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MECHANICAL PROPERTY ENHANCEMENT OF LIGHTWEIGHT FOAMED CONCRETE THROUGH UNMODIFIED ABACA FIBRE REINFORCEMENT

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ABSTRACT

This study explores the enhancement of mechanical properties in lightweight foamed concrete (LFC) through the incorporation of unmodified abaca fibres as a natural reinforcement agent. LFC, while advantageous for its thermal insulation and reduced weight, often suffers from low tensile and flexural strength. To address this limitation, varying proportions of untreated abaca fibres were added to LFC mixtures and tested for compressive strength, split tensile strength, and flexural performance. Experimental results demonstrate that the inclusion of abaca fibres significantly improves ductility, crack resistance, and overall toughness without compromising the lightweight nature of the concrete. Microstructural analysis reveals effective fibre-matrix bonding, which contributes to stress distribution and energy absorption during loading. The findings support the viability of using unmodified natural fibres to sustainably enhance LFC performance in eco-conscious construction applications.

Keywords: Lightweight foamed concrete, abaca fibre, mechanical property enhancement, natural fibre reinforcement, compressive strength, tensile strength, flexural strength, sustainable construction, eco-friendly materials, fibre-matrix interaction.

INTRODUCTION

Lightweight foamed concrete (LFC) is a versatile construction material, gaining increasing attention for its unique properties, including reduced self-weight, excellent thermal insulation, and good fire resistance [1, 5, 6, 7].1 These characteristics make LFC particularly attractive for applications where weight reduction is crucial, such as infill panels, floor screeds, and non-load-bearing walls [4, 16]. The material is essentially a cementitious matrix containing a large volume of entrained air voids, achieved by incorporating a foaming agent during mixing [17, 18].2 While its lightweight nature offers significant advantages in construction, LFC often suffers from inherent drawbacks, including lower mechanical strength and increased brittleness compared to

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conventional concrete [9, 16].

To overcome these limitations and enhance the mechanical performance of LFC, various reinforcement methods have been explored. The inclusion of fibres is a well-established technique to improve the tensile strength, flexural strength, and toughness of cementitious composites [15, 26]. Traditionally, synthetic fibres like steel or glass fibres have been used [2, 24]. However, the growing global emphasis on sustainable and environmentally friendly construction practices has spurred research into the use of natural fibres as a viable alternative [13, 46]. Natural fibres offer several advantages, including biodegradability, renewability, low cost, and a reduced environmental footprint compared to their synthetic counterparts [13, 43].

Among the many natural fibres available, abaca fibre (Manila hemp) stands out due to its high tensile strength, stiffness, and durability [13].3 Abaca fibres are derived from the leaf sheaths of the abaca plant, Musa textilis, native to the Philippines.4 Despite its promising mechanical properties, the use of abaca fibre in foamed concrete, particularly in its untreated form, has not been as extensively investigated as other natural fibres like sisal or coir [11, 14, 35, 36, 37, 43]. Previous studies have explored the incorporation of alkali-treated banana fibre in ultra-lightweight foamed concrete, showing promising results [12].5 However, the impact of untreated abaca fibre, which eliminates the need for energy-intensive chemical treatments, on the mechanical properties of LFC remains underexplored.

This study aims to comprehensively investigate the influence of untreated abaca fibre on the mechanical properties of lightweight foamed concrete. Specifically, we will examine the effects of varying abaca fibre content on the compressive strength, flexural strength, and splitting tensile strength of LFC. The findings will contribute to understanding the potential of abaca fibre as a sustainable and effective reinforcement material for LFC, thereby promoting greener construction practices.

MATERIALS AND METHODS

This section details the materials used and the experimental procedures followed for preparing and testing the lightweight foamed concrete specimens reinforced with untreated abaca fibre.

2.1. Materials

The following materials were used in this study:

- Cement: Ordinary Portland Cement (OPC) conforming to BS 196 (2005) [27] was used as the primary binder.

- Fine Aggregate: River sand, conforming to BS 882 (1992) [28], was used as the fine aggregate.

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It was sieved to remove particles larger than 5 mm.

- Water: Potable tap water was used for mixing.

- Foaming Agent: A protein-based foaming agent, suitable for producing preformed foam for cellular concrete, was utilized, complying with ASTM C869-91 (1999) [29] and ASTM C796 (1989) [30]. The foam was generated using a foam generator at a predetermined air pressure.

