Alkaline Pretreatment Of Banana Pseudostem Waste For Green Cellulose Fiber Composite Materials

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Cellulose fiber from banana pseudostem waste (CFBP) was obtained from Chonburi, Thailand. After the ripening and harvesting of bananas, the pseudostem is cut down and repurposed into waste biomass. However, its recent integration into engineering applications, such as reinforced concrete and composite materials, aims to optimize its utilization. This strategy not only eliminates the practice of burning these residues but also underscores the use of sustainable materials. Utilizing CFBP as a reinforcing or composite material requires a pretreatment process to alter the physical structure of the fibers, enhancing the contact area for improved adhesion and reducing impurities on the fibers. The pretreatment involved a sodium hydroxide (NaOH) solution with concentrations of 2%, 4%, 6%, 8%, and 10%(w/v). The results indicated that CFBP with 2% NaOH exhibited low weight loss and yielded the highest water retention and tensile strength index. Furthermore, an observed trend suggests that increasing sodium concentration leads to greater weight loss and lower water retention and tensile strength, accompanied by microstructural changes. The fiber surface becomes rough, fostering good adhesion, and the elemental composition reveals peaks in carbon (C) and oxygen (O), with reduced amounts of magnesium (Mg) and silica (Si). When integrating fibers into mortar with 2%NaOH-treated CFBP at proportions of 0.25%, 0.5%, 0.75%, and 1%, the study revealed that using 0.25% CFBP in cement led to the highest compressive strength.

Keywords: Banana pseudostem, Cellulose fiber, Waste, Alkaline pretreatment, Green composite materials

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1. Introduction

Natural fibers derived from plants represent an age-old connection between human civilizations and the bounties of nature. They are inherently natural, sourced directly from renewable and biodegradable resources, establishing a sustainable synergy with the environment. These fibers, each with its unique story to tell, encompass a diverse range of exceptional properties and benefits that render them highly valuable across a wide array of applications. Examples of natural fibers include silk, hemp, jute, and banana fibers, each carrying its own narrative, distinctive characteristics, and utilitarian potential. As society traverses the path toward sustainability, natural fibers have emerged as an embodiment of eco-consciousness in materials sourcing. Their allure lies not only in their versatility but also in their inherent sustainability, biodegradability, and significantly reduced environmental impact when juxtaposed with their synthetic counterparts [1–4]. They symbolize a return to the roots of textile and material production, where innovation is interwoven with respect to the Earth's natural resources.

Banana fiber is extracted from the pseudo stems (false stems) of specific banana plant species. It has been used for centuries in various cultures for making textiles, ropes, and other products. Predominantly, Musa textilis, referred to as abaca or Manila hemp, and Musa sapientum, a common edible banana, are exploited for banana fiber products. The strength of banana fiber further enhances its appeal. However, it is important to note that while banana fiber has several advantages, it also has limitations [5, 6].

Preparing banana fibers for various applications, such as textiles, papermaking, composites, and other industrial uses, requires a preliminary pretreatment step. Banana fibers are extracted from the pseudo stems of banana plants, and several processes involve the elimination of all natural and incidental impurities, such as oils, waxes, and fats, to create a hydrophilic and composite material [7, 8]. Previous studies have explored different approaches, ranging from scrubbing plant fibers to using solutions such as NaOH or sulfuric acid (H2SO4). For instance, past research has utilized NaOH to remove lignin from coconut husks (MCH), resulting in a 21.15% reduction in lignin. Similarly, research employing NaOH to treat rice straw (RS) revealed that a NaOH concentration of 1.5% exhibited the highest potential for cellulose production. Thus, the use of an alkaline solution facilitates the breakdown of lignocellulose ester and glycosidic bonds, leading to lignin degradation and increased cellulose content [9, 10].

The pretreatment of banana fibers can impact weight loss [1, 11], especially during the extraction and cleaning stages, as noncellulosic components and impurities are removed. Treating natural or plant fibers with alkalis induces alterations in the morphology and properties of the fibers, particularly affecting hydrophilicity and water retention properties [12–15]. Alkaline pretreatment, particularly with sodium hydroxide (NaOH), can positively affect the tensile strength and flexural strength [16–19]. Given the considerable potential of natural fibers, such as banana fibers, and the growing demand for sustainable materials, this research investigated the impact of alkaline pretreatment on cellulose fibers from banana pseudostem (CFBP) waste. This study comprehensively analyzed various properties of pretreated CFBP, including density, weight loss, tensile strength, water retention value (WRV), microstructure, and elemental composition (EDS). Furthermore, this study explored the practical application of banana fibers to determine the compressive strength of cement mortar.

By delving into the pretreatment of banana pseudostem (CFBP) waste using different concentrations of sodium hydroxide, this research sheds light on potential avenues for future studies of plant-based composite materials. The outcomes are expected to provide valuable insights into the pretreatment of diverse plant fibers, contributing to further exploration of the use of fibers from banana or other plant sources as reinforcing materials or composites, such as their integration into concrete for reinforcement. The application of plant fibers in environmentally friendly tiles or their incorporation into lightweight materials presents an intriguing challenge for future exploration.

