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Enhancement of Flexural Strength in Fiber–Cement Composites through Modification of Sisal Fiber with Natural Rubber Latex and Expanded Perlite

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Abstract: This study presents a novel approach in enhancing the flexural strength of sisal fiber cement composites by employing a dual coating technique with natural rubber latex and expanded perlite to the sisal fibers. The effects of different fiber content (0.25, 0.5, 0.75, 1, 1.25, and 1.5 wt%) and fiber length (1, 2, and 3 cm) on the physical and mechanical properties of sisal fiber cement were also studied. The physical properties, including bulk density and water absorption, were evaluated via the Archimedes method. Flexural strength was measured using the 3-point bending method, and microstructure was observed using a scanning electron microscope (SEM) and an optical microscope (OM). As the fiber content and length increase, the bulk density of the sisal fiber cement decreases. However, composites utilizing coated fibers consistently exhibit a higher bulk density than those utilizing uncoated fibers, attributed to enhanced adhesion and reduced porosity. The water absorption of sisal fiber cement increases with fiber content, but it is mitigated by the natural rubber latex coating, which prevents fiber–water absorption, and by expanded perlite, which reduces voids in the matrix. Composites containing coated fibers consistently exhibit superior flexural strength compared to those with uncoated fibers. The highest flexural strength values of 5.58 MPa were observed in composites utilizing 3 cm of coated fiber with 0.25 wt% fiber content. Microstructure analysis reveals a well-bonded interface in coated fibers, emphasizing the positive impact of coating on mechanical performance. The incorporation of coated sisal fibers effectively improves adhesion, water resistance, and flexural strength, offering sustainable and durable construction materials. The achieved results can serve as the guidelines for the development of a high-performance bio-based construction materials with improved durability and reduced environmental impact.

Keywords: fiber cement; sisal fibers; natural rubber latex; expanded perlite; construction materials

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1. Introduction

Nowadays, natural fibers have gained more interest for various applications, including their use as reinforcement in cementitious composites [1–3]. Natural fibers are widely available, cost-effective, and eco-friendly. Moreover, natural fibers have the potential to improve the mechanical properties of cementitious composites, including flexural strength, toughness, and impact resistance [4–7]. Additionally, natural fibers can provide thermal and acoustic insulation properties to the composites [8–10], which are suitable for various construction applications. Many researchers have focused on optimizing the combination

of natural fibers and cement mortar and the treatment method of natural fibers to achieve the desired performance characteristics for specific applications.

In recent years, sisal fibers have received significant attention as a promising natural fiber for reinforcement in cementitious composites. Sisal fiber has been reported that it is the most extensively studied natural fiber for this purpose [11], owing to its superior mechanical properties, durability, eco-friendliness, and cost-effectiveness. Sisal fibers are cultivated on a large scale worldwide, with an annual global extraction estimated at around 4.5 million tons [12]. Therefore, the abundant availability of sisal plants ensures a steady supply of sisal fibers. The main reinforcing component in sisal fibers is cellulose, a natural polymer that forms a substantial portion of the fiber. In sisal fibers, cellulose molecules align to form strong, rigid structures that contribute to the fiber mechanical properties [11]. In addition, cellulose molecules contain hydroxyl (-OH) groups that form hydrogen bonds, enhancing the interaction between fibers and the cement matrix which could improve mechanical properties [2,3]. With a high cellulose content ranging from 60% to 78%, sisal fibers possess a high tensile strength, which typically ranges from 458 to 720 MPa [11]. A comparative study by Chandrasekaran et al. [13] was conducted focusing on the incorporation of different fibers into cement mortar mixes, including banana, palmyra, coir, and sisal fibers. The results revealed that cement mortar containing sisal fibers exhibited a superior performance compared to the other fiber types tested. The optimal results for sisal fiber composites were obtained after 28 days of curing with 1.5% fiber content and 20 mm fiber length. This combination resulted in a maximum compressive strength of 26.10 MPa, a flexural strength of 5.37 MPa, and a split tensile strength of 2.73 MPa.

Similar to other natural fibers, sisal fiber used in cementitious composites is susceptible to biodegradation and environmental degradation, posing a critical concern. The alkaline nature of cementitious bodies causes the mineralization of plant fibers, wherein hydration products like calcium hydroxide ($CaOH_2$) migrate into the cell walls and lumen of fibers. This process leads to the alkaline hydrolysis of cellulose, reducing the polymerization degree of macromolecular chains within the fiber and affecting the lignin and hemicellulose structure. Consequently, the toughness of cementitious composites decreases [14,15]. Moreover, environmental moisture can cause the swelling and shrinking of the natural fibers, which can further affect the mechanical integrity of the cementitious composites [15–17]. To address these challenges, various approaches have been proposed to enhance the durability of natural fiber-reinforced cement composites. These include adjusting the matrix composition to minimize alkaline compounds and treating the fibers to improve their stability within the cementitious matrix [18].

To reduce the matrix alkalinity, researchers have investigated the possibility of modifying the matrix by incorporating pozzolanic materials, including silica fume, metakaolin, fly ash, and calcined waste clay [15,19–24]. Pozzolanic reactions occur when pozzolanic materials, which are silica-rich substances, react with calcium hydroxide in the presence of moisture. This reaction causes the formation of calcium silicate hydrate (C-S-H), a compound that exhibits greater stability and is less aggressive toward natural fibers. Therefore, adding pozzolanic materials to cement has shown promise in preserving the strength of natural fibers within the composite. Perlite, a volcanic glass with a silica content of approximately 70–75%, has the potential to exhibit a pozzolanic effect in cementitious materials. Incorporating perlite into the cement matrix, as a substitute for cement or fine aggregate, has been observed to maintain or enhance the strength of cement composites [25–27]. Interestingly, while the benefits of perlite in enhancing cement composites have been explored, there remains a research gap regarding the integration of natural fibers and perlite.

To improve the stability of natural fibers in cement composites, various methods including physical and chemical modification, were previously examined. Among physical treatments, one of the most utilized methods is hornification [28,29] due to its simplicity

and cost-effectiveness. This treatment involves drying and rewetting the fibers in cycles, which increases crosslinks among the microfibrils through hydrogen bonding bridges. As a result, hornification effectively reduces water absorption, enhances the dimensional stability of the fibers, and improves fiber adherence to the cement matrix. For example, Ferreira et al. [30] reported that hornification improved the tensile strength and strain at failure of sisal fibers, thereby enhancing then pull-out resistance and bending strength of the fiber cement composites. Similarly, Santos and Lima [31] investigated the effect of wetting-drying cycles on the bonding strength between sisal fiber and cement mortar and reported that subjecting the fiber to 10 cycles resulted in a substantial 23% improvement in bonding strength compared to untreated fiber.