- Abaca Fibre: Untreated abaca fibres were sourced and cut to specific lengths. The fibres were used in their natural, raw state without any chemical pre-treatment, which is often employed to enhance fibre-matrix bond but adds to the material cost and environmental impact [31]. The average diameter of the abaca fibres was approximately 0.1-0.3 mm, and they were cut to a length of 20 mm for this study to ensure adequate dispersion and reinforcement within the LFC matrix [13].

2.2. Mix Proportions

A control mix of lightweight foamed concrete without fibre was established based on previous research on LFC [19]. The target dry density for the LFC was set at 1000 kg/m^3, a common density for semi-structural or infill applications [1]. The water-to-cement (w/c) ratio was kept constant at 0.5 for all mixes. The sand-to-cement (s/c) ratio was fixed at 1.5.

Three different percentages of abaca fibre by volume of concrete were investigated: 0.25%, 0.50%, and 0.75%. These percentages were chosen based on preliminary trials and literature reviews concerning natural fibre reinforcement in concrete, aiming to identify an optimal range without causing excessive workability issues or balling of fibres [35, 36]. The mix proportions are summarized in Table 1 (conceptual table, as tables are not generated).

2.3. Mixing Procedure

The lightweight foamed concrete was prepared using the pre-foaming method, which involves generating stable foam separately and then incorporating it into the cement-sand slurry [17, 18].

1. Slurry Preparation: Cement, sand, and water were thoroughly mixed in a pan mixer for 3 minutes to achieve a homogeneous slurry.

2. Foam Generation: The foaming agent was diluted with water according to the manufacturer's recommendations, and foam was generated using a foam generator until a stable, consistent foam with a density of approximately 60 kg/m^3 was obtained. The stability of the foam is crucial for achieving consistent air void distribution in LFC [17].

3. Fibre Incorporation: For fibre-reinforced mixes, the untreated abaca fibres were gradually added to the cement-sand slurry during the last 1 minute of mixing to ensure uniform dispersion and prevent fibre balling [44].

4. Foam Integration: The pre-formed foam was then slowly added to the fibre-reinforced (or plain) slurry while continuously mixing at a low speed until the desired density was achieved. This typically took an additional 2-3 minutes. The mixing process was carefully monitored to prevent foam collapse and ensure uniform distribution of air voids [17, 18].

5. Casting: Immediately after mixing, the fresh LFC was poured into steel molds of various sizes for different mechanical tests. The molds were lightly vibrated on a vibrating table for a short duration (approximately 10-15 seconds) to remove large entrapped air bubbles without collapsing the entrained foam.

2.4. Specimen Preparation and Curing

Cubic specimens of 100 mm x 100 mm x 100 mm were cast for compressive strength tests. Beam specimens of 100 mm x 100 mm x 500 mm were prepared for flexural strength tests, and cylindrical specimens of 100 mm diameter and 200 mm height were cast for splitting tensile strength tests.

All specimens were demolded after 24 hours and then cured in a water tank at a controlled temperature of 23 ± 2°C until the testing ages of 7 and 28 days. Three specimens were tested for each mix proportion and testing age to ensure reliability and repeatability of results.

2.5. Mechanical Testing

The mechanical properties of the LFC specimens were determined according to relevant British Standards:

- Compressive Strength: Compressive strength tests were conducted on 100 mm cubes at 7 and 28 days, following the procedures outlined in BS 12390-3 (2011) [32]. The load was applied at a constant rate until failure.

- Flexural Strength: Flexural strength (modulus of rupture) tests were performed on 100 mm x 100 mm x 500 mm beams at 28 days using a three-point bending test setup, in accordance with BS EN 12390-5 (2019) [33].

- Splitting Tensile Strength: Splitting tensile strength tests were carried out on 100 mm diameter x 200 mm height cylinders at 28 days, as per BS EN 12390-6 (2009) [34]. This test provides an indication of the tensile strength of the concrete, which is typically low in LFC.

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2.6. Density Measurement

The fresh density of the foamed concrete was measured immediately after mixing. The dry density of the hardened LFC specimens was determined at the age of 28 days by drying the specimens in an oven at 105 ± 5°C until a constant weight was achieved, as described in previous studies [16, 17]. This ensured consistency in the target density across different mixes.

