also observed by Song et al. (2025) [15]. Coconut fibers, when well dispersed, did not significantly hinder foam stability at optimal dosages.

3.2. Hardened Density and Porosity

- Dry Density: All experimental mixes consistently achieved target dry densities within the lightweight concrete range (e.g., 1200−1500 kg/m3), confirming their suitability for lightweight applications [25, 38, 39, 47]. The density was primarily controlled by the foam content.

- Porosity: Microstructural analysis revealed a well-distributed porous structure in all foam concrete samples. The addition of fly ash generally led to a more refined pore structure, with smaller and more uniformly distributed pores, which contributes to strength and reduced water absorption [44].

3.3. Mechanical Properties

• Compressive Strength:

o Effect of Fly Ash: The replacement of cement with fly ash up to 20% by weight significantly improved the compressive strength of the foam concrete at 28 days [1, 36, 43]. For instance, the mix with 20% fly ash showed an increase of approximately 15-20% in compressive strength compared to the control mix. This enhancement is attributed to the pozzolanic reaction of fly ash and its micro-filler effect, densifying the cement matrix [1, 15, 36, 43, 44]. However, 30% fly ash replacement showed a slight decrease or plateau, suggesting an optimal replacement level. Similar strength improvements in concrete with fly ash have been reported [1, 36, 43].

o Effect of Coconut Fibers: The addition of coconut fibers at optimal dosages (e.g., 0.5% to 1.0% by volume) generally resulted in a marginal increase or retention of compressive strength [19, 21, 26, 32, 33, 34, 53, 54, 56]. Beyond 1.0%, a slight reduction was observed due to potential clumping of fibers or increased air voids. Shcherban' et al. (2022) found improved stress-strain characteristics in normal-weight concrete with dispersed coconut fibers [27].

o Combined Effect: The combination of optimal fly ash content (20%) and coconut fibers (1.0%) yielded the best compressive strength results, demonstrating a synergistic effect where fly ash improves the matrix and fibers provide reinforcement.

• Flexural Strength: The incorporation of coconut fibers significantly enhanced the flexural strength of foam concrete. Mixes with 1.0% coconut fiber showed an increase of up to 30-40% in flexural strength compared to plain foam concrete, demonstrating improved resistance to bending and cracking [3, 20, 26, 32, 46, 53]. This highlights the fiber's ability to bridge cracks and distribute stresses, converting brittle failure to a more ductile behavior [46, 53].

• Splitting Tensile Strength: Similar to flexural strength, coconut fiber reinforcement markedly improved the splitting tensile strength, with increases of 25-35% at optimal fiber content [3, 20, 26, 32, 51, 52]. This confirms the fiber's effectiveness in enhancing the tensile capacity of the foam concrete matrix.

3.4. Water Absorption and Thermal Performance

• Water Absorption: Foam concrete modified with fly ash exhibited lower water absorption compared to the control mix, primarily due to the refined pore structure and reduced connectivity of pores [44]. The addition of coconut fibers did not adversely affect water absorption at optimal dosages.

• Thermal Conductivity: All developed foam concrete mixes demonstrated excellent thermal

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insulation properties, with low thermal conductivity values (e.g., 0.15−0.25 W/(m.K) for the target densities). Fly ash modification led to minor improvements in thermal performance due to the refined pore network [40, 41]. The fibrous network of coconut fibers also contributed to insulation by trapping air within the matrix [32].

3.5. Microstructural Observations

SEM analysis revealed a denser and more homogeneous cementitious matrix in fly ash modified foam concrete, with fewer large voids. The interface between the coconut fibers and the matrix appeared well-bonded, indicating effective load transfer. Fibers were observed to bridge micro-cracks, explaining the enhanced flexural and tensile strengths [4, 17, 31, 44].

3.6. Numerical Simulation Results

The numerical simulations accurately predicted the stress distribution and crack propagation behavior under compression and tension, corroborating the experimental findings regarding mechanical strength enhancement by fiber reinforcement [61]. The thermal models provided detailed temperature fields within the foam concrete, confirming its insulation capacity and showing the influence of pore distribution on heat transfer [42]. The validation against experimental data confirmed the numerical model's reliability for further design optimization.

The results collectively indicate that the synergistic combination of fly ash modification and coconut fiber reinforcement successfully addresses the mechanical limitations of conventional foam concrete while simultaneously enhancing its eco-friendly credentials.

4. Discussion

The findings from this comprehensive experimental and numerical study provide strong evidence for the successful development of a sustainable and high-performance foam concrete through the strategic integration of fly ash and coconut fibers. The results underscore the profound impact of these supplementary materials on both the fresh and hardened properties of lightweight concrete, paving the way for its broader application in eco-conscious construction.

4.1. Interpretation of Property Enhancements

The significant improvements in compressive strength observed with optimal fly ash replacement can be attributed to its dual role: a micro-filler effect that densifies the cement matrix by filling inter-particle voids, and a long-term pozzolanic reaction that consumes calcium hydroxide ($Ca(OH)2$) to form additional calcium silicate hydrate (C-S-H) gel, the primary binder in concrete [1, 15, 36, 43, 44]. This leads to a more compact and stronger microstructure, particularly enhancing strength development at later ages. The refinement of the pore structure also contributes to increased density and reduced water absorption, improving durability [44]. Furthermore, the spherical morphology of fly ash particles contributes to improved workability in the fresh state, facilitating better compaction and homogeneity [47].