Various chemical treatments, including alkali treatment, silane treatment, and acetylation treatment are commonly employed to enhance the compatibility of natural fibers with the matrix in polymer composites [32]. Furthermore, some treatments demonstrated their effectiveness in enhancing the properties of fiber–cement composites. Among these, alkali treatment is the most utilized chemical treatment due to its cost-effective method. In this treatment, the fibers are immersed in an alkaline solution, typically sodium hydroxide (NaOH), which removes the hydrophilic hydroxyl groups, thereby reducing moisture absorption of the fiber [11,32,33]. Furthermore, this treatment effectively eliminates impurities, waxes, lignin, and hemicellulose from the fibers, resulting in increased fiber surface roughness and improved adhesion with the matrix [11,32,33]. For instance, Sedan et al. [34] found that, when hemp fibers were treated with a NaOH solution, the fiber cement composite exhibited a flexural strength that showed a remarkable 39% improvement compared to the composites containing untreated hemp fibers. According to Li et al. [35], cement mortar with alkalized coir fiber has a higher toughness than that with untreated coir fiber. Moreover, the use of alkalized coir fiber reduced the requirement for chemical additives such as dispersing agents in cement composites because it facilitated more uniform mixing than untreated fiber [35]. Additionally, treated fiber composites demonstrated superior toughness at long-term aging due to enhanced fiber–matrix bonding [35].

To improve the compatibility of natural fiber with the cementitious matrix, many researchers modified the specialized coating on the fiber surface. Filho et al. [19] reported that treating sisal fiber with a silica fume slurry before mixing with the cement matrix considerable improved the long-term durability of the composite. After exposure to 46 wet–dry cycles, composites utilizing treated sisal fibers exhibited substantial enhancements, with flexural strength and toughness increasing by up to 80% and 270%, respectively, in comparison to composites employing untreated fibers. These improvements can be attributed to the presence of silica fume, which created a localized area of low alkalinity at the interface between the fibers and the cement matrix, effectively protecting the fibers from the degradation caused by alkaline attack. Firreira et al. [36] reported that the application of carboxylated styrene butadiene rubber (XSBR) enhances the mechanical properties of natural fibers. Based to their results, the tensile strength of XSBR-coated sisal fibers increased by 59%, resulting in an improvement in pull-out bonding strength from the cement matrix of around 104%. The XSBR polymer contributes higher interaction to cellulose with higher crystallinity, then it forms chemical bonds between the fiber and the matrix via anchor points which enhance the performance of composites. Silva et al. [37] introduced a novel treatment approach for coconut fiber involving the application of natural latex and pozzolanic materials in fiber–cement composites. When coconut fiber was immersed in natural latex and subsequently coated with metakaolin or silica fume, improvements in the flexural strength of the composite were observed, with enhancements of 16% and 42%, respectively, compared to the use of uncoated fiber. Furthermore, following an accelerated wetting and drying cycle, the performance of composites incorporating coated metakaolin and silica fume exhibited significant increases, of approximately 70% and 60%, respectively, in comparison to the untreated fiber composites. The combination of natural latex and pozzolan effectively protected natural fiber by reducing the localized alkaline attack and the formation of mineral.

In this research, we aim to combine various methods to enhance the utilization of sisal fiber in strengthening cement composites. This includes two primary strategies: firstly, reducing the alkaline environment by adding perlite as pozzolanic materials to the cement matrix; and secondly, modifying sisal fiber through an alkaline treatment followed by coating it with natural rubber latex and expanded perlite. By implementing these processes, this study has potential to decrease water absorption and increase the flexural strength of sisal fiber cement composites, thereby contributing to the development of sustainable and durable cementitious construction materials.

2. Materials and Methods

2.1. Materials

The raw materials used in this experiment included ordinary Portland cement (conformed to ASTM C–150 Type I), river sands, expanded perlite, sisal fiber, and natural rubber latex. Table 1 displays the chemical compositions of Portland cement and expanded perlite. Table 2 presents the physical properties of Portland cement and expanded perlite. Ordinary Portland cement was sieved through No.35 (0.5 mm) mesh sieves and the river sand was sieved through No. 16 (1.18 mm) mesh sieves. The particle size distribution of expanded perlite was initially assessed using sieves. The majority of particles fell within the range of 100–300 μm, constituting 38.70% of the total weight fraction. Additionally, the particles sized between 300 and 500 μm accounted for 26.66% of the weight fraction, while those smaller than 100 μm comprised 16.75%. A smaller fraction, representing particles larger than 500 μm, constituted 17.90% of the total weight. The sisal fibers were sourced from a local farmer in Phetchaburi, Thailand. The sisal fibers were extracted from *Agave sisalana* plant leaves by a semi-auto scraping machine. Table 3 shows the physical properties of the composition of sisal fiber. Table 4 presents the physical and chemical properties of natural rubber latex.

Table 1. Chemical compositions of Portland cement and expanded perlite.

Materials	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	K_2O	Na_2O	TiO_2	P_2O_5	SiO_3
Portland cement	66.2	17.8	4.13	3.20	2.95	0.55	0.37	-	-	3.67
Expanded perlite	1.42	74.2	13.3	1.70	0.37	6.27	1.72	0.29	0.58	0.25

Table 2. Physical properties of Portland cement and expanded perlite.

Physical Properties	Portland Cement	Expanded Perlite
Bulk density (g/cm^3)	3.15	0.191
Specific surface area (m^2/g)	0.3359	72.99
Particle geometry	Quasi-sphere	Irregular
Color	Grey	White

Table 3. Physical properties of composition of sisal fiber.