2. Methodology

The objective of this research was to investigate the pretreatment of banana pseudostem with 0%, 2%, 4%, 6%, 8% and 10% concentrations of sodium hydroxide (NaOH). The weight loss, tensile strength, tensile index, and water retention value (WRV) of the pretreated cellulose fiber banana pseudostem (CFBP) were analyzed, and the microstructure (SEM) and elemental composition (EDS) were examined. Additionally, CFBP (2% NaOH) is utilized as an ingredient in cement mortar, and the compressive strength of the mortar is tested. The methodology for this study is illustrated in Fig. 1.

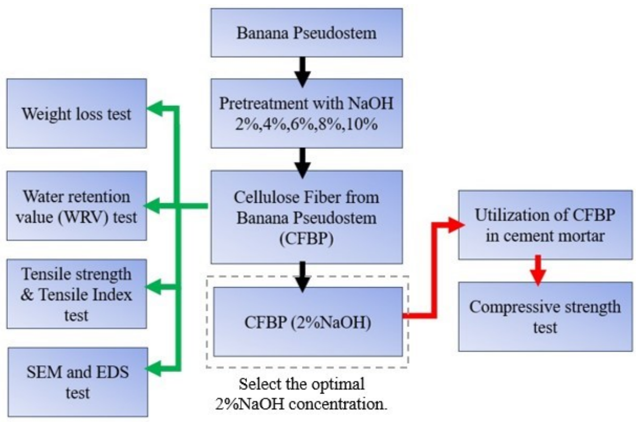


Fig. 1. Schematic diagram showing the methodology.

2.1. Materials

In this study, cellulose fiber from banana pseudostem (CFBP) waste was obtained from Chonburi, Thailand, by pretreating banana fiber with sodium hydroxide (NaOH) at concentrations of 2%, 4%, 6%, 8% and 10% (by weight) via wet-state NaOH pretreatment. Ordinary Portland Cement (OPC) Type 1, manufactured to meet quality criteria specified in the Portland Cement Industry Standard (ASTM C150) [20], was used. Pure, impurity-free water, compliant with ASTM C1602/C1602M-22 standards [21], was obtained from the Laboratory Department of Civil Engineering for concrete mixing. Standardized fine aggregates of river sand, conforming to ASTM C33 specifications [22], were utilized.

2.2. Pseudostem of banana pretreatment

In the CFBP preparation process modified according to previous studies [6–13, 17], as depicted in Fig. 2, the first step involved meticulous cutting and stripping of the banana pseudostem for 3 minutes to increase the fiber surface area, facilitating its reaction with alkaline pretreatment (NaOH). The second step included thoroughly washing the fibers with clean water to eliminate any remnants of the pseudostem that might have detached. In the third step, the fibers are then dried at 45°C for 48 hours. When cutting fresh banana pseudostems, the moisture content is high. Consequently, these pseudostems need to be dried at 45°C for 48 hours to reduce the moisture content and adjust the physical structure. The fourth step involved immersing thirty grams of these cleaned banana fibers in sodium hydroxide (NaOH) solutions with concentrations ranging from 2%, 4%, 6%, 8% and 10%. The choice of sodium hydroxide (NaOH) concentration for CFBP pretreatment was guided by previous research [6–13, 17] on conditioning banana fibers and plant fibers. In the fifth step, the fibers are allowed to soak in the solution for 90 minutes, after which they are removed and rinsed thoroughly with water to eliminate any residual NaOH, which is essential for preventing damage from excessive alkali exposure. The last step involved drying the treated fibers for 24 hours, after which the fibers were ready for property testing and subsequent incorporation into the mortar mixtures.

2.3. Weight loss test

In the weight loss test, the raw natural CFBP fibers were weighed before pretreatment (W_{initial}) at 0%NaOH and after pretreatment with NaOH concentrations ranging from 2% to 10%. After pretreatment, the treated CFBP was dried at 45°C for 24 hours, after which the weight of the dried CFBP was measured $\left(W_{dry}\right)$. The weight loss was calculated using the formula outlined in ASTM D3175 [23], as shown in Eq. (1).

$$\%Weight\ loss = \frac{W_{initial} - W_{dry}}{W_{dry}} \times 100 \quad (1)$$

2.4. Water retention value (WRV) test

The water retention value (WRV) test was used to assess the water retention capacity of the fibers (CFBP). Testing was conducted according to TAPPI UM 256 [24]. The initial step involved preparing dry fibers pretreated with sodium hydroxide (NaOH), which weighed approximately 1 g. Subsequently, the fibers were soaked in distilled water for 24 hours to allow them to fully swell. The fibers were centrifuged at a speed of 4000 grams for 10 minutes, after which the fibers were weighed to obtain the wet weight. Next, the fibers were baked at 105 degrees Celsius for 4 hours; then, the fiber samples were placed in a desiccant to allow the fibers to cool. Finally, the fibers were weighed to obtain the dry weight. The water retention value of the fiber can then be calculated according to Eq. (2).

