DEVELOPMENT OF FIBER CEMENT TILE USING PERLITE AND SISAL FIBER

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Thesis Title	Development of fiber cement tile using perlite and sisal fiber
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Abstract

This research aims to develop natural fiber cement composites utilizing sisal fiber for reinforcement and substituting sand with perlite to decrease weight. To fabricate fiber cement composite, the mass ratio of Portland cement, sand, and perlite was maintained at 1:1.8:0.2, with a water-to-cement ratio of 0.5 by weight. Various lengths (1, 2, and 3 cm) and contents (0.25%, 0.5%, 0.75%, 1%, 1.25%, and 1.5% by weight of total mixture) of sisal fiber are utilized to assess their impact on properties of composite. Then, specimens underwent a curing period of 28 days. Additionally, the study involves comparing fiber coated with natural latex to prevent degradation and reduce water absorption. The physical properties, including bulk density and water absorption, were investigated using Archimedes principle. Microstructure observation was conducted using a scanning electron microscope (SEM) and optical microscope (OM). The mechanical property, specifically flexural strength, was determined using the principle of 3-point bending. The results demonstrate that while increasing fiber content and length generally decrease bulk density, composites with coated fibers exhibit consistently higher density compared to those with uncoated fibers. This is attributed to enhanced adhesion and reduced porosity due to the coating. Water absorption increases with fiber content, but the coating effectively mitigates this by preventing fiber water absorption with the latex and reducing matrix voids with the perlite. The flexural strength of coated fiber composites was higher than that of uncoated fiber composites. Additionally, longer length and lower content led to higher flexural strength. Microstructural analysis demonstrates that coated fibers have the

capability to reduce porosity and effectively bond to cement, thereby enhancing both mechanical and physical properties. From this research, the optimal conditions for fiber cement development as utilizing coated sisal fibers with a length of 3 cm and a content of 0.25 wt%. This condition resulted in a bulk density of 1,709 kg/m^3, water absorption of 15.8%, and flexural strength of 5.58 MPa.

Keyword: fiber cement, natural fiber, natural rubber latex, sisal fiber

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Chapter 1

Introduction

1.1 Background and significance of the research

Several types of roofing tiles depending on the utilized materials are available in Thailand. The majority of low- to middle-income customers often use asbestos cement roofing tile because it is inexpensive and has suitable properties including low density, low water absorption, good thermal insulator, and high compressive strength. However, asbestos is a toxic substance when it enters the body through the respiratory system for a period. Asbestos causes various diseases such as lung cancer, mesothelioma, asbestosis, and others [1].

Many studies have reported that natural fibers can be used to replace harmful asbestos in fiber-cement products. Natural fibers show the potential to improve the physical and mechanical properties of the cement product. However, natural fiber length and strength as well as the consistency and adhesion of natural fiber to the mortar matrix, have a significant impact in the qualities of cement products. In order to develop high-performance fiber cements, it is necessary to investigate these parameters. Sisal fiber is one of the most widely used natural fibers in various applications and can be easily cultivated in any part of the world. Sisal fiber offers numerous advantages, such as being cost-effective, serving as a thermal insulator, and possessing high strength and toughness [2]. These qualities make it an ideal candidate for use as a reinforcing material in composites. Moreover, due to its low density, high strength, and affordability, sisal fiber holds promise for applications in construction materials [3].

In this study, sisal fiber will be utilized in the fabrication of fiber cement. Expanded perlite will be incorporated into the fiber cement to substitute silica sand aggregate, aiming to enhance its lightweight and strength properties. Perlite has been reported as a component of traditional cementitious materials or as a source material for geopolymers. Perlite provides good thermal and sound insulation, fire resistance, and low density when using in building materials [4]. Furthermore, the durability of

fiber cement will be enhanced through the application of a natural rubber latex coating on the sisal fiber. This rubber coating serves to mitigate the degradation of natural fibers within cement products. The objective of this research is to investigate the impact of varying natural fiber addition content, fiber length, and the application of natural rubber coating on the physical, mechanical, and thermal properties of perlite fiber cement. The results of this study are expected to be the guidance for the development of the construction industry.

1.2 Objectives

1.2.1 To investigate the influence of sisal fiber length and content on the physical, thermal, and mechanical properties of natural fiber perlite cement products.

1.2.2 To examine the impact of natural rubber coating on the durability of natural fiber in perlite cement.

1.2.3 To assess optimal conditions for enhancing natural fibers to improve perlite fiber cement properties.

1.3 Research Scope

This research focuses on the production of natural fiber perlite cement, utilizing various raw materials including ordinary Portland cement, silica sand, perlite, natural fiber (sisal fiber), natural rubber, and water.

1.3.1 Investigation was conducted on sisal fiber lengths of 1, 2, and 3 cm.

1.3.2 The addition of natural fiber content ranged from 2.5 to 15 g (in a total mass of 1000 g).

1.3.2 Comparison was made between fiber cements using uncoated natural fiber and natural rubber-coated fiber.

1.4 Benefits

By integrating natural fibers like sisal and perlite into cement-based materials, this research enhances their physical, thermal, and mechanical properties, thereby offering environmentally sustainable and long-lasting building solutions. These

additions improve tensile strength, impact resistance, and thermal insulation, promoting energy efficiency and reducing environmental impact. Furthermore, the renewable nature of natural fibers contributes to sustainable construction practices. Ultimately, this research serves as a valuable guideline for developing eco-friendly building materials that prioritize durability and environmental responsibility.

Chapter 2

Theory and Literature Review

2.1 Cement

Cement is a finely gray powder that is an important material for construction building. When cement is mixed with water and aggregate, it will cause a chemical reaction to happen. This chemical reaction is called Hydration reaction. The strength of cement results from hydration reaction. In 1824, Cement was patented for the first time by Joseph Aspdin. Cement was discovered in Portland city of England, then it is called “Portland cement”. After that, Portland cement was published to the world’s construction industry.

2.1.1 The method of producing cement

Raw materials of Portland cement consist of 3 compounds: (1) Calcareous materials (limestone, Marl or Chalk), (2) Argillaceous materials (shale or clay) and (3) Iron Oxide materials (Iron Ore or Laterite). Usually, there are 2 production processes that are employed for the manufacturing of Portland cement.

1. Wet Process: Chalk and Clay are mixed. Then the mixtures are crushed into smaller pieces while the water is added during crushing to make a homogeneous mixture. After that, bring both into kiln. The flow diagram of the wet process is shown in Figure. 2.1.

2. Dry Process: Limestone and Shale are mixed and crushed into smaller pieces and then put into kiln. The flow diagram of the dry process is shown in Figure. 2.2.

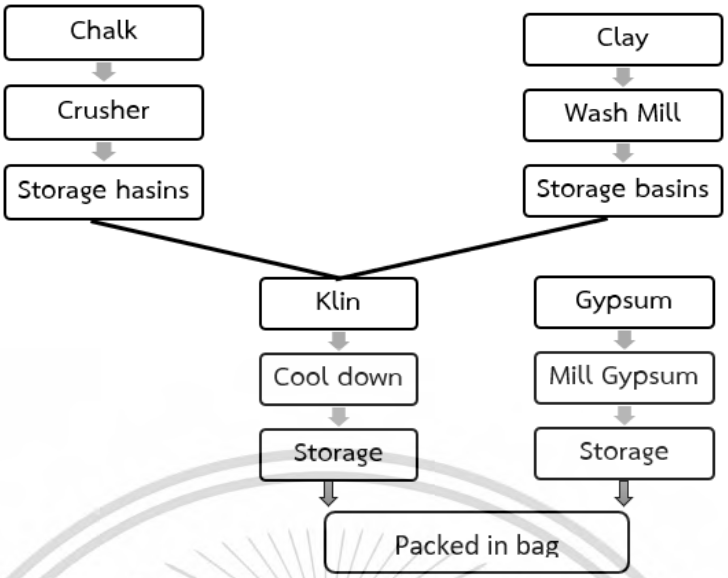


Figure 2.1 Flow diagram of wet process of cement manufacturing.

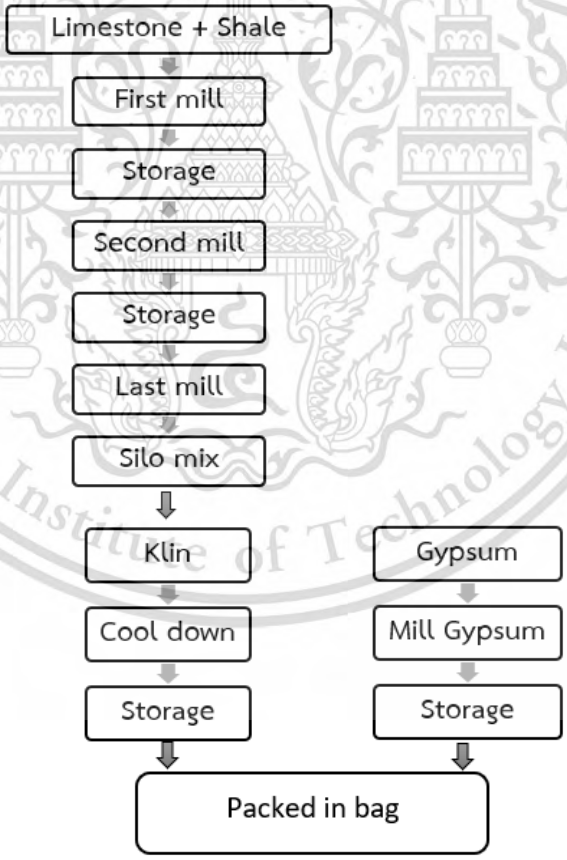


Figure 2.2 Flow diagram of dry process of cement manufacturing.

2.1.2 Chemical composition

While raw materials are burned in a kiln, the chemical reaction takes place in the following steps. First, the water will evaporate from all the ingredients. Second, carbon dioxide is excreted from the limestone and chalk, leaving only CaO. Third, oxide fusion occurs between silica, alumina, iron and calcium (limestone or clay). Last, the combination of oxide chemicals is followed by a crystallization process upon cooling. The chemical composition of Portland cement can be divided into two oxide groups, which are shown in Table 2.1. The main oxide will agglomerate to form a cement clinker, which contains 4 important components as shown in Table 2.2.

Table 2.1 Chemical composition of Potland Cement.

