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Research Article

Effect of Fiber Treatments on the Mechanical Properties of Sisal Fiber-Reinforced Concrete Composites

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The mechanical behavior of fiber-cement composites is significantly influenced by the interfacial bonding between the fiber and the cement matrix. However, natural fibers are less chemically compatible with the cement matrix. As a result, it is essential to modify the surface of natural fibers to achieve good fiber-matrix interfacial bonds. In the current study, sisal fibers intended for use as a reinforcement in concrete matrices were alkali treated with NaOH solutions (2%, 5%, and 10%) for 12 hrs, 24 hrs, and 48 hrs. Water absorption, tensile strength, and surface morphological changes in fibers were studied. The effect of fiber treatment on the concrete was also assessed by measuring its slump, compressive strength, flexural strength, and toughness. Alkali treatment was discovered to reduce the water absorption capacity of sisal fiber. On the contrary, fiber surface morphology and mechanical properties improved up to a point and then gradually declined. The addition of treated sisal fiber considerably increases concrete's flexural strength and toughness. However, an insignificant change in compressive strength was observed.

1. Introduction

The construction industry is booming around the globe. Unfortunately, this industry accounts for a significant share of climate change caused by carbon dioxide emissions worldwide. According to reference [1], the construction industry accounts for roughly 30% of global carbon dioxide emissions. Using renewable resources and green materials is one of many ways to reduce the carbon footprint of the construction sector to achieve more sustainable and eco-friendly development [2]. Among them, natural fibers obtained from renewable vegetables, such as sisal, jute, cotton, flax, and so on, seem to be a good alternative, considering their environmental friendliness [3]. As a result, using natural fibers as reinforcing materials in cement-based composites have taken a significant step toward more sustainable construction [4]. Using such fibers in concrete and cement products is thus appealing to developing countries, where natural fibers of various types are abundant.

Out of various vegetable natural fibers, sisal fiber, extracted from the Agave Sisalana plant in the form of long fiber bundles, is one of the most commonly cultivated natural fibers in tropical and subtropical regions such as Brazil, Tanzania, Kenya, and Ethiopia [5]. World sisal fiber production is estimated to be around 250,000 tons per year. According to FAO [5], Ethiopia accounts for nearly 0.3 percent of the global sisal production. Due to its low cost, low density, high strength, and widespread availability in many countries, sisal fiber ranks highly among the natural fibers available for use as a reinforcement in the construction industry [6].

Plant-based fibers are not ideal chemical bond partners for composite formation with a cement matrix. The high water absorption capacity of natural fibers causes volume expansion when fibers are added to the fresh cementitious matrix and results in contraction when the matrix dries, resulting in a partial loss of physical contact with the matrix and a formation of a very porous region [7]. For this reason,

surface treatments were generally applied to natural fibers to improve fiber-matrix interfacial adhesion in composite manufacturing [8].

The type of treatment is important as some treatments are more effective than others. Alkaline treatment is one of the most widely used chemical treatment methods for natural fibers. As mentioned by the authors of reference [9], two effects on the fiber surface resulting from the alkaline treatment are as follows: (1) a rough fiber surface resulted, which might also improve the adherence of the fiber with the matrix and (2) remove some hemicelluloses, waxes, and impurities from the fiber surface. Thus, the surface of the fibers becomes chemically more homogeneous, and the amount of cellulose exposed on the fiber surface is enhanced, generating better compatibility between the fiber and the matrix. Both the chemical concentration and the duration of the chemical treatment have an impact on the enhancement of fiber mechanical properties [10].

Jo et al. [11] studied the effect of alkali (NaOH) treatment on the mechanical properties of jute fiber-reinforced cement composite and fiber-matrix interface interaction. Their findings show that the alkali treatment of jute fibers increases tensile strength and percent elongation, which contributes to an increase in the mechanical strength of cement composites. Furthermore, the fibrillation of the fibers caused by the alkali treatment increases the effective surface area for bonding at the interface between the fiber and the matrix. Andiç–Çakir et al. [8] also reported that, after the NaOH treatment, due to the removal of some hemicelluloses, waxes, and impurities from the coir fiber surface, a rough fiber surface resulted, which might also improve the adherence of the fiber with the cement matrix. The upgrading contact between the fibers and the matrix results in the enhancement of the mechanical properties, especially the flexural strength of the composites.

As pointed out by Zhou et al. [12] the pretreatment of hemp fiber using Ca $(OH)_2$ solution altered the bond strength of concrete composite considerably. They observed that the 28-day tensile and compressive strength of treated hemp fiber reinforced concrete (THFRC) were 16.9 and 10% higher, respectively, than untreated hemp fiber reinforced concrete (UHFRC) and that the fracture toughness of THFRC at 28 days was 7–13% higher than UHFRC. The authors attributed this improvement to treated hemp fiber's higher interfacial adhesion strength.

The high moisture absorption capacity and durability issue of vegetable fibers in the alkaline environment of the cement matrix is the primary concern in encouraging the widespread use of natural fibers in cementitious composites [13]. Ardanuy et al. [14] suggested that this durability problem of natural fibers in the cement matrix is associated with an increase in fiber fracture and a decrease in fiber pull-out due to a combination of weakening of the fibers by alkali attack and fiber mineralization provoked by migration of hydration products (mainly Ca $(OH)_2$) to the fiber structure. The volume variation in the fibers due to their high-water absorption is another reason for to decrease in the durability of natural fiber in a cement-based composite [15].

Several approaches have been investigated to ensure the durability of natural fiber-reinforced cement-based composites. Among them, De Klerk et al. [10] investigated the effects of sisal fiber treatments such as NaOH, acetylation and combined alkali and acetylation on composite degradation. They discovered that the most effective treatment condition was a combination of alkali treatment and acetylation, followed by alkali treatment at low concentrations of sodium hydroxide, thereby improving the durability of sisal fibers in concrete. A significant decrease in strength was observed at higher sodium hydroxide concentrations. Moreover, Wei and Meyer [16] also evaluate the effects of thermal and Na_2CO_3 treatment on the degradation resistance of sisal fiber and the durability of sisal fiber-reinforced concrete. They found that both thermal and Na_2CO_3 surface treatments were shown to have the potential to improve the durability of sisal fiber in concrete.

Given the international trend toward green engineering and the development of sustainable building materials, the use of sisal fiber in cement-based composites was investigated to develop a sustainable building material. Even though there have been some recent studies [8, 11, 12] that attempt to address the effect of different natural fiber treatments on the durability and some other mechanical properties such as compressive strength and tensile strength of cement paste and mortar, the present study tries to investigate the impact of fiber treatment, exclusively NaOH treatment, in terms of the concentration of alkali solution and exposure periods of the chemical treatment, on the reinforcing sisal fiber properties and the corresponding concrete composite's compressive strength, flexural strength, and energy absorption characteristics (since the main contribution of fiber is shown in the postcracking stage of cement-based composites), thereby providing a theoretical foundation to be able to develop a sustainable and eco-friendly building unit.

2. Experimental Program

2.1. Materials. Sisal fiber obtained from the local Agave Sisalana plant was used as a reinforcing natural fiber for this research. The fibers are characterized as summarized in Table 1. Concerning aggregate, locally available river sand, and crushed gravel that satisfies the grading limits and other properties of ASTM C33 [17] were used.

