E-ISSN 2586-9027
Homepage : *https://tci-thaijo.org/index.php/SciTechAsia* **Science & Technology Asia**
Vol.30 No.1 January - March 2025 Page: [260-270]
Original research article

Enhancing Geopolymer Mortar with Coir and Pineapple Leaf Fibers through Various Curing Methods

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Received 7 July 2024; Received in revised form 15 December 2024
Accepted 17 January 2025; Available online 24 March 2025

ABSTRACT

This study investigates the properties of geopolymer mortar blended with natural biofibers (GMBf), focusing on density, water absorption, and compressive strength. Coir and pineapple leaf fibers were utilized to enhance the mechanical properties and sustainability of geopolymer composites. The results indicate that coir fibers, with higher lignin content, significantly improve compressive strength compared to pineapple leaf fibers. Microwave curing, employed to enhance GMBf properties, proved effective in increasing density and compressive strength while reducing water absorption by quickly removing moisture and promoting better matrix-fiber bonding. The findings align with the Thai Industrial Standard (TIS) No. 878-2566 for high-density cement-bonded particleboards, demonstrating that GMBf can be a viable, sustainable alternative in construction materials.

Keywords: Biofibers; Coir fiber; Geopolymer mortar; Pineapple leaf fiber; Microwave curing

1. Introduction

Thailand, a leading agricultural country, produces substantial quantities of natural products, including coconut and pineapple, with annual outputs reaching 652 million tons and 173 million tons, respectively, in 2021 [1]. While the agro-industry significantly contributes to the economy, it also generates large amounts of agricultural byproducts, such as natural fibers. Coir fiber, extracted from coconut husks, is abundant due to Thailand's high coconut production and is recognized for its resilience, durability, and resistance to

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saltwater, making it suitable for industrial applications. Similarly, pineapple leaf fiber, often considered agricultural waste, is rich in cellulose and possesses excellent tensile properties. Utilizing these fibers transforms low-value byproducts into high-performance materials, supporting a circular economy and aligning with Sustainable Development Goals (SDGs) such as SDG 9 (Industry, Innovation, and Infrastructure), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action).

The integration of natural fibers into geopolymer matrices presents significant potential to enhance mechanical and durability properties while addressing sustainability challenges. Geopolymers, first introduced by Davidovits in 1978 [2], are synthesized from aluminosilicate materials [3, 4] and provide an eco-friendly alternative to traditional Portland cement, offering reduced carbon emissions and lower energy consumption [5] Previous studies have demonstrated that blending geopolymers with natural fibers improves compressive strength, flexural strength, and shrinkage resistance. Curing methods, such as conventional vinyl plastic wrapping, hot-air curing, and modern microwave (MW) curing, are critical in determining the final composite properties[6]. Notably, MW curing accelerates setting time and enhances early-age strength, making it an energy-efficient and effective option, as highlighted by Jumrat S. et al. [7]; moreover, Kesikidou F. et al.[8] added tree types of natural fibers: jute, coconut, and kelp as additives in 1.5% by mortar volume. They found the advantages that can be gained in cement and lime mortars but certain aspects should be taken into account such as the adhesion to the mortar matrix and the water content of the mixture.

This study explores the effects of biofiber mixture proportions (type and quantity) and curing methods on the hardened properties of geopolymer mortar blended with biofibers (GMBf). The results are compared to the Thai Industrial Standard (TIS) No. 878-2566 for high-density cement-bonded particleboards, ensuring relevance to both scientific advancements and practical applications [9]. By addressing these key areas, this research highlights the innovative potential of GMBf in contributing to sustainable and high-performance construction materials.