Oxide	Percent by weight
Main Oxide	
CaO	60-67
SiO_2	1-25
Al_2O_3	3-8
Fe_2O_3	0.5-6.0
Secondary Oxide	
MgO	0.1-5.5
Na_2O, K_2O	0.5-0.3
TiO_2	0.1-4.0
P_2O_5	0.1-0.2
SO_3	1.0-3.0

Table 2.2 Main compounds of Portland Cement.

Compounds	Chemical composition	Abbreviation
Tricalcium Silicate	3 CaO • SiO_2	C_3S
Dicalcium Silicate	2 CaO • SiO_2	C_2S
Tricalcium Aluminate	3 CaO • Al_2O_3	C_3A
Tetracalcium Aluminoferrite	4 CaO • Al_2O_3 • Fe_2O_3	C_4AF

The properties and characteristics of 4 main compounds in Portland cement are detailed as follows.

1. Tricalcium Silicate (C_3S): The structure of Tricalcium Silicate (C_3S) is a hexagonal shape. It is grey in color. When tricalcium silicate (C_3S) is mixed with water, it will set and harden in 2-3 h. During the reaction, around 500 J/g of heat is emitted. This compound is responsibility of early strength.

2. Dicalcium Silicate (C_2S): The structure of Dicalcium Silicate (C_2S) is a circle shape. When mixed with water, it produces a hydration reaction that produces of heat about 250 J/g. Dicalcium Silicate (C_2S) hardens slowly and is response to increase in strength after 1 week.

3. Tricalcium Aluminate (C_3A): The structure of Tricalcium Aluminate (C_3A) is a faceted shape. When mixed with water, Tricalcium Aluminate (C_3A) will set and harden immediately. Heat is emitted at a rate of around 850 J/g. This compound causes the development of strength in the first few days.

4. Tetracalcium Aluminoferrite (C_4AF): Tetracalcium Aluminoferrite (C_4AF) reacts with water immediately but has little effect on strength. Its use allows for lower kiln temperatures in the production of Portland cement. C_4AF is responsible for the majority of the color variations in Portland cement.

2.1.3 Setting and hardening of cement

Portland cement is characterized by fine power, which can be set and hardened when reacts with water. The setting and hardening processes are called “Hydration reaction”. These reactions of cement give the ability to load-bearing properties.

When water is added to cement, it will become a liquid cement paste and can flow for a period in which the properties of cement paste will be unchanged. This time of reaction is called “Dormant Period”. After that, cement paste will begin to stiff or set. This time of reaction is called “Initial Set”. Although cement paste will be set, it will be soft and can unworkable. The setting of cement paste will continue over time until it becomes a rigid solid. This period is called “Final Set”. However, the cement paste continues to set and harden. All processes are called “Setting and Hardening” as shown in Figure. 2.3.

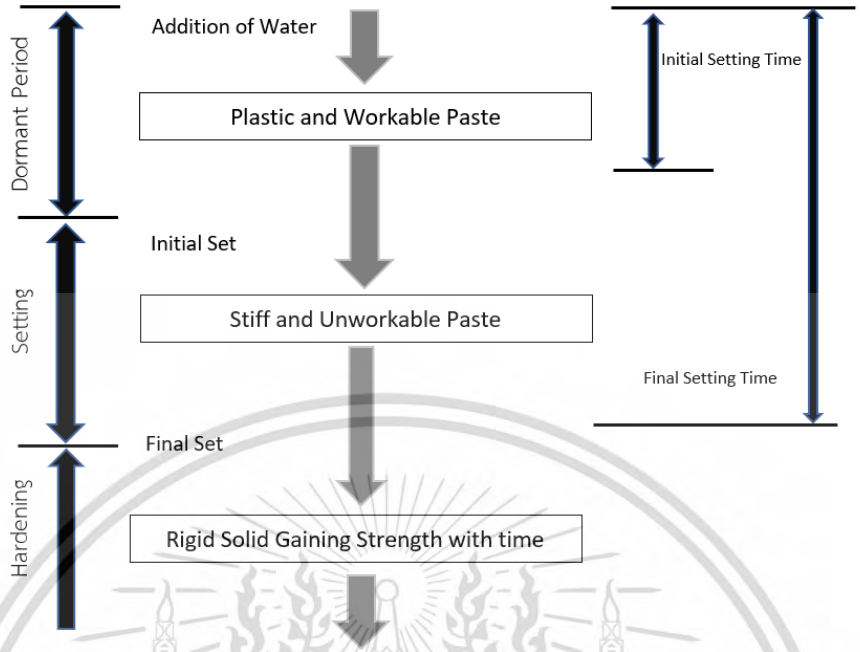


Figure 2.3 Setting and Hardening process of cement paste.

2.1.4 Hydration reaction

The hydration reaction causes setting and hardening of Portland cement compound. The reaction involves two steps as follows.

1. Solution formation: Cement is dissolved by water and generates ions in solution. When ions are mixed, they generate a new compound. This solution reaction occurs at the beginning.

2. Solid state reaction: This reaction directly occurred on the surface of solid, which is not necessary to form the solution.

Cement contains many compounds, when the hydration reaction takes place, new compounds are formed and might continue to form the new products. Therefore, the hydration reaction of the main compounds of each type of cement is considered as follows.

- **Hydration of Calcium Silicate (C_3S, C_2S)**

Calcium silicate reacts with water and generates calcium hydroxide ($Ca(OH)_2$) about 15-25% and calcium silicate hydrate (CSH) which is a binder and provides the

strength. The illustration of the products from the hydration of calcium silicate is shown in Figure 2.4. The chemical reaction equations are as follows.

Equation of C_3S

$$2(3CaO \bullet SiO_2) + 6H_2O \rightarrow 3CaO \bullet 2SiO_2 \bullet 3H_2O + 3Ca(OH)_2$$

or $$2C_3S + 6H_2O \rightarrow C_3S_2H_3 + 3Ca(OH)_2$$

Equation of C_2S

$$2(2CaO \bullet SiO_2) + 4H_2O \rightarrow 3CaO \bullet 2SiO_2 \bullet 3H_2O + Ca(OH)_2$$

or $$2C_3S + 4H_2O \rightarrow C_3S_2H_3 + Ca(OH)_2$$

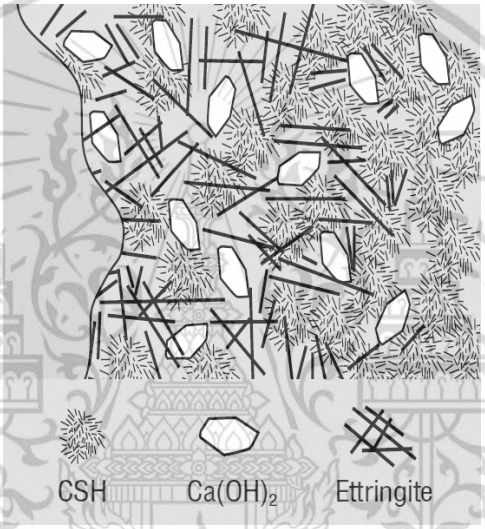


Figure 2.4 Illustration of the products of hydration of calcium silicate.

From the hydration reaction, gel product is formed. When the gel hardens, it has two characteristics: irregular structure and porous. The chemical component of calcium silicate hydrate (CSH) depends on age, temperature, and ratio water to cement. $Ca(OH)_2$ obtained from hydration reaction cause the cement paste to have alkaline properties (pH about 12.5).

- **Hydration of Tricalcium Aluminate (C_3A)**

This reaction immediately occurred and causes a rapid hardening of cement paste. The reaction is as follows.

Equation of C_3A

$$3CaO \bullet Al_2O_3 + 6H_2O \rightarrow 3CaO \bullet Al_2O_3 \bullet 6H_2O$$

or $$2C_3A + 6H_2O \rightarrow C_3AH_6$$

During cement grinding process, gypsum is added in the mixture to retard the hydration reaction of C_3A. The gypsum will react with C_3A to form the layer of ettringite on the surface C_3A particle. The reaction is as follows.

$$3CaO \bullet Al_2O_3 + CaSO_4 \bullet 2H_2O \rightarrow 3CaO \bullet Al_2O_3 \bullet 3CaSO_4 \bullet 31H_2O$$

or C_3A + Gypsum → Ettringite

- **Hydration of Tetracalcium Aluminoferrite (C_3AF)**

The hydration reaction of C_4AF occurs at the beginning state. C_4AF will react with gypsum and $Ca(OH)_2$ resulting in the formation of needle-like shape of sulphoaluminate and sulphoferrite. The reaction is as follows.

$$4CaO \bullet Al_2O_3 \bullet Fe_2O_3 \bullet 2H_2O + Ca(OH)_2 \rightarrow 3CaO \bullet (Al_2O_3, Fe_2O_3) \bullet 3CaSO_4$$

Or C_4AF Gypsum + $Ca(OH)_2$ → Sulphoaluminate and Sulphoferrite

Factors that influence the rate of hydration reaction

During cement setting, various factors influence the hydration reaction rate which also has an impact on the properties of the hard cement. The following are some factors that influence the rate of hydration reaction.

1. Age of cement paste: The rate of hydration reaction is highest at the beginning, except dormant period. The reaction rate will be gradually reduced until it is completed.

2. Composition of cement: In the beginning, the rate of hydration reaction depends on the main compounds. The reaction of cement which contains C_3S and C_3A will occur rapidly. However, at the final state, the hydration reactions of each main component are not different.

3. Fineness of cement: The high of fineness cement allows a lot of water to contact the surface, causing the hydration reaction to proceed rapidly at the beginning.

4. Ratio water to cement: In the beginning, the ratio of water to cement has no effect on the rate of hydration reaction. In the latter, if the ratio of water to cement decreases, the rate of hydration reaction will also decrease.

5. Temperature: In the beginning, the rate of hydration reaction will increase with increasing temperature.

2.1.5 Type of Portland cement

Standard of Portland cement can be divided into 5 types:

Type 1 Ordinary Portland Cement: This type of cement is the most used one. Usually, it is used in general work such as pouring cement, making pillars, tanks and building or another.

Type 2 Modified Portland Cement: This type of cement is suitable for heat and moderate sulfate resistance work.

