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SAGO PALM FIBERS AND GGBFS FOR SUSTAINABLE HIGH-TENSILE-STRENGTH SELF-COMPACTING CONCRETE

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ABSTRACT: This study uses palm stem fibers, notable as a by-product of industry, and ground granulated blast furnace slag (GGBFS) to assess the mechanical properties of concrete that potentially lead to sustainable and high tensile-strength performance. We aim to enhance the mechanical characteristics of palm stem fibers in self-compacting concrete mixtures, with and without NaOH treatments. The study used 25% GGBFS as a substitute for cement and non-treated fiber, along with treated fiber with 0.25%, 0.5%, and 0.75% binder content. Substituting 25% GGBFS into the cement and adding 0.5% treatment fiber to the binder content produced the highest compressive strength of 73.90 MPa. Substituting 25% GGBFS into the cement and adding 0.75% non-treatment and treatment fibers to the binder volume yields optimum tensile strengths of 6.03 MPa and 6.23 MPa, respectively. A Scanning Electron Microscope (SEM) was used to analyze the morphological features of the surface of a concrete mixture. The study then utilized X-ray fluorescence (XRF) and X-ray diffraction (XRD) for mineral characterization, with the different molecular compositions confirmed by FTIR spectroscopy. The SEM images indicate that the fibers did not successfully adhere to the cement paste in the untreated fiber concrete, while fiber-treated concrete, by contrast, bonded with the cement paste due to the reduction of the lignin present. We conclude by demonstrating that the incorporation of treated palm stem fibers and GGBFS increased both the tensile and compressive strengths of SCC, therefore offering an eco-friendly and effective alternative to high-performance concrete.

Keywords: GGBFS, Palm stem fiber, SCC, SEM, Tensile strength, X-ray diffraction

1. INTRODUCTION

The construction industry has progressively explored and utilized sustainable resources, leading to increased interest in replacing fibers and supplementary cementitious materials. The rationale is that global concrete production reaches approximately 25 billion tons annually. The need for concrete for construction projects worldwide is estimated at 6.25 billion tons annually. Increased use of natural resources in concrete production can lead to environmental degradation.

One proposed alternative to support ecological sustainability is to utilize industrial waste as a component in concrete production, considering that natural resources are increasingly limited [1]. Palm stem fibers and ground granulated blast furnace slag (GGBFS) are preferred among these alternatives due to their accessibility, mechanical characteristics, and ecological advantages. These materials offer the potential for more sustainable construction.

Studies have shown that using natural fibers from materials such as bamboo, coconut, and sisal in concrete can enhance its mechanical properties, particularly tensile strength and crack resistance [2]. A study by Ahmad and his colleagues showed that adding 0.5% bamboo fibers increased tensile strength by 1.3%, and incorporating coconut fibers improved the tensile strength of high-strength concrete by 5-7% [3]. Despite this, using palm stem fibers derived from sago flour waste in self-compacting concrete (SCC) remains relatively underexplored, particularly in comparison with these other natural fibers.

The palm stem flour-making industry generates significant waste, including fibers and cassava pulp, which pose environmental hazards if not properly managed [4]. As much as 659 tons of unprocessed waste is produced annually, which would harm the environment. To reduce pollution caused by the disposal of flour industry waste, particularly fiber, one solution is to use this fiber waste as a material to add to concrete.

Palm stem fibers offer several advantages over other fibers like bamboo and sisal. First, palm stem fibers are a by-product of industrial waste, unlike bamboo, which requires dedicated cultivation and harvesting. Unlike bamboo, which requires dedicated cultivation and harvesting, they offer a more sustainable and cost-effective solution. Palm stem fibers were used in treated and untreated forms, showing improvements of 6.34 MPa and 6.03 MPa, respectively, compared to the control tensile strength of 4.11 MPa. This result demonstrates the significant contribution of these fibers to the enhancement of the tensile properties of SCC. Additionally, bamboo fibers showed only a 1.3% increase in tensile strength compared to previous studies [2].

Palm stem fibers are both sustainable and exhibit superior mechanical properties, such as high tensile strength and flexibility. This makes them indispensable for simultaneously increasing the strength and ductility of concrete, particularly by effectively linking ruptures and improving elasticity [5]. The coarse surface structure of palm stem fibers facilitates enhanced mechanical interlocking with cement paste, thereby improving bonding and overall performance [6]. By contrast, other natural fibers like bamboo may have difficulties bonding because of their smooth surfaces and elevated lignin content, which may prevent efficient adhesion [7].

Another potential alternative for a cement substitute is ground granulated blast furnace slag (GGBFS), which is well-established for its environmental and mechanical benefits [8]; replacing 30% of cement with GGBFS improved compressive strength by 5.04% [9]. They reported that using 20-40% GGBFS increased concrete's workability by 3.02-7.19%. In their study, replacing 25% of the cement with GGBFS led to a compressive strength of 73.76 MPa in the self-compacting concrete (hereafter referred to as SCC) mix with treated fibers, a 9.71% increase over the control concrete (67.23 MPa), highlighting GGBFS's effectiveness in improving mechanical properties.

While fly ash and silica fume have been extensively used as supplementary cementitious materials (SCMs) to improve concrete properties, GGBFS offers several distinct advantages. Regarding availability, fly ash supplies have become less reliable because of the global reduction in coal-fired power plants. Conversely, GGBFS, a by-product of the steel industry, provides a more consistent and sustainable supply—furthermore, Majhi and his colleagues found that adding 25% GGBFS reduced the heat of hydration and improved concrete's durability, especially in large-scale applications [10].