2. Materials and Methods

2.1 Materials

In this investigation, lignite fly ash (LFA) sourced from the Rayong province's electrical power plant in Thailand was utilized as a geopolymer. The chemical composition of LFA, which was analyzed by X-ray fluorescence spectrometer at the Office of Scientific Instrument and testing, Prince of Songkla University Hat-Yai Campus, consisted of 72.04% SiO_2, 17.21% Al_2O_3, 3.05% Fe_2O_3, 1.30% CaO, 0.49% MgO, 1.24% K_2O, and 0.42% SO_3. River sand was washed with tap water and dried under solar; then it was sieved with mesh No.4 (4.75 mm openings) and retained on No.100 (0.15 mm openings). Two biofibers were a coir fiber, which underwent the mesocarp of coconut tissue boiling in hot water at 80 °C for 2 hours to remove small particles, and a pineapple fiber, which was obtained by cutting fresh pineapple leaves to approximately 20 cm, immersing them in a 10 M NaOH commercial grade solution for 12 hours, and pressing to extract fibers. Afterward, they were oven-dried at a temperature of 60 °C for 12 hours to obtain dry fibers, which were then cut to a length of about 5 mm (Tangjuank, 2011).

Table 1. CMixture proportions of the geopolymer mortar blended with biofibers (GMBf).

Specimen series	Weight (g)					
	Sand	LFA	Bio fiber	Na_2SiO_3	NaOH	Total
GM	600.00	300.00	-	40.00	80.00	1,020
P1	594.75	297.38	8.92	38.66	80.29	1,020
P2	589.60	294.80	17.69	38.22	79.60	1,020
C1	594.75	297.38	8.92	38.66	80.29	1,020
C2	589.60	294.80	17.69	38.32	79.60	1,020

The tensile strength of coir and pineapple fibers after alkaline treatment was reported as 95-230MPa [10, 11] and 84.67-331.53 MPa [12], respectively.

2.2 Mixture ratio and casting method

Lignite fly ash (LFA), biofibers, and NaOH solution were mixed in the Hobart mixer bow with the agitator blade rotation speed 285±10 rpm for 2 min; after that, the river sand was blended and mixed for 2 min. Finally, Na_2SiO_3 solution was filled into the bowl and mixed for 2 min. The total mixing time was 6 min. The specimens were called the geopolymer mortar blended with biofibers (GMBf) and they were tested for properties in two stages (fresh and hardened) as shown in Fig.1. They were cast into cubes 5.0×5.0×5.0 cm bronze molds, and demolded at the final setting time. The composition ratios of the mortar-based geopolymers used to study the influence of natural fibers are shown in Table 1. It should be noted that the geopolymer mortar (GM) refers to the controlled specimen without the biofiber blended, P1 refers to geopolymer blended with pineapple fiber 1%wt/wt LFA, P2 refers to geopolymer blended with pineapple fiber 2%wt/wt LFA, C1 refers to geopolymer blended with coir fiber 1%wt/wt LFA, and C2 refers to geopolymer blended with coir fiber 2%wt/wt LFA, respectively.

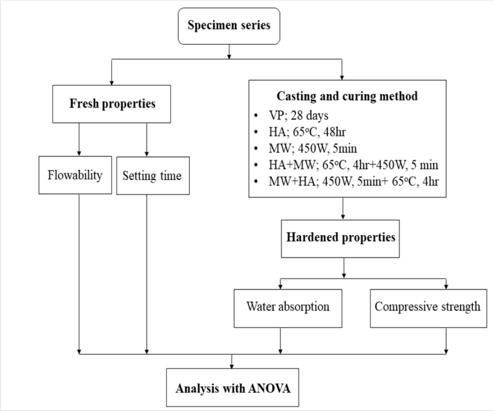

Fig. 1. Flowchart of GMBf treated with alternative curing methods and testing of the properties. (VP is vinyl plastic, HA is hot air, and MW is microwave).

The curing methods were selected to cover a wide range of practical applications, including conventional (hot air and vinyl plastic), modern (microwave), and hybrid techniques, reflecting common industrial and experimental practices. Hot air curing at 65 °C ensures effective geopolymerization without thermal degradation, while MW curing at 2.45 GHz and 450 W enhances mechanical properties, as reported in prior studies [7, 13]. To maintain consistency and comparability, all methods used standardized curing durations and post-curing ambient conditions, minimizing external variability and ensuring accurate evaluation of their effects on geopolymer composites.