Type 3 High Early Strength Portland Cement: This type of cement gives a high compressive strength in the beginning. Mostly, it is suitable for concrete work that requires quick setting such as electric pole, prestressed pile, railway sleepers and prestressed floor slab. However, it is not proper for construction work because the heat of hydration reaction is very high at early state which could cause a crack of structure.

Type 4 Low Heat Portland Cement: This type of cement gives volume and the low heat of hydration reaction rate. It takes longer to build strength than type 1 cement. It is suitable for mass concrete work such as embankment.

Type 5 Sulphate Resistance Portland Cement: This type of cement has low content of C_3A, about 5% or less to protect external sulfates attack into concrete and has lower strength than type 1 cement.

2.2 Pozzolan

Pozzolan is a commonly used material in cement. The addition of pozzolan reduces cost and improves properties of cement such as thermal isolation, strength, and durability of cement.

2.2.1. Pozzolanic Material

Pozzolanic material is mostly a compound of SiO_2 and Al_2O_3. It can cause a chemical reaction with calcium hydroxides at room temperature. Particle size of pozzolanic material is small so it can penetrate any voids or pores in cement, resulting in a dense cement product. The advantages of mixing pozzolanic materials are as follows.

1. Pozzolanic materials reduce the expansion of cement products.

2. Pozzolanic reaction generates lower heat compared to hydration reaction resulting in higher strength than ordinary cement.

3. Pozzolanic materials increase the durability of cement.

4. Pozzolanic materials improve the durability from sulfates attack.

2.2.2 Pozzolanic reaction

This chemical reaction of pozzolanic occurs after hydration reaction due to pozzolanic reaction require to calcium hydroxide ($Ca(OH)_2$) from hydration reaction. $Ca(OH)_2$ will react with silica (SiO_2) or alumina (Al_2O_3) of pozzolanic material, then generates calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH). The reaction equation is as follows.

$$3Ca(OH)_2 + 2SiO_2 \rightarrow 3CaO{\bullet}2SiO_2{\bullet}3H_2O$$

or

$$3Ca(OH)_2 + Al_2O_3 \rightarrow 3CaO{\bullet}2Al_2O_3{\bullet}3H_2O$$

The pozzolanic reaction is similar to the hydration reaction but the reaction rate is slower. So, pozzolanic material can used to reduce heat of the hydration reaction.

2.3 Perlite

Perlite is a glassy volcanic rock, which is formed by lava. When lava cools rapidly, it becomes obsidian. Then, obsidian rock reacts with water to form a perlite stone. When perlite stone is heated to a high temperature around 850-900 °C, it expands rapidly, transforming into a lightweight substance and high porosity. The chemical compositions of perlite are shown in Table 2.3.

Perlite structure is composed of approximately 70% silica and approximately 3% water. When perlite is heated, the water within it vaporizes and evaporates quickly, causing perlite to expand, similar to how popcorn is made. Perlite expands up to 7-16 times its original volume and shows a completely different structure. The unique characteristic of perlite is a light weight, which is due to its density of 34-400 kg/m^3. It has a low thermal conductivity and is resistant to acid and alkali. Because of its high SiO_2 content and light weight, perlite is an ideal pozzolanic material for cement.

Table 2.3 Chemical composition of perlite.

Chemical composition	Percent by weight
SiO_2	70-75
Al_2O_2	12-15
Na_2O	3.0-4.0
K_2O	3.0-5.0
Fe_2O_3	0.5-2.0
MgO	0.2-0.7
CaO	0.5-1.5
H_2O	3.0-5.0

2.4 Sisal Fiber

The sisal plant is widely utilized for producing natural fibers, which are employed in the creation of various products such as hats, bags, ropes, etc. The scientific name of sisal plant is *Agave sisalana*. The original country of sisal plant is Central and South America. The sisal plant was found for the first time as a trading place in Mexico. Around 1839, sisal plants were planted in Florida, USA and Africa. In 1893, sisal plant was planted in the first European country, Germany. In South-east Asia, it was planted in 1905 in Malaysia. Then, sisal plant was imported and planted in Thailand before World War II.

Sisal plant is a monocot. The appearance of the sisal trunk is similar to the pineapple trunk. The trunk is short, about 3 feet tall. The leaves protrude from the lobes of the stems. The appearance of the leaves is thick and about 4-6 feet long, with a smooth, gray-green edge. After 4 years of planting, the leaves of sisal plant can be cut to produce sisal fibers.

Sisal fibers are obtained from the leaves of the sisal plant. Currently, these fibers are extracted using machinery to either remove the fleshy leaves or ferment them in water to facilitate manual stripping of the fibers. Subsequently, the fibers undergo cleaning with water and are dried either under sunlight or in ovens. Finally, the fibers are brushed to ensure uniformity. The characteristic of sisal fiber is very high in tension

and has a rough surface. The main properties of sisal fiber are very durable and good mechanical strength. These properties bring a variety of benefits, including:

1. Industrial production: rope, sacks bag, paper pulp to the components of the roof tile,
2. Wickerwork production: hat, carpet, broom, bag, etc.,
3. Agriculture production: compost, animal feed (either fresh or ground mixed with other types of feed).

The composition of sisal fiber includes cellulose, lignin, hemicellulose, and moisture, as outlined in Table 2.4. The properties of sisal fiber vary depending on factors such as age, location, and soil type. Sisal fiber typically exhibits a density ranging from 1.33 to 1.5 g/cm^3, a tensile strength between 400 and 700 MPa, and a Young's modulus ranging from 9.0 to 38.0 GPa [5]. The physical properties of sisal fiber are summarized in Table 2.5.

Table 2.4 Composition of sisal fiber.

Compositions	Percent by weight
Cellulose	65-68
Hemicellulose	10-22
Lignin	9.9-14
Moisture content	10-22

Table 2.5 Physical properties of sisal fiber.

Properties	Result
Fiber diameter	0.26 mm
Shape	Straight
Density	1.59 g/cm^3
Water absorption	67.5%
Specific gravity	0.73 g/cm^3

2.5 Literature review

2.5.1 Study of composition ratio of cement, sand, and water

Singh et al. [6] reported the effect of water/cement proportions on strength development of cement mortar. Five mixes of Portland cement to sand proportions (1:3, 1:4, 1:5, 1:6 and 1:7) and varying water/cement ratio are studied. The compressive strength of cement mortar decreased with increasing cement to sand proportion, while the split strength and compressive strength of mortar cement decreased with increasing water/cement ratio. This study suggested that the suitable water to cement ratio is 0.5.

Mollo et al. [7] studied the influence of cement/sand ratio on strength of cement mortar. The mixtures were prepared with constant water/cement ratio of 0.5 while the cement/sand was varied from 1:32 to 32:32. The results show that the strength of cement mortar tended to increase with the increasing cement/sand ratio. However, when the cement/sand ratio is higher than 16:32, the strength reaches the maximum value. The suitable conditions obtained from this study are cement/sand ratio of 1:2 at the fixed water/cement ratio of 0.5.

Risdanareni et al. [8] studied the use of protein foam agent to produce lightweight concrete, and investigated the effects of water/cement ratio, and cement/sand ratio. In this study, the protein foam content was constant at 1080 g, while the cement/sand ratio were 2:1 and 1:2, and the water/cement ratio were 0.5 and 0.4. The results showed that the composition of cement/sand ratio of 1:2 along with water/cement ratio of 0.5 provided the optimum mechanical properties.

Table 2.6 Summary of the study of composition ratio of cement, sand, and water.

Reference	Mixture	Characterization	Result
Singh et al. [6]	Varying cement:sand ration (1:3, 1:4, 1:5, 1:6, 1:7) and varying water/cement ratio.	split strength and compressive strength	The split strength and compressive strength of mortar cement decreased and there was an increase in the w/c ratio. This study suggested that the water to cement ratio is 0.5.
Mollo et al. [7]	Fixed water/cement ratio of 0.5 and cement/sand varying from 0:00 to 1:1.	Compression and flexural strength	When cement/sand ratio was increased with increased the strength until cement/sand ratio of 1:2 was increased, the strength value was similar.
Risdanareni et al. [8]	Using protein foam constant 1080 g. the cement/sand ratio are variation ratio of 2:1 and 1:2, the water/cement ratio are varied from 0.5 to 0.4.	compressive strength	The composition of cement/sand ratio of 1:2 with water/cement ratio of 0.5 showed high mechanical properties.

2.5.2 Effect of perlite composition in cement products

Patthanavarit et al. [9] reported the effect of expanded perlite on physical and mechanical properties of cement mortar. In this study, the content of sand was replaced by perlite varying from 0%wt to 15%wt, and the specimen molding pressure was varied from 20 to 40 kN. The results show that the optimum conditions were 10 wt% perlite at 40 KN. The flexural strength of cement mortar reached 12.50 MPa while the density and water absorption of cement mortar were 1773 kg/m^3 and 14.0%, respectively.

Sengul et al. [10] studies the effects of expanded perlite on the mechanical properties and thermal conductivity of lightweight concrete. In this study, natural sand was replaced by expanded perlite at 0-100% with steps of 20%. The results show that compressive strength and modulus of elasticity decreased with the increasing in perlite content. In addition, the high content of perlite resulted in moisture content causing the thermal conductivity to increase.

Zulkifeli et al. [11] investigated the compressive and flexural strength of expanded perlite aggregate mortar subjected to high temperatures. The replacement of sand with perlite was at 0%, 10%, 20%, 30% and 40% by weight. The proportion of water–cement and sand-cement were 0.5 and 2.5, respectively. The addition of perlite replacement of sand improved the flexural strength and compressive strength by using the replacement perlite at 10% and 20%.

Table 2.7 Summary of the effect of perlite composition in cement products.

Reference	Mixture	Characterization	Result
Patthanavarit et al. [9]	Addition perlite replace sand from 0% to 15% by weight and varying specimen of pressed from 20 to 40 KN.	flexural strength, density and water absorption	Perlite should be replaced 10 wt% and specimens of pressed 40 kN.
Sengul et al. [10]	Natural sand was replaced with expanded perlite at 0-100%	Compressive strength Thermal conductivity Water absorption	compressive strength and thermal conductivity decrease, and water absorption increases while high perlite content.
Zulkifeli et al. [11]	Addition perlite replace sand from 0% to 40% by weight of sand	compressive and flexural strength	Replacement perlite 10% or 20% of weight sand shown good compressive and flexural strength.