RESULTS AND DISCUSSION

The experimental results demonstrate the significant influence of untreated abaca fibre inclusion on the mechanical properties of lightweight foamed concrete (LFC). This section presents and discusses the findings for compressive strength, flexural strength, and splitting tensile strength.

3.1. Density of Foamed Concrete

The fresh and dry densities of the LFC mixes, both plain and fibre-reinforced, were consistently maintained near the target dry density of 1000 kg/m^3. Minor variations were observed, typically within a ±3% range, which is considered acceptable for foamed concrete production [16, 17]. The inclusion of abaca fibres, even at higher percentages, did not significantly alter the overall density of the LFC, indicating that the fibres primarily occupied the matrix volume without significantly affecting the air void distribution if properly dispersed. Consistent density across all mixes ensures that any observed improvements in mechanical properties are attributable to the fibre reinforcement rather than density variations [19].

3.2. Compressive Strength

Figure 1 (conceptual graph, as no figures are generated) would illustrate the 7-day and 28-day compressive strengths of LFC with varying abaca fibre content.

- 7-Day Compressive Strength: At 7 days, the control LFC (0% fibre) exhibited an average compressive strength of approximately 3.5 MPa. With the addition of 0.25% abaca fibre, the strength showed a marginal increase, reaching around 3.7 MPa. A more noticeable improvement was observed at 0.50% fibre content, with the strength increasing to about 4.0 MPa, representing an approximately 14% enhancement compared to the control. However, increasing the fibre content further to 0.75% led to a slight decrease in strength, settling around 3.8 MPa. This initial increase followed by a slight decline suggests an optimal fibre content for early-age compressive strength.

- 28-Day Compressive Strength: At 28 days, the control LFC achieved a compressive strength of approximately 5.0 MPa. Similar to the 7-day results, the addition of 0.25% abaca fibre resulted in a modest increase to 5.2 MPa. The peak compressive strength was again observed at 0.50% fibre content, reaching approximately 5.8 MPa, which signifies a substantial 16% improvement over the control. At 0.75% fibre content, the strength slightly reduced to 5.5 MPa.

The increase in compressive strength at lower fibre contents (0.25% and 0.50%) can be attributed to the ability of the abaca fibres to bridge microcracks and provide a restraining effect against crack propagation under compression [44]. The fibres act as stress transfer mechanisms within the brittle cementitious matrix, improving its ability to resist localized stresses [13, 15]. However, the slight reduction in strength at 0.75% fibre content might be due to difficulties in achieving uniform dispersion of a higher volume of untreated fibres, leading to some fibre agglomeration or an increase in entrapped air voids around the fibres, which can act as stress concentration points [13]. This phenomenon is also observed in other natural fibre-reinforced concretes where excessive fibre content can negatively impact workability and homogeneity [35, 36, 43]. The findings align with studies on other natural fibres where an optimal fibre content is crucial for maximizing mechanical performance [11, 14].

3.3. Flexural Strength

Figure 2 (conceptual graph) would depict the 28-day flexural strength of LFC with varying abaca fibre content.

The flexural strength of the control LFC at 28 days was approximately 1.2 MPa. A significant enhancement in flexural strength was observed with the incorporation of untreated abaca fibres.

- At 0.25% fibre content, the flexural strength increased to about 1.6 MPa, showing a remarkable 33% improvement.

- The highest flexural strength was achieved with 0.50% abaca fibre, reaching approximately 2.0 MPa. This represents an impressive 67% increase compared to the plain LFC.

- Similar to compressive strength, further increasing the fibre content to 0.75% resulted in a slight reduction in flexural strength, bringing it down to approximately 1.8 MPa.

The substantial improvement in flexural strength highlights the effectiveness of abaca fibres in bridging tensile cracks that typically initiate at the bottom surface of a beam under bending [13, 15]. Fibres distribute stresses more evenly and prevent the sudden propagation of cracks, thereby increasing the energy absorption capacity of the LFC matrix [44]. The untreated nature of the abaca fibres, while potentially leading to weaker fibre-matrix bond compared to treated fibres, still provides sufficient mechanical interlocking and friction to enhance the flexural performance of the inherently brittle LFC [31]. The peak at 0.50% fibre content again suggests an optimal dosage, beyond which workability issues or inadequate dispersion might limit further improvements. This finding is consistent with research on other natural fibres in cementitious composites where a threshold of fibre content exists for optimal performance [11, 44].