2.3 Properties testing of GMBf in the fresh state

The percentage flow value is an index indicating the amount of water that allows the mixture to be in a fluid state and formable. In this research, the flowability of GMBf was tested using a flow table according to ASTM C1437 standard, in 110±5% flow range. To examine the impact of time delay post-mixing before solidification, a Vicat needle apparatus was used to evaluate the "setting time." Fresh GMBf was mixed with water to match the flow value outlined in the ASTM C191 standard. Subsequently, the cured GMBf underwent property assessments outlined in the following sections. Refer to Fig. 1 for a flowchart detailing the curing and testing process of GMBf.

2.4 Curing methods

The various curing methods were investigated: conventional, modern, and hybrid. In the conventional approach, samples were wrapped in vinyl-plastic sheets (VP) to retain moisture, and cured using hot air heating (HA) at 65 °C for 48 hours. For the modern method, electromagnetic heating via microwave (MW) at 2.45 GHz, 450 W power, and 5-minute curing time was applied. The hybrid method combined hot air and MW curing (HA+MW), with sequential hot air heating at 65 °C for 4 hours followed by MW heating (450W at 2.45 GHz) for 5 minutes. Alternatively, the sequence was reversed (MW+HA), starting with MW heating for 5 minutes followed by hot air heating at 65 °C for 4 hours. After curing, all samples were left to harden at ambient room temperature for 28 days before testing. It's important to mention that the 28-day strength serves as a standard indicator of cement mortar quality.

2.5 Properties of the GMBf

After curing and aging processes, the geopolymer mortar blended with biofibers (GMBf) samples were studied for how the properties of hardened GMBf depended on the mixture proportions in Table 1 and it should be noted that four samples of each specimen series were sampled to measure their properties as below.

2.5.1 Density

For the density of specimens, a vernier caliper was used to measure sample dimensions and weight with a digital balance, so that the density of GMBf specimens could be calculated as Eq. (2.1).

$$\rho = \frac{m}{V}, \qquad (2.1)$$

where ρ is the density in kg/m^3, m is the mass of the cube-shaped GMBf sample, and V is its volume (m^3).

2.5.2 Water absorption (%)

The percentage of water absorption (WA%) was tested according to an industry standard (ASTM C:426-70 and TIS No. 49-2516) for the hardened GMBf samples. This involved immersing the sample cubes in water for 24 hours and the difference in weight before and after immersion gave the absorbed water amount. Therefore the percentage was

$$WA\% = \frac{(W_2 - W_1)}{W_1} \times 100, \qquad (2.2)$$

where W_1 is the weight of the GMBf sample cube before immersion (g), and W_2 is the weight of the GMBf sample cube after immersion (g).

2.5.3 Compressive strength

Finally, all the cured GMBf samples at the age of 28 days were subjected to compressive strength testing according to the ASTM C109 standard for testing cement mortar, using the THAITHAMRONG compression testing machine, model KC-2000.

3. Results and Discussion

The properties of geopolymer mortar blended with biofibers (GMBf) were analyzed at two stages: fresh and hardened.

3.1 Flow characteristics

The flowability of GMBf in the fresh state can be measured by the percentage of

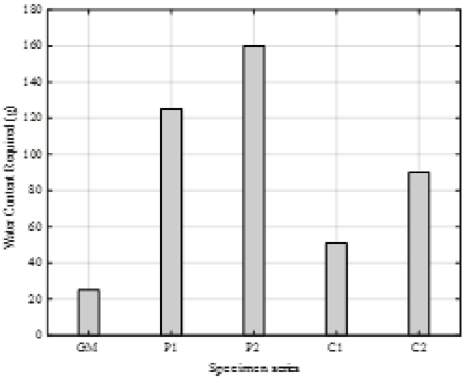

Fig. 2. The additional amount of water required to achieve the desired percentage of flow for GMBf samples, according to the ASTM C1437 standard.

flow according to ASTM C1437 (110±5%), indicating the amount of water content required to keep the mix in a fluid state for molding. The test results, shown in Fig. 2, revealed that increasing the water content was necessary for GMBf samples.

As depicted in Fig. 2, both pineapple leaf and coir fiber GMBf required more water than plain geopolymer mortar to meet the ASTM C1437 standard. This is due to the biofibers' natural components, such as cellulose, a hydrophilic polysaccharide with hydroxyl (OH) groups that readily absorbs water. Pineapple fiber, with a higher cellulose content (70-83 wt%) compared to coir fiber (32-43 wt%) [12], required more water. Consequently, the water content required for GMBf with pineapple fiber was higher than GMBf with coir fiber, which will affect the water absorption (WA%) discussed in the next section.