2.5.3 Study of natural fiber in cement products

Wongsa et al. [2] investigated the natural fiber reinforced high calcium fly ash geopolymer mortar. The natural fibers used in this study were sisal fiber and coconut fiber which were compared with glass fiber. Natural fiber will cut into lengths of 35-40 mm and the proportion varied from 0% to 1.0% volume fraction. The results showed that the addition of natural fiber improved tensile and flexural strength, and the mechanical properties were similar to those using glass fiber. The flexural and splitting tensile strength of fiber cement mortar were found to increase with the increasing fiber volume fraction.

Chandrasekaran et al [12] studied four types of natural fibers to improve the mechanical properties of cement. The type of natural fibers used in this study consisted of sisal fibers, palmyra fiber, coconut fiber, and banana fiber. The natural fibers are cut to lengths of 10 mm, 15 mm and 20 mm, which are mixed with cement in content of 0.5%, 1% and 1.5% for each condition. The fiber-cement is cured for 7 days and 28 days. From the experimental results, it was observed that sisal fiber demonstrates superior enhancement of mechanical properties compared to other natural fibers, particularly in terms of tensile strength and compressive strength.

Okeola et al. [13] reported the investigation of the physical and mechanical properties of sisal fiber-reinforced concrete. Sisal fiber was added in the mixture from 0.5% to 2.0% by weight of cement, and the length of sisal fiber was about 30 mm. The results show that sisal fiber improved the split tensile strength and young modulus of concrete.

Fujiyama et al. [14] reported the mechanical characterization of sisal reinforced cement mortar. The main materials consisted of sisal fiber, cement and sand. The effect of sisal fiber length between 25 mm and 45 mm was investigated. The sisal fiber amount was kept constant at 3% of the combined weight of cement and sand. The results showed that the longer length of sisal fiber improved the compressive strength of cement mortar.

Table 2.8 Summary of the study of natural fiber in cement products.

Reference	Mixture	Characterization	Result
Wongsa et al[2]	Natural fiber was cut into length of 35-40 mm and varying proportion from 0% to 1.0% of volume fraction.	flexural strength and splitting tensile strength	Flexural and splitting tensile strength of fiber cement mortar increase when increasing fiber volume fraction.
Chandrasekaran et al [12]	Natural fibers were cut from 10-20 mm and vary content fiber from 0.5-1.5%.	tensile strength and compressive strength	Sisal fiber can improve properties better than others natural fiber.
Okeola et al. [13]	Sisal fiber was added in the mixture from 0.5% to 2.0% by weight of cement.	The split tensile strength and young modulus	The results show sisal fiber can improve split tensile strength and young modulus of concrete.
Fujiyama et al. [14]	Sisal fiber was cut into length of 25 mm and 45 mm and mix with cement and sand.	compressive strength	When length of fiber increased, strength also increased.

Chapter 3

Research Methodology

The method for producing fiber cement to improve physical properties, thermal conductivity and mechanical properties will be described in this chapter.

3.1 Materials and Preparation method

3.1.1 Materials

The experimental raw materials comprised ordinary Portland cement (complying with ASTM C–150 Type I standards), river sand, expanded perlite, sisal fiber, and natural rubber latex. The chemical compositions of Portland cement and expanded perlite are provided in Table 3.1, while Table 3.2 displays the physical properties of these materials. Ordinary Portland cement was sieved using No.35 (0.5 mm) mesh sieves, and river sand was sieved using No. 16 (1.18 mm) mesh sieves. The particle size of expanded perlite ranges from 0.1 to 0.5 mm. Figure 3.1 shows the raw material Portland cement, sand, and expanded perlite.

Table 3.1 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 3. 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

(a) (b) (c)

Figure 3.1 (a) Portland cement (Type I), (b) sand, and (c) expanded perlite.

The sisal fibers were procured from a local farmer in Phetchaburi, Thailand, and extracted from the leaves of the Agave sisalana plant using a semi-automatic scraping machine. Table 3.3 outlines the physical properties and composition of sisal fiber. Additionally, Table 3.4 provides details on the physical and chemical properties of natural rubber latex.

Table 3.3 Physical properties of composition of sisal fiber.

Physical properties		**Composition (wt%)** [15]	
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 3.4 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%

3.1.2 Sisal fiber preparation

Figure 3.2(a) displays a photograph of the sisal fibers as received. Prior to incorporation into the cement mortar mixture, the sisal fibers underwent treatment. Initially, the fibers were cut into three different lengths (1, 2, and 3 cm) and washed with water to eliminate surface contaminants. Following this, they were air-dried in an oven at 60 ℃ for 24 h. Figure 3.2(b) depicts the cut and cleaned sisal fibers after treatment. After that, the fibers underwent an alkali treatment process. They were submerged in a 1 wt% sodium hydroxide (NaOH) aqueous solution for 1 h. Subsequently, the treated fibers were rinsed several times with a 1 wt% acetic acid (CH_3COOH) solution to neutralize the alkaline base. They were then cleaned with distilled water until the pH reached a neutral level and dried at 60 ℃ for 24 h. The resulting alkali-treated sisal fibers, termed uncoated sisal fiber, are depicted in Figure 3.2(c). Finally, the fibers were immersed in natural rubber latex for 1 min and uniformly coated with expanded perlite powder, as illustrated in Figure 3.2(d). This coated sisal fiber sample is referred to as coated sisal fiber.

Figure 3.2. The photographs of (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.

3.1.3 Sisal fiber cement preparation

The sisal fiber cement specimens were fabricated following the established standards outlined in ASTM C1186. In this study, expanded perlite served as a pozzolanic material by replacing sand, thereby reducing the alkalinity of the cement matrix. Previous research indicated that substituting 10 wt% of sand with expanded

perlite yielded the highest flexural strength alongside optimal bulk density and water absorption. For the preparation of the cement mortar mixture, the mass ratio of Portland cement, sand, and expanded perlite was consistently set at 1:1.8:0.2, with a water-to-cement ratio (W/C) of 0.5 by weight. The proportions of materials in the composite are presented in Table 3.5.

This study investigated the use of two types of sisal fibers: uncoated sisal fibers and coated sisal fibers. Sisal fibers were integrated into the mortar mixture in varying lengths and quantities. Fiber lengths of 1 cm, 2 cm, and 3 cm were utilized. 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. Preliminary studies were conducted to validate the practicality of this range, balancing the advantages of longer fibers (enhanced strength) with effective dispersion within the cement matrix.

Table 3.5 The proportion of mixture for sisal fiber-cement composites.

Sample No.	Cement (g)	Expanded perlite (g)	Sand (g)	Water (g)	Sisal fiber (g)
1	333	67	600	166.5	2.5
2	333	67	600	166.5	5.0
3	333	67	600	166.5	7.5
4	333	67	600	166.5	10.0
5	333	67	600	166.5	12.5
6	333	67	600	166.5	15.0

Specimen preparation commenced with dry mixing of cement, sand, and expanded perlite in the mortar mixer for 5 min, followed by the addition of sisal fibers and an additional mixing period of 2 min. Subsequently, water was gradually introduced into the mixer until a homogeneous mixture was attained. The blended composition was then transferred into a steel mold, and a hydraulic pressing machine applied a load of 5.3 MPa to the mold for 1 min. The equipment utilized for specimen preparation is depicted in Figure 3.3. The specimens were then carefully extracted

from the mold, resulting in rectangular bar specimens measuring approximately 2.5 cm x 2.5 cm x 15 cm. These specimens underwent a curing period of 28 days.

Figure 3.3 (a) Steel mold and (b) hydraulic pressing machine.

3.2 Characterization method

3.3.1 Microscopic study

3.3.1.1 Scanning electron microscopy (SEM)

Microscopic analyses were performed on all sisal fibers, including the as-received sisal fiber, alkali-treated sisal fiber, and coated sisal fiber, utilizing scanning electron microscopy (SEM; FEI, Quanta 250, USA). These SEM images served to ascertain the average diameter of sisal fibers and assess the impact of alkali treatment and coating on the surface microstructure of sisal fibers. Additionally, the morphology of pull-out fibers was examined using SEM to evaluate bonding characteristics with the cement matrix.

3.3.1.2 Optical Microscope (OM)

The microstructures of the sisal fiber cement composites were analyzed using an optical microscope (OM; OLYMPUS, OLS5000, Japan). These images offered a visual depiction of the adhesion between sisal fibers and the cement matrix, facilitating a comparison between the utilization of uncoated sisal fibers and coated sisal fibers. The examination aimed to clarify the influence of coating on the interaction and bonding at the interface of sisal fibers and the cement matrix within the composite material.

3.3.2 Physical properties

The physical properties, water absorption and density, were analyzed according to ASTM C20 [16] and ASTM C1185 [17]. The experimental steps are shown in Figure 3.4. The specimens were cut into 2.5 cm x 2.5 cm x 2.5 cm and died in oven at 105 °C for 24 h then left cooling and weighed for dry weight (D). Next, the specimen was put in boiling water at 100 °C for 2 h then soaked for 24 h and weighed in water to obtain suspended weight (S). The specimens were then blotted with a damp cloth before being weighed in the air to obtain saturated weight (W). The bulk density and water absorption of the specimens are calculated using the following equation.

$$\text{Bulk density} = \frac{D}{W-S} \times 1000 \quad (3.1)$$

$$\text{Water absorption} = \frac{W-D}{D} \times 100\% \quad (3.2)$$

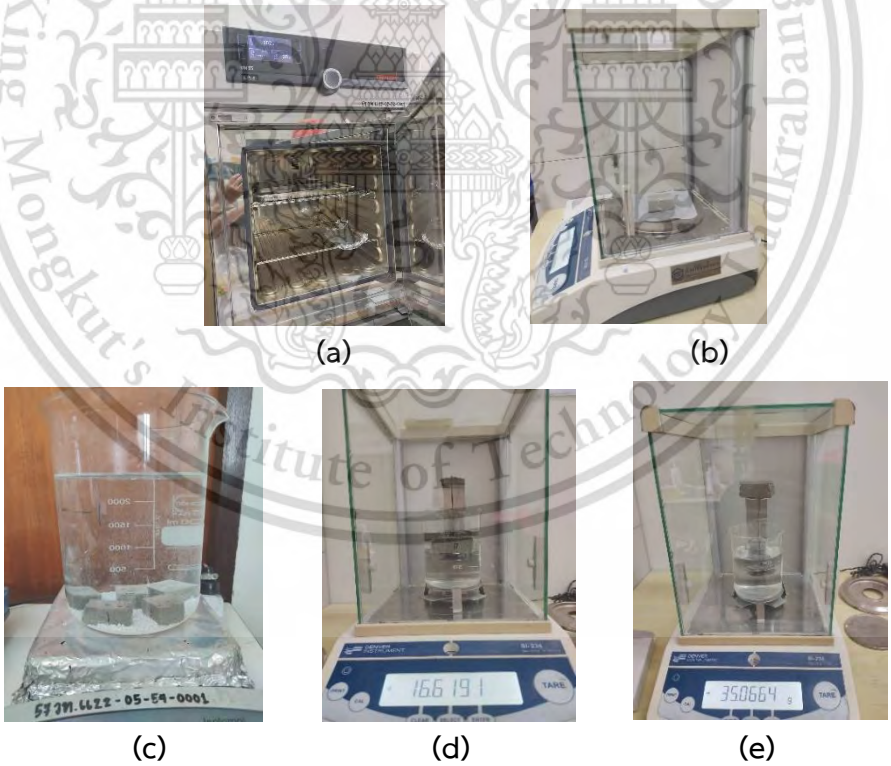


Figure 3.4 (a) Put specimen in oven at 105 °C for 24 h, (b) measure dry weigth (D), (c) put in boiling water , (d) measure suspended weight (S), and (e) measure saturated weight (W).