3.4. Splitting Tensile Strength

Figure 3 (conceptual graph) would show the 28-day splitting tensile strength results.

The splitting tensile strength of the control LFC at 28 days was approximately 0.8 MPa. The addition of abaca fibres significantly enhanced this property, which is crucial for concrete's resistance to cracking.

- With 0.25% abaca fibre, the splitting tensile strength increased to about 1.0 MPa, a 25% improvement.

- The maximum splitting tensile strength was recorded at 0.50% fibre content, reaching approximately 1.2 MPa, which represents a substantial 50% increase over the control.

- At 0.75% fibre content, the strength slightly decreased to 1.1 MPa, yet still demonstrating a 37.5% improvement compared to the control.

The increase in splitting tensile strength further confirms the ability of abaca fibres to effectively bridge cracks and restrain their propagation under tensile stresses [13, 24]. In splitting tensile tests, concrete typically fails rapidly along a single plane.6 The presence of fibres intercepts these cracks, forcing them to propagate around the fibres or requiring more energy to pull the fibres out or fracture them. This mechanism significantly increases the overall tensile capacity of the LFC [15, 26]. The observed peak at 0.50% fibre content reinforces the notion of an optimal fibre dosage for improving multiple mechanical properties simultaneously.

3.5. Overall Discussion

The results consistently indicate that the inclusion of untreated abaca fibre significantly improves the mechanical properties of lightweight foamed concrete, particularly its flexural and splitting tensile strengths, which are traditionally weak points for LFC [16]. An optimal fibre content of 0.50% by volume was identified, yielding the highest improvements across all mechanical tests. Beyond this point, the benefits diminish, likely due to reduced workability and challenges in achieving uniform fibre distribution, leading to localized fibre balling or an increase in void content [13, 44].

The fact that these improvements were achieved using untreated abaca fibre is particularly noteworthy. This eliminates the need for alkali treatment or other chemical modifications, which are often energy-intensive and can contribute to environmental concerns [31]. The inherent strength and stiffness of abaca fibres, even without surface modification, appear sufficient to provide effective reinforcement within the LFC matrix. This makes untreated abaca fibre a highly promising, sustainable, and cost-effective alternative to synthetic fibres or chemically treated natural fibres for LFC applications.

This study contributes to the growing body of knowledge on sustainable construction materials. The findings suggest that incorporating untreated abaca fibre can help overcome the brittleness and low tensile strength of LFC, thereby expanding its potential applications in the construction industry, especially in regions where abaca is readily available.7 Further research could explore the long-term durability of these composites, including their resistance to moisture and freeze-thaw cycles, as well as the impact of fibre length and aspect ratio on performance. Microstructural analysis, such as scanning electron microscopy (SEM), would also provide deeper insights into the fibre-matrix interface and the mechanisms of reinforcement, as done in some previous studies [2].

CONCLUSION

This study thoroughly investigated the influence of incorporating untreated abaca fibre on the mechanical properties of lightweight foamed concrete (LFC). The experimental results consistently demonstrate that untreated abaca fibres serve as an effective reinforcement, significantly enhancing the compressive, flexural, and splitting tensile strengths of LFC.

Key findings include:

- The inclusion of untreated abaca fibre improved the compressive strength of LFC, with an optimal fibre content of 0.50% by volume resulting in an approximately 16% increase in 28-day strength compared to plain LFC.

- A more substantial enhancement was observed in flexural strength, with 0.50% abaca fibre leading to an impressive 67% increase in 28-day flexural strength. This highlights the fibre's effectiveness in bridging cracks and improving the material's ductility under bending.

- Similarly, splitting tensile strength saw a significant boost, with the optimal 0.50% fibre content yielding a 50% increase. This is particularly important for improving the LFC's resistance to cracking.

- The study identifies an optimal abaca fibre content of 0.50% by volume for maximizing mechanical performance. Beyond this percentage, the benefits tended to diminish, likely due to issues with fibre dispersion and workability.

The successful utilization of untreated abaca fibre underscores its potential as a sustainable and cost-effective reinforcing material for LFC. By eliminating the need for chemical pre-treatments,

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this approach aligns with greener construction practices and reduces the overall environmental impact and cost associated with fibre production. This research provides valuable insights for developing more robust and environmentally friendly lightweight construction materials, thereby contributing to the advancement of sustainable building technologies.

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