The amalgamation of palm stem fibers and GGBFS produces a synergistic effect that improves the mechanical characteristics of self-compacting concrete (SCC). The pozzolanic properties of GGBFS enhance the bonding capacities of palm fibers, yielding a composite material with superior tensile and compressive strength [11]. Furthermore, Zhao's study on workability tests also showed that SCC with GGBFS and palm stem fibers maintained acceptable flowability, with slump flow values ranging from 55.5 cm to 58.5 cm, consistent with other studies reporting enhanced workability with GGBFS use [9].

Therefore, using palm stem fibers and GGBFS in this work is motivated by their sustainability, mechanical benefits, and compatibility, which collectively improve SCC performance and encourage ecologically responsible initiatives. The combination of palm stem fibers and GGBFS presents a novel approach for the sustainable production of high-performance SCC. Palm stem fibers not only increase tensile strength but also improve fracture resistance. GGBFS works as a reliable replacement for cement, contributing to a decrease in concrete's carbon footprint. Combining a waste-derived fiber and an industrial by-product ensures that the end-product concrete mix adheres to mechanical performance criteria while advancing sustainability objectives by reducing resource consumption and waste production.

This research tackles a critical deficiency in interpreting the use of palm stem fibers made from sago flour waste and GGBFS in SCC, namely the lack of comparison analyses between treated and untreated fibers. Although previous studies have focused on the advantages of GGBFS and various natural fibers, such as that by Olonade and Sayastano on the combination of GGBFS and coconut fibers, the potential of palm stem fibers in SCC applications has not been sufficiently investigated [7]. Using waste-derived materials like palm stem fibers promotes resource efficiency and sustainability by reducing reliance on non-renewable resources while mitigating industrial waste. This work, therefore, aims to address this gap by assessing the mechanical characteristics of SCC, including both treated and untreated palm stem fibers, along with GGBFS. We strive to offer new insights into sustainable, high-tensile, and practical alternatives.

As demonstrated by Jayabal and his colleagues, fiber treatment plays a crucial role in improving the bond between fibers and the cement matrix [12]. Treating fibers with NaOH increased their surface roughness, promoting better adhesion with the cement paste. SEM analysis supported these findings, revealing that treated palm stem fibers bonded more effectively with the cement matrix, reducing the formation of gaps and improving the overall mechanical performance. By contrast, untreated fibers showed weaker adhesion due to lignin while enhancing the tensile strength. This comparative analysis of treated versus untreated fibers adds significant value to the body of research on natural fibers in concrete, demonstrating that while treatment enhances performance, untreated fibers still offer considerable benefits, especially in terms of cost and sustainability.

In a study, FTIR analysis was performed to evaluate the molecular groups in concrete specimens with and without palm fiber [13]. The study found that the Fourier spectrum of transom infrared spectroscopy can be divided into three segments, observed in the range 1485–1270, 1175–980, and

875–490 cm^{-1}, respectively. This segment is characterized by CO32–, O-Si-O, and C–S–H particles. The study found that fibers in concrete samples did not affect the spectrum significantly. XRD analysis conducted by Olenade and his colleagues showed that using fiber treatment in concrete increased the intensity of the crystalline phase [7]. The minor peak found at 18° was considered the amorphous phase (cellulose), while the significant peak observed at an angle of 22° indicated the presence of crystalline material. The study found a good bond between the fiber and cement paste, increasing mechanical properties [3].

2. RESEARCH SIGNIFICANCE

This study explores the innovative integration of palm stem fibers from sago flour waste and Ground Granulated Blast Furnace Slag (GGBFS) as substitutes in self-compacting concrete, thereby addressing sustainability and performance concerns. These waste materials reduce reliance on traditional, nonrenewable resources and mitigate environmental impacts by diverting waste from landfills. By significantly improving the tensile strength of concrete, the study contributes to high-performance, eco-friendly construction materials. This research can influence industry practices and environmental policies, promoting a shift toward greener, more sustainable infrastructure development.

3. EXPERIMENTS AND METHODS

3.1 Materials

In this study, palm stem fiber was obtained from Bandung (Fig.1 (a), Original Portland Cement (OPC) type 1 (Tiga Roda), and Ground Granulated Blast Furnace Slag (GGBFS) from PT. Krakatau Semen, Indonesia. Fine aggregates were obtained from MBS Bogor Indonesia (fineness modulus of 2.88; specific gravity 2.53 and water absorption of 2.84) screening (diameter of 5-10 mm, specific gravity of 2.50 and water absorption of 1.81), coarse aggregates were obtained from Sunda Manik (diameter of 10-20 mm, specific gravity 2.60 and water absorption 1.68) and superplasticizer polyneva from PT. Neval Indonesia. Table 1 shows the chemical compositions of OPC and GGBFS using X-ray fluorescence (XRF) analysis (EPSILON 5 analyzer instrument from PANalytical). This study was conducted in several laboratories: PT Jaya Beton Indonesia, Universitas Trisakti Concrete Laboratory, and BRIN Integrated Laboratory of Bioproduct (iLaB) at the Research Center for Biomass and Bioproducts.