To reduce hardening retardation caused by the glucose found in most natural fibers, the cement used for manufacturing the specimens was ordinary portland cement type I, manufactured by Dangote Cement PLC. OPC is identified as portland cement CEM I 42.5 R that conforms to the 42.5 R strength class of EN 197-1:2000 [18]. Commercially available sodium hydroxide, containing 99% concentration, was used as a surface modifier of the sisal fibers.

2.2. Fiber Preparation and Treatment. Before stepping into fiber treatment, the extracted sisal fiber was washed with pure water to remove any impurities from the extraction

Table 1: Properties of sisal fiber.

Fiber properties	Result
Fiber length	30 mm
Fiber diameter	0.15–0.18 mm
Aspect ratio	166–200
Tensile strength	517.2–602.7 MPa
Modulus of elasticity	9.2–13.1 GPa
Elongation (%)	2–2.4%
Color	Creamy white
Shape	Straight
Water absorption	93.05%

process, such as mucilage, and it was thoroughly dried in the open air. The sisal fiber bundle was then manually straightened and combed with a comb to remove any entanglement. Finally, because the isolated sisal fibers were too long to be used in the composite fabrication, they were cut to the required length of 30 mm with a pair of scissors.

The fiber treatment was made in 2, 5, and 10% (w/w; i.e., the mass percentage of solute in solution) sodium hydroxide (NaOH) solutions for 12, 24, and 48 hours, in which the fiber-to-solution weight ratio was 1 : 25. The alkaline treatment involved dissolving NaOH pellets according to the designated concentration. For instance, to make 1 kg of 2% NaOH concentrated solution, dissolve 20 g of NaOH pellet in 980 g of distilled water at a liquor ratio of 25 : 1. As reported by [10, 19], the treated sisal fibers were subsequently washed several times with distilled water containing acetic acid (1% w/w) to neutralize the excess NaOH from the sisal fiber surface (neutral pH measured for the fiber washing water), and then, the sample was thoroughly rinsed with distilled water. The pH of the rinse water was checked periodically using a pH meter. The rinsed sisal fibers were then spread out in the open air and left to dry for 2-3 days until constant weight measurements were attained. Treatment conditions are identified using the codes presented in Table 2.

2.3. Mix Design and Specimen Production. In this research, each mixture consisting of 389.5 kg/m^3 cement, 743.06 kg/m^3 sand, 1050.1 kg/m^3 coarse aggregate, and a water-cement ratio of 0.494 was proportioned for the specified compressive strength class of C-25 (i.e., a target strength of 33.3 MPa) following ACI mix design methods [20].

The mix design for sisal fiber reinforced concrete (SFRC) was the same as that of control plain concrete, except those fibers were added. The mix designation of the concrete specimens is presented in Table 3. For clarity, an explicit nomenclature system for the samples is used in this study. For example, CM-N indicates concrete reinforced with sisal fiber treated with M% sodium hydroxide (NaOH) solution and soaked for N hours.

Six concrete cubes of size 150 mm were molded from each mix to determine the 7th-and 28th-day compressive strengths, and three prisms of size 100 mm × 100 mm × 500 mm are cast to determine flexural strength and flexural toughness, as shown in Figure 1. The concrete specimens were set in the relevant molds for 24 hours under ambient conditions. After being removed from the molds, the casted cube and prism specimens were kept in a water-curing tank until testing.

Table 2: Treatment conditions on sisal fiber.

NaOH (%)	Duration (hrs.)	Sample designation
0	0	Raw
2	12	2%–12 hr
2	24	2%–24 hr
2	48	2%–48 hr
5	12	5%–12 hr
5	24	5%–24 hr
5	48	5%–48 hr
10	12	10%–12 hr
10	24	10%–24 hr
10	48	10%–48 hr

Table 3: Experimental mixture design.

Mix designation	Sisal fiber (percent by cement weight)	NaOH (%)	Duration (hours)
Control	0	0	0
C0-0	1	0	0
C2–12	1	2	12
C2–24	1	2	24
C2–48	1	2	48
C5–12	1	5	12
C5–24	1	5	24
C5–48	1	5	48
C10–12	1	10	12
C10–24	1	10	24
C10–48	1	10	48

2.4. Test Methods

2.4.1. Test Methods for Fiber

(1) Water Absorption. A water absorption test was performed to determine how the alkali treatment affected the fiber's water absorption capability. Six samples, each bundle of raw and treated sisal fibers weighing approximately 5 g, were initially dried in an oven at 80°C for 24 hours until they reached constant mass. The dried fiber bundle was then immersed in a beaker of distilled water, maintaining room temperature. After 24 hours, each bundle of fiber was removed from the water bath one by one, and all surface water was wiped off with a lint-free dry cloth. The amount of absorbed water in fiber (W_C%) was calculated using the following equation [21].

$$W_C = \frac{m_s - m_d}{m_d} * 100\%, \quad (1)$$

where W_C is water absorption in percent, m_s is the mass of surface dried fiber bundle, and m_d is the mass of oven dried fiber bundle.

(2) Scanning Electron Microscopy (SEM). The fiber's microstructure was investigated using SEM (JCM-6000Plus Benchtop SEM (JEOL), Japan) to characterize the sisal

(a) (b)

Figure 1: Test samples. (a) Cube specimens and (b) beam specimens.

fiber surface morphological change and fiber condition as a function of the applied alkali treatment. The microscope was operated under an accelerating voltage ranging from 10 kV to 15 kV and a working distance of 19 mm for different magnifications. The samples of sisal were coated with a thin layer of silver before observation to eliminate the effects of charging during image collection. The obtained images were postprocessed using Image*J*, a Java-based image processing program. The components that are used for surface roughness analysis consideration (based on profile parameters from ISO 4287 [22]) are $\mathbf{R_p}$ (highest peak), $\mathbf{R_v}$ (lowest valley), R_t (the total height of the profile), and R_a (average roughness). A visualization of the roughness parameter values can be seen in Figure 2 [23].

(3) Mechanical Properties. The effect of chemical treatment on the mechanical properties of sisal fibers in terms of tensile strength, tensile modulus, and % elongation was determined using a 1 kN capacity texture analyzer (LLOYDЖ, TA plus Ametek, UK 2007). The tensile strength of the treated and untreated sisal fibers was measured following the standard test method for a single fiber tensile test ASTM D 3822-07 [24]. A gauge length of 100 mm was employed with a fixed loading rate of 15 N/min. The mechanical properties of a total of 5 single strand samples of sisal fiber from each alkali treatment condition were measured in this investigation, and the average results were recorded.

The tensile strength of the treated and untreated sisal fibers was measured based on equations (2) as per ASTM D 3822-07 [24].

$$\sigma_u = \frac{P}{5A}, \tag{2}$$

where P is the failure load in N and A is the average cross-sectional area of a single fiber determined by scanning the electron microscopy (SEM) in mm^2.