3.2 Setting time

The test results for the setting time of the GMBf, from the initial setting time until full hardening, are shown in Table 2. This includes both the initial setting time and the final setting time of the samples.

Table 2. Setting time of geopolymer mortar blended with biofibers (GMBf)

Specimen series	Setting time (hours)	
	Initial setting time	Final setting time
GM	18	24
P1	55	90
P2	112	120
C1	27	34
C2	30	39

When considering the quantity of natural fibers per unit time during both the initial and final setting stages, it was found that as the quantity of natural fibers (pineapple and coconut fibers) increased, the setting times for both stages also increased. Specifically, for the sample set without natural fibers (sample set GM), the initial setting time was 18 hours and the final setting time was 24 hours. In contrast, for the sample set with 1% coconut fibers by weight of the floating slurry (sample set C1), the initial setting time was 27 hours and the final setting time was 34 hours. Similarly, for the sample set with 2% coconut fibers (sample set C2), the initial setting time was 30 hours and the final setting time was 39 hours. For the sample set with 1% pineapple fibers (sample set P1), the initial setting time was 55 hours and the final setting time was 90 hours. Finally, for the sample set with 2% pineapple fibers (sample set P2), the initial setting time was 112 hours and the final setting time was 120 hours. Due to the high water absorption rate of the samples containing natural fibers, more water had to be added as the quantity of fibers increased, resulting in extended setting times.

3.3 Properties of hardened GMBf

In this section, the properties of hardened geopolymer mortar blended with biofibers (GMBf), including water absorption (%) and compressive strength, were studied. Hypothesis testing was conducted using a one-way analysis of variance (ANOVA) in MS Excel with the Analysis ToolPak add-in to determine if all group means were similar without statistical differences. At a statistically significant 95% confidence level, a p-value ≤ 0.05 was used as the threshold to reject the null hypothesis (H_0) and accept the alternative hypothesis (H_1).

3.3.1 Density

To determine the effects of each biofiber mixture proportion at a fixed curing method, the hypotheses were as follows: H_0: the means (μ) of density were the same for each biofiber mixture proportion (H_0: $\mu_{GP} = \mu_{P_1} = \mu_{P_2} = \mu_{C_1} = \mu_{C_2}$), and H_1: the means of density were not the same (H_1: $\mu_{GP} \neq \mu_{P_1} \neq \mu_{P_2} \neq \mu_{C_1} \neq \mu_{C_2}$). The density and p-values (P-val) are shown in Fig. 3. Since the P-val for every curing method was less than the threshold value, we reject H_0 and accept H_1, indicating that the means of density differed between mixture proportions. Similarly, to determine the effects of the curing method at a fixed mixture proportion, the hypotheses were: H_0: the means (μ) of density were the same for each curing method (H_0: $\mu_{VS} = \mu_{HA} = \mu_{MW} = \mu_{HM} = \mu_{MH}$), and H_1: the means of density were not the same (H_1:$\mu_{VS} \neq \mu_{HA} \neq \mu_{MW} \neq \mu_{HM} \neq \mu_{MH}$). The means of density and p-values are shown in Fig. 4. As the P-val for every mixture proportion was less than the threshold value, we rejected H_0 and accepted H_1, concluding that the means of density differed between curing methods.

As shown in Fig. 3, the density of the control specimen (GP) is higher compared to specimens blended with natural fibers. This is due to the lower density of fibers like coir and pineapple leaf, which generally have lower densities than the geopolymer matrix. Adding these fibers increases the porosity of the composite by introducing more air voids. Additionally, the volume occupied by fibers reduces the volume of the denser geopolymer matrix, contributing to an overall decrease in density. In Fig. 4, the MW curing method at 2.45 GHz, 450 W power for 5 minutes showed a trend of higher density. This is because MW curing provides uniform and rapid heating, reducing moisture loss and promoting better compaction. The rapid heating helps distribute moisture evenly, leading to a denser microstructure with fewer voids. Further-