3.2 Experimental Design

This study used an alkali treatment to remove lignin and hemicellulose and improve the performance of palm stem fibers. The palm stem fibers were initially treated with a 5% sodium hydroxide (NaOH) solution to increase bonding with the cement matrix. The fibers were soaked in NaOH solution for 24 hours at room temperature (23°C ± 2°C) to eliminate lignin and hemicellulose, which hinder adhesion. The fibers were carefully washed with water until the pH reached neutral (pH 7). The fibers were then sun-dried for 48 hours to remove any moisture. The alkali treatment enhanced the fiber surface roughness, allowing for better bonding with the cement matrix and increasing the tensile strength from 671.66 MPa (untreated) to 1222.39 MPa (treated). In total, 42 specimens with a diameter of 10 cm and a height of 20 cm were used. Three different compositions were used for mixing concrete. Table 2 lists the properties of palm stem fibers.

The experimental design utilized the American Concrete Institute Technique to determine the optimal cement-to-concrete ratio by substituting equal amounts of cement with GGBFS and Fiber [14]. This allows for a systematic examination of how GGBFS and fibers affect the alteration of concrete characteristics.

Compared to standard concrete mixtures, two compositions were designed using treated and non-treated fibers as a reference. The proportion of the mix of concrete is presented in Table 3, with the use of 25% GGBFS as a substitute for cement, the addition of non-treated palm fiber (0.25%; 0,5%; 0.75%) as the binder volume, and the addition of treatment fiber (0.25%; 0,5%; 0.75%) as the binder volume. Binder and aggregate were mixed for 3 minutes in a "mini mixer" with a rotation speed of 60 rpm, after which water, superplasticizer, and fiber were added and stirred for 5 minutes until the dough was homogeneous. Workability testing refers to EFNARC 2002.

Following the mixing procedure, the freshly created self-compacting concrete (SCC) was poured into cylindrical molds measuring 10 cm in diameter and 20 cm in height, according to ASTM C31/C31M-19a, Standard Practice for Making and Curing Concrete Test Specimens in the Field. The concrete was cured in the molds for 24 hours at an ambient temperature of 23°C ± 2°C and relative humidity of 60-80%. Following the initial curing period, the samples were demolded and water-cured, i.e., they were immersed in a water tank at a steady temperature of 23°C ± 2°C, following ASTM C511-13 for testing hydraulic cement and concrete. The samples were submerged for 28 days to ensure proper hydration and curing of the cement mixture. The curing technique was critical for maintaining the hydration of the cement and improving its compressive and tensile strength over time. Following the curing phase, the samples were assessed for mechanical characteristics by ASTM C39/C39M-18 and ASTM C496/C496M-

17 for compressive and tensile strength at 28 days.

Table 1. OPC and GGBFS Cement Properties

Parameters	Unit	GGBFS	OPC Tiga Roda
SiO2	%	34.97	18.45
Al2O3	%	13.67	4.96
Fe2O3	%	0.88	2.86
CaO	%	44.62	63.2
MgO	%	2.04	3.52
SO3	%	0,90	2,18
LOI	%	1.72	3.42
Na2O	%	0.10	0.15
K2O	%	0.29	0.31
TiO2	%	0.67	-
Mn2O3	%	0.14	-
f-Value	%	1.70	-
Basicity(CaO/SiO_2)	%	1.28	-
(CaO+MgO)/SiO2	%	1.33	-
(CaO+MgO+SiO2)	%	81.63	-
C3S	%	-	68.72
C3A	%	-	8.3
C4AF	%	-	8.7

Table 2. Palm Stem Fiber Properties

Testing	Treatment (FT)	Non-treatment (FNT)
Water content	0.60%	0.70%
Ash content	1.54%	2.74%
Tensile strength	1222.39 MPa	671.66 MPa

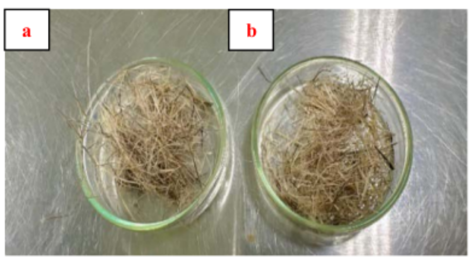

Fig. 1 a) Non-Treated Fiber (FNT) b) Treated Fiber (FT)

3.3 Methods

The compressive strength was calculated according to ASTM C470 regulations. The compressive strength of concrete was tested at the age of 28 days. The compressive strength was measured using a 2000-kN universal testing machine (UTM) tool. The tensile strength was calculated according to the ASTM C1583 standard. The tensile strength of concrete was tested at the age of 28 days. The compressive strength was measured using a 2000-kN universal testing machine (UTM) (Nusantara Lab). The load was applied by a hydraulic press controlled by an automatic system until it was damaged, and the load application speed was 1290 N/s. The fiber tensile strength was ASTM D 3379–75 with a 5 KN Universal Testing Machine (UTM) instrument. The two fiber samples used were non-treated (hereafter referred to as FNT) and treated fibers (referred to as FT). XRD was used to analyze the chemical composition of concrete. The instrument used was the Shimadzu XRD-7000 model.

The samples used in this test were reference concrete, non-treated fiber concrete, and treated concrete with the maximum compressive strength. The sample used in the X-ray diffraction (XRD) test sample should be smooth to obtain maximum results. XRD is based on Bragg's law. Using the XRD test results, a graph was obtained between the wave diffraction angle and the X-ray intensity. The XRD test was performed on the sample on day 28. A diffractometer with a Cu source had a wavelength χ = 1.54Å at a scanning speed of 2 seconds/step, and a diffraction angle between 5° and 50° was used for conduction testing.