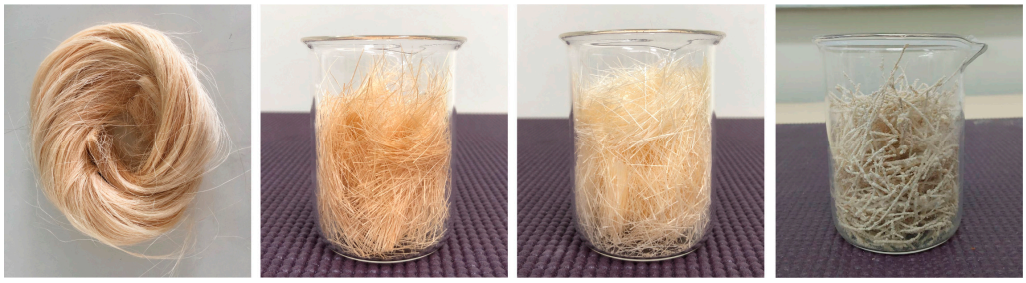
Physical Properties		Composition (wt%) [11]	
Shape	Straight	Cellulose	60–78
Color	Creamy white	Hemicellulose	10–14
Density	1.59 g/cm^3	Lignin	2–14
Water absorption	67.5%	Wax	1–2

Table 4. Physical and chemical properties of natural rubber latex.

Properties	Specification
Form	Liquid
Color	Milky white
pH value	8–9
Total solid content	60.9%
Dry rubber content	57.6%

2.2. Preparation of Sisal Fibers

The photo of as-received sisal fibers is shown in Figure 1a. The sisal fibers were treated before being employed in the cement mortar mixture. Firstly, the sisal fibers were cut into three different lengths (1, 2, and 3 cm) and cleaned with water to remove the contaminants from the surface. Subsequently, they were air-dried in an oven at 60 °C for 24 h. The cut and cleaned sisal fibers are shown in Figure 1b. After that, they were subjected to the alkali treatment process. The sisal fibers were immersed in a 1 wt% sodium hydroxide (NaOH) aqueous solution for 1 h. Subsequently, the treated sisal fibers were rinsed multiple times using a 1 wt% acetic acid (CH_3COOH) solution to neutralize the alkaline base. Afterward, they were cleaned with distilled water until the pH was neutral and then dried at 60 °C for 24 h. The alkali-treated sisal fibers, termed uncoated sisal fibers, are shown in Figure 1c. Finally, the sisal fibers were soaked in natural rubber latex for 1 min and uniformly coated with expanded perlite powder, as shown in Figure 1d. This coated sisal fiber sample is referred to as a coated sisal fiber.



(**a**) (**b**) (**c**) (**d**)

Figure 1. The images showing the sisal fibers characteristics: (**a**) as-received sisal fibers; (**b**) cut and cleaned sisal fibers; (**c**) alkali-treated sisal fibers or uncoated sisal fibers; and (**d**) natural rubber latex and expanded perlite-coated sisal fibers.

2.3. Preparation of Sisal Fiber–Cement Specimens

The sisal fiber–cement specimens were prepared in accordance with the established standards specified in ASTM C1186 [38]. In this study, expanded perlite was incorporated as a pozzolanic material by the substitution of sand to reduce the alkalinity of the cement matrix. According to a previous study, the replacement of sand with 10 wt% expanded perlite provided the highest flexural strength with an optimum bulk density and water absorption [39]. For the preparation of the cement mortar mixture, the mass ratio of Portland cement, sand, and expanded perlite was fixed at 1:1.8:0.2 with water-to-cement ratio (W/C) of 0.5 by weight. The utilization of two types of sisal fibers, uncoated sisal fibers and coated sisal fibers, was investigated. Sisal fibers were incorporated into the mortar mixture in varying lengths and amounts. Fiber lengths of 1 cm, 2 cm, and 3 cm were employed. Each length was assigned different sisal fiber mass percentages: 0.25%, 0.5%, 0.75%, 1%, 1.25%, and 1.5% relative to the total mass of 1 kg of dry cement mortar mixture. A wide range of fiber lengths and amounts is often explored in previous studies investigating the impact on fiber-reinforced composites. The chosen lengths and amounts were based on observations from previous research on similar sisal fiber–cement composites [5,13,40–42]. Additionally, preliminary studies were conducted to confirm that this range is practical,

balancing the benefits of longer fibers (improved strength) with good dispersion within the cement matrix. The experimental setup was designed to evaluate the impact of fiber coating, as well as the influence of sisal fiber length and content, on the physical and mechanical properties of the cement mortar.

The specimen preparation started with the dry mixing of cement, sand, and expanded perlite in the mortar mixer for 5 min, followed by the addition of sisal fibers and further mixing for an additional 2 min. After that, water was gradually added to the mixer until a homogeneous mixture was achieved. Subsequently, the mixed composition was put into a steel mold, and a hydraulic pressing machine applied a load of 5.3 MPa to the mold for 1 min. After that, the specimens were carefully removed from the mold, obtaining a rectangular bar specimen with dimensions of approximately 2.5 cm × 2.5 cm × 15 cm. These specimens were subjected to a curing period of 28 days. At 28 days, cementitious materials typically reach a significant level of strength development [43,44]. Therefore, this aging time is widely considered the most appropriate for evaluating the mechanical properties of cementitious materials.

2.4. Characterization Methods

2.4.1. Microscopic Study

The microscopic analyses were conducted on all sisal fibers, including the as-received sisal fiber, alkali-treated sisal fiber, and coated sisal fiber, using scanning electron microscopy (SEM; Quanta 250, FEI, Hillsboro, OR, USA). These SEM images were used to determine the average diameter of sisal fibers and examine the effects of alkali treatment and coating on the surface microstructure of sisal fibers. The morphology of pull-out fibers was also examined using SEM to evaluate the bonding characteristics with cement matrix.

Microstructures of the sisal fiber–cement composites were examined using an optical microscope (OM; OLS5000, OLYMPUS, Tokyo, Japan). The images provided a visual representation of the adhesion between sisal fibers and the cement matrix, allowing for a comparison between the use of uncoated sisal fibers and coated sisal fibers. This examination aimed to elucidate the impact of coating on the interaction and bonding at the interface of sisal fibers and the cement matrix in the composite material.