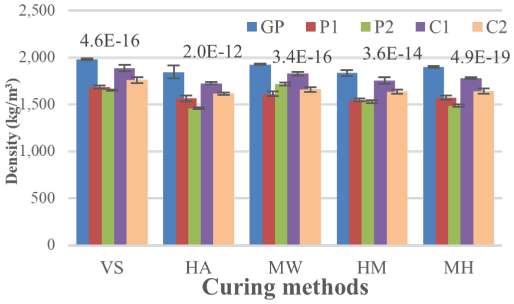

Fig. 3. Average density for all specimen series at 28 days, with varying biofiber mixture proportions and a fixed curing method (Numbers in this figure indicate the p-value).

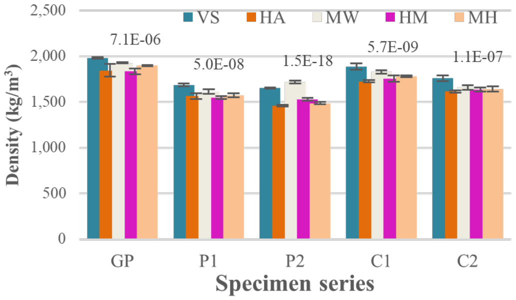

Fig. 4. Average density for all specimen series at 28 days, with varying curing methods and a fixed biofiber mixture proportion. (Numbers in this figure indicate the p-value).

more, it accelerates the geopolymerization process, resulting in a more compact matrix with improved bonding between the geopolymer and fibers [14, 15].

3.3.2 Water Absorption (WA%)

Two scenarios were conducted to study the water absorption (WA%) in the hardened state of geopolymer mortar blended with biofibers (GMBf). Firstly, to determine the effects of different biofiber mixture proportions with a fixed curing method, the following hypotheses were tested: H_0 (null hypothesis): the means (μ) of WA% are the same for each biofiber mixture proportion ($H_0 : \mu_{GP} = \mu_{P_1} = \mu_{P_2} = \mu_{C_1} = \mu_{C_2}$), and H_1 (alternative hypothesis): the means of WA% are different ($H1 : \mu_{GP} \neq \mu_{P_1} \neq \mu_{P_2} \neq \mu_{C_1} \neq \mu_{C_2}$). The average WA% and p-value (P-val) are shown in Fig. 5. Since the P-val results for every curing method were less than the threshold value, H_0 was rejected and H_1 accepted, indicating that the means of WA% differed between mixture proportions. Secondly, to determine the effects of the curing method with a fixed mixture proportion, the hypotheses were: H_0: the means (μ) of WA% are the same for each curing method ($H_0 : \mu_{VS} = \mu_{HA} = \mu_{MW} = \mu_{HM} = \mu_{MH}$), and H_1: the means of WA% are different ($H_1 : \mu_{VS} \neq \mu_{HA} \neq \mu_{MW} \neq \mu_{HM} \neq \mu_{MH}$). The average WA% and P-val are depicted in Fig. 6. As the P-val results for every mixture proportion were less than the threshold value, H_0 was rejected and H_1 accepted, indicating that the means of WA% differ between curing methods.

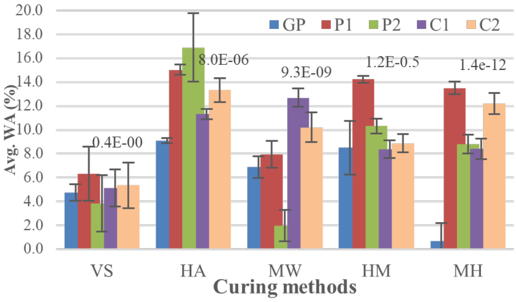

Fig. 5. Average water absorption percentage (WA%) of all specimen series at 28 days, with varying biofiber mixture proportions and a fixed curing method. (Numbers in this figure indicate the *p*-value).