FTIR test was conducted using an Infrared spectra photo meter instrument. The data acquisition frequency for FTIR spectrometry was 5 seconds with a range of 400 cm^{-1} - 4000 cm^{-1} with a spectral resolution of 1 cm^{-1}. SEM test was also done using the JSM– IT200 testing instrument. As also in the XRD test, the samples used in this test were regular concrete, non-treated fiber concrete, and treated fiber concrete with maximum compressive strength. SEM images were obtained by refraction of reverse electrons at 500x magnification. Workability testing was done using slump flow, a V-funnel, and a J-ring was conducted according to the EFNARC 2002 standard [15].

4. RESULTS AND DISCUSSIONS

4.1 Workability

The material testing results of the concrete binders showed specific gravity values for OPC and GGBFS cement of 3.148 and 2.69, respectively. Material testing results of concrete constituents included specific gravity, moisture content, and absorption, with results as follows. The specific gravity of fine aggregate, coarse aggregate, and screening was 2.53, 2.60, and 2.50, respectively. The fine aggregate water content, coarse aggregate, and screening results were 2.41, 0.68, and 0.91, respectively. The fine aggregate absorption, coarse aggregate, and screening results were 2.83, 1.68, and 1.81. The European Federation conducts workability testing for specialist construction chemicals and concrete systems (EFNARC) [15]. Table 3 presents the concrete mixture proportion per kg/m^3 for FNT and FT.

Table 3. The proportion of concrete mixture (kg/m^3) for FNT and FT

Material	CONTROL	BFS25 FNT0.25	BFS25 FNT0.5	BFS25 FNT0.75	BFS25 FT0.25	BFS25 FT0.5	BFS25 FT0.75
OPC Cement	552.75	414.56	414.56	414.56	414.56	414.56	414.56
GGBFS	-	138.19	138.19	138.19	138.19	138.19	138.19
Coarse aggregate	529.16	529.16	529.16	529.16	529.16	529.16	529.16
Screening	227.30	227.30	227.30	227.30	227.30	227.30	227.30
Fine Aggregate	858.68	858.68	858.68	858.68	858.68	858.68	858.68
Water	160.46	160.46	160.46	160.46	160.46	160.46	160.46
Fiber	-	0.471	0.943	1.410	0.471	0.943	1.410
SP (1%)	5.53	5.53	5.53	5.53	5.53	5.53	5.53

We established concrete variations using GGBFS (BFS) as much as 25% as a substitute for cement, along with FNT and FT by 0.25%, 0.5%, and 0.75% as added material from binder volume. Six variations were made, namely BFS25FNT0.25, using 25% GGBFS and FNT by 0.25%, BFS25FNT0.5 with 25% GGBFS and FNT by 0.5%, BFS25FNT0.75 with 25% GGBFS and 0.75% FNT (Table 3), as well as BFS25FT0.25 with 25% GGBFS and FT by 0.25%, BFS25FT0.55 with 25% GGBFS and FT by 0.5%, and BFS25FT0.75 with 25% GGBFS and fiber 0.75% of FT. In all variations, Superplasticizer (SP) was added at 1% (Table 3).

Table 4 shows the workability of concrete with NFT and FT. In the slump flow test, there was no significant difference in the slump flow spread of SCCs with different fiber contents on concrete with FNT. In concrete subjected to FT, the slump flow spread of the SCC decreased when the fiber content increased. The fiber addition affected the filling workability of the SCC by decreasing the slump flow [11]. Adding palm stem fiber can reduce the workability of specimens with and without treatment [16]. The slump-flow values of all specimens were 555–585 mm. According to EFNARC, all specimens were SF1 class.

All specimens required more than 16 seconds to fall through the V-funnel after concrete placement in the V-funnel. They were bounded within 9-25 seconds. Therefore, the fibers treated did not significantly affect the plastic viscosity of SCC. Hence, according to EFNARC, all specimens are classified as VF2 with an acceptable viscosity limit [15].

However, the addition of fiber affected the passing ability of the SCC. The characteristic of passing ability for SCC is determined by counting the acceptable flow differences (slump and J-ring flow) and the blocking step. All specimen fibers exceeded the 0-25 mm range for slump and J-ring flow difference but were less than 10 mm for the blocking step. The slump and J-ring flow differences and blocking steps between concrete with and without treatment fiber were not significantly different.

The fiber addition significantly affected the workability of concrete (Table 4). With the addition of GGBFS and fiber, workability decreased with the addition of concrete variations; this result agreed with other similar studies [3, 13]. The workability of fiber concrete was reduced due to the fibers being the absorbent material [5]. The role of GGBFS as a substitute material is as high as 25%. Workability on concrete dropped too drastically. In reference to previous research, adding 25% GGBFS as a substitute material may increase the workability [10].

