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Review

Concrete Reinforced with Sisal Fibers (SSF): Overview of Mechanical and Physical Properties

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Abstract: Concrete is a commonly used building material; however, it is subject to abrupt failure and limited energy absorption when yielding. The use of short discrete fibers has displayed a lot of potential in overcoming these issues. Sisal is a natural fiber that is renewable, inexpensive, and readily accessible. SSF is a potential reinforcement for use in concrete because of its cheap cost, low density, high specific strength and modulus, negligible health risk, easy accessibility in certain states, and renewability. In current centuries, there has been growing importance in discovering new uses for SSF-reinforced concrete, which is normally utilized to make ropes, mats, carpets, and other decorative items. This article gives an overview of current advancements in SSF and composites. The qualities of SSF, the interface between SSF and the matrix, and SSF-reinforced properties such as fresh, mechanical strength, and durability have all been examined. The results show that SSF increased strength and durability while decreasing its flowability. The review also provides suggestions for further work.

Keywords: concrete; sustainable concrete; natural fibers; durability; compressive strength

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1. Introduction

The building industry is seeing increased demand as the world's population grows [1–3]. Due to its exceptional inherent features, such as strong compressive capacity, excellent resilience, fire resistance, and low penetrability, the industry significantly depends on concrete, which is the best extensively used building material [4]. Apart from these positive characteristics, there are certain disadvantages, such as less tensile capacity, brittleness, poor fracture resistance, and less impact resistance [5]. These flaws necessitated the development of methods to enhance the qualities of concrete. Some of these flaws, such as poor tensile strength, may be addressed by utilizing traditional reinforcing steel bars and, to a degree, by inserting the right number of specific fibers into concrete [6–8].

Incorporating fibers into construction materials has been practiced in various regions of the globe since ancient times. The desire to improve the tensile strain of the material's "perceived" fragile qualities was the driving force behind this work. This method was used to create fiber-reinforced concrete in the 20th century, which has gained popularity and use in the building sector owing to its enhanced strength and stiffness. Natural fibers are an environmentally beneficial alternative to artificial fibers when used as secondary reinforcement in concrete [9]. Fibers are tiny, discrete reinforcement materials created from a variety of materials, natural as well as artificial, and they come in a variety of forms and sizes [10–12]. Sisal is one of several natural fibers that have proven to show significant promise throughout time; it has several beneficial features, including sustainability, great tensile stain, and cheap cost [13].

In terms of sustainability and biodegradability, natural fibers are now one of the most popular choices for concrete reinforcement [14], due to being environmentally friendly and non-toxic [15], qualities that are especially advantageous for the production of natural fibers. Alternatively, they aid in the reduction of CO_2 emissions into the environment. In a range of sectors, such as automotive, building, architectural, and biomedical, biocomposites are increasingly famous as attractive materials [16]. Natural fibers are also less expensive than synthetic fibers, have greater stiffness, are recyclable, and can be found all over the globe [17]. Coir is a common natural fiber made from harvesting the shells of ripe coconut, which is employed to create hard, high-strength items [18]. Natural fiber-based biocomposites have essentially replaced synthetic plastics for a wide range of purposes due to their numerous benefits, including their broad availability, biodegradability, light weight, low cost, and ease of fabrication [19]. A range of natural fiber concretes has been suggested by several researchers for work in a variety of technological applications [14,20–22]. Coconuts are grown in numerous nations all over the world, especially in tropical and subtropical locations, and they act as an important role in economic development. According to a recent study, coir fibers from approximately fifty billion coconuts are collected around the world [23]. Sisal is gaining popularity among natural fibers such as kenaf, jute, oil palm, cotton, flax, banana, and hemp since it is widely accessible, less expensive, environmentally beneficial, and has comparable mechanical qualities to hemp, banana, and jute [24].

Sisal Fibers (SSF)

Sisal may be readily grown in a short amount of time. Field hedges and railway lines are natural habitats for the plant [25]. According to a study, SSF is harvested around the globe at a pace of roughly 4.5 million tons per year [26]. It is made from the leaves of the sisal plant (Agave sisalana), which is now grown in tropical African, Caribbean, and Asian countries [27]. A sisal plant typically has 200–250 sisal leaves, each of which may have at least 1000–1200 fiber bundles. A sisal plant comprises 4% fiber, 0.75% cuticle, 8% dry matter, and 87.25% water in total [28]. In general, SSF is removed using retting, scraping, and mechanical processes such as decorticators [29].

Fiber production was 281,000 tons worldwide in 2013, with Brazil generating 150,584 tons. Tanzania (34,875 tons per year), Kenya (28,000 tons per year), Madagascar (18,950 tons per year), China (16,500 tons per year), Mexico (12,000 tons per year), and Haiti (9000 tons per year) all produce sisal. It is economically possible for the country's underdeveloped northeast religion, which supports roughly 800,000 people. Sisal ranks as sixth among fiber plants, accounting for 2% of the global plant fiber output [30]. Figure 1 shows the worldwide production of sisal plants.

Several researchers reported different chemical compositions of SSF. Sisal, for example, comprises 4356% cellulose, 79% lignin, 2124% pentosan, and 0.61.1% ash, according to Rowell [31]. Joseph et al. [32] recently found that sisal contains 85 to 88 percent cellulose. The considerable differences in chemical contents of SSF are due to its various sources, ages, testing techniques, and other factors. A study [33] discovered that the cellulose and lignin content of sisal varies between 49.62 $\pm$ 60.95 and 3.75 $\pm$ 4.40 percent depending on the plant's age, which may be due to different sources or regain of SSF.