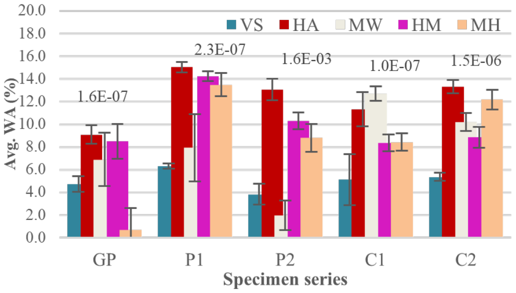

Fig. 6. Average water absorption percentage (WA%) of all specimen series at 28 days, with varying curing methods and a fixed biofiber mixture proportion (Numbers in this figure indicate the *p*-value).

The results indicate that both fiber content and fiber type influence WA%. Increasing fiber content generally leads to higher WA%, a trend also observed by Wongsa et al. [16] and reported in Ref. [11]. Additionally, the WA% of geopolymer with pineapple fiber is significantly higher than that with coir fiber, reflecting the characteristics of each fiber. The higher WA% with pineapple fiber is due to its higher cellulose content (70-83 wt%) compared to coir fiber (32-43 wt%). Cellulose is a highly hydrophilic polysaccharide with hydroxyl (OH) groups that form hydrogen bonds with water molecules, resulting in increased water absorption.

3.3.3 Compressive Strength (CS)

To investigate this property, two tests were conducted to study the compressive strength (CS) of the specimens in their hardened state. Firstly, to determine the ef-

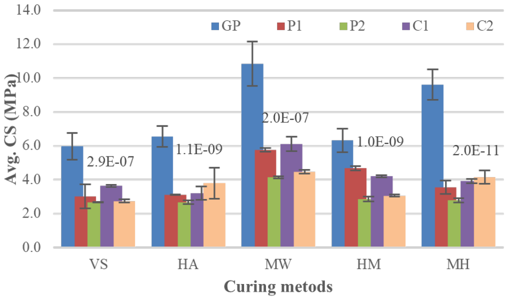

Fig. 7. Average compressive strength (CS) of all specimen series at 28 days, with varying biofiber mixture proportions and a fixed curing method (Numbers in this figure indicate the *p*-value).

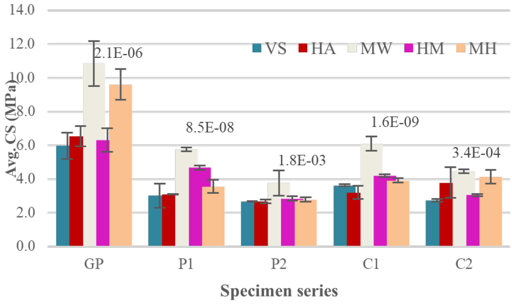

Fig. 8. Average compressive strength (CS) of all specimen series at 28 days, with varying curing methods and a fixed biofiber mixture proportion (Numbers in this figure indicate the *p*-value).

fects of each biofiber mixture proportion at a fixed curing method, the hypotheses were as follows: H_0 (null hypothesis): the means (μ) of CS are the same for each biofiber mixture proportion ($H_0 : \mu_{GP} = \mu_{P_1} = \mu_{P_2} = \mu_{C_1} = \mu_{C_2}$), and H_1 (alternative hypothesis): the means of CS are not the same ($H_1 : \mu_{GP} \neq \mu_{P_1} \neq \mu_{P_2} \neq \mu_{C_1} \neq \mu_{C_2}$). The average CS values and p-values (P-val) are depicted in Fig. 7. The P-val results for each curing method were less than the threshold value, leading to the rejection of H_0 and acceptance of H_1. This indicates that the means of CS differ between the various mixture proportions. Secondly, to determine the effects of the curing method at a fixed mixture proportion, the hypotheses were: H_0 (null hypothesis): the means (μ) of CS are the same for each curing method ($H_0 : \mu_{VS} = \mu_{HA} = \mu_{MW} = \mu_{HM} = \mu_{MH}$), and H_1 (alternative hypothesis): the means of CS are not the same ($H1 : \mu_{VS} \neq \mu_{HA} \neq \mu_{MW} \neq \mu_{HM} \neq \mu_{MH}$) The average CS values and P-values are depicted in Fig. 8. Since the P-val results for each mixture proportion were less than the threshold value, H_0 was rejected and H_1 was accepted, concluding that the means of CS differ between the curing methods.