3.3.3 Mechanical properties

The mechanical properties of cement mortar were assessed via a static flexural test employing the three-point bending method outlined in ASTM C1185 [18], [19]. Utilizing a universal testing machine (Shimadzu AG-X, Japan) illustrated in Figure 3.5 (a), an in-house three-point bending fixture was installed as depicted in Figure 3.6 (b). Bending tests were executed with a support span length (L) of 100 mm and a consistent loading rate of 0.1 mm/min. Flexural strength was determined using equation (3.3).

$$\sigma = \frac{3PL}{2bd^2} \tag{3.3}$$

When σ is flexural strength (MPa)

P is maximum load

L is length of span

b is width of specimen

d is average thickness of specimen.

(a) (b)

Figure 3.5 (a) Three-point bending test setup and (b) Universal testing machine.

3.3.4 Thermal conductivity Test

The thermal conductivity test operates based on the principle of heat transfer [20]. The specimen for testing was prepared with a dimension of 125 mm × 75 mm × 20 mm and left at a temperature of 25 °C for 24 h. Subsequently, the specimen is positioned within the thermal insulator gap, and temperatures are allowed to stabilize on each side. An incandescent lamp bulb, emitting a maximum heat of 150 °C with an

electric power of 120 W, illuminates the heat plate. Infrared thermal cameras are positioned on both the heat plate and cold plate, as illustrated in Figure 3.6. Temperature measurements of the fiber cement are recorded over a duration of 20 minutes. The obtained values are then calculated using the following equation.

$$k = \frac{QL}{A\Delta T} \tag{3.4}$$

When k = Thermal conductivity (W/m•K)

Q = Electric power input to the center heater (W)

A = The are surface of fiber-cement (m^2)

L = Thickness of fiber-cement(m)

ΔT = The different between temperature of the surface (K).

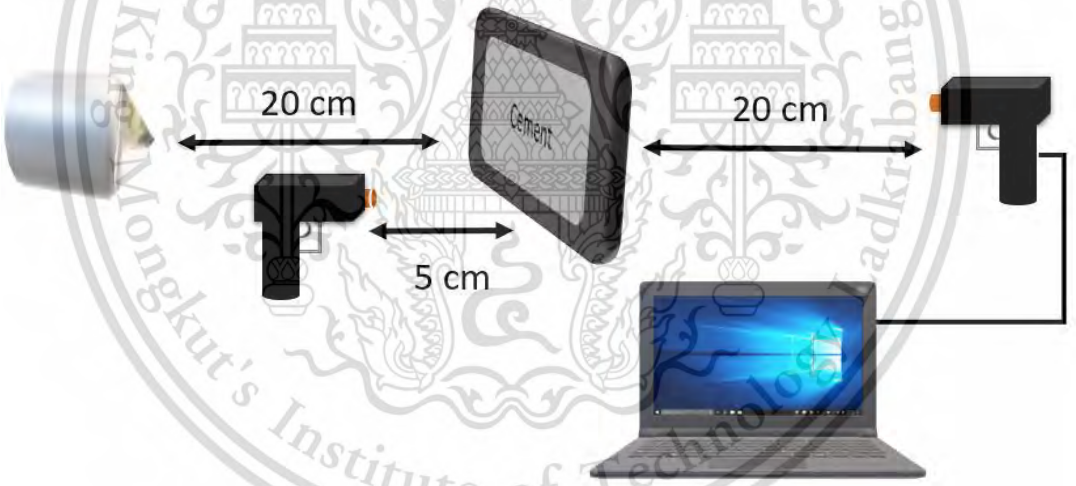


Figure 3.6 Diagram of thermal conductivity test.

Chapter 4

Results and Discussions

4.1 Microscopic analysis

The analysis results obtained from the microscope are discussed as follows: Scanning electron microscopy (SEM) was employed to study the structure or surface characteristics of sisal fibers, while optical microscopy (OM) was utilized to analyze the morphology of sisal fibers within the cement matrix.

4.1.1 Microstructure of sisal fibers

Scanning electron microscopy was employed to analyze the surface of the sisal fiber, as depicted in Figure 4.1, which illustrates various stages of the microstructure. Figures 4.1(a) and (b) represent the surfaces of the sisal fiber before and after alkali treatment, respectively. Prior to treatment (Figure 4.1(a)), the sisal fiber exhibited significant roughness and impurities. Previous research has identified layers of cellulose, hemicellulose, lignin, wax, and other components on the surface of sisal fibers, with cellulose playing a crucial role in fiber strength [21]. Following alkaline treatment (Figure 4.1(b)), the surface of the fibers displayed a reduction in impurities and roughness. Studies have indicated that NaOH solutions can effectively treat fiber components such as hemicellulose, lignin, and wax, without affecting cellulose [22]. Additionally, the average diameter measurement of the sisal fiber before and after treatment was found to be 0.26 mm and 0.22 mm, respectively. The reduction in fiber diameter indicates the removal of impurities.

Figure 4.1(c) illustrates the surface structure of coated fibers with latex and expanded perlite. SEM image analysis reveals that the expanded perlite adheres to the latex-coated fibers, resulting in a rough surface. This coating technique contributes to a reduction in water absorption of sisal fiber. Water absorption of the sisal fiber was evaluated using the Archimedes principle, revealing water absorption of 67.5% for untreated fiber, 62.5% for alkali-treated fiber, and 23.1% for coated fibers. The coated fibers demonstrate a considerable reduction in water absorption.

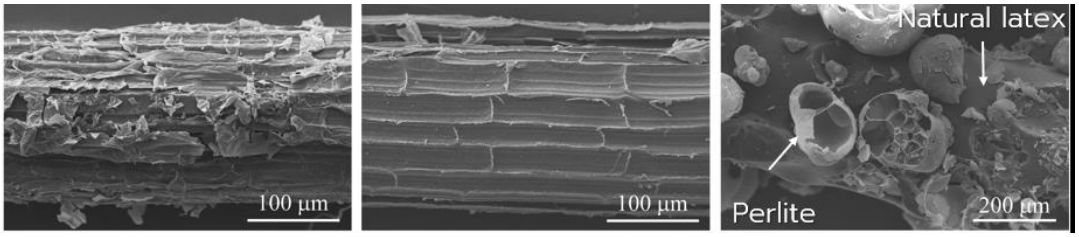


Figure 4.1 SEM micrographs of (a) as-received sisal fiber, (b) alkali-treated sisal fiber and (c) coated sisal fiber

4.1.2 Microstructure of sisal fiber cement composites

The adhesion characteristics between fibers and cement were observed using the optical microscope. Figure 4.2 illustrates the internal structure of fiber cement. In Figure 4.2(a), a mixture of untreated fibers and cement revealed heterogeneity, with voids or gaps present between the uncoated fibers and the matrix. Conversely, Figure 4.2(b) demonstrates that the coated fibers exhibit strong adherence to the matrix, resulting in homogeneity with the cement. The presence of coated fibers significantly reduces porosity within the cement, leading to decreased water absorption, increased density, and enhanced flexural strength of the fiber cement.

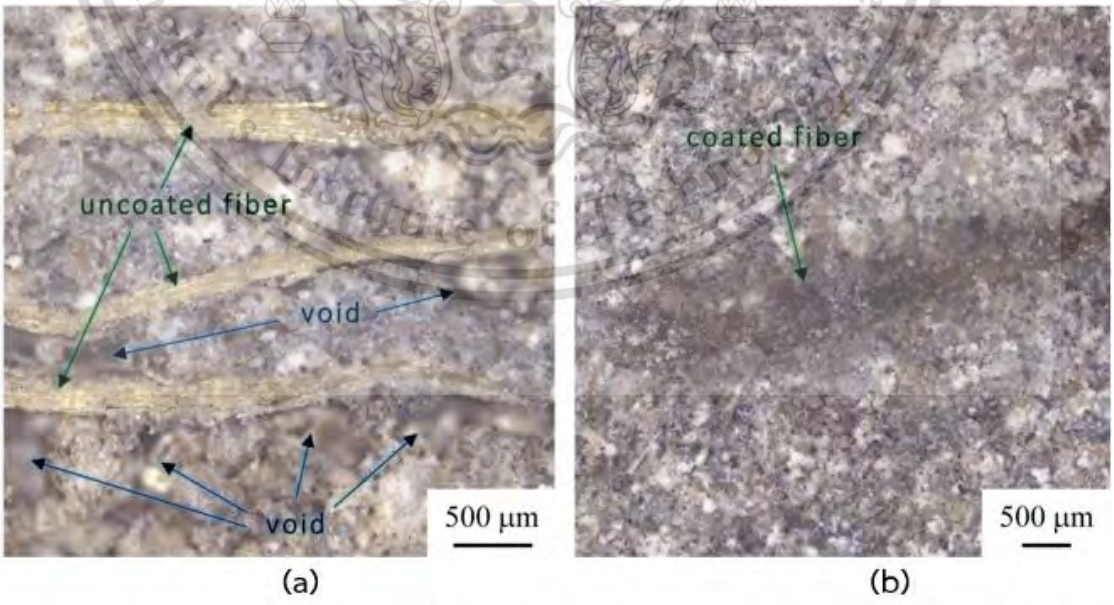
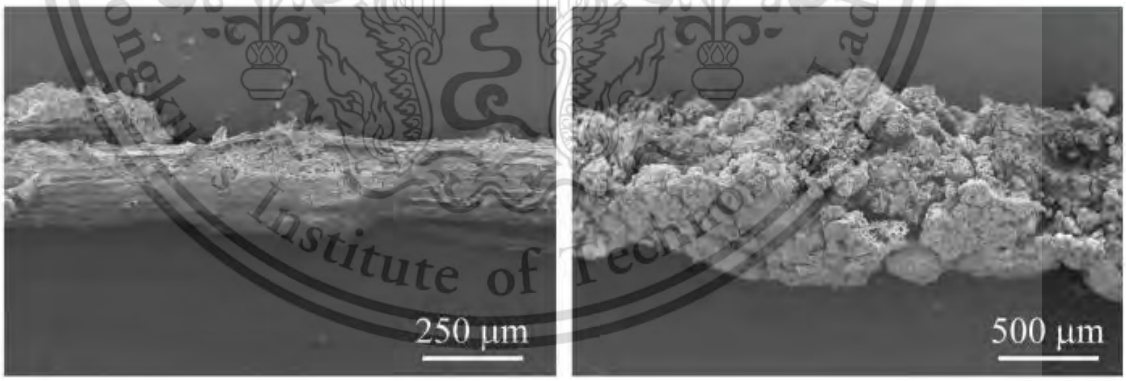