2.4.2. Physical Properties

The physical properties of fiber–cement samples, including bulk density and water absorption, were examined using Archimedes principle, which was modified from the certified standards ASTM C20 [45] and ASTM1185 [46]. The fiber cement bars were cut into cubic specimens of 2.5 cm × 2.5 cm × 2.5 cm. The specimens were dried at 105 °C for 24 h, and then cooled to room temperature in a desiccator to determine their dry weight (D). Subsequently, these specimens were placed in boiling water for 2 h, then cooled down to room temperature and immersed in water for 48 h. Then, the weights of the specimens in water (suspended weight, S) and in the air (saturated weight, W) were measured. The bulk density and water absorption of the specimens were calculated using the equations as follows.

$$\text{Bulk density} = \frac{D}{W - S} \quad (1)$$

$$\text{Water absorption} = \frac{W - D}{D} \times 100\% \quad (2)$$

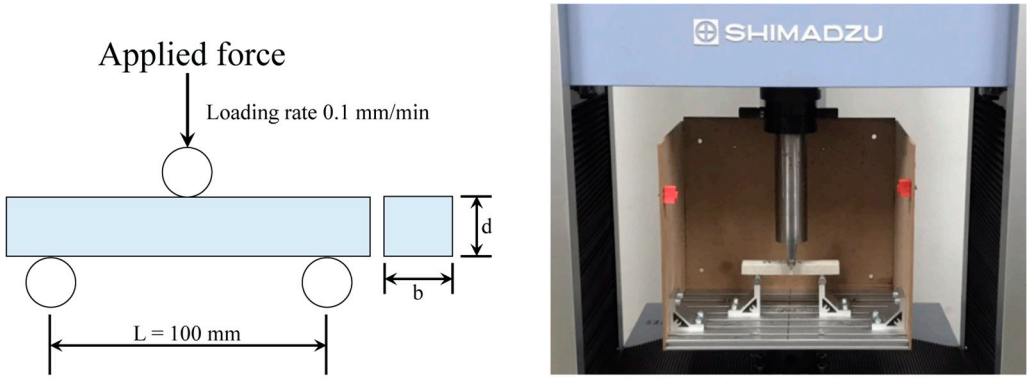
2.4.3. Mechanical Properties

The mechanical property of the sisal fiber cement specimen after aging for 28 days was assessed through a static flexural test. The flexural strength was determined using a three-point bending test, adapted from ASTM C1185 [46]. The experimental setup involved an in-house three-point bending fixture installed in the universal testing machine (AG-X, Shimadzu, Kyoto, Japan). The bending tests were performed with a support span length (L)

of 100 mm and a constant loading rate of 0.1 mm/min. The schematic representation of the three-point bending setup and testing apparatus are depicted in Figure 2a,b, respectively. The flexural strength was determined using the following equation.

$$\text{Flexural strength} = \frac{3PL}{2bd^2} \quad (3)$$

where P represents the maximum load, L is the length of span, b and d denote the width and thickness of the specimen, respectively. The reported flexural strength represents the average values measured from testing five specimens for each specific mixture condition.



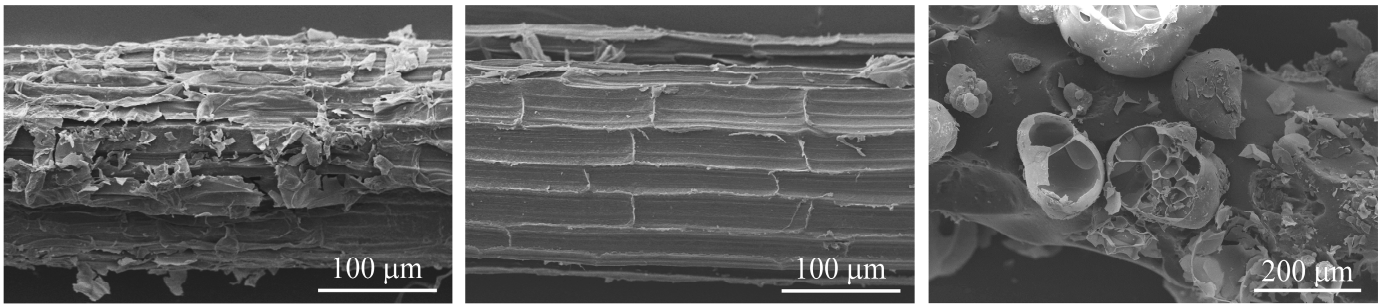
(**a**) (**b**)

Figure 2. (**a**) Schematic representation of the three-point bending setup and (**b**) testing apparatus setting in universal testing machine.

3. Results and Discussion

3.1. Microstructure Analysis and Water Absorption of Sisal Fibers

The surface microstructure of sisal fibers was observed using SEM. Figure 3 depicts various stages of sisal fibers, illustrating their morphologies before and after alkali treatment, as well as after coating with natural rubber latex and expanded perlite. The average diameter of each fiber was estimated from SEM images using the Image J program. In Figure 3a, the as-received sisal fiber is presented with a rough surface containing many impurities. The surface of sisal fibers is covered by a layer of hemicellulose, lignin, and wax, aligning along the longitudinal axis of the fiber, consistent with observations in existing literature [47]. In this study, the average diameter of as-received sisal fiber was estimated to be approximately 0.26 mm.



(**a**) (**b**) (**c**)

Figure 3. SEM images showing the surface of sisal fibers: (**a**) as-received sisal fibers; (**b**) alkali-treated sisal fibers; and (**c**) natural rubber latex and expanded perlite-coated sisal fibers.

Figure 3b illustrates the surface of sisal fibers after alkali treatment, revealing a clean surface in the treated fibers. Treated sisal fibers exhibit a reduction in impurities compared

to untreated fibers, indicating the effectiveness of NaOH in removing contaminants from the fiber surfaces. Additionally, previous studies have reported that NaOH solutions can partially dissolve hemicellulose and lignin from the sisal fiber while leaving cellulose unaffected, contributing to the enhanced strength of the fibers [16]. The average diameter of the alkali-treated sisal fiber was determined to be 0.22 mm. The slight reduction in fiber diameter might be attributed to the degradation of hemicellulose and lignin and aggregation of cellulose microfibrils due to the treatment [43]. The compaction of fibers after alkali treatment could be beneficial in reducing fiber swelling, thereby enhancing the stability of the fiber within the cement matrix.

Figure 3c depicts the morphology of sisal fibers after alkali treatment, followed by the impregnation with natural rubber latex and coating with expanded perlite. It is seen that the entire surface of the sisal fiber is covered with a smooth layer of natural rubber latex, indicating a compatible adhesion between the sisal fiber and natural rubber latex. The coating layer of natural rubber latex holds expanded perlite and its debris on the fiber surface. The sisal fibers, when covered with natural rubber latex, exhibit an average diameter of approximately 0.35 mm. After coating with expanded perlite, the diameter varies within the range of 0.42–0.98 mm, depending on the particle size of the adhered perlite.