2.4.2. Test Methods for Sisal Fiber-Reinforced Concrete (SFRC)

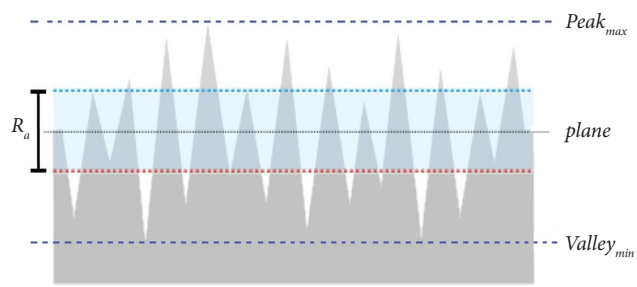

Figure 2: Surface roughness profile.

(1) Workability. A slump test was conducted following ASTM C143 [25] to evaluate the workability (which indicates its fresh properties) of concrete and to infer variation in the workability with the addition of raw and treated sisal fibers in concrete. For a water cement ration of 0.494, the target mix was assumed to have a slump of 25 to 75 mm.

(2) Compressive Strength. The compression behavior of each casted cube was evaluated following the British Standard Specification [26] using a compression testing machine equipped with a capacity of 3000 kN and a loading rate of 0.28 MPa/s (in compliance with a standard loading rate of 0.2–0.4 MPa/s). The experimental setup is shown in Figure 3. The compression stress is calculated using the following equation.

$$\sigma_c = \frac{P}{A}, \tag{3}$$

where σ_c is the compression stress, in MPa, P is the maximum applied force indicated by the testing machine, in N, and A is the cross-sectional area of specimen, in mm^2.

(3) Flexural Performance Parameters. This test method evaluates the effect of fiber treatment conditions on the flexural performance of sisal fiber reinforced concrete (SFRC) using parameters derived from the load-deflection curve obtained by testing a simply supported beam under a third-point loading testing setup, as shown in Figure 4. The

Figure 3: Compressive strength testing setup.

beams were tested using a universal testing machine with an external data acquisition system connected to two transducer sensors (to measure the midspan deflection of the prism without a support settlement).

The flexural modulus, toughness index, residual strength factor, flexural toughness, and equivalent flexural strength ratio from the recorded load-deflection curve, as defined in Figure 5, were determined using ASTM C1018 [27] and ASTM C1609 [28] standards, as follows:

(i) The flexural strength is calculated using the first maximum load (the load value at the first point on the load-deflection curve where the slope is zero) and can be obtained using the following equation.

$$f = \frac{P_1 L}{bd^2}, \tag{4}$$

where b and d are the average width and depth of specimen at the section of failure, respectively.

(ii) According to reference [27], the flexural toughness of fiber reinforced concrete (FRC) is characterized by energy dimensionless toughness indices (I_5, I_{10}, and I_{20}). These indices are determined by dividing the area underneath the load-deflection curve upto a limiting deflection of 3, 5.5, and 10.5 times the first-crack deflection (δ), by the first-crack toughness (area OAL in Figure 5), respectively, as shown in Figure 5. In this study, only I_5 and I_{10} were investigated.

(iii) The residual strength factor ($R_{5,10}$) is intended to represent the average postcracking load that the specimen may carry over a specific deflection interval, and it is derived from the toughness indices as follows:

$$R_{5,10} = 20\left(I_{10} - I_5\right). \tag{5}$$

(iv) ASTM C1609 specifies a single toughness value (T^D_{150}). Toughness is defined as the absolute area beneath the load-deflection curve upto the deflection of certain values (δ = L/150) for a given load-deflection curve, as shown in the area OABCDEFG of Figure 5.

(v) In addition to the energy-based toughness measure T^D_{150}, the ASTM C1609 standard recommends the use of an equivalent flexural strength ratio ($R^D_{T,150}$), which is a parameter that relates the first peak flexural strength (modulus of rupture) to the toughness of the composite [29]. The equivalent flexural strength ratio is computed using the following equation.

$$\left(R^D_{T,150}\right) = \frac{150 * T^D_{150}}{f_1 * b * d^2} * 100\%. \tag{6}$$

3. Results and Discussion

3.1. Fiber Properties

3.1.1. Water Absorption. Table 4 shows that in its natural state, sisal fiber can absorb water approximately 93.05% of its weight. Meanwhile, all the applied treatments to sisal fiber resulted in a decrease in the water absorption capacity of the fiber, of which 10%–48 hr treatment had the lowest percentage. The absorption of alkali-treated sisal fiber was between 53.3% and 86%, depending on the concentration and time of the treatment. The alkali concentration and treatment time were inversely proportional to the water absorption of the treated fiber, which agrees with the previous report [30]. The phenomenon behind this

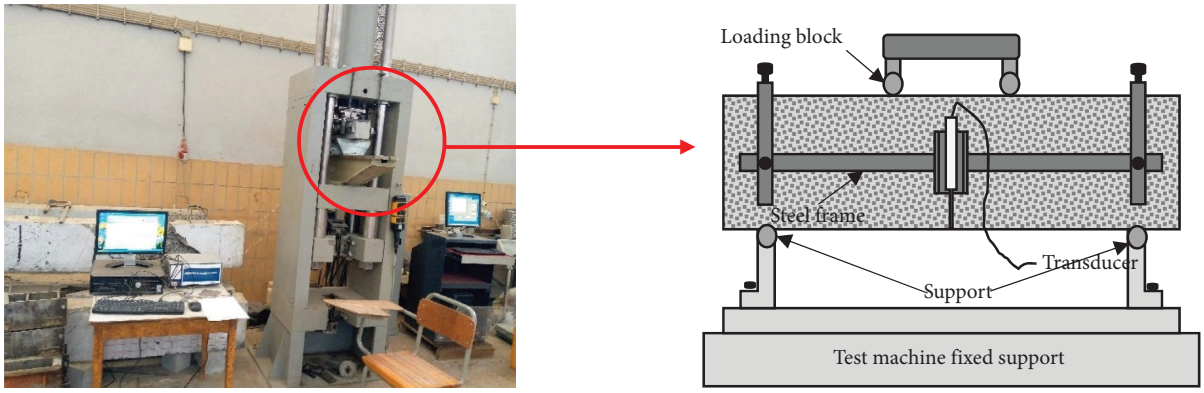

Figure 4: Flexural strength testing setup.