As a result, the compressive strength (CS) of the specimens depended on the type and mixture ratio of the natural fibers. Coir fiber, with its high lignin content, provided better compressive strength compared to pineapple leaf fiber. This trend was also observed in the review article by Camargo M. M., et al. [17]. Additionally, the MW heating curing method for 5 minutes, followed by 28 days at ambient room temperature, significantly improved the CS property. This trend aligns with the density property discussed in the previous section. MW curing can quickly remove moisture from the specimen, reducing the water molecules absorbed onto the hydrophilic groups of the plant fibers. This rapid moisture removal prevents the formation of a large number of hydrogen bonds, which would otherwise create a physical barrier between the fiber and the matrix, leading to weakened interface adhesion and fiber debonding [18, 19].

As the property results, the GMBf will be compared to the Thai Industrial Standard (TIS) No. 878-2566 for high-density cement-bonded particle boards, that are blended with lignocellulosic material. Thus, the density of the GMBf specimens varies depending on the type and mixture ratio of the natural fibers used. Typically, the addition of biofibers such as coir and pineapple leaf results in a decrease in density compared to the control specimen without fibers. This is due to the lower density of the fibers and the increased porosity they introduce into the matrix. The results indicate that the density of GMBf can still be optimized to meet the high-density requirements of TIS 878-2566 by adjusting the fiber content and curing methods. The water absorption (WA%) of GMBf specimens is significantly influenced by the type and amount of natural fibers used. Pineapple leaf fibers, with their higher cellulose content, exhibit greater water absorption compared to coir fibers. This is because cellulose is highly hydrophilic, meaning it attracts and holds water. The curing method also plays a role, with MW curing showing a trend towards lower water absorption due to more efficient moisture removal during the curing process. Thus, while GMBf may show higher water absorption than standard cement-bonded particleboards, by optimizing fiber content and curing methods improvements can still be obtained.. Finally, the compressive strength (CS) of GMBf specimens is determined by the type and mixture ratio of the natural fibers, as well as the curing method. Coir fibers, with their higher lignin content, provide better compressive strength compared to pineapple leaf fibers. The use of MW curing has been shown to significantly improve compressive strength, likely due to rapid moisture removal and better compaction, leading to a denser and more robust matrix. These findings suggest that GMBf can achieve compressive strengths comparable to high-density cement-bonded particleboards by carefully selecting fiber types and optimizing curing processes.

4. Conclusions

This study highlights the potential of incorporating natural biofibers, specifically coir and pineapple leaf fibers, into geopolymer mortar to enhance its mechanical properties and sustainability. The findings demonstrate that coir fiber, due to its higher lignin content, provides superior compressive strength compared to pineapple leaf fiber, making it a more effective reinforcement material for certain applications. The use of microwave (MW) curing emerged as a pivotal factor, significantly improving the density and compressive strength of the GMBf while reducing water absorption. These improvements are attributed to MW curing's ability to efficiently remove moisture, enhance fiber-matrix adhesion, and promote a more compact microstructure. The study's significance lies in its innovative integration of natural fibers and advanced curing techniques, bridging a critical knowledge gap in sustainable construction materials. Moreover, the properties of GMBf were found to meet and, in some cases, exceed the requirements of the Thai Industrial Standard (TIS) No. 878-2566 for high-density cement-bonded particleboards. This underscores the practical relevance of GMBf in real-world applications. By providing a sustainable and eco-friendly alternative to traditional construction materials, this research supports global sustainability initiatives and advances Thailand's efforts toward achieving Sustainable Development Goals (SDGs), particularly in innovation, climate action, and resource efficiency.

For future research, optimizing the mixture design by adjusting precursor ratios and incorporating fine aggregates and supplementary materials, such as nano-silica, basalt fiber, and graphene oxide, will be explored to enhance compressive strength, setting time, ductility, and crack resistance. Additionally, an economic analysis of various curing methods will be conducted to evaluate cost efficiency.

Acknowledgements

The authors thank the Research and Development Office (RDO), Prince of Songkla University, Hat-Yai Campus, and Prince of Songkla University, Surat-Thani Campus, and we thank Mrs. Kanitta Nookaew, Mrs.Natawika Saelieo, and Mrs. Suprang Sttipakdee who carried out the experiments.

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