$$WRV(g/g) = \frac{W_w}{W_d} - 1 \quad (2)$$

where:

- Wet weight (W_w) is the weight of the fibers after centrifugation (g)
- Dry weight (W_d) is the initial dry weight of the fibers (g)

2.5. Tensile strength test

In the tensile strength test, following ISO 1924 [25], the CFBP has a physical appearance in sheets paper. Testing using the same method as that used for paper allows for a direct assessment of the tensile strength.

The test sample consists of rectangular strips of CFBP sheets oriented in the machine direction (MD) and measuring 180 mm in length and 15 mm in width. These strips are subjected to a rate of elongation of 20 mm/min using a tensile testing machine, which uniformly elongates the specimen until it fractures. The CFBP is securely mounted in the grips of the testing machine to prevent damage, and the maximum force applied to it before breaking is divided by its initial cross-sectional area to determine the tensile strength, as depicted in Fig. 3.

2.6. Scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS)

To evaluate the structural characteristics of CFBP, microstructural analysis was performed utilizing scanning electron microscopy (SEM). For each test sample, three small CFBP specimens were prepared. These specimens underwent a series of steps: drying in an oven (at a specific temperature and time), polishing to achieve a smooth surface using sandpaper, and placement in a dehumidifier. Subsequently, the specimens were coated with a layer of gold and secured with carbon tape before being introduced into the machine. The SEM microstructure image was then generated using CFBP samples prepared in accordance with this procedure.

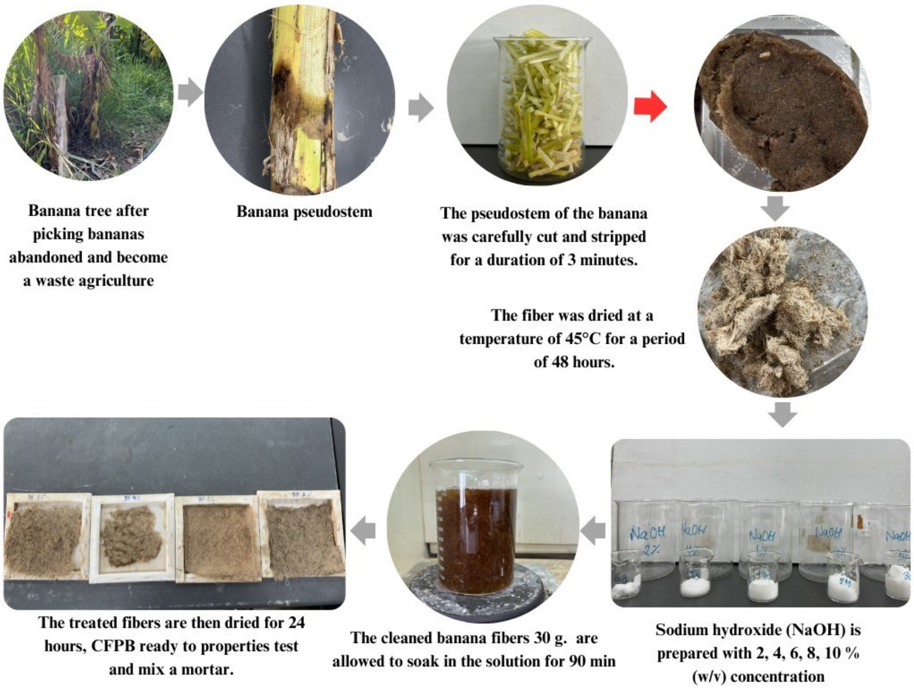
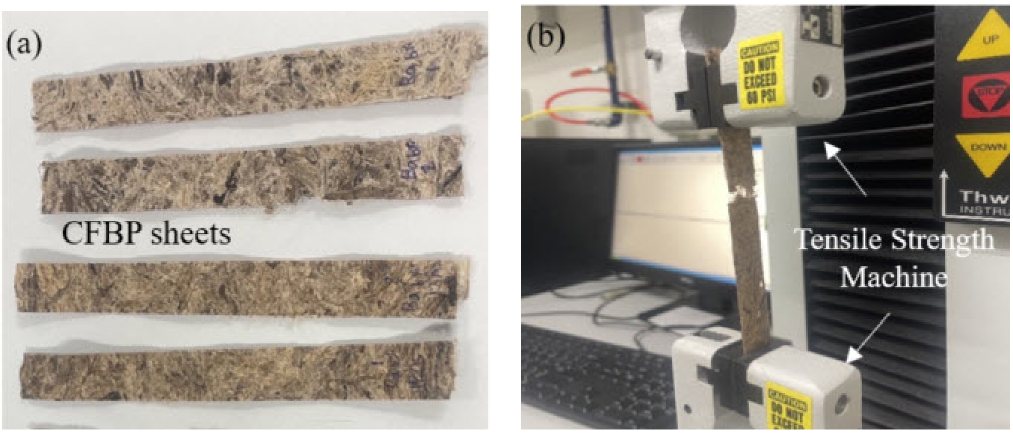


Fig. 2. Schematic diagram showing the NaOH pretreatment process of the raw fiber obtained from the banana pseudostems.