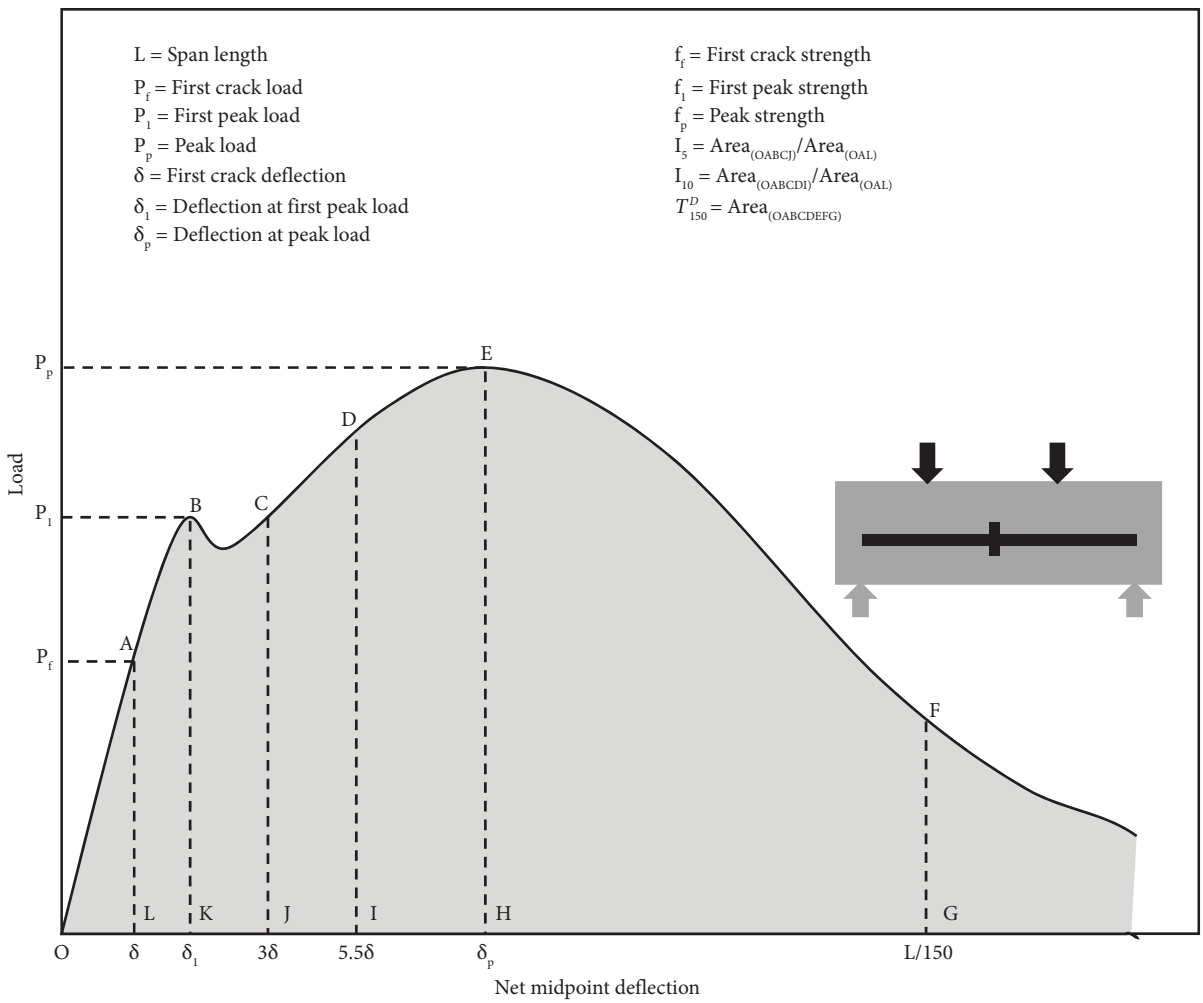

Figure 5: Schematic of load vs. deflection curve and definition of toughness parameters according to ASTM C1018 and ASTM C1609.

reduction in the water absorption capacity for the alkali-treated sisal fibers can be explained as follows: according to Ferreira et al. [31], this reduction is correlated with the change in the surface morphology of the fibers due to the removal of hydrophilic chemical compounds, such as hemicelluloses and lignin, by surface alkali treatment, which consequently reduces the capacity of water absorption of the fibers. Furthermore, the changes in the flexible bonds between cellulose and hemicellulose by stiffer cellulose-cellulose bonds make the fibers more hydrophobic, which promotes a reduction in the fiber water intake capacity [32].

Table 4: Water absorption of sisal fibers.

Fiber treatment conditions	Water absorption (%)
Raw	93.05
2%–12 hr	86
2%–24 hr	79.4
2%–48 hr	73.6
5%–12 hr	76.8
5%–24 hr	71.4
5%–48 hr	67.5
10%–12 hr	69.7
10%–24 hr	60.2
10%–48 hr	53.3

3.1.2. Scanning Electron Microscopy. Using the SurfCharJ 1q, an Image*J* plugin, the surface morphological characteristics of sisal fiber were analyzed in terms of different roughness parameters (R_a, R_v, R_p, and R_t). As shown in Table 5, the R_a (average roughness) values show an increment with fiber alkali treatment. In addition, average roughness shows improvement with increases in alkali concentration and fiber exposure time in the solution. Similar to R_a, the value of R_v (the lowest point) increases with increasing concentration and exposure. This observation had good agreement with recent research work reported by Zin et al. [33], which found that as alkali concentration further increased, damage on the fiber surface became more severe due to the corrosive effect of the alkaline solution, which led to excessive delignification that caused fiber deterioration. Observing R_p (the highest peak point) and R_t (the absolute distance between the highest and the lowest peak), improvement shows upto 5%–24 hr, and beyond this treatment condition, a gradual decrease in those properties was observed. Sample SEM images of raw and treated sisal fibers are shown in Figure 6.

3.1.3. Mechanical Properties of Fibers. The results of tensile strength, modulus, and % elongation of untreated and alkali-treated sisal fibers for different treatment conditions are presented in Table 6, which shows a gradual increase in mechanical properties with an increase in the concentration of NaOH upto 2% and then deterioration in properties. Compared to untreated sisal fibers, the highest improvements in tensile strength, modulus, and % elongation recorded were about 9, 58, and 109%, respectively, corresponding to 2%–48 hr. A similar pattern is also observed by Akram Khan et al. [34], where there is an increase in the tensile strength of fiber upto 2%, and beyond that, it shows a reducing trend. As the NaOH concentration went higher than 2%, the tensile properties of sisal fiber started to show a decreasing pattern. These could have been attributed to the substantial delignification and degradation of crystalline cellulose chains of the sisal fibers in high NaOH concentrations and longer-duration alkali treatments, resulting in weak or damaged sisal fibers [35]. Similar effects were seen on modulus and elongation following treatment. Unlike the results for the tensile strength, young's modulus, and % elongation, these decrease slightly with an increase in the concentration of NaOH and soaking time.

3.2. SFRC Properties

3.2.1. Workability. The measured slump of the fresh concrete mixes is presented in Table 7. The addition of sisal fibers to the concrete matrix resulted in a general decrease in workability. This is due to the absorption of a significant portion of the water required for cement hydration by the hydrophilic natural fibers from the concrete mixture [36]. This trend is consistent with the information found in the literature [37], and it is explained by the fact that the excess absorption of mixing water by the reinforcing sisal fiber makes it difficult for the concrete to be workable. Although the treated SFRC mix has lower workability than the unreinforced concrete mix, the improvement is observed compared to the raw SFRC mix. Of all the reinforced concrete mixes, the increased slump of 45 mm is achieved for mix C10–48. The percentage increase of C10–48 is about 80% compared to the raw SFRC (C0-0). Furthermore, it was noticed that the workability of the concrete increased when increasing the alkali concentration and fiber immersion periods. This improvement in the workability of concrete may be ascribed to the less hydrophilic nature of the treated sisal fibers that change the mixture's workability due to less absorption of mixing water. Therefore, the higher the NaOH concentration and soaking time, the harder it is for the fiber to absorb the mixing water, and thereby, the higher the slump of the mix. Nonetheless, the measured slump values for all the concrete mixtures considered in this study were within the design slump limit (25–75 mm).