Table 4. Workability of Self-Compacting Concrete

Concrete variations	Slump Flow (cm)	V – Funnel (Seconds)	J- ring	
			SFJ (cm)	BJ (mm)
CONTROL	59.00	16.00	57.50	8.70
BFS25FNT0.25	56.70	16.50	57.00	9.25
BFS25FNT0.5	56.50	17.00	56.75	9.25
BFS25FNT0.75	562.5	20.00	56.75	9.25
BFS25FT0.25	58.50	16.00	55.50	8.50
BFS25FT0.5	55.75	17.00	55.00	8.75
BFS25FT0.75	55.50	20.00	55.00	8.625

4.2 Mechanical Properties of Concrete

The compressive and tensile strengths of the SCC are listed in Table 5. Based on this result, the compressive strength of the control was determined to be 67.23 MPa. The maximum compressive strength of 73.76 MPa was recorded for BFS25FT0.5, containing 50% of the fiber treatment, at 28 days. Moreover, a higher compressive strength of 72.57 MPa was indicated by BFS25FNT0.25, which is a different dosage of non-treated fiber. It can be concluded that compressive strength has a significant effect on specimens with treated fibers. The palm stem fibers treated with 5% NaOH could improve its mechanical properties. However, the compressive strength was enhanced by increasing the percentage of palm-steamed fiber until it reached 50%; after that, the compressive strength declined in concrete treated with treated fiber.

Two specimens were examined to determine the splitting tensile strength with different palm stem fiber contents (25%, 50%, and 75% by binder volume). We can see in Table 6 that the fiber addition increased the splitting tensile strength. The increase was up to 17% for SCC with FNT and 26% for SCC with FT. The maximum splitting tensile strength was 6.03 MPa for concrete with FNT and 6.37 MPa for concrete with FT. Thus, adding palm stem fiber to

SCC up to 75% and using treated fiber resulted in the greatest splitting tensile strength.

Table 5. Compressive and tensile strengths

Concrete Variations	Compressive Strength (MPa)	Tensile Strength (MPa)
CONTROL	67.23	4.11
BFS25FNT0.25	72.57	5.14
BFS25FNT0.5	59.33	5.52
BFS25FNT0.75	63.07	6.03
BFS25FT0.25	69.99	5.04
BFS25FT0.5	73.76	5.19
BFS25FT0.75	63.87	6.34

Fig. 2 shows that concrete with the addition of 0.25% FNT and 0.25% FT increased compressive strength by 7.92% and 4.10%, respectively, whereas, with the addition of 0.5% and 0.75% FT, the compressive strength increased by 11.75% and 6.18%, respectively, compared to the concrete reference/control. For replenishment with fiber treatment, the 0.5% compressive strength increased by 9.71% from the reference concrete, and in the 0.75% FT, compressive strength decreased by 4.99% from the reference concrete. It can be concluded that treating fiber can increase compressive strength significantly and optimally compared to adding non-treated fiber. This agrees with previous studies that showed that adding treated fiber can improve the mechanical properties, especially in the fiber tensile strength, due to NaOH immersion [3, 15–17].

The long-term durability of concrete incorporating ground granulated blast furnace slag (GGBFS) and palm stem fibers is vital for evaluating its performance under various environmental conditions. GGBFS is known for its pozzolanic characteristics, which increase concrete durability by developing calcium silicate hydrate (C-S-H) gel over time. This gel fills the empty spots in the concrete matrix, forming a denser and more impermeable structure that effectively decreases the penetration of harmful substances such as chlorides and sulfates, which can lead to degradation [6, 9].

Incorporating palm stem fibers into the concrete mix increases the tensile strength, fracture resistance, and overall durability. Fibers can improve the concrete's resistance to cracking due to thermal expansion and contraction, particularly in situations with considerable temperature variations [5]. Under these conditions, the potential of palm stem fibers to extend across fissures might maintain concrete's structural strength, thereby reducing the possibility of moisture penetration that may result in further degradation [2].

Furthermore, combining GGBFS and palm stem fibers may enhance the resilience against cyclical moisture-induced stress. This is particularly important in regions characterized by alternating phases of humidity and dryness, during which conventional concrete may experience scaling and spalling. The moisture-absorbing characteristics of palm stem fibers may facilitate the control of moisture levels in concrete, thereby enhancing the control of freeze-thaw cycles. This treatment is essential in avoiding rupture expansion due to the enlargement of confined moisture under freezing conditions [10].

GGBFS exhibits a decreased heat of hydration compared with regular Portland cement, leading to reduced thermal stresses in mass concrete applications. This attribute is advantageous in settings with significant temperature fluctuations because it reduces the probability of thermal cracking [8]. Moreover, using palm stem fibers can decrease the weight of concrete, thereby reducing the forces generated under varying temperatures.

Integrating GGBFS and palm stem fibers into concrete increases its strength and long-term durability. This concrete mix enhances resistance to moisture, temperature variations, and cracking, allowing it to withstand various climatic conditions. Thus, it presents a viable alternative for sustainable building applications.

Fig. 3 shows that using GGBFS in combination with FT and FNT by 0.25% to 0.75% can increase the tensile strength of REF concrete (Control) by 22.62%–46.71% and 25.06% to 54.25%, respectively. It can be concluded that adding fibers and GGBFS can increase the tensile strength; this study conforms to similar studies [2, 18–21].

The optimum ratios of palm stem fiber incorporation into self-compacting concrete (SCC) were established at 0.75% for tensile strength and 0.5% for compressive strength. The selection of 0.75% markedly increases tensile strength owing to the fibers' capacity to bridge fissures efficiently and release stress, consequently improving the concrete's overall ductility. The improvement is due to better adhesion of the treated fibers to the cement matrix, facilitating more effective load transmission. Studies have shown that alkali treatment of fibers reduces the removal of lignin and hemicellulose, increasing adhesion and augmenting tensile strength[5]. Additionally, incorporating treated fibers allows phenomena such as fiber pull-out, which enhances concrete's tensile strength. [2]. A fiber content of 0.5% optimizes the compressive strength. The fibers improve the concrete's durability at this stage without causing substantial internal instabilities. Increasing the fiber content can reduce the compressive strength because excess fibers can create voids within the matrix and affect the overall density [10]. This conclusion emphasizes the importance of maintaining an appropriate fiber dosage to ensure the concrete is sufficiently strong. A series of mechanical experiments was conducted to determine the optimum balance between the tensile and compressive strengths. These experiments revealed that although increasing the fiber content improves the tensile characteristics, it can adversely affect the compressive strength if it exceeds the ideal threshold. Mekki and Hamad highlighted the need to modify the fiber dose to achieve the necessary mechanical characteristics in fiber-reinforced concrete [18].