(a) CFBP sample before testing. (b) CFBP sample during testing.

Fig. 3. Schematic diagram showing the NaOH pretreatment process of the raw fiber obtained from the banana pseudostems.

Concurrently, EDS data collection commences, facilitated by the electron beam's excitation of sample atoms, leading to the emission of characteristic X-rays unique to each element present. EDS data take the form of X-ray energy spectra, displaying peaks at specific energy levels corresponding to X-rays emitted by CFBP elements. The EDS spectrum was analyzed to identify the elements within the CFBP, leveraging the characteristic X-ray peaks of each element. SEM images aid in comprehending surface morphology and features, while EDS data interpretation reveals element identities and their relative concentrations. The correlation of the SEM images with the EDS elemental data provides a holistic understanding of the sample characteristics.

2.7. Utilization of banana fiber in cement mortar

To evaluate the efficiency of CFBP for cement mortar composites, compressive strength tests were conducted on mortar samples following ASTM C109 standards [26]. The mortar samples contained CFBP pretreated with 2% NaOH because the fibers at this concentration exhibited the greatest water retention and tensile strength. These fibers have the potential to improve water retention as an internal curing material, thereby enhancing the compressive strength of the mortar. Due to their high tensile index, selecting these CFBP may have a positive impact on the cement mortar mixture. Given their high tensile index, selecting these CFBP may positively impact the cement mortar mixture. CFBP used as an ingredient in the mortar was cut into square pieces with a width and length of 1 cm. The process of cutting the CFBP into small pieces enables it to disperse effectively in the cement mortar and allows the CFBP to act as an excellent internal curing material. Subsequently, the cut CFBP was soaked in water. The water retention value (WRV) of the CFBP in 2% NaOH, with a WRV of 5.19 g/g, was used to calculate the amount of water needed for soaking the CFBP for 24 hours. After this soaking period, the CFBP was in a saturated state. This allows the CFBP fiber to function as an internal curing material, releasing moisture during the hydration process, and it is mixed into the mortar, as shown in Fig. 4. CFBP at ratios of 0.25%, 0.5%, 0.75%, and 1% was added to the mortar mixture. Compressive strength tests were performed on these mortar samples at 7, 14, and 28 days. Table 1 presents the mixing proportion test, which included 5 groups of mortar samples. Fig. 5 shows a mortar sample measuring 5x5x5 cm. is used for compressive strength testing.

3. Results and discussion

3.1. Weight loss tests

The impact of NaOH pretreatment on the CFBP structure is evident in the results presented in Fig. 6. When subjected to various NaOH concentrations, it becomes clear that the use of 2% NaOH leads to minimal weight loss, whereas 10% NaOH results in the most significant reduction in weight for CFBP. When treated with alkali (NaOH), the fibers undergo a process in which the bark and impurities are removed. The alkali effect increases the proportion of amorphous cellulose relative to that of crystalline cellulose. This alteration reduces the size of the crystalline structure by removing lignin and hemicellulose, leading to a loss of weight [1]. This phenomenon can be attributed to changes in surface characteristics observed during pretreatment when examining the fiber microstructure, which may affect weight loss. This observed weight loss aligns with previous research showing that the weight of banana fibers decreases as the alkali concentration increases [1, 11, 15]. However, it is crucial to note that excessive concentrations of NaOH can potentially harm banana fibers, resulting in substantial fiber loss, emphasizing the need for careful consideration of pretreatment conditions.

3.2. Water retention value (WRV) test

The pretreatment of CFBP with NaOH significantly affects its water retention value (WRV). According to the test results illustrated in Fig. 7, CFBP treated with 2% NaOH exhibited the highest WRV. The water retentions for CFBP treated with 0%, 4%, and 10% NaOH were similar, but CFBP treated with 6% and 8% NaOH demonstrated the lowest water retentions. This increase can be attributed to the expansion of the fiber surface area and the exposure of a greater number of hydrophilic sites. Consequently, pretreated banana fibers tend to possess an enhanced capacity for water absorption and retention. In contrast, CFBP pretreated with 8% NaOH demonstrated the lowest WRV. However, the WRV of 6% NaOH was 0.54% greater than that of 8% NaOH, which was similar. This variation can be attributed to the varying degrees of NaOH pretreatment, as an excessively high solution concentration can negatively affect the CFBP structure. Pretreatment with NaOH may lead to the removal of oils and waxes from the surface of the fibers, facilitating enhanced water absorption and retention by the fibers. However, an excessive NaOH concentration may harm the cellulose within the fibers, consequently diminishing their water retention capacity. The 10% NaOH solution could lead to higher values. This could be due to the finer breakdown of the fibers, resulting in a softer and more absorbent material. The obtained test results align with earlier research, indicating that treating plant fibers with alkali influences the water retention properties of the fibers. Higher alkali concentrations may lead to a reduction in water retention [19, 27]. Therefore, a high WRV in CFBP would prove advantageous as an internal curing agent in mortar or cement composites. This is because such fibers can effectively retain and subsequently release water during the hydration process, thereby enhancing moisture.

