Surface-Modified Bamboo Fibre-Reinforced LC3 Concrete: Microstructure, Hydration and Durability

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1. Introduction

Concrete is a carbon-intensive material that significantly contributes to global CO_2 emissions. To reduce its impact, supplementary cementitious materials (SCMs) such as calcined clay, fly ash, and silica fume have been used to partially replace clinker without compromising key properties such as strength and durability [1]. Limestone Calcined Clay Cement (LC3), produced from clinker, calcined clay, limestone, and gypsum, can reduce clinker usage and CO_2 emissions by up to 30% [2]. LC3 offers high strength, durability, and lower energy demand, but faces challenges such as autogenous shrinkage, low tensile strength, and limited fracture toughness, leading to cracking and reduced durability [3]. These shortcomings highlight the need for reinforcement strategies to control cracking and improve tensile and post-cracking performance.

Adding fibres is an effective method to toughen concrete by bridging cracks and preventing their propagation [4]. However, fibre–matrix bonding and dispersion greatly influence the workability and long-term durability of the composite [5]. Natural fibres provide a sustainable alternative, offering improved toughness, strain capacity, and flexural strength while using renewable, low-carbon reinforcements [6]. Among them, bamboo fibre is notable for its high tensile strength (140–230 MPa), short growth cycle, and large annual yield (3×10^8 t) [7], making it particularly promising for enhancing both toughness and sustainability in concrete. However, bamboo fibres also exhibit drawbacks such as high hydrophilicity, limited thermal stability, and poor compatibility with cementitious matrices [8]. Natural fibre-reinforced cementitious composites (NFRCCs) suffer from fibre degradation and weak fibre–matrix interfaces, primarily due to alkaline attack, excessive water absorption, and insufficient bonding [9]. These issues limit durability but can be alleviated through suitable modification techniques.

2. Materials and Methods

Raw bamboo fibres were purchased from Haibosi Technology Co., Ltd. (Fujian, China). The fibres had an average density of 1.575 g/cm³, with an average diameter of about 0.37 mm. The cement used was ordinary Portland cement of grade 52.5 in accordance with EN 197–1:2019, with a specific surface area of 344 m^2/kg. The supplementary cementitious materials included limestone, metakaolin, with specific surface areas of 569.4, 1287.1 m^2/kg, respectively. The LC3 binder consisted of 50 wt% cement, 30 wt% calcined clay, and 15 wt% limestone, blended with 5 wt% gypsum. The water-to-binder ratio was 0.50, and the sand-to-binder ratio was 2.0. Superplasticiser (SP) was added at 1 wt% of binder mass, as determined through preliminary mix design.

This study investigates the effects of surface modification on the fibre–matrix interfacial bonding, microstructure, hydration behaviour, and durability of bamboo fibre-reinforced LC3 mortar. A triple-modification approach, consisting of NaOH alkali treatment [10], KH-550 silane coupling [11], and alkyl ketene dimer (AKD) coating [12], was adopted to overcome the inherent hydrophilicity and alkaline degradation of bamboo fibres, thereby enhancing fibre–matrix interfacial bonding, water resistance, and dimensional stability in LC3 mortar.

Water absorption and single-fibre tensile tests were conducted to investigate the influence of alkali treatment concentration and duration on bamboo fibres' mechanical properties and water absorption behaviour. Pull-out tests were performed to quantify fibre–matrix interfacial bond strength, while flexural strength tests evaluated the mechanical performance of the composites. Fracture surfaces were examined by SEM to reveal fibre–matrix bonding mechanisms. The durability of the composites was evaluated through wet–dry cycling to simulate environmental exposure and assess long-term mechanical stability.

3. Results

Preliminary experiments indicated that the concentration and duration of alkali treatment significantly influenced the tensile strength of modified bamboo fibres. Treatments with different concentrations (2%, 4%, 6%, 8%, 10%) and durations (2 h, 3 h, 4h, 5 h, 6 h) were compared, and the optimal conditions were identified as 8% concentration and 3 h treatment. To investigate dimensional changes upon water absorption, fibres were immersed in water until constant mass and measured for length and diameter. The results showed that fibre length remained nearly unchanged, whereas the diameter exhibited noticeable swelling after water absorption.

Building on these findings, it is expected that triple-modified bamboo fibres (NaOH, KH-550, AKD) will exhibit reduced water absorption and improved dimensional stability compared to untreated fibres. Enhanced fibre–matrix interfacial bonding is anticipated, resulting in higher pull-out strength and improved flexural performance of LC3 composites. Microstructural analysis is expected to show a denser interfacial transition zone, while wet–dry cycling tests are predicted to confirm superior durability and retention of mechanical properties.

4. Conclusion

This study highlights the potential of surface modification to improve the performance of bamboo fibres in LC3 mortar. Preliminary results confirmed that alkali treatment conditions strongly affect fibre tensile strength, with 8% NaOH for 3 h identified as optimal. Fibre swelling upon water absorption was also observed. Building on these findings, the proposed triple-modification strategy is expected to reduce hydrophilicity, enhance fibre–matrix bonding, and improve toughness and durability of LC3 composites. These outcomes would support the development of sustainable, low-carbon construction materials with enhanced long-term performance. To evaluate the effects of surface modification, Fourier transform infrared spectroscopy (FTIR), X-ray diffraction (XRD), and scanning electron microscopy (SEM) will be used to characterise changes in chemical composition, cellulose crystallinity, and fibre microstructure

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