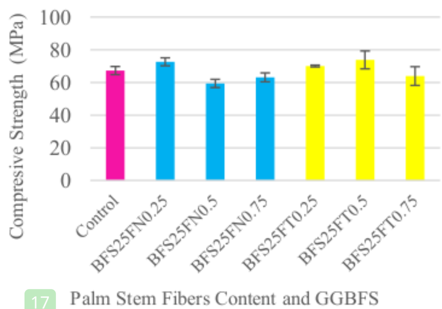

Fig.2 Compressive strength of concrete

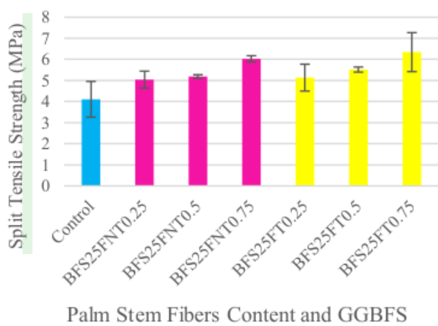

Fig.3 Tensile Strength Results

Recognizing that the most suitable percentages may require adjustment depending on specific applications is essential. In structural components subjected to increased tensile loads, such as slabs and beams, expanding the fiber content to above 0.75% enhances the reinforcing effect. In compression-dominant applications, such as columns and load-bearing walls, a fiber concentration of approximately 0.5% is recommended to maintain compressive strength [11]. Understanding the distinct loading conditions and structural requirements is crucial for determining the appropriate fiber dosage for diverse applications.

4.3 Scanning Electron Microscope (SEM)

SEM analysis was used to examine the transition zone between fiber and aggregate (ITZ) pastes. In Fig. 5, for non-treatment fiber concrete (BFS25FNT0.25), visible fibers fail to bind with cement paste. This is because fibers without treatment still have lignin content. Cellulose. Hemiselilose provides a smoother surface, making it more difficult for fibers to bond with the paste. Fig. 6 shows visible fibers bind with cement paste during fiber concrete treatment (BFS25FT0.25). This is because fibers treated with may reduce lignin content. Cellulose and Hemicellulose give the fiber a rough surface, making it more accessible for bonding with cement paste. This research is in line with the one conducted by Ahmad and his colleagues in 2022 [22]. There was a good bond between fiber and cement paste, so there were no gaps, and the mechanical properties increased.

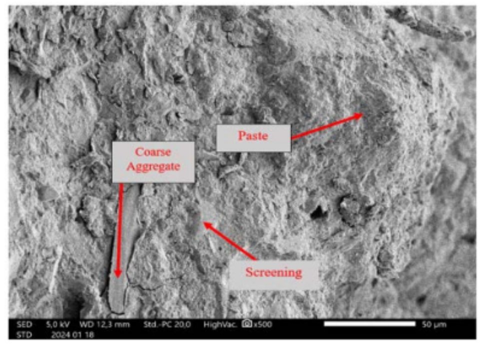

Fig. 4 SEM micrographs of concrete (CONTROL)

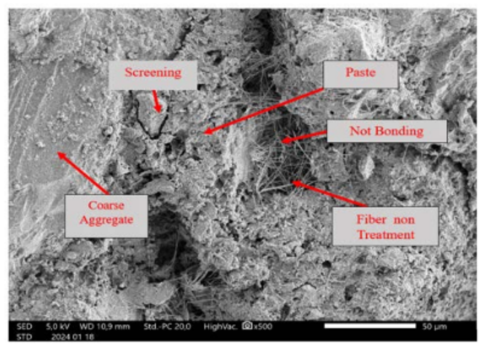

Fig. 5 SEM images of the non-treated fiber concrete (BFS25FNT0.25)

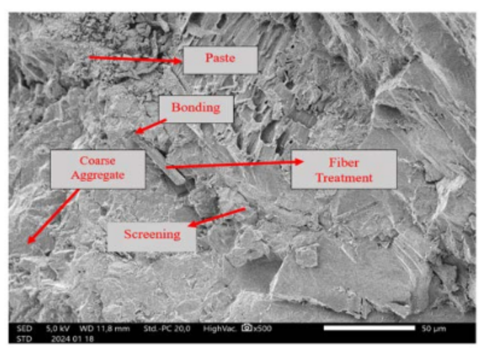

Fig. 6 SEM images of the concrete fiber treatment (BFS25FT0.25)

4.4 Fourier- Transform Infrared Spectroscopy (FTIR)

In Fig. 7, palm fiber without treatment has a functional group—OH visible at wave 3296.80 cm^{-1}. Stretch C–H is seen at wavenumber 2920.20 cm^{-1}. The wavenumber range of the OH groups was 3100–3600. Meanwhile, the C–H wavenumber ranges from 2850 to 2970 cm^{-1} and 2350 to 2480 cm^{-1} [23].