3.3. Tensile strength test

The use of appropriate proportions of %NaOH has the potential to enhance the tensile properties of CFBP. As indicated in Fig. 8, when compared to 0% NaOH, CFBP pretreated with 2% and 4% NaOH exhibited a greater tensile strength and tensile index. Conversely, NaOH concentrations of 6%, 8%, and 10% tended to decrease both the tensile strength and the tensile index. This phenomenon is attributed to the ability of 2% and 4% NaOH to effectively remove lignin, hemicellulose, wax, and impurities from CFBP, contributing to its superior tensile strength. However, CFBP treated with higher NaOH concentrations exhibited a reduced tensile strength and index, consistent with the findings of the weight loss test. In general, fibers with higher densities, indicating lower weight loss, may of-

(a) (b)

Fig. 4. CFBP sample. (a) CFBP (b) Prepared CFBP sample for the saturated state.

(a) Samples for the compressive strength test. (b) Compressive strength test.

Fig. 5. Compressive strength test of the mortar reinforced with CFBP.

Table 1. Comparison of time performance and performance with different superpixel methodsMix proportions for the mortar reinforced with CFBP pretreated with 2% NaOH.

Mixture	CFBP (%)	CFBP (g)	Cement (g)	Fine aggregate (g)	Water (g)
Mortar 1	0.00	0	417	1146	202
Mortar 2	0.25	1.04	417	1146	202
Mortar 3	0.50	2.09	417	1146	202
Mortar 4	0.75	3.13	417	1146	202
Mortar 5	1.00	4.17	417	1146	202

fer superior tensile strength compared to fibers with lower densities. The results of the tensile strength test are in line with past research, suggesting that the treatment of fibers with alkali can influence their tensile properties. This is due to changes in the morphology and microstructure of the fibers, ultimately affecting their tensile strength [15, 18].

3.4. SEM and EDS tests

The analysis of fiber microstructures yielded insightful results, as illustrated in Fig. 9, providing valuable information regarding the texture, morphology, presence of impurities, wax content, and ash content in NaOH-pretreated raw CFBP. In Fig. 9(a), impurities are evident on the surface. However, it seems that impurities provide a layer for the surface of the fibers for fiber-matrix adhesion. Fig. 9(b) shows that pretreatment of CFBP with 2% NaOH removed

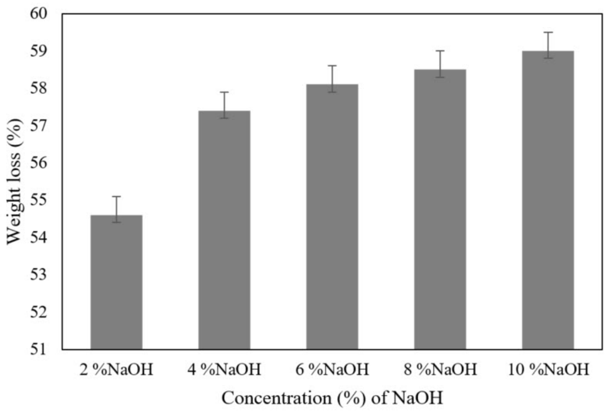


Fig. 6. Weight loss of CFBP after pretreatment with different concentrations of NaOH.

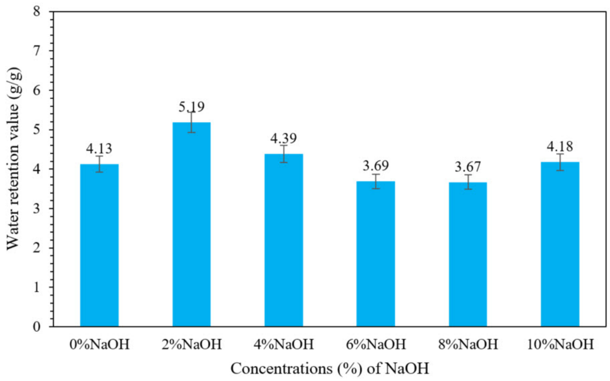


Fig. 7. Water retention value (WRV) of CFBP after pretreatment with different concentrations of NaOH.