Figure 4.2 Microstructure of the sisal fibers cement using (a) uncoated fiber and (b) coated fiber.

The SEM analysis of pulled-out fibers was conducted to assess fiber damage. Figure 4.3(a) illustrates the pulled-out uncoated fiber. The characterization shows minimal cement matrix adhered to the fiber surface, indicating limited interaction between the uncoated fibers and the cement matrix. Additionally, the uncoated fibers appeared damaged, which contributed significantly to the overall strength. In contrast, Figure 4.3(b) depicts the surface of the coated fibers. The coated fibers display a rough surface with a substantial amount of cement matrix attached, indicating strong interaction between the cement matrix and the fibers. This strong adhesion contributes to improved mechanical properties of the fiber-cement composite.

The microstructural analysis of fibers reveals significant interaction between the fibers and the cement matrix. The rough surface of the coated fibers indicates strong adhesion. This strong adhesion between the cement matrix and the fibers leads to improved mechanical and physical properties by significantly reducing gaps within the cement. Additionally, the natural latex coating helps to reduce water absorption and the risk of degradation. Therefore, the SEM analysis demonstrates a positive impact on the properties of fiber cement.



(a) (b)

Figure 4.3 The pulled-out of SEM images (a) uncoated and (b) coated.

4.2 Investigation of Physical Properties

In this section, the test results of the physical properties of fiber cement are examined. Following a curing period of 28 days, physical property tests were

conducted, focusing on density and water absorption, with comparisons made between composites using coated and uncoated fibers. Subsequently, the discussion will address the implications of the physical property test results.

4.2.1 Density of sisal fiber-cement

The test results for the bulk density of sisal fiber cement are depicted in Figure 4.4 and the values are shown in Table 4.1. Analysis of bulk density results compares coated and uncoated fibers across variations in fiber length and content. Increasing the content of fibers results in a consistent decrease in bulk density, aligning with findings in the literature [13]. Microstructural analysis using optical microscopy indicates that increasing fiber content leads to clustering within the matrix, resulting in the formation of gaps or cracks.

When comparing the effects of coated and uncoated sisal fibers, the composite containing coated fibers exhibited a slightly higher density. The fiber cement composites utilizing uncoated sisal fiber showed a density ranging from 1453 to 1659 kg/m^3, whereas those employing coated fiber displayed a density ranging from 1542 to 1709 kg/m^3. Conversely, the densities of composites using coated fibers were slightly elevated. Specifically, for composites utilizing 1 cm sisal fibers, those using coated fibers demonstrated a density 0.1–2.3% higher than those employing uncoated sisal fibers. Similarly, for composites with 2 cm sisal fibers, those using coated fibers exhibited a density 0.5–2.5% higher than those with uncoated sisal fibers. Furthermore, in composites with 3 cm sisal fibers, those employing coated fibers showcased a density 3.0–10.9% higher than those utilizing uncoated sisal fibers.

However, the bulk density results consistently show higher densities in composites using coated sisal fibers across different fiber lengths. This increase in density is attributed to the coating of sisal fibers with natural rubber latex and expanded perlite, which enhances adhesion between the fibers and the cement matrix. As a result, the porosity of the fiber cement composites is reduced.

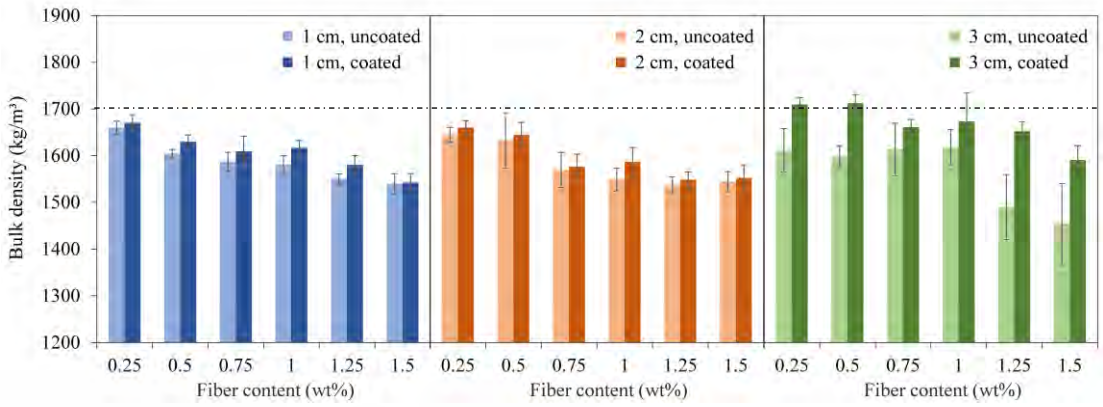


Figure 4.4 Bulk density of sisal fiber-cement.

Table 4.1 The bulk density of sisal fiber cements.

Fiber content (g)	Bulk density (Kg/m^3)					
	Uncoated 1 cm	Coated 1 cm	Uncoated 2 cm	Coated 2 cm	Uncoated 3 cm	Coated 3 cm
2.5	1659.42	1670.18	1645.65	1659.91	1611.51	1709.44
5.0	1604.15	1629.84	1633.72	1644.75	1598.85	1711.99
7.5	1586.59	1609.00	1569.71	1576.59	1613.50	1661.11
10.0	1580.15	1616.60	1548.77	1586.82	1618.29	1673.10
12.5	1550.06	1580.15	1537.39	1547.98	1490.22	1652.26
15.5	1539.95	1542.14	1544.42	1552.04	1453.48	1590.48

4.2.2 Water absorption of sisal fiber-cement

The test results for water absorption in sisal fiber cement are illustrated in Figure 4.5, with the corresponding values provided in Table 4.2. It is observed that water absorption tends to increase with the fiber content. This trend is attributed to the hydrophilic properties of natural fibers, as explained in the report [13]. Optical microscope analysis indicates that the increase in fiber content leads to the formation of voids or gaps within the material, contributing to the elevated water absorption.

However, it is noted that the increase in water absorption with fiber content is less pronounced for composites using coated sisal fiber. For 1 cm sisal fiber cement, water absorption ranges from 20.1% to 24.8% for uncoated fiber and from 19.8% to 20.7% for coated fiber. In the case of 2 cm sisal fiber cement, water absorption ranges

from 20.6% to 23.0% for uncoated fiber and from 20.1% to 22.7% for coated fiber. Additionally, for 3 cm sisal fiber cement, water absorption ranges from 20.6% to 27.9% for uncoated fiber and from 15.8% to 20.5% for coated fiber. The coating of sisal fibers appears to reduce water absorption compared to uncoated fibers, particularly at higher fiber content and longer fiber length.

In this study, the utilization of a hydrophobic coating of natural rubber latex on sisal fiber was found to offer initial resistance against water absorption. Furthermore, the incorporation of expanded perlite as a secondary coating on sisal fiber facilitated interaction with the cement matrix, establishing a well bond and consequently reducing pores within the cement matrix.

According to ASTM C1530/C1530M [23], non-asbestos fiber-cement roofing products should have a water absorption rate of less than 25%. Fiber cement utilizing uncoated fiber, particularly those with high fiber content at 1.25–1.5 wt%, showed water absorption levels that approached or exceeded this specified limit. In contrast, composites with coated sisal fibers exhibited significantly lower water absorption. For instance, in the case of 1.5 wt% content of 3 cm coated sisal fiber cement, the composite reduced water absorption by 20% compared to uncoated fiber cement. These findings underscore the importance of coating treatments in mitigating water absorption in fiber cement composites. This aligns with the objective of enhancing the durability and performance of natural fiber-reinforced cementitious materials, especially in applications where exposure to moisture is a concern, such as roofing products.

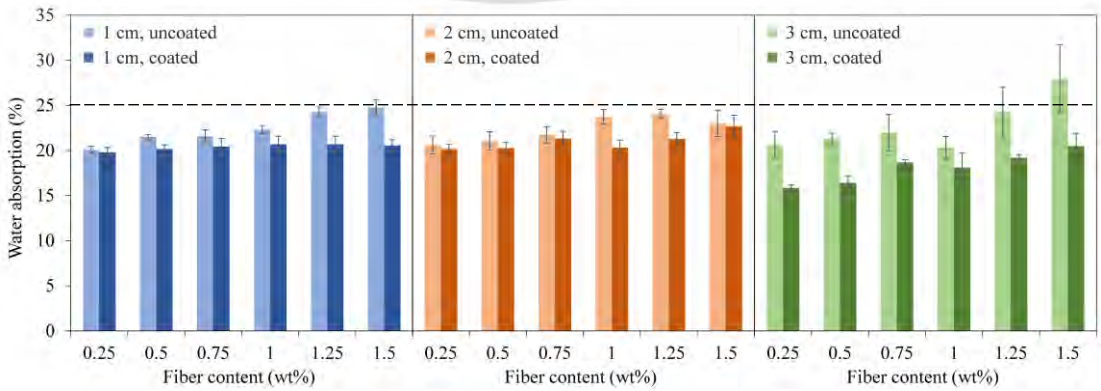


Figure 4.5 Water absorption of sisal fibers cement.