The effect of alkali treatment on fiber functional groups was analyzed using FTIR. Fig. 7 shows the FTIR spectra of FNT and palm fibers. The spectra show that FNT and FT presented the major transmittance peak at 3311 cm^{-1}, related to the cellulose structure's hydroxyl (O-H) stretching vibration. [24, 25]. The band around 2922 cm^{-1} is assigned to C-H stretching, corresponding to the cellulose, hemicellulose, and methylene groups (Johannes Leonard, Harry Abrido, 2013). The band at 1732 cm^{-1} is associated with C=O groups in hemicellulose and lignin [26]. The bands at 1421 and 1242 cm^{-1} presented symmetric bending of CH2 and CO stretching, which corresponds to vibrations of the acetyl groups present in lignin and hemicellulose [27]. The peak of 1009 cm^{-1} was attributed to the bending vibration of C-H and C-O of aromatic rings of polysaccharides. Meanwhile, the peak at 1642 cm^{-1} corresponds to C=O stretching with different transmittance intensities. In alkali-treated fibers, these bands decreased in intensity, confirming the elimination of pectin and hemicellulose [28].

In Fig. 8, palm fiber after treatment has a functional group–OH being 3333.91 cm^{-1}. Furthermore, C–H at wavenumber 2919.83 cm^{-1}. We can see from Figs. 7 to 8, there was a shift in functional groups after palm fiber treatment. Cluster–OH at wavenumber 3296.80 cm^{-1} changed to a new -OH cluster at wavenumber 333.91 cm^{-1}. Moreover, the C–H cluster initially detected at wavenumber 2920.20 cm^{-1} changed to a new cluster at 2919.83 cm^{-1}. Regarding influence, Fiber Treatment serves to remove lignin, as well as Hemicellulose and other impurities [24].

FTIR spectroscopy was used to assess the bands of molecular groups contained in concrete specimens with and without palm fibers after 28 days of immersion, as illustrated in Fig. 7. The Fourier spectrum of transform infrared spectroscopy is divided into three segments. These segments are observed in the range 1485–1270, 1175–980, and 875–490 cm^{-1}. This is characterized by a collection of particles (CO32–) (O-Si-O). Furthermore, C–S-H is simplified from a set of molecules in concrete samples, either with or without palm fibers [13]. The results of FTIR spectroscopy showed that the same compound was obtained in concrete REF (reference), FNT, and FT, regardless of the presence or absence of fiber in the concrete mixture.

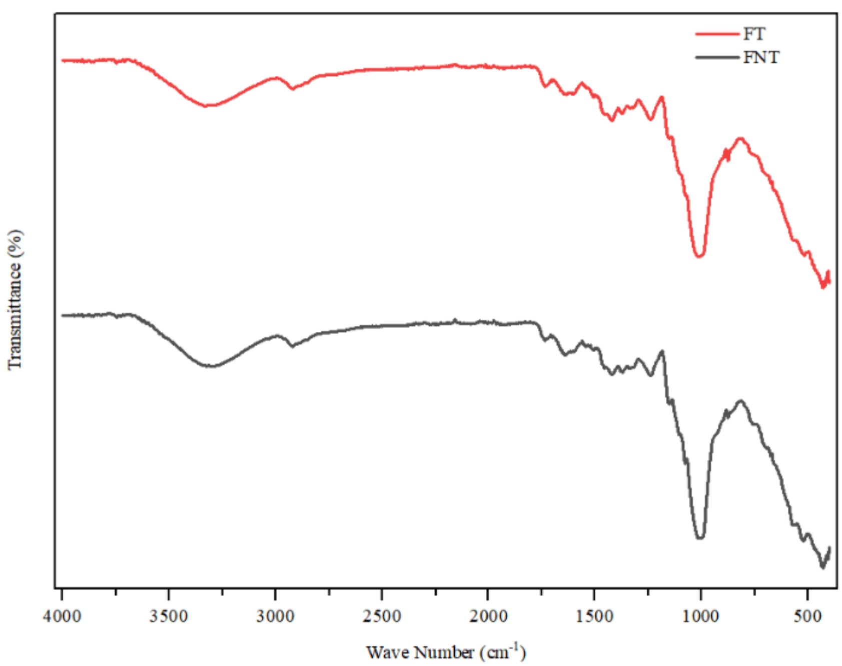

Fig.7 Relationship between transmittance and wavenumber for treated and non-treated fibers using FTIR