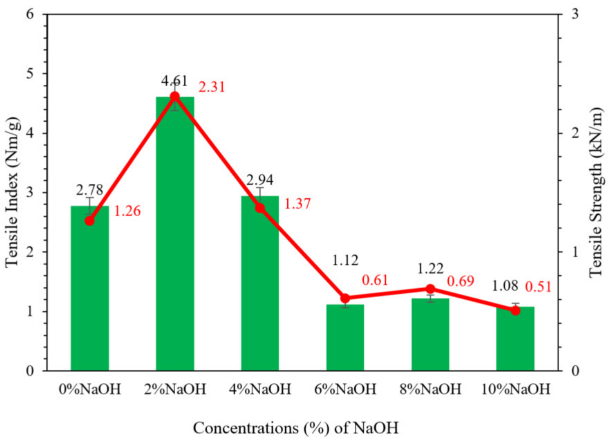


Fig. 8. Effect of different NaOH pretreatment methods on the tensile index of CFBP.

minor impurities, resulting in bundled fibers. Fig. 9(c) shows the results for CFBP pretreated with 4% NaOH, emphasizing the development of a smoother surface attributed to the removal of the outer layer. Fig. 9(d) and Fig. 9(e), representing fibers pretreated with 6% and 8% NaOH, respectively, reveal a distinct roughness due to the higher concentrations of NaOH, facilitating the removal of wax and impurities from the fiber surface. This leads to improved fiber adhesion, accompanied by a reduction in the content of lignin and hemicellulose. Fig. 9(f) displays fibers pretreated with 10% NaOH, exhibiting the highest surface roughness owing to the elevated concentration, although some cellulose fibers may have undergone corrosion, potentially affecting adhesion.

The microstructural results obtained via SEM after treating the fibers with alkali were consistent with previous research. The treatment induces alterations in the morphology and texture of plant fibers. As the concentration increases, the fiber surface undergoes substantial changes, effectively eliminating outer tissue, wax, and various impurities from the fiber [14, 15].

The EDS analysis results revealed alterations in the surface chemical composition of CFBP. Table 2 and Figs. 10 to 12 show that the spectroscopic analysis conducted using energy-dispersive X-ray spectroscopy (EDS) revealed changes in the elemental composition of the CFBP surface during the delignification treatment when CFBP was applied to a NaOH solution. The spectrum exhibits two distinct peaks, carbon (C) and oxygen (O), both of which are clearly visible. Pretreatment with higher concentrations of sodium hydroxide led to a slight reduction in carbon and oxygen levels compared to those of CFBP with 0% NaOH. Given that these two elements form the main components of cellulose fibers, their strong bonds minimize decomposition. An analysis of the elemental composition of the untreated fibers revealed elevated levels of Si and Mg. However, post-NaOH treatment, there was a significant reduction in the content of Si and Mg. These elements consist not only of calcium and chloride but also of cellulose ($C_6H_{10}O_5$), lignin, and hemicellulose.

3.5. Utilization of CFBP in cement mortar

Fig. 11 illustrates the results of compressive strength tests conducted at 7, 14, and 28 days for mortar samples containing untreated CFBP. In comparison to 0% CFBP, the inclusion of 0.25% and 0.5% CFBP led to enhancements in compressive strength of 12% and 1.4%, respectively. However, for CFBP proportions of 0.75% and 1%, the compressive strength decreased by 9.9% and 88.4%, respectively.

Fig. 12 shows the compressive strength test results at 7, 14, and 28 days for the mortar samples containing CFBP pretreated with 2% NaOH. In contrast to 0%, the addition of 0.25% and 0.5% CFBP improved the compressive strength

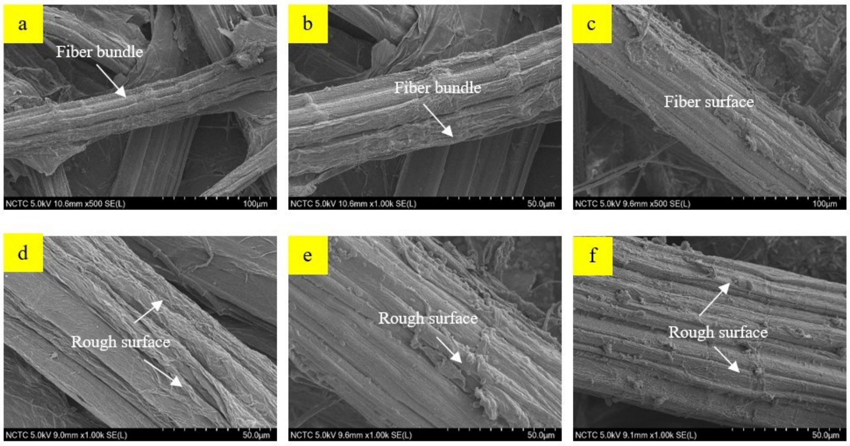


Fig. 9. SEM images of CFBP: (a) 0% NaOH, (b) 2% NaOH, (c) 4% NaOH, (d) 6% NaOH, (d) 8% NaOH, and (f) 10% NaOH.