Table 4.2 The water absorption of sisal fiber cement.

Fiber content (g)	Water absorption (%)					
	Uncoated 1 cm	Coated 1 cm	Uncoated 2 cm	Coated 2 cm	Uncoated 3 cm	Coated 3 cm
2.5	20.05	19.77	20.61	20.12	20.61	15.81
5.0	21.49	20.16	21.06	20.23	21.29	16.39
7.5	21.60	20.40	21.72	21.30	21.95	18.66
10.0	22.29	20.67	23.72	20.30	20.29	18.07
12.5	24.24	20.66	24.05	21.25	24.26	19.18
15.5	24.76	20.52	22.99	22.65	27.94	20.48

4.3 Investigation of mechanical properties

The mechanical properties of fiber-cement are evaluated through flexural strength tests, aiming to compare the effects of varying lengths and contents of sisal fibers in the cement matrix. These tests adhere to ASTM C1185 standards to ensure accuracy and reliability in the assessment of flexural strength. The flexural test results for sisal fiber cement are depicted in Figure 4.6, accompanied by the corresponding data presented in Table 4.3.

For 1 cm fiber cement composites, the highest flexural strength values were observed at 3.87 MPa with 0.5 wt% for uncoated fiber and 4.04 MPa with 0.25 wt% for coated fiber. In the case of 2 cm fiber cement composites, the highest flexural strength was 4.58 MPa with 0.25 wt% for uncoated fiber. Conversely, for coated fiber, the flexural strength increased from 4.65 MPa to a peak of 4.84 MPa as fiber content rose from 0.25 wt% to 0.75 wt%, before declining to 2.07 MPa with further increases to 1.5 wt%. Similarly, in 3 cm fiber cement composites, both uncoated and coated fibers exhibited similar trends, with peak 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 higher fiber content. The optimal result in this experiment was observed in the 3 cm coated fiber cement composites with 0.25 wt% fiber content, demonstrating the highest flexural strength.

Comparing low fiber content at 2.5 g, an increase in sisal fiber length led to enhanced flexural strength, indicating that longer fibers, when used in optimal quantities, contribute to a more robust structure, reducing the likelihood of cracking while ensuring even distribution. However, especially noticeable in 3 cm fiber composites, a rise in fiber content tended to reduce flexural strength. This is primarily attributed to excessive fiber addition, resulting in fiber clustering. This clustering phenomenon induces more cracks within the cement matrix, consequently diminishing its overall strength.

Upon considering the impact of utilizing coated sisal fibers, it becomes evident that their flexural strength surpasses that of uncoated ones. In 1 cm sisal fiber composites, the incorporation of coated fibers yields a flexural strength that is 1–55% higher compared to composites with uncoated sisal fibers. Similarly, for 2 cm sisal fiber composites, those employing coated fibers exhibit a flexural strength 2–62% higher than those with uncoated sisal fibers. Moreover, in 3 cm sisal fiber composites, the utilization of coated fibers demonstrates a flexural strength 2–73% higher than composites with uncoated sisal fibers. This suggests that applying a coating to sisal fibers significantly enhances the flexural strength of the composites. The robust bonding between the coated sisal fibers and the cement matrix enhances resistance against cracks. Consequently, it can be inferred that sisal fibers coated with natural rubber latex and expanded perlite contribute to an increase in flexural strength, offering a promising avenue for enhancing the mechanical properties of fiber-cement composites.

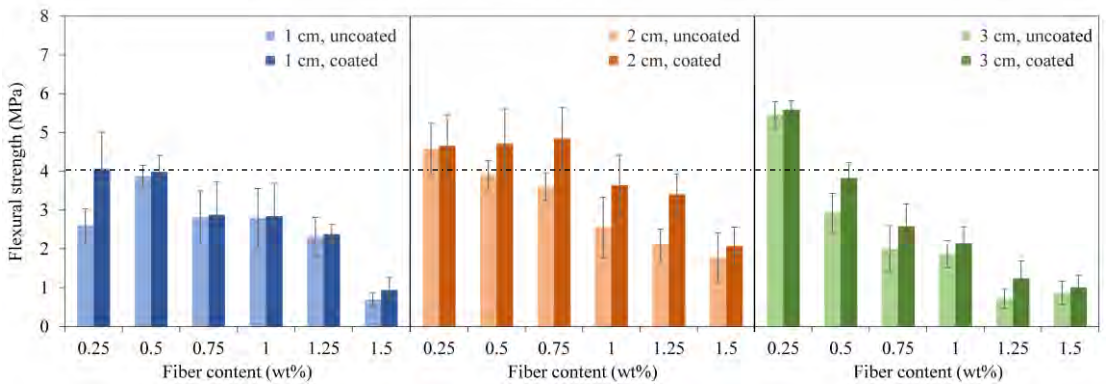


Figure 4.6 Flexural strength of sisal fibers cement.

Table 4.3 The flexural strength of sisal fiber cements.

Fiber content (g)	Flexural strength (MPa)					
	Uncoated 1 cm	Coated 1 cm	Uncoated 2 cm	Coated 2 cm	Uncoated 3 cm	Coated 3 cm
2.5	2.60	4.04	4.58	4.65	4.77	5.59
5.0	3.87	3.98	3.90	4.70	3.74	3.83
7.5	2.81	2.87	3.60	4.84	2.15	2.58
10.0	2.80	2.84	2.55	3.64	1.87	2.14
12.5	2.31	2.16	2.10	3.40	0.72	1.24
15.5	0.70	1.56	1.78	2.07	0.87	1.01

4.4 Investigation of thermal conductivity

Figure 4.7 illustrates the thermal conductivity of fiber cement with varying content and lengths of sisal fibers, with corresponding values presented in Table 4.4. Thermal conductivity testing revealed that increasing fiber content and length led to a decrease in thermal conductivity. Hence, it is evident that natural fibers serve as effective thermal insulators even without being coated with natural latex. However, experimental results show that fibers coated with natural latex exhibit superior insulating properties compared to uncoated fibers. The natural latex coating on sisal fibers acts as an additional insulating layer, resulting in lower thermal conductivity for the coated fibers compared to the uncoated ones.

The standard value for the thermal conductivity test is typically set to be less than 0.5 W/m•K [24][25]. Both coated and uncoated fibers composites exhibited thermal conductivity values lower than this standard threshold. Consequently, it can be inferred that the incorporation of sisal fibers in fiber-cement renders it suitable for use as an insulator. Moreover, the application of a coating of natural latex further enhances the insulation properties, making the coated fibers even more effective in reducing thermal conductivity.

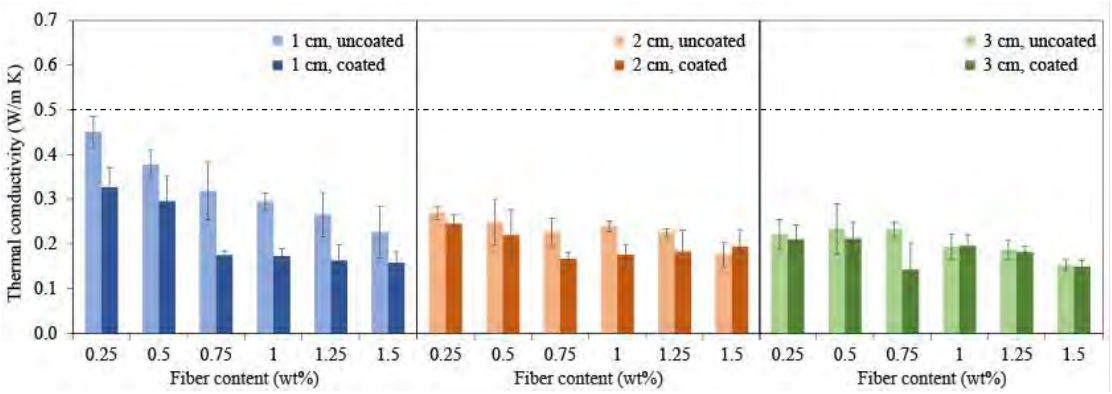


Figure 4.7 Thermal conductivity of sisal fibers cement.

Table 4.4 The thermal conductivity of sisal fiber cement.

Fiber content (g)	Thermal conductivity (W/m•K)					
	Uncoated 1 cm	Coated 1 cm	Uncoated 2 cm	Coated 2 cm	Uncoated 3 cm	Coated 3 cm
2.5	0.45	0.33	0.27	0.25	0.22	0.21
5.0	0.38	0.30	0.25	0.22	0.23	0.21
7.5	0.32	0.18	0.23	0.17	0.23	0.14
10.0	0.30	0.17	0.24	0.18	0.19	0.20
12.5	0.27	0.16	0.23	0.18	0.19	0.18
15.0	0.23	0.15	0.18	0.19	0.15	0.15

4.5 Comparison of properties with literature

In this section, the results regarding the physical, mechanical, and thermal conductivity properties obtained in study are compared with existing literature. The comparison is shown in Table 4.5. This study concludes that utilizing coated sisal fibers with a length of 3 cm and a content of 2.5 g yields optimal results, with a density of 1709 kg/m^3, water absorption of 15.8%, flexural strength of 5.5847 MPa, and thermal conductivity of 0.2102 W/mK. These values generally meet standard requirements, except for the density value.

Chandrasekaran et al.[12] investigated four types of natural fibers (sisal fiber, palmyra fiber, coconut fiber, and banana fiber) by assessing the fiber content and curing time of fiber cement. Their findings revealed that sisal fiber exhibited the highest

flexural strength of 5.37 MPa after a curing period of 28 days, with a fiber content of 1.5% and a length of 20 mm.

Okela et al.[13] investigated sisal fiber cement with a fiber length of 20 mm and varying fiber content. Their study concluded that a fiber content of 1.0% resulted in the lowest density and water absorption. Specifically, the density and water absorption values were measured at 2048 kg/m³ and 6.410%, respectively.