This SEM analysis indicates the effectiveness of alkali treatment and natural rubber latex coating in modifying the surface morphology of sisal fibers. Alkali treatment reduces impurities on the fiber surface and enhances the fiber stability, while the natural rubber latex coating provides a protective layer and facilitates the adherence of expanded perlite. These modifications hold significant promise in enhancing the compatibility of fibers with cementitious matrices, ultimately leading to improved mechanical performance in fiber cement composites.

The water absorption of sisal fibers was evaluated before and after the alkali treatment process, along with the subsequent coating process. The results indicate a significant reduction in water absorption after treatment. Specifically, the water absorption values were 67.5% for as-received sisal fibers, 62.5% for alkali-treated sisal fibers, and 23.1% for coated sisal fibers. This reduction in water absorption can be attributed to the removal of impurities and the enhancement of fiber surface properties through the treatment processes. Alkali treatment effectively removes contaminants and reduces the hydrophilicity of the fibers, while the coating further seals the fiber surface, minimizing the moisture uptake. This improvement in water resistance is crucial for enhancing the durability and performance of sisal fiber–cement composites, as it helps mitigate degradation due to moisture exposure. Therefore, the combination of alkali treatment and coating presents a promising approach for enhancing the water resistance of sisal fibers in cementitious applications.

3.2. Physical Properties of Sisal Fiber Cement Composites

Figure 4 shows the bulk density of fiber cement composites, comparing those utilizing uncoated and coated sisal fibers, with varying fiber lengths and contents. The bulk density of fiber cement composites tends to decrease with an increase in fiber content. These trends align with the observations of Okeola et al., who reported a decrease in the density of sisal fiber-reinforced concrete as the fiber content increased [42]. The lower density of sisal fibers (1.59 g/cm^3) compared to the cement matrix (density of matrix components; cement = 3.15 g/cm^3; sand = 1.75 g/cm^3; expanded perlite = 0.191 g/cm^3) resulted in an inverse relationship between the fiber content and density.

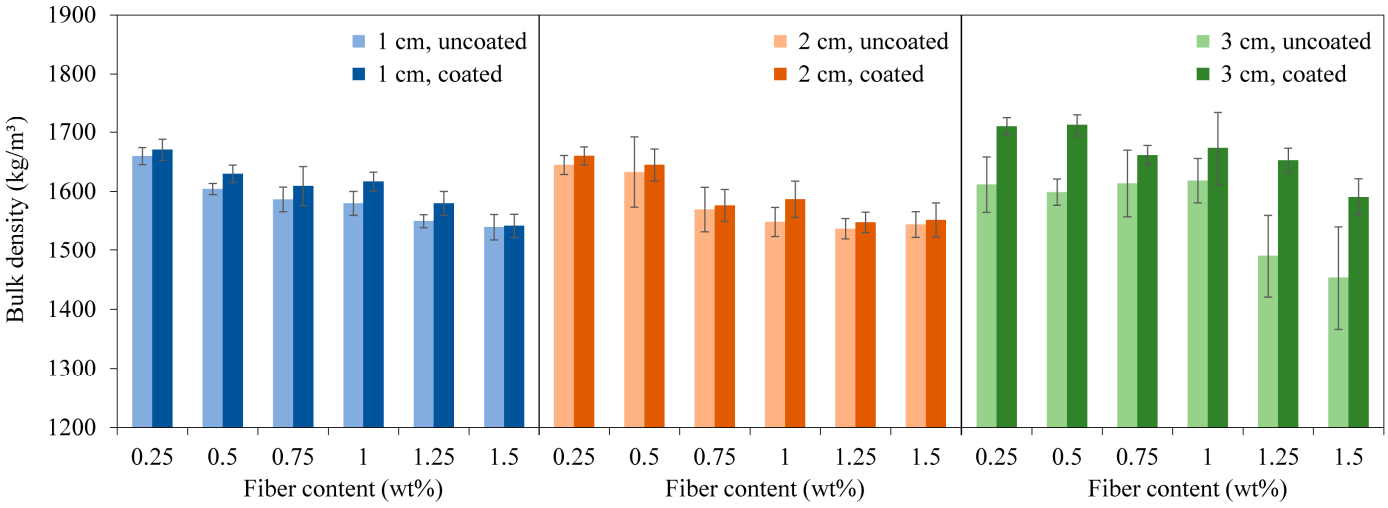


Figure 4. Bulk density of fiber–cement composites using uncoated and coated sisal fibers, with varying fiber lengths and contents.

When comparing the effect of coated and uncoated sisal fibers, the composite containing coated fibers demonstrated a slightly higher density. The fiber cement composites using uncoated sisal fiber exhibited a density ranging from 1453 to 1659 kg/m^3, while those using coated fiber exhibited a density in the range of 1542–1709 kg/m^3. The densities of composites using uncoated fibers are in the same range as the density of natural fiber cement reported in other studies [2]. On the other hand, the densities of the composites using coated fibers were slightly higher.

In the case of composites utilizing 1 cm sisal fibers, those using coated fibers exhibit a density that is 0.1–2.3% higher than the composites with uncoated sisal fibers. Similarly, for composites with 2 cm sisal fibers, those using coated fibers have a density 0.5–2.5% higher than those with uncoated sisal fibers. Furthermore, in composites with 3 cm sisal fibers, those using coated fibers demonstrate a density 3.0–10.9% higher than composites with uncoated sisal fibers. The similarity in bulk densities between the fiber cement composites with 1 cm uncoated sisal fibers and 1 cm coated sisal fibers can be attributed to the distribution and arrangement of the shorter fibers within the cement matrix. While longer fibers may provide more reinforcement and affect the density of the composite due to their alignment and interaction with the matrix, shorter fibers tend to be dispersed more throughout the matrix. This distribution of shorter fibers can disrupt the continuity of the matrix, leading to a similar bulk density compared to composites with longer fibers. Nevertheless, the bulk density results indicate a consistent trend of higher density in composites employing coated sisal fibers across varying fiber lengths. The enhanced density is attributed to the coating of sisal fibers with natural rubber latex and expanded perlite, which improves the adhesion between sisal fibers and the cement matrix, thereby reducing the porosity of the fiber–cement composites.