Table 2. Composition of CFBP after different NaOH pretreatments.

NaOH Pretreatment	Composition of CFBP(Wt%)					
	C	O	Ca	Na	Mg	Si
0%NaOH	50.2	49.2	1.9	0.3	2.1	1.8
2%NaOH	49.7	47.3	1.9	0.2	0.3	0.8
4%NaOH	49.7	48.2	1.5	0.2	0.2	0.4
6%NaOH	47.8	47.1	3.4	1	-	0.3
8%NaOH	48.4	44.3	4.8	1.7	-	-
10%NaOH	48.2	47	3.5	0.6	0.2	0.2

by 14.5% and 2.9%, respectively. Conversely, for CFBP ratios of 0.75% and 1%, the compressive strength decreased by 7.3% and 78.2%, respectively.

Comparing the compressive strength of the mortars containing untreated CFBP versus those with CFBP pretreated with 2% NaOH, it became evident that the pretreated CFBP exhibited superior improvements in compressive strength owing to the pretreatment process. Conditioning the fibers at the optimal concentration enhances the surface contact between the fibers and the cement matrix, leading to a stronger bond [28].

Upon assessing all the samples, it was determined that the most suitable proportion for utilizing CFBP as a reinforcing material in cement composites was 0.25%, as it yielded the highest compressive strength. However, excessively high fiber proportions may lead to improper distribution and arrangement within the cement mixture, potentially causing voids or inhomogeneity and subsequently reducing compressive strength [18].

4. Conclusion

In this study, cellulose fibers from the pseudostem of banana (CFBP) waste were pretreated with alkaline solutions (0%, 2%, 4%, 6%, 8%, and 10% NaOH). The objective of this study was to investigate the effects of varying NaOH concentrations on the properties of CFBP, including weight loss, water retention value (WRV), tensile strength, microstructure observed via EDS analysis, and the utilization of CFBP in cement mortar. The findings can be summarized as follows:

The preparation of CFBP with NaOH results in greater weight loss. Higher sodium concentrations lead to increased weight loss. The reduction in the mass of CFBP occurs due to fluid loss, bark, hemicellulose, lignin, etc. This loss allows the proportion of cellulose to increase and enhances the texture of the fibers. When mixed with cement materials, this process may have a positive effect. However, pretreatment with NaOH still has limitations and necessitates the use of an appropriate concentration.

The highest water retention value (WRV) was observed for CFBP pretreated with 2% NaOH, whereas the lowest WRV was found for CFBP pretreated with 8% NaOH. This difference can be ascribed to the diverse levels of NaOH pretreatment, where an excessively high solution concentration may adversely impact the CFBP structure, impeding its water retention capability.

CFBP treated with a 2% NaOH solution demonstrated the highest tensile strength and tensile index, while increasing the NaOH concentration tended to cause a decrease in both the tensile strength and tensile index.