3.2.2. Compressive Strength. On the 7th day, the compressive strength of the raw SFRC specimen is increased by 17.73% compared to that of the reference conventional control specimen (its 7-day compressive strength is 24.31 MPa). An alkali-treated SFRC composite displays an average increment of about 4.33%. However, compared to the untreated SFRC composite, the alkali-treated SFRC composites show an 11.38% average decrease. With increased curing time, the compressive strength of treated sisal fiber-reinforced concrete composites starts to decline with an increase in the concentration and duration of treatment, as shown in Figures 7 and 8. This increment in concentration and treatment duration could create voids and pores in the fiber structure that generates more interface zones between the sisal and the concrete constituent's interfaces [38]. Consequently, the number of permeable and microcrack regions in the concrete composites increased, which brought about insufficient compaction, and as a result, the compressive strength deteriorated, which agrees with some previous findings [39].

In the present work, it is found that the optimum treatment condition of fiber that is treated with a 5% concentrated alkali solution for 24 hours increased the compressive strength of the concrete composite by approximately 0.46% and 13.12% after 28 days compared to the raw sisal fiber reinforced concrete and conventional unreinforced concrete (its 28-day compressive strength is 37.37 MPa), respectively. This is possibly owing to the manifestation of good fiber-cement compatibility [11].

Table 5: Roughness parameters of sisal fiber at different treatment conditions.

Fiber treatment conditions	R_a (μm)	R_v (μm)	R_p (μm)	R_t (μm)
Raw	19.4	−78.6	42.6	121.3
2%–12 hr	25.6	−83.9	45.8	129.7
2%–24 hr	25.7	−93.3	51.2	144.5
2%–48 hr	26.5	−94.0	55.4	149.4
5%–12 hr	26.9	−96.7	57.0	153.7
5%–24 hr	27.0	−103.6	60.3	163.9
5%–48 hr	27.6	−103.9	57.6	161.5
10%–12 hr	27.6	−107.9	51.1	158.9
10%–24 hr	29.9	−110.4	38.7	149.0
10%–48 hr	32.4	−112.4	35.7	148.1

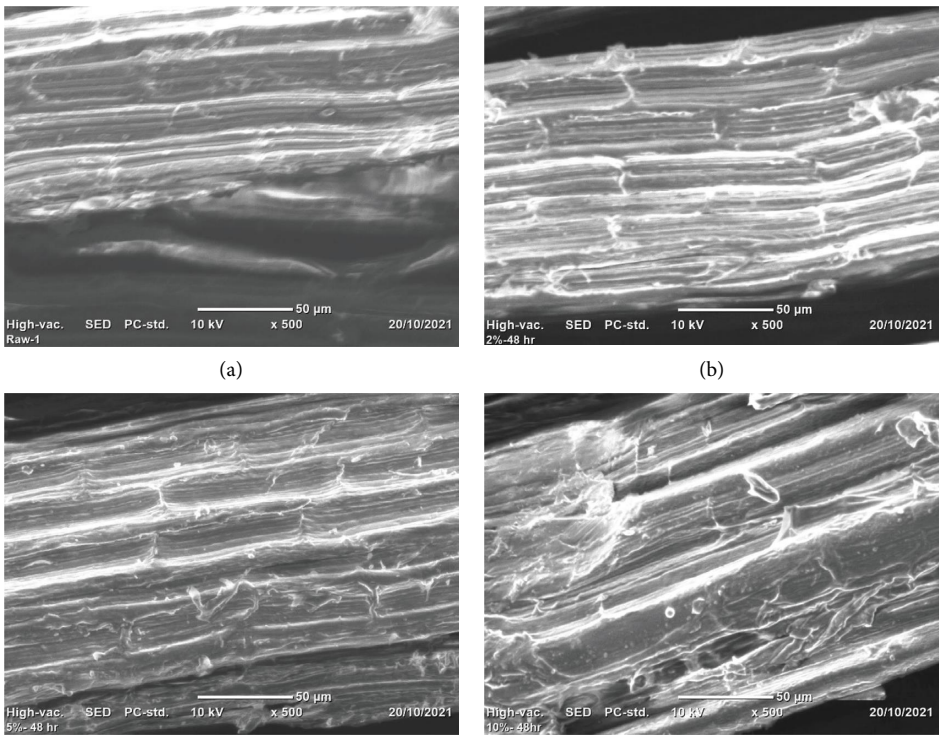

Figure 6: Sample morphology of sisal fiber: (a) raw, (b) 2%–48 hr, (c) 5%–48 hr, and (d) 10%–48 hr.

Table 6: Effect of treatment conditions on mechanical properties of sisal fiber.

Fiber treatment condition	Tensile strength (MPa)	Young's modulus (GPa)	Elongation at break (%)
Raw	556.2	10.4	2.2
2%–12 hr	560.7	12.7	2.7
2%–24 hr	587.6	14.4	4.3
2%–48 hr	607.7	16.7	4.6
5%–12 hr	591.2	15.6	4.1
5%–24 hr	580.7	13.1	3
5%–48 hr	561.8	12.4	2.7
10%–12 hr	512.4	10.6	2.4
10%–24 hr	494.2	9.7	2.1
10%–48 hr	324.1	9	2

Table 7: Slump of SFRC and plain concrete.

Mix designation	Slump (mm)	% reduction in slump
Control	65	0
C0-0	25	61.55
C2–12	30	53.85
C2–24	30	53.85
C2–48	35	46.15
C5–12	35	46.15
C5–24	35	46.15
C5–48	40	38.45
C10–12	40	38.45
C10–24	40	38.45
C10–48	45	30.75

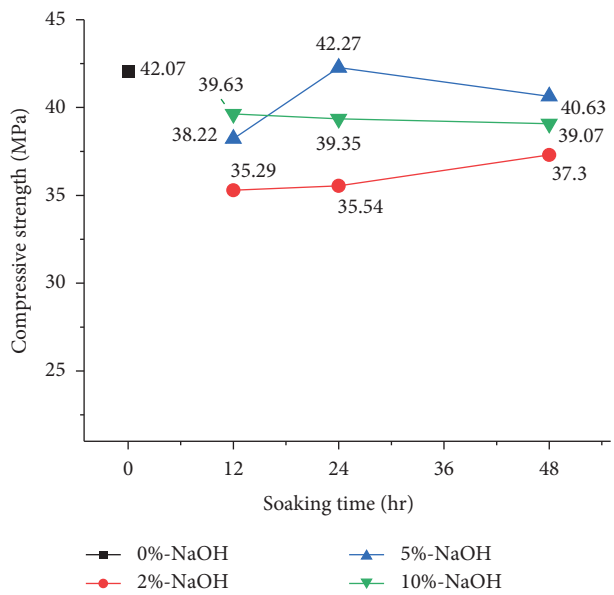

Figure 7: 7 days compressive strength.

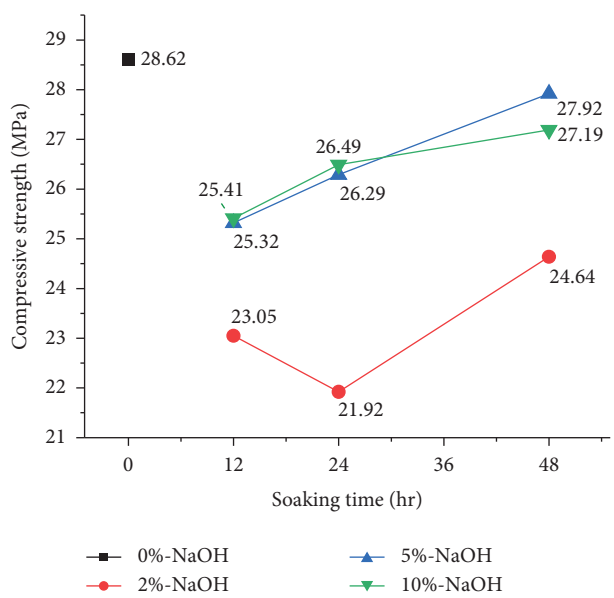

Figure 8: 28 days compressive strength.