Figure 5 illustrates the water absorption of the fiber–cement composites, comparing those employing uncoated and coated sisal fibers, with varying fiber lengths and contents. The water absorption of the fiber–cement composites shows an increasing trend with a higher sisal fiber content. However, it is observed that this increase in water absorption with fiber content is less pronounced for the composite using coated sisal fiber. For a 1 cm sisal fiber cement, the water absorption is 20.1–24.8% for uncoated fiber and 19.8–20.7% for coated fiber. In the case of 2 cm sisal fiber cement, water absorption is in the range of 20.6–23.0% for uncoated fiber and 20.1–22.7% for coated fiber. Moreover, for 3 cm sisal fiber–cement, water absorption is in the range of 20.6–27.9% for uncoated fiber and 15.8–20.5% for coated fiber. The coating of sisal fibers seems to reduce the water absorption compared to uncoated fibers, especially at a higher fiber content and longer fiber length.

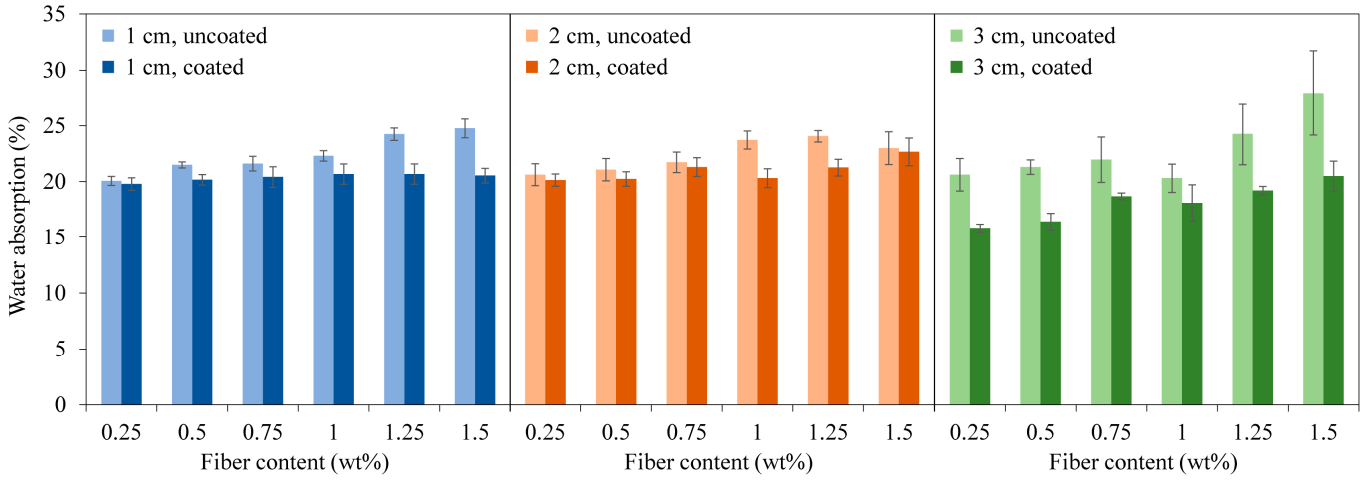


Figure 5. Water absorption of fiber–cement composites using uncoated and coated sisal fibers, with varying fiber lengths and contents.

Natural fibers, in general, tend to be hydrophilic and porous. Consequently, the incorporation of sisal fibers into cement composites leads to a rise in water absorption, particularly with increasing the fiber content and length [2,7,42,48]. Furthermore, the poor bonding of embedded fibers with cement can cause voids within the cement matrix, contributing to an increase in water absorption [2]. In this study, the application of a hydrophobic coating of natural rubber latex on sisal fiber could provide initial resistance against water absorption. Additionally, the expanded perlite as a secondary coating on sisal fiber could interact with the cement matrix, establishing a strong bond and thereby reducing pores in the cement matrix.

According to ASTM C1530/C1530M [49], the water absorption of non-asbestos fiber-cement roofing products should be less than 25%. The fiber cement utilizing uncoated fiber, particularly those with a high fiber content at 1.25–1.5 wt%, exhibited water absorption levels that approached or exceeded the specified limit. Conversely, coated sisal fibers showed a substantially lower water absorption. For example, in the case of 1.5 wt% content of 3 cm coated sisal fiber–cement, the composite reduced the water absorption by 20% when compared to that of uncoated fiber–cement. These results demonstrate the significance of coating treatments in reducing water absorption in fiber–cement composites. It aligns with the goal of enhancing the durability and performance of natural fiber-reinforced cementitious materials, particularly in applications where exposure to moisture is a concern, such as roofing products.

3.3. Flexural Strength of Sisal Fiber–Cement Composites

Figure 6 presented the flexural strength of sisal fiber composites after 28 aging days, comparing those utilizing uncoated and coated sisal fibers, with varying fiber lengths and contents. The flexural strength testing involves aspects of both compression and tension. During a flexural strength test, the top of the bar specimen experiences compressive forces, while the bottom experiences tensile forces. This is due to the bending of the specimen under the applied load, which causes a compression on the top surface and tension on the bottom surface. Therefore, while the primary focus of flexural strength testing is on the ability of a material to resist bending or flexural loads, it inherently provides information about both the compression and tension properties of the material. The utilization of fibers with different lengths is observed to result in different trends in flexural strength as the amount of fiber increases.

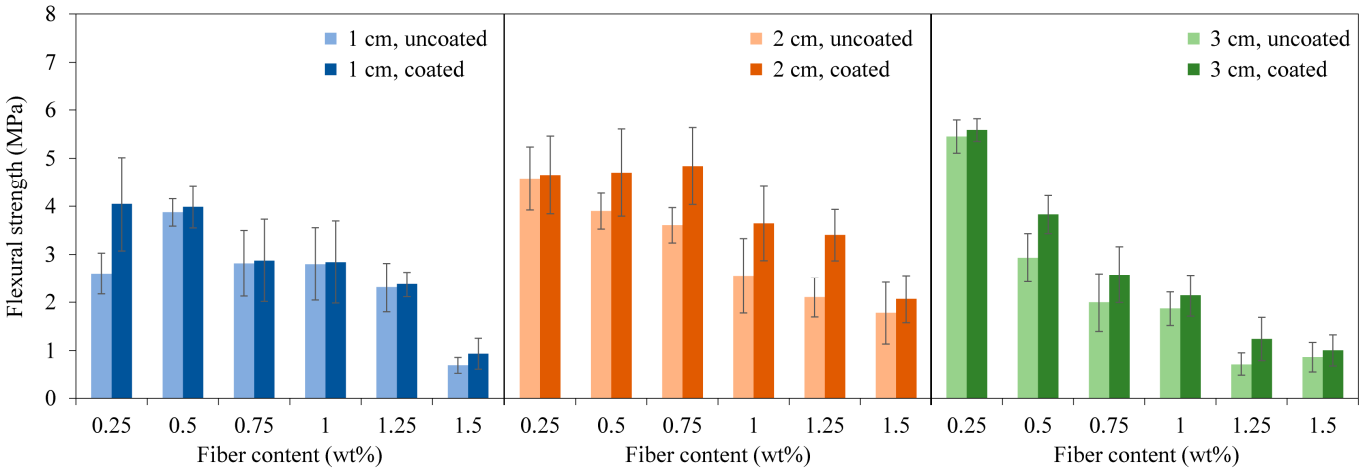


Figure 6. Flexural strength of fiber–cement composites after 28 aging days, and a comparison between specimens using uncoated and coated sisal fibers, with varying fiber lengths and contents.