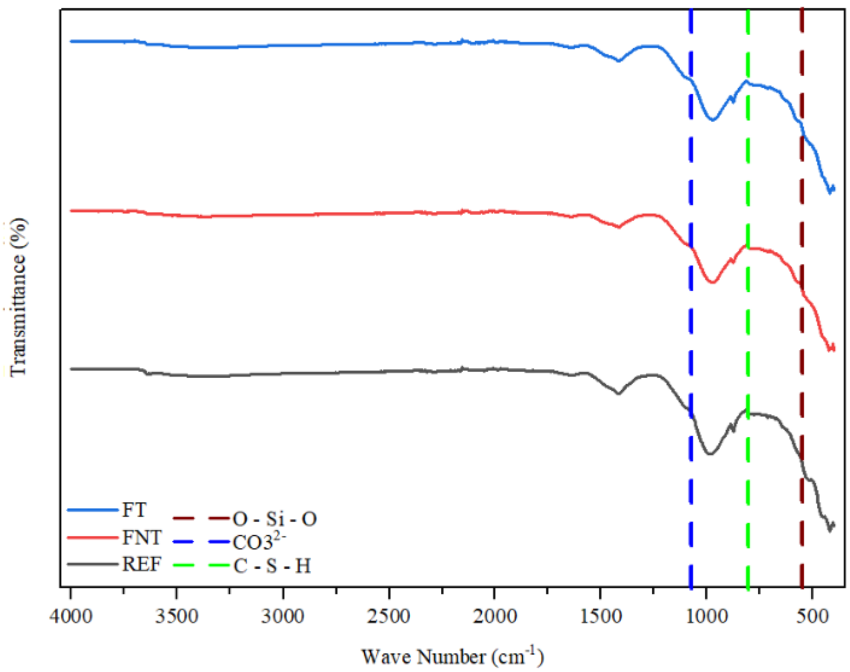

Fig. 8 Relationship of Transmittance and wavenumber for the concrete REF, non-treated fiber concrete (BFS25FNT0.25) or FNT, and treated fiber concrete (BFS25FT0.25) or FT using FTIR

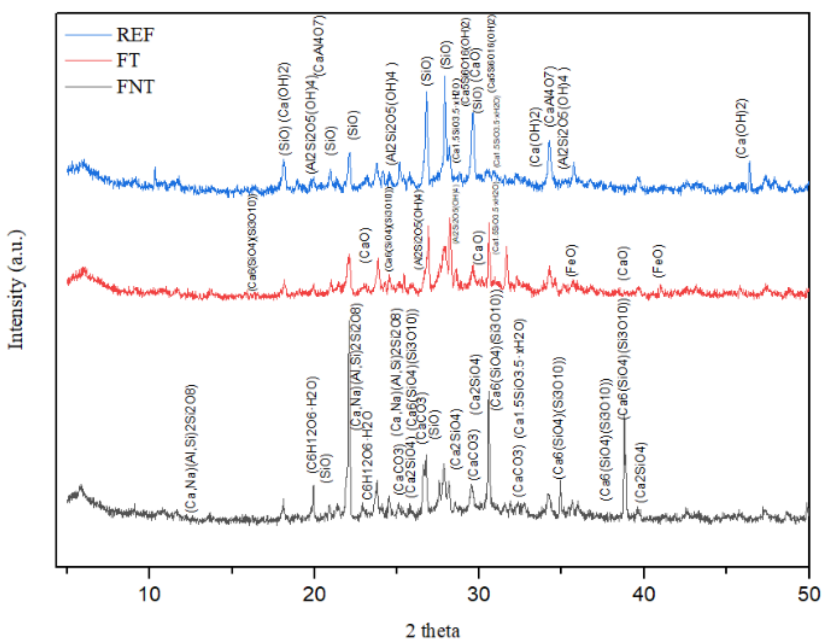

Fig. 9 XRD test results of concrete REF/control, non-treated Fiber Concrete (BFS25FNT0.25), and concrete fiber treatment (BFS25FT0.25)

4.5 X-Ray Diffraction (XRD)

The X-ray diffraction (XRD) investigation determined the predominant crystalline phases in the concrete samples. The peak at 22° showed cellulose's crystalline structure, whereas a smaller peak at 18° represents the amorphous phase containing hemicellulose and lignin. During fiber treatment, the amorphous peaks decreased, indicating a reduction in non-crystalline constituents and an enhancement in crystallinity, thereby enhancing mechanical performance. In the cement matrix, significant peaks corresponding to calcium silicate hydrate (C-S-H) and portlandite ($Ca(OH)_2$) were detected at 34.1° and 41.9°, respectively, indicating improved strength and durability. The treatment increased the bonding between the fibers and cement paste, minimizing voids in the interfacial transition zone (ITZ), as verified by scanning electron microscopy (SEM) studies.

Fig. 9 shows the dominant chemical element in REF concrete. Non-treated fiber concrete and treated fiber concrete both contain SiO. CaO. $CaCO_3$. H_20 and FeO at different theta angles. This study detected a minor peak at 18° minor peaks. Furthermore, a peak of 22° was found. According to Olonade and his colleagues [7], a minor peak is observed at 18°, which indicates an amorphous phase (cellulose). Meanwhile, a significant peak appears at an angle of 22, which is thought to indicate crystalline material; the intensity of the crystalline phase increases when using fiber treatment. Unlike untreated fiber, fiber treatment reduces the amorphous phase and increases crystalline material due to reduced cellulose and lignin after the NaOH treatment.

5. CONCLUSION

The results of this study lead to a few conclusions:

1. This study indicates that replacing 25% of cement with GGBFS and including palm stem fibers could significantly enhance the mechanical properties of self-compacting concrete (SCC). The ideal mixture of 25% GGBFS and 0.5% fibers (FT) achieved a maximum compressive strength of 73.76 MPa, representing a 9.7% enhancement over control concrete. Incorporating 0.75% treated fibers (FT) yields a maximum tensile strength of 6.34 MPa.
2. The SEM study verifies that treated fibers enhance the bond between fibers and cement paste, improving mechanical performance, whereas untreated fibers exhibit worse adhesion due to residual lignin. FTIR and XRD investigations indicate comparable chemical compositions for treated and untreated concrete, with NaOH treatment reducing lignin content and enhancing cellulose crystallinity, improving fiber-matrix interaction.
3. Incorporating treated palm stem fibers and GGBFS increased both the tensile and compressive strengths of SCC, offering an eco-friendly and effective alternative to high-performance concrete.

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