Table 8: ANOVA test for the compressive strength of SFRC.

	Source of variation	SS	df	MS	F	P value	F crit	Remarks*
7 days	Alkali concentration	134.29	3	44.76	47.08	0	3.01	Significant
	Soaking time	15.52	2	7.76	8.16	0.002	3.4	Significant
	Interaction	10.87	6	1.81	1.91	0.121	2.51	Insignificant
	Within	22.82	24	0.95				
	Total	183.5	35					
28 days	Alkali concentration	174.03	3	58.01	51.64	0	3.01	Significant
	Soaking time	7.77	2	3.89	3.46	0.048	3.4	Significant
	Interaction	24.76	6	4.13	3.67	0.01	2.51	Significant
	Within	26.96	24	1.12				
	Total	233.52	35					

Significant at 5% probability ($p < 0.05$). df, degrees of freedom; F, F-test for ANOVA two-way; MS, mean square; SS, sum of squares; P value, calculated probability.

Table 9: Flexural strength test results.

Mix designation	Mean flexural strength (MPa)	Relative strength gain compared to raw SFRC (%)
Control	3.931	
C0-0	3.950	
C2–12	4.079	3.285
C2–24	4.160	5.336
C2–48	4.440	12.403
C5–12	4.549	15.180
C5–24	4.337	9.795
C5–48	4.259	7.843
C10–12	4.336	9.775
C10–24	4.037	2.219
C10–48	3.908	−1.064

Table 10: ANOVA test for the flexural tensile strength of SFRC.

Source of variation	SS	df	MS	F	P value	F crit	Remarks*
Alkali concentration	0.9198	3	0.3066	9.65464	0.00023	3.00879	Significant
Soaking time	0.07955	2	0.03977	1.25244	0.30383	3.40283	Insignificant
Interaction	0.55891	6	0.09315	2.9333	0.02725	2.50819	Significant
Within	0.76216	24	0.03176				
Total	2.32043	35					

Table 8 shows the ANOVA results for the compressive strength of SFRC. The analysis is conducted at a significance level of $\alpha = 0.05$. The concentration of NaOH is the most significant parameter in this table because the calculated value of the F-ratio is higher than F critical for a given confidence interval and the P value is considerably lower than $\alpha = 0.05$ for both 7th- and 28th-day compressive strength. The interaction between alkali concentration and soaking time is statistically insignificant in the case of 7-day curing age.

3.2.3. Flexural Strength. Table 9 depicts the effect of various fiber treatment conditions on the flexural strength of a concrete composite. When untreated sisal fibers are replaced with NaOH-treated sisal fibers, a significant impact on flexural properties is observed. The flexural strength behavior of the specimen reinforced with treated sisal fiber increases with increasing alkali concentration and soaking time upto 5%–12 hr and afterward decreases with increasing concentration and duration. The optimum sisal fiber treatment concentration of NaOH suggested is 5%, with flexural strength increased from 4.259 to 4.549 MPa for different treatment periods. Among various treatment durations corresponding to 5% alkali concentration, reinforcing sisal fiber that was treated for 12 hours (C5–12) yields an approximate 15.7% and 15.18% improvement in flexural strength as compared to the conventional and raw sisal fiber reinforced concrete specimen, respectively. Next to C5–12, C2–48 shows better performance and is almost 12.9% and 12.4% greater than unreinforced concrete and raw SFRC, respectively.

Except for the concrete reinforced with sisal fiber treated with 10% NaOH solution for 48 hours, the modules of rupture of other treated SFRC were higher than those of

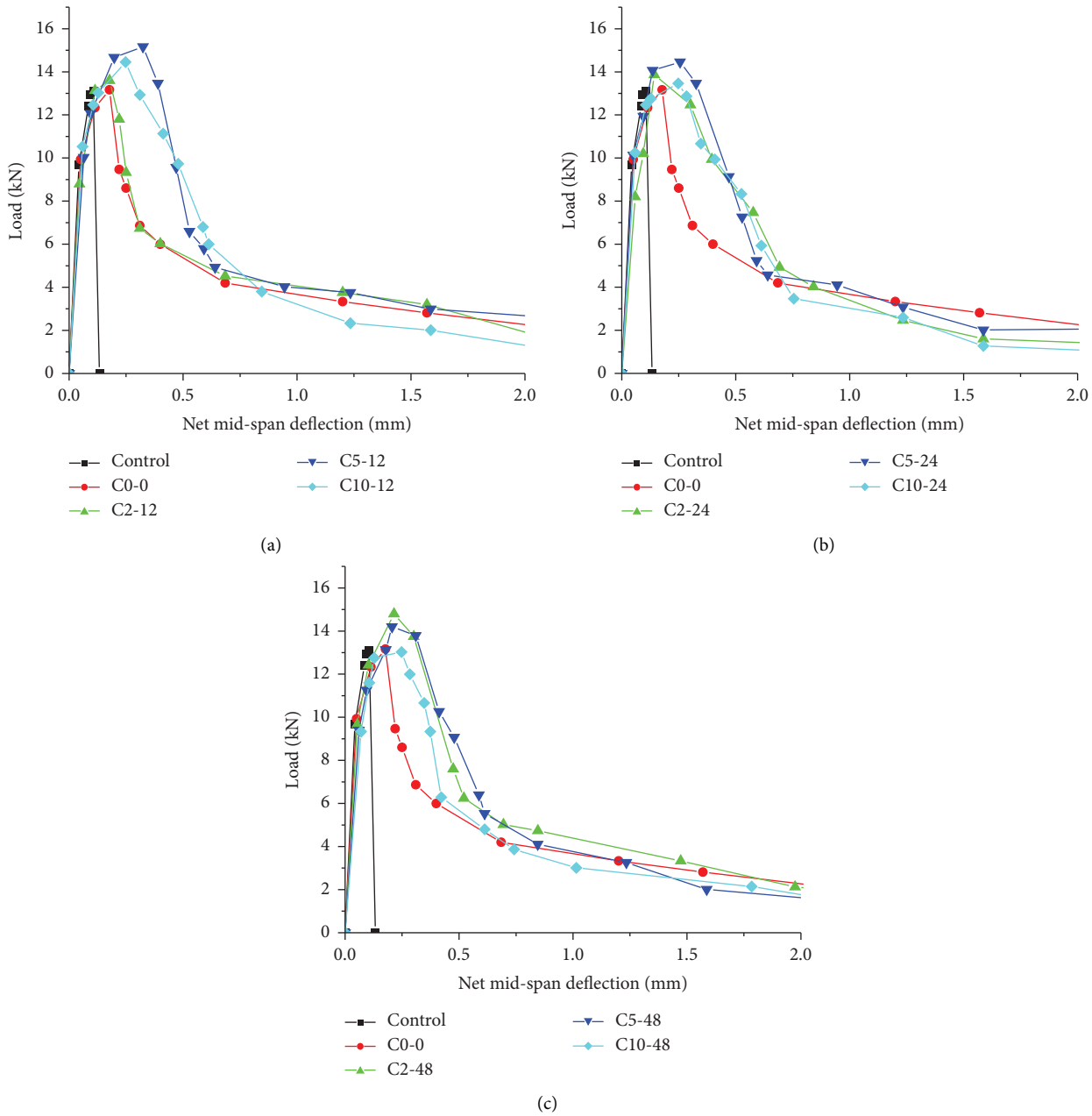

Figure 9: Load vs. mid-span deflection curves for different soaking time; (a) 12 hr, (b) 24 hr, and (c) 48 hr.