Sisal fibers may be added to cement to slow down the cement's hydration process and to extend the setting durations [34]. Natural fiber composites are increasingly preferred over synthetic fiber composites due to inherent benefits, including affordability and environmental friendliness [35]. Comparing concretes that include fibers to those that do not, significant improvements in the primary strength parameters were found [36].

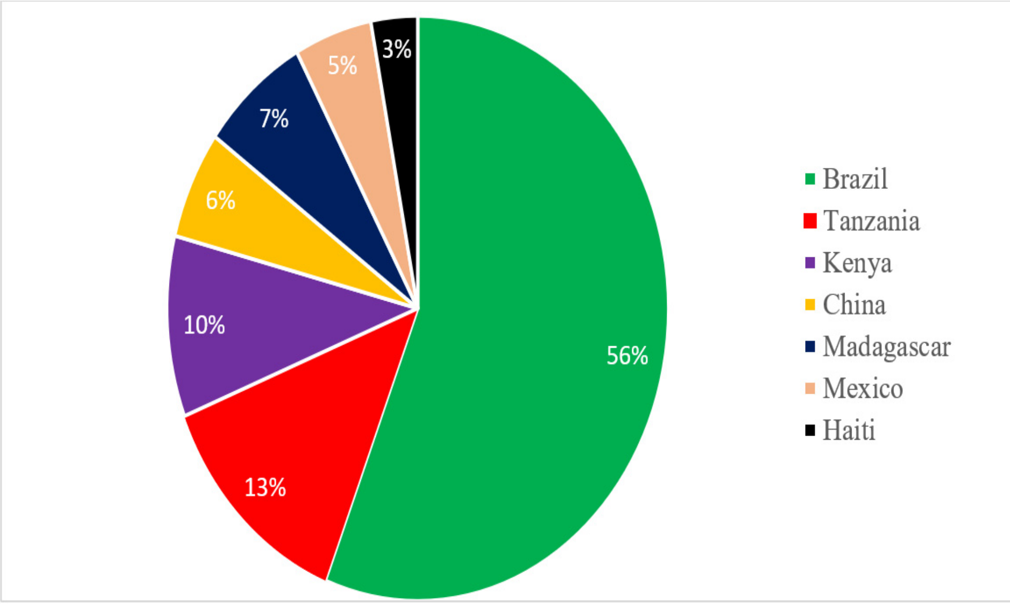

Figure 1. Worldwide production of sisal plants.

SSF is mostly a white, creamy color as shown in Figure 2 and ranges in length and diameter. Other qualities, such as tensile capacity and elastic modulus, change according to the source and intended use. The physical qualities of SSF have been described by several researchers. Table 1 lists the many physical characteristics of fibers as determined by previous studies.

Figure 2. Sisal fibers (SSF) [42].

Table 1. Characteristics of SSF.

Authors	[37]	[38]	[39]	[40]	[41]
Specific gravity	0.73	-	-	-	1.4
Water Absorption (%)	43.58	-	-	-	-
Color	Creamy white	-	-	-	-
Elongation at Break (%)	-	5–14	5–14	14.8	-
Density (g/cm^3)	0.113	-	1.45	-	-
Tensile capacity (MPa)	371 $\pm$ 28	400–700	400–700	31–221	560
Elastic modulus (GPa)	12.43 $\pm$ 2.23	9–20	9000–20000	-	-
Fiber length (mm)	30	-	-	180–600	12

2. Treatments of SSF

To minimize the hydrophilicity of the fiber, two basic kinds of fiber treatments were used: bulk and surface treatments. The key difference between both treatments is that the first causes a drastic modification of the whole fiber, which nearly invariably changes its morphology and semi-crystalline phase, while the second leaves these traits practically unchanged, except for a thin outer layer [43].

Heat treatments of sisal fibers, such as wetting–drying cycles [44] or mechanical pression [45], result in a decrease in fiber area and lumen dimension, lowering moisture absorption.

The most common way to improve fiber–matrix interaction is to treat the fibers' surfaces with different coupling agents. Coupling agents are molecules with two functions: the first is to react with the OH groups of cellulose (pore sealing) and the second is to react with the matrix's functional groups (increased chemical linkages) [46]. Coupling agents increase the degree of crosslinking at the interface and provide perfect bonding [47]. Several studies have researched the impact of the surface treatment of sisal fibers with different coupling agents on fiber durability and fiber–matrix interaction. Silane coupling agents are efficient in altering the natural fiber–matrix interface; silane treatment of sisal fibers alters the surface topography, surface chemical structure, and thermal degradation [48]. Canovas et al. [49] impregnated sisal fiber with wood extracts (colophony, tannin, and vegetable oil), which showed excellent results in reducing water absorption (more than 50%) despite a modest drop in fiber tensile strength. Flexural experiments show that mortar reinforced with impregnated fibers has superior durability to mortar reinforced with unimpregnated fibers. Toledo Filho et al. [50] investigated the impact of treating aligned long sisal fiber with silica fume on the durability of cement-based composites, concluding that this treatment is a viable strategy for improving the composites' strength and toughness over time.

When sisal fibers were treated with 5 and 10 percent NaOH, the moisture absorption increased by 30 and 40 percent, respectively [51]. The findings obtained indicate that the mechanical and physical characteristics of block material were enhanced by the combined effects of fibers and cement [52]. The silica treatment produced the most effective barrier against fiber biodegradation because of the inorganic basis, which increased the longevity of the composite over eight months [53]. It was discovered that the sisal fiber's crystalline form would switch from cellulose I to cellulose II as the sodium hydroxide concentration increased [54].

The impact of the treatment on the fiber composition and appearance was examined using scanning electron microscopy (SEM). The images in Figure 3a,b were captured at a magnification of 100. The fiber's surface seems to be smooth, with some