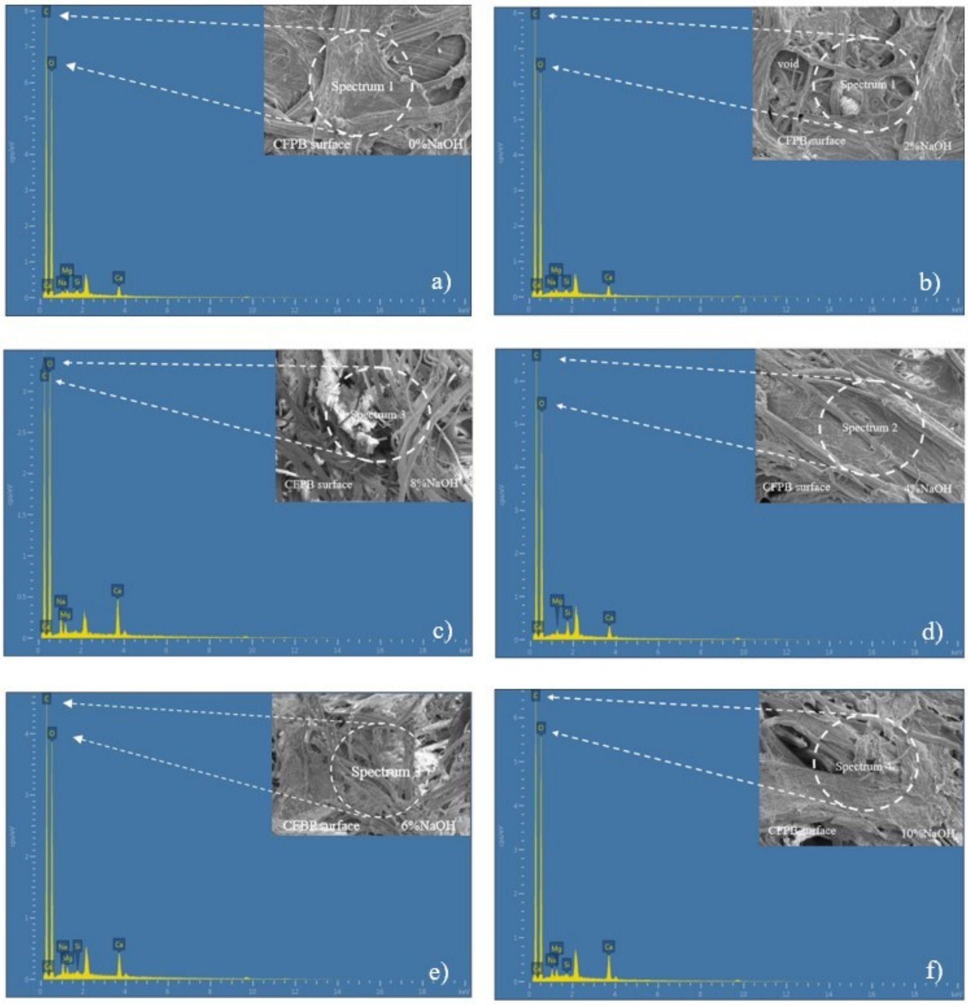


Fig. 10. EDS of CFBP: (a) 0% NaOH, (b) 2% NaOH, (c) 4% NaOH, (d) 6% NaOH, (e) 8% NaOH (f) 10% NaOH.

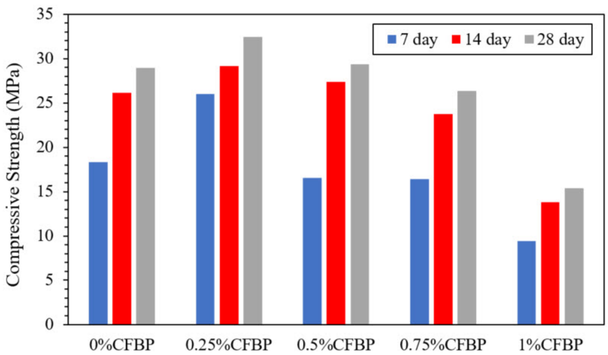


Fig. 11. Compressive strength of the CFBP (0% NaOH treatment)-reinforced mortar.

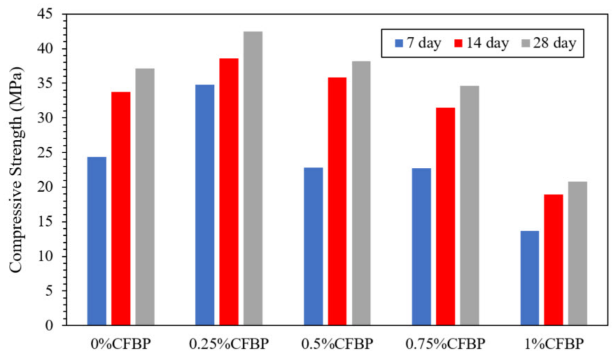


Fig. 12. Compressive strength of the CFBP (2% NaOH treatment)-reinforced mortar.

Microstructural analysis of CFBP after NaOH pretreatment revealed substantial removal of wax impurities from the outer surface. The internal structure of CFBP included more monofilaments with a coarser surface, potentially enhancing bonding when used in composite materials. EDS analysis indicated that the fibers primarily consisted of carbon (C) and oxygen (O). An increase in the NaOH concentration led to a decrease in the magnesium (Mg) and silicon (Si) contents, which serve as the primary impurities.

The utilization of CFBP (2% NaOH) in cement mortar demonstrated that incorporating fibers in appropriate proportions (0.25% CFBP) served as reinforcement within the cement mortar matrix. These fibers seamlessly blended into the mortar mixture, creating a fibrous network throughout the material. The results of this test can be used to develop and test additional properties for use as composite cement materials and to use waste materials that provide sustainable value.

In future studies, the durability of NaOH-treated CFBP as a construction material should be evaluated. Additionally, further investigations could explore the feasibility of leveraging CFBP for construction applications. Emphasis should be placed on materials suitable for accommodating low loads, such as tiles or lightweight walls. Thus, forthcoming research promises both challenging and captivating avenues to explore.

Declaration of Competing Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement: Conceptualization, S.P., T.C. and S.C.; methodology, S.P., P.N., and T.C.; validation, S.P., T.C., K.S., and S.C.; formal analysis, S.P. and P.N.; investigation, S.P., P.N., T.C., L.J., K.S., and S.C.; writing—original draft preparation, S.P., P.N., and T.C.; writing—review and editing, T.C., L.J. and P.L.; supervision, T.C. and P.L.; project administration, T.C., L.J., and K.S.; funding acquisition, S.P., T.C., L.J., and K.S. All authors have read and agreed to the published version of the manuscript.

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