control specimens of plain concrete, ranging from 2.7 to 15.7%. Furthermore, except for C10–48, alkali-treated SFRC outperforms raw sisal-reinforced concrete. The reason for the observed increase in flexural strength is the enhanced fiber surface roughness and removal of fiber surface impurities resulting from the chemical treatment process [40]. Concerning fibers that are treated in a highly concentrated alkali medium for a longer duration, the effect of the treatment on the flexural strength of the concrete composite is detrimental. Indeed, it permits substantial delignification and degradation of crystalline cellulose chains of the fiber, resulting in weaker or damaged fiber [35].

Table 10 shows the ANOVA results at a 95% confidence interval, and it is found that the duration of sisal fiber treatment has no significant effect on the flexural strength performance of the concrete composite with a P value of <0.05, indicating that the null hypothesis is true. In contrast, the concentration of NaOH has a statistically significant effect on the flexural tensile strength of SFRC. There was also a significant effect from the interactions between fiber soaking time and NaOH concentration.

3.2.4. Postcracking Behaviors. In this study, the postcrack behaviors of concrete composites are characterized by the load-deflection curve of the flexural test following ASTM

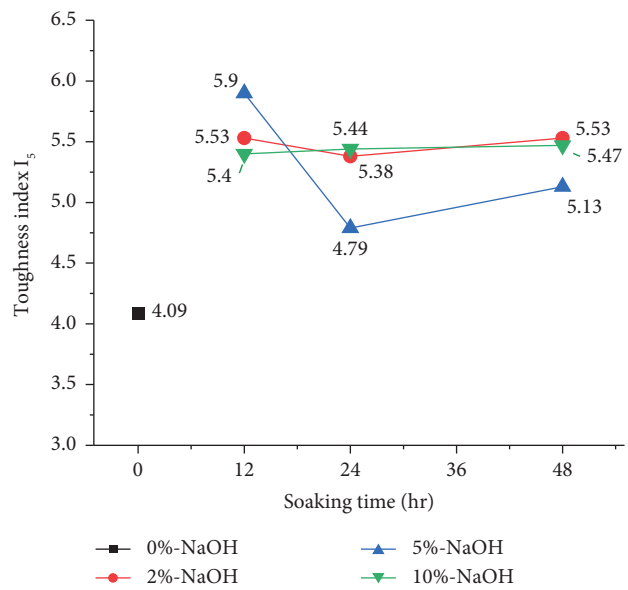

Figure 10: Toughness index I_5.

C1018 and ASTM C1609 standards. Figure 9 shows a typical load-deflection curve for control, raw SFRC, and alkali-treated SFRC beam specimens. Three samples from each batch of concrete were tested to get the average value of the postcrack behaviors. For each category, one average curve was presented from three load-deflection curves of each sample code.

(1) ASTM C1018 Toughness Parameters. In this study, two flexural toughness indexes, I_5 and I_{10}, are calculated from the averaged load vs. deflection curve, as shown in Figure 9. It can be observed in Figures 10 and 11 that a notable effect in toughness indexes is recorded when untreated sisal fibers are replaced by NaOH-treated sisal fibers. The increase in toughness indexes implies that the crack-arresting behavior of the composite increases with the treatment of reinforcing fiber. The reasons for these experimental results are mainly due to the removal of the fiber surface impurity and the increased surface roughness, thus increasing the fiber-matrix compatibility and fiber-matrix interfacial bonding, resulting in better performance in the relative postpeak behavior. Compared to control conventional concrete ($I_5 = I_{10} = 1$), the toughness index of fiber-reinforced concrete has increased significantly regardless of treatment condition. These could be due to the inhibition of crack propagation by the fibers after the appearance of the first crack in raw and treated fiber-reinforced concrete composites [11].

The maximum value of I_5 and I_{10} is given by reinforcing fiber treated for 12 hours in a 5% alkali-concentrated solution (C5–12), which is 44% and 105% greater than that of raw SFRC. As observed from the flexural strength result, C2–48 also shows better performance in toughness indexes next to C5–12, and it is almost 35.2% and 86.6% greater than that of raw SFRC specimens for I_5 and I_{10}, respectively.

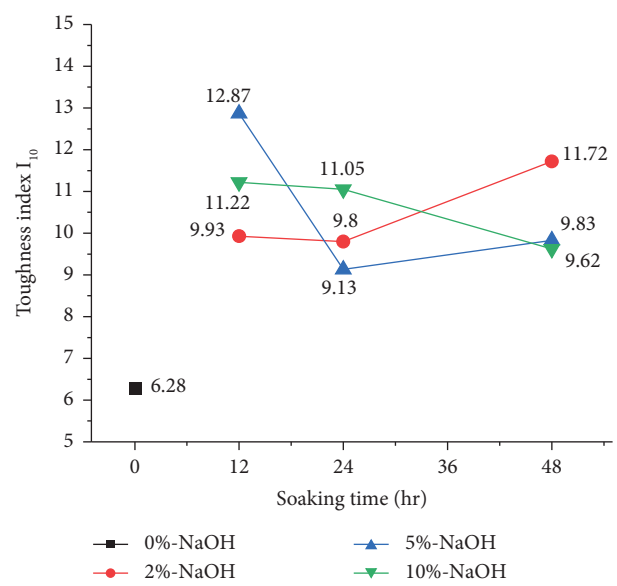

Figure 11: Toughness index I_{10}.

The second observation that can be made based on the Figure 11 is that the effect of fiber alkali treatment is more pronounced in I_{10} than in I_5 for all mixtures. These were because the contribution of fibers to postcrack toughness came into play and accurately reflected at higher deflection (5.5δ) [27].

Residual strength factors characterize the remaining strength after the first crack in fiber-reinforced concrete and are derived from the toughness index. The designated residual strength chosen for this study was $R_{5,10}$, which represents the average strength retained between 3δ and 5.5δ. As shown in Figure 12, the ASTM residual strength factor

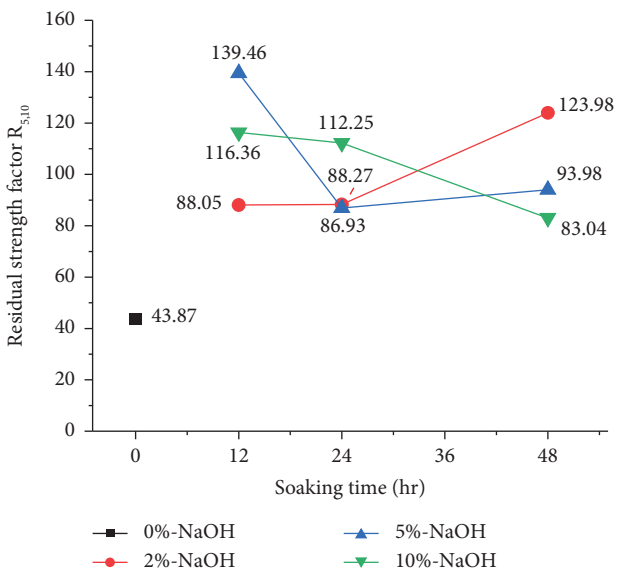

Figure 12: Residual strength factor ($R_{5,\ 10}$).