Wongsa et al.[2] conducted a study comparing sisal fibers, coconut fiber, and glass fiber in fiber cement with varying fiber content. Their findings indicated that sisal fibers exhibited a density of 1850 kg/m³, water absorption of 5.6%, thermal conductivity of 0.984 W/mK, and flexural strength of 19.9 MPa.

Table 4.3 Comparison of properties with literature.

Authors	Density (kg/m^3)	Water absorption (%)	Thermal conductivity (W/mK)	Flexural Strength (MPa)
Standard value	Commercial <1700	ASTM C1185 <25	ASTM C177 <0.5	ASTM C1185 >4
This research (3 cm,0.25 wt%)	1709.44	15.8117	0.2102	5.5847
Chandrasekaran[12] (2 cm,1.0 wt%)	-	-	-	5.37
Okeola[13] (2 cm,1.0 wt%)	2048	6.410	-	-
Wongsa[2] (3 cm,1.0 wt%)	1850	5.6	0.984	19.9

Chapter 5
Conclusion

This study investigated the effects of fiber content and length in cement composites, while also comparing the performance of fibers coated with natural latex and expanded perlite. After a 28-day curing period, the physical and mechanical properties were analyzed as follows:

- Alkali treatment led to a minor reduction in fiber diameter, while subsequent coating displayed a smooth layer of natural rubber latex, effectively anchoring expanded perlite homogeneously.
- Bulk density of sisal fiber cement composites decreased with increasing fiber content and length. Employing coated sisal fibers yielded higher density than uncoated ones, attributed to enhanced adhesion and reduced porosity facilitated by the coating.
- Water absorption of sisal fiber cement composites demonstrated an increase with sisal fiber content. The coating of natural rubber latex effectively mitigated water absorption by sisal fibers, while expanded perlite played a vital role in minimizing voids between fiber and cement matrix.
- The flexural strength of sisal fiber cement composites utilizing coated sisal fibers consistently surpassed those employing uncoated fibers. Flexural strength varied with fiber content and length.
- Coating sisal fibers with natural latex led to a reduction in thermal conductivity, enhancing the insulation properties of the fiber cement composites.

The experimental results demonstrate that coating sisal fibers with natural latex and perlite, with a length of 3 cm and a content of 0.25%, results in optimal mechanical and thermal properties. The maximum flexural strength achieved is 5.58 MPa, while the thermal conductivity is reduced to 0.21 W/mK. However, the density slightly exceeds the standard at 1709 kg/m^3, while water absorption remains within

acceptable limits at 15.81%. This research provides valuable guidance on selecting appropriate fiber length and quantity for fiber cement applications and highlights the effectiveness of latex coating in improving the efficiency of natural fibers.

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Appendix

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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, homification 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 homification 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 [36]. 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. [14] 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. Ferreira 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.

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.

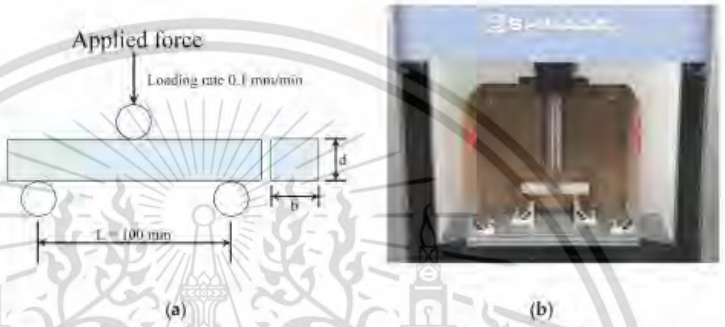

Figure 2. (a) Schematic representation of the three-point bending setup and (b) testing apparatus setting in universal testing machine.

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.

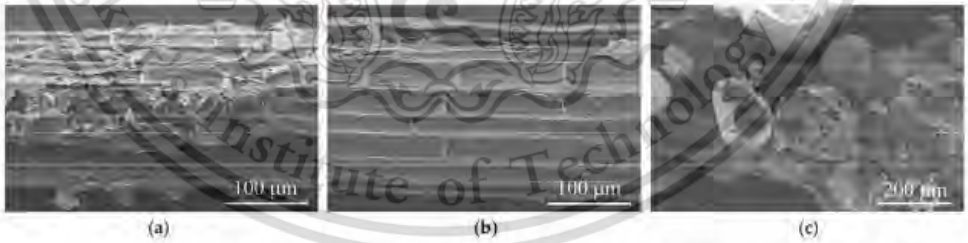

Figure 3. SEM images showing the surface of sisal fibers: (a) as-received sisal fibers; (b) alkali-treated sisal fibers; and (c) natural rubber latex and expanded perlite-coated sisal fibers.

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.

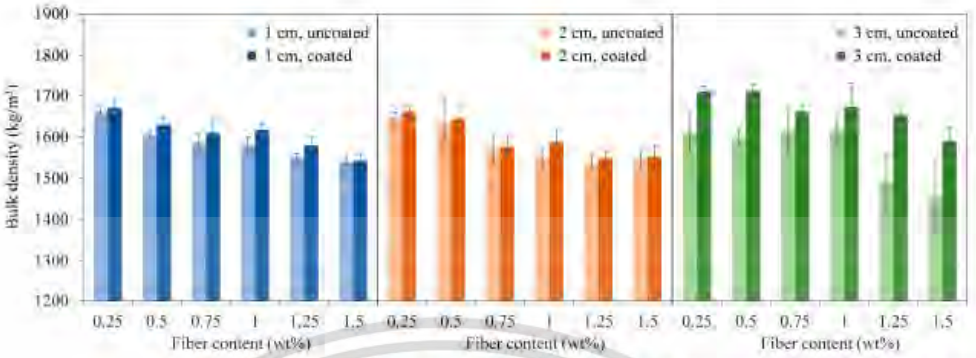

Figure 4. Bulk density of fiber–cement composites using uncoated and coated sisal fibers, with varying fiber lengths and contents.

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.

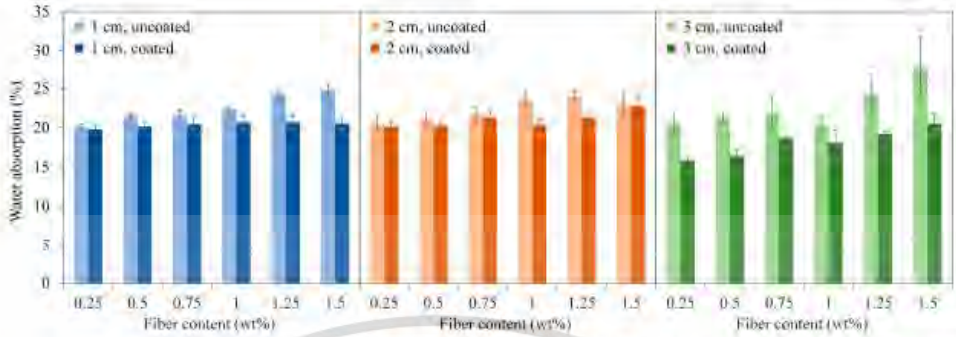

Figure 5. Water absorption of fiber–cement composites using uncoated and coated sisal fibers, with varying fiber lengths and contents.

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.

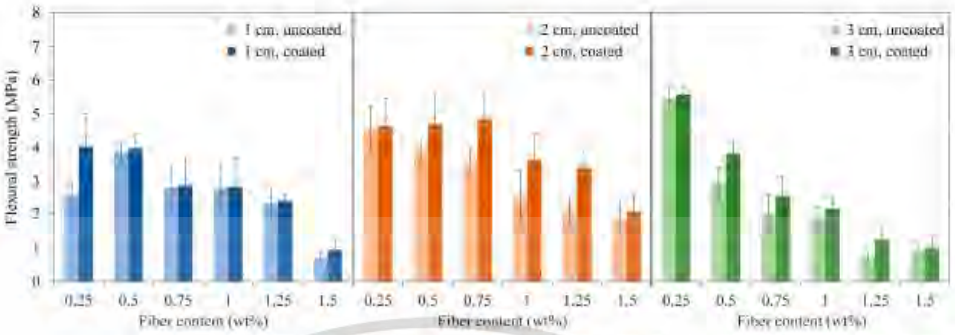

Figure 6. Flexural strength of fiber–cement composites after 28 aging days, and a comparison between specimens using uncoated and coated sisal fibers, with varying fiber lengths and contents.

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.

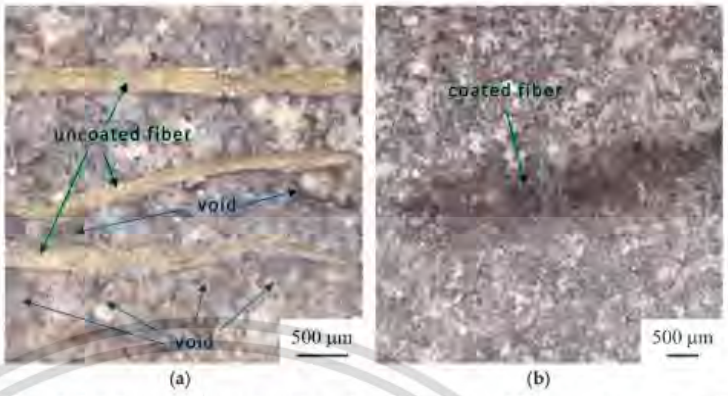

Figure 8. Optical microscope images of the surface microstructure of fiber–cement composites with (a) uncoated and (b) coated sisal fibers.

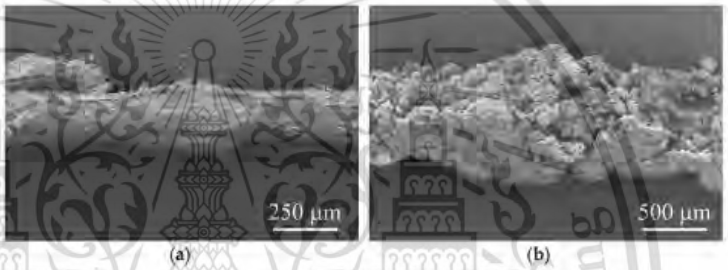

Figure 9. SEM images of the pulled-out fibers: (a) uncoated; and (b) coated sisal fibers.

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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