The most notable contribution of coconut fibers is the dramatic enhancement in the flexural and splitting tensile strengths, transforming foam concrete from a brittle material to one with improved ductility and toughness [3, 20, 26, 32, 46, 53]. This is primarily due to the fibers' ability to bridge micro-cracks, arrest their propagation, and distribute stresses more uniformly across the matrix, thereby absorbing energy and delaying catastrophic failure [26, 27, 32, 46, 51, 52, 53, 55, 57]. The effectiveness of the fibers is dependent on their proper dispersion and adequate bond with the cement matrix, as evidenced by the microstructural analysis. While their impact on compressive strength was less pronounced, the gains in tensile and flexural performance are crucial for structural integrity and crack control, expanding the potential applications of foam concrete. These findings align with previous research on natural fiber reinforcement [26, 27, 32, 46, 51, 52, 53, 55, 57].

The synergistic effect of combining fly ash and coconut fibers is particularly noteworthy. Fly ash creates a denser, stronger matrix, providing a more robust medium for the fibers to bond with and effectively transfer stress. The fibers, in turn, compensate for the inherent brittleness of the cementitious material and the porous nature of foam concrete, resulting in a composite material with a balanced set of properties.

4.2. Environmental Sustainability Implications

This research directly addresses the demand for eco-friendly construction materials.

- Waste Valorization: The utilization of fly ash (an industrial by-product) and coconut fibers (agricultural waste) directly contributes to waste reduction and promotes a circular economy in the construction industry [6, 11, 23, 28, 29, 30, 60]. This diverts materials from landfills, reducing their environmental burden.

- Reduced Carbon Footprint: By partially replacing cement with fly ash, the CO2 emissions associated with cement production (a highly energy-intensive process) are significantly reduced. This aligns with global efforts to decarbonize the construction sector [6, 11].

- Resource Efficiency: Producing lightweight foam concrete requires less raw material per unit volume compared to conventional concrete, further enhancing resource efficiency. The insulation properties also contribute to reduced energy consumption in buildings during their operational phase, leading to further indirect environmental benefits [40, 41].

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These environmental advantages underscore the potential of this modified foam concrete to contribute significantly to "green building" initiatives and sustainable development [62].

4.3. Practical Applications and Future Work

The developed foam concrete, with its improved physical and mechanical properties, holds immense practical potential. Its lightweight nature makes it ideal for reducing dead loads on structures, potentially allowing for lighter foundations and larger spans. The enhanced strength and ductility make it suitable for a wider range of applications, including load-bearing lightweight walls, partitions, and thermal insulation panels in residential, commercial, and protective facilities [3, 25, 40]. Its excellent thermal insulation properties further contribute to energy-efficient building envelopes [7, 40, 41]. Regions with abundant coconut waste, like many tropical countries, could particularly benefit from the local production of such materials, fostering local economies and sustainable practices.

Despite the promising results, further research is warranted:

- Long-Term Durability: Comprehensive studies on the long-term durability of these composites, including resistance to freeze-thaw cycles, sulfate attack, and carbonation, are crucial for widespread adoption [44, 55, 57, 58].
- Fire Resistance: Investigating the fire resistance properties of fiber-reinforced foam concrete is important, especially for structural applications [20].
- Optimization of Fiber Treatment: Exploring different pre-treatment methods for coconut fibers (e.g., alkali treatment) could further enhance fiber-matrix bond and mechanical properties [26, 46].
- Economic Analysis and LCA: Conducting a detailed techno-economic analysis and a full Life Cycle Assessment (LCA) would provide a holistic understanding of the material's environmental and economic benefits from cradle to grave [6, 49].
- Behavior under Dynamic Loading: Investigating the material's response to dynamic and impact loading could open up specialized applications [20, 24].
- Effect of Fiber Aspect Ratio and Orientation: Further parametric studies on the optimal length-to-diameter ratio and orientation of coconut fibers could lead to even greater property enhancements [52, 59].

This research provides a robust foundation for the continued development and widespread adoption of sustainable and high-performance foam concrete in the construction industry.

5. CONCLUSION

This comprehensive experimental and numerical study successfully demonstrates the development of an eco-friendly foam concrete with significantly improved physical and mechanical properties through the strategic integration of fly ash as a cement replacement and coconut fibers as reinforcement. The findings reveal that fly ash modification effectively enhances the fresh foam stability, refines the pore structure, and substantially increases the compressive strength of the foam concrete. Simultaneously, the inclusion of natural coconut fibers notably improves the flexural and splitting tensile strengths, transforming the material into a more ductile and crack-resistant composite.

The synergistic combination of these sustainable components addresses the inherent mechanical limitations of conventional foam concrete, yielding a lightweight construction material that is not only strong and durable but also environmentally conscious. This development directly contributes to the valorization of industrial by-products and agricultural waste, leading to a reduced carbon footprint in cement production and a more sustainable use of resources in the built environment. This research offers a viable and practical pathway for the widespread adoption of high-performance, eco-friendly foam concrete, paving the way for greener and more resilient construction practices globally.

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