For the 1 cm fiber–cement composites, the highest flexural strength values were 3.87 MPa at 0.5 wt% for uncoated fiber and 4.04 MPa at 0.25 wt% for coated fiber. In the case of the 2 cm fiber–cement composites, the highest flexural strength was 4.58 MPa at 0.25 wt% for uncoated fiber. However, for coated fiber, the flexural strength increased from 4.65 MPa to the highest value of 4.84 MPa as the fiber content increased from 0.25 wt% to 0.75 wt%. It then declined to 2.07 MPa with further increases in content to 1.5 wt%. In the case of the 3 cm fiber–cement composites, the trends for both uncoated and coated fibers were similar, with maximum values observed at 0.25 wt% fiber content, 5.45 MPa for uncoated fiber and 5.58 MPa for coated fiber, followed by a decrease with increasing fiber content. The optimal result in this experiment, observed in the 3 cm coated fiber cement composites with 0.25 wt% fiber content, demonstrated the highest flexural strength.

When comparing at a low fiber content of 2.5 g, increasing the length of sisal fiber resulted in an improvement in flexural strength. This suggests that, with an optimal quantity, longer sisal fibers contribute to a stronger bridge and prevent cracking while maintaining homogeneous dispersion. However, particularly for 3 cm fiber composites, an increase in fiber content tended to a decrease in flexural strengths. This is mainly due to the addition of excessive fibers, causing fiber clumping. The clustering of fibers induces more cracks within the cement, consequently diminishing its strength.

When the effect of using coated sisal fibers was considered, it was found that the flexural strength of the coated fibers is higher than that of the uncoated ones. In 1 cm sisal fiber composites, the utilization of coated fibers results in a flexural strength that is 1–55% higher than composites with uncoated sisal fibers. Similarly, for 2 cm sisal fiber composites, those using coated fibers exhibit a flexural strength 2–62% higher than those with uncoated sisal fibers. Furthermore, in 3 cm sisal fiber composites, those using coated fibers demonstrate a flexural strength 2–73% higher than composites with uncoated sisal fibers. This suggests that the application of coating to sisal fibers significantly improves the flexural strength of the composites. The strong bonding between the coated sisal fibers and the cement matrix contributes to an improved resistance against cracks. Consequently, it can be inferred that sisal fiber coated with natural rubber latex and expanded perlite contributes to an increase in flexural strength, offering a promising approach for enhancing the mechanical properties of fiber–cement composites.

Figure 7 depicts the failure mode of the specimens containing 0.25 wt% of 3 cm sisal fiber after the flexural strength testing. The observed modes of failure in the flexural testing included fiber pull-out, fiber breakage, and matrix cracking. In both specimens using coated and uncoated sisal fiber, the main failure line exhibited a direction parallel to the loading with a slight shear away from the axis. However, in the specimen containing uncoated sisal fiber (Figure 7a), many lateral cracks branching from the primary crack line were observed.

The reason is due to the poor bonding between uncoated fiber and cement matrix, which creates pre-existing cracks within the specimen. When subjected to force, the direction of the failure line follows these existing cracks. Conversely, the failure observed in specimens using coated sisal fiber displayed fewer lateral cracks and mainly exhibited a pull-out fiber. This mechanism can contribute to strengthening by preventing crack propagation and increasing the overall toughness. The coated fibers act as reinforcements, bridging cracks, and providing additional resistance to deformation [50].

(**a**) (**b**)

Figure 7. Failure mode of specimens containing 0.25 wt% of 3 cm sisal fiber: (**a**) uncoated sisal fiber cement; and (**b**) coated sisal fiber cement.

3.4. Microstructure Analysis of Sisal Fiber–Cement Composites

An optical microscope was used to examine the surface of the fiber–cement composites, specifically to observe the bonding characteristics between the fiber and the cement matrix. Figure 8a reveals gaps and voids between the uncoated fiber and the cement matrix, whereas Figure 8b shows a perfectly bonded interface between the coated sisal fibers and the cement matrix that is free of any voids. The optical microscope observations indicate that uncoated sisal fibers exhibit poor bonding with the cement, leading to internal pores that contribute to increased water absorption. Conversely, the coated fibers display effective bonding with the cement matrix, resulting in fewer internal pores. The strong bond of coated sisal fibers not only reduces water absorption but also enhances the flexural strength of composite. Microscopic analysis provides valuable insights into the importance of coating in promoting favorable interactions between fibers and the cement matrix, thereby influencing the overall performance of fiber–cement composites.

The microstructure of fibers that were pulled out from the cement matrix at the fracture surface of the flexural strength test specimens were examined using SEM to determine the morphology and bonding characteristics between the fibers and the cement matrix. In Figure 9a, the surface of uncoated fibers reveals a weak bond with the cement matrix, evidenced by a small amount of adhering cement matrix crumble on the fiber surface. Moreover, the uncoated fiber appears to be damaged due to the penetration of cement matrix, resulting in a weakening of the reinforced fiber. In contrast, Figure 9b shows coated fibers with a rough surface and a significant amount of adhering cement matrix fragments. The microstructural analysis of the pulled-out fiber is crucial for understanding the interaction between fibers and the cement matrix. The rough surface of the coated fibers indicates a stronger bond, which enhances the load-carrying capacity of the composite. This strong adhesion can be attributed to the modification coating of natural rubber latex and expanded perlite, which provides an intermediate layer that promotes better fiber integration with the cement matrix. Therefore, the microstructural examination confirms the positive influence of coating on the mechanical performance of sisal fiber cement composites.