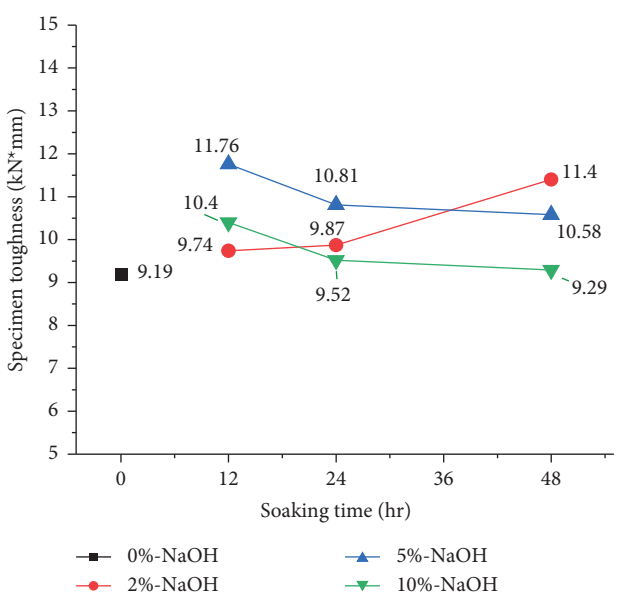

Figure 13: Specimen toughness of SFRC.

($R_{5,10}$) seemed to be improved by the fiber alkali treatment compared to that of raw sisal fiber-reinforced concrete. Similarly to flexural strength and toughness indexes, the highest residual strength factors were obtained with a 5%–12 hr fiber treatment.

(2) ASTM C1609 Toughness Parameters. The two performance parameters (specimen toughness and equivalent flexural strength ratio) from the ASTM C1609 standard have been summarized using Figures 13 and 14. As seen in Figure 13, changing the surface morphology of the reinforcing fiber by alkali treatment affects the toughening performance of the SFRC mixture composites. The results indicate that treated SFRC has a greater overall energy

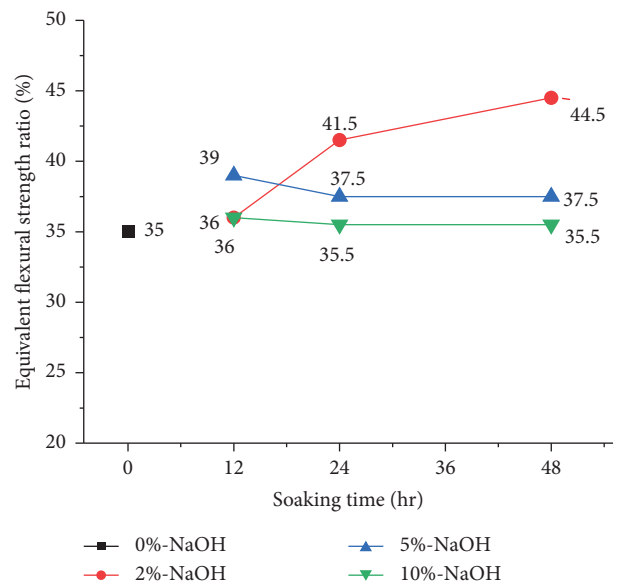

Figure 14: Equivalent flexural strength ratio.

absorption capacity than untreated SFRC. The increase in toughness values is between 1.1% and 28% of the raw sisal fiber-reinforced concrete specimen. The ability to sustain loads after cracking is very much dependent on the tensile strength of individual fibers and the bond between the fiber and matrix [41]. Therefore, the enhanced mechanical properties of alkali-treated sisal fiber due to the removal of surface impurity correlated with a change of the morphological and chemical structures in microfibrils of the fiber lead to get a superior result in terms of flexural toughness compared to the raw SFRC counterpart.

Another noticeable observation in the toughness development among the mixtures is that the rates of toughness development with different treatment conditions are quite different. For all treated reinforcing sisal fibers, the toughness showed a gradual increment with increasing alkali concentration and fiber soaking time upto 5% and 24 hours, respectively. With further increases in concentration and duration, the specimen flexural toughness values gradually reduced. The possible explanations for this result are that as the alkali concentration and soaking time increased, a highly rough fiber surface resulted, which led to a strong interface bond between the matrix and reinforcing fiber. Accordingly, no debonding and slippage take place, and the result is a strong but brittle material [42]. Furthermore, as alkali concentration further increased, damage on the fiber surface became more severe and consequently reduced the tensile strength of the reinforcing sisal fiber. These, in turn, promote a reduction in the fiber-bridging effect.

The equivalent flexural strength ratio ($R^{D}_{T,150}$) is another ASTM C1609 toughness performance parameter used in this study to characterize the flexural toughness of sisal fiber-reinforced concrete and is expressed as a percentage. As shown in Figure 14, for various treatment conditions on the reinforcing sisal fiber, the equivalent flexural strength ratio increases with increasing alkali concentration and fiber

soaking time up to 2% and 48 hours, respectively, and gradually decreases with further increases in treatment concentration and duration. The increase in $R^{D}_{T,150}$ values is between 1.4% and 27% of the raw sisal fiber-reinforced concrete specimen.

4. Conclusions

The following conclusions are drawn from experimental work performed in relation to the study's objectives:

(i) All applied treatments resulted in a reduction of the water absorption capacity and an increase in the surface roughness of the sisal fiber. Significant improvements in the mechanical properties (tensile strength, modulus, and % elongation) of sisal fibers were obtained by treating them for 48 hours in a 2% NaOH solution. When sisal fiber was treated with more than 2% NaOH solutions, mechanical property values dropped consistently, owing to excessive delignification of sisal fiber.

(ii) Regardless of the treatment conditions used, the inclusion of sisal fiber in the concrete matrix reduced the workability of the SFRC. Except for the concrete reinforced with 10%–48 hr treated sisal fiber, the flexural strength of the concrete composites reinforced with alkali-treated sisal fibers improved. However, compared to their untreated SFRC counterparts, treating sisal fiber did not improve the compressive strength of the composites at any age.

(iii) The toughness of fiber-incorporated concrete has revealed a considerable enhancement. This effect becomes more significant for alkali-treated sisal fibers. However, at higher concentrations and treatment durations, the increase becomes minimal and even experiences a reduction.

Based on the abovementioned remarks, it becomes evident that treating sisal fiber is an excellent method for enhancing the flexural and postcrack performance of SFRC, thus bringing new trends in composite materials.

Data Availability

The data used to support the findings of this study are available upon request from the corresponding author.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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