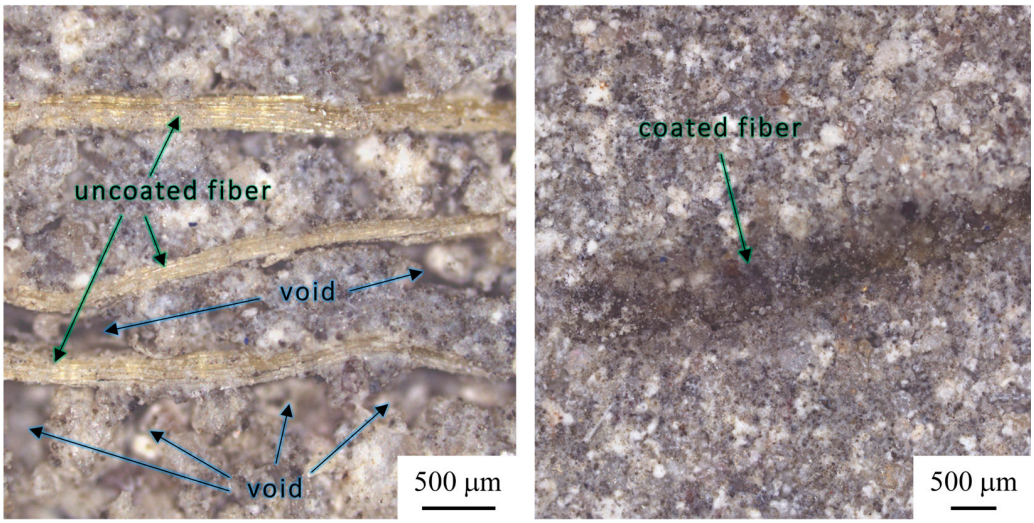


Figure 8. Optical microscope images of the surface microstructure of fiber–cement composites with (**a**) uncoated and (**b**) coated sisal fibers.

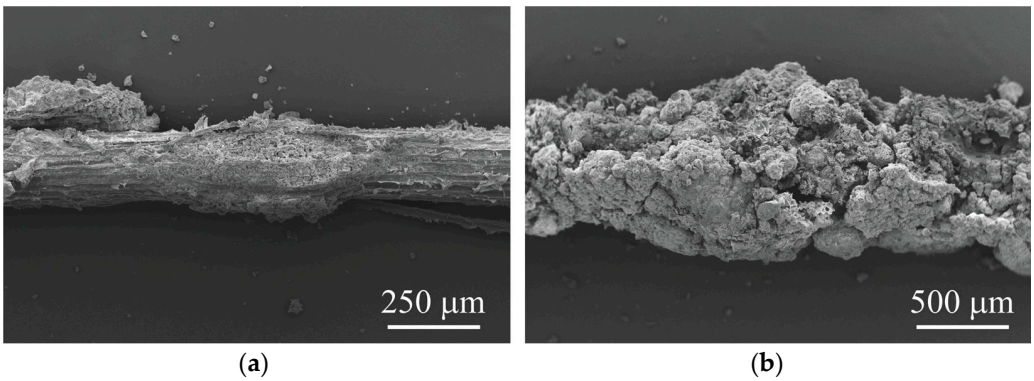


Figure 9. SEM images of the pulled-out fibers: (**a**) uncoated; and (**b**) coated sisal fibers.

There are several advantages of using natural rubber latex-coated sisal fibers compared to uncoated fibers. Coating the sisal fibers with natural rubber latex enhances their adhesion to the cement matrix, thereby improving the overall mechanical properties of the composites. The coating acts as a protective barrier, reducing water absorption by the fibers and minimizing the potential for degradation over time. Additionally, the presence of the coating helps to fill voids and improve the interfacial bonding between the fibers and the cementitious matrix, resulting in enhanced strength and durability of the composite material. Incorporating coated sisal fibers also contributes to the sustainability and eco-friendliness of the construction materials. By utilizing natural rubber latex as the coating material, which is derived from renewable resources, the composites become more environmentally friendly compared to those containing synthetic additives. Furthermore, the improved performance of the coated fibers may lead to the development of more durable and long-lasting construction materials, reducing the need for frequent maintenance and replacement.

4. Conclusions

This study investigated the enhancement of sisal fiber–cement composites by coating the surface of sisal fibers with natural rubber latex and expanded perlite. The investigation also determined the optimal fiber content and length for improving physical and mechanical properties. The following conclusions can be drawn.

- SEM analysis revealed the morphological changes in sisal fibers before and after alkali treatment and coating. The alkali treatment resulted in a slight reduction in fiber diameter, and the subsequent coating demonstrated a smooth layer of natural rubber latex and homogeneously anchoring expanded perlite.
- The bulk density of sisal fiber–cement composites decreased with increasing fiber content and length. Using coated sisal fibers resulted in a higher density than uncoated ones, attributed to improved adhesion and reduced porosity.
- The water absorption of the sisal fiber–cement composites increased with sisal fiber content, but this increase was less pronounced for coated sisal fibers. The coating of natural rubber latex prevented sisal fiber from absorbing water, and expanded perlite played a crucial role in reducing the void between the fiber and cement matrix.
- The flexural strength of sisal fiber–cement composites using coated sisal fibers consistently exhibited higher flexural strength compared to those using uncoated fibers. Flexural strength varied with fiber content and length, with the highest value of 5.58 MPa observed in a composite comprising 3 cm coated fiber composites with 0.25 wt% fiber content.
- The microstructure analysis revealed that coated sisal fibers displayed a perfectly bonded interface, free of voids, implying effective bonding with the cement matrix. The morphology of pulled-out fiber reveals the rough surface of coated fiber, with a significant presence of adhering cement matrix fragments, indicates a stronger bond. These results emphasize the positive impact of coating on the mechanical performance of the sisal fiber–cement composites.

In conclusion, the study successfully investigated the enhancement of sisal fiber–cement composites through surface coating with natural rubber latex and expanded perlite. The findings indicate that the coating treatment effectively improved adhesion, reduced water absorption, and enhanced the flexural strength of the composites. The optimal fiber content and length were determined, providing valuable insights for the formulation of high-performance cementitious materials. This research contributes to the development of sustainable and durable construction materials, highlighting the importance of surface coating treatments in optimizing the performance of natural fiber-reinforced cementitious composites. Additionally, investigating the long-term durability and environmental sustainability of these materials would be beneficial for their practical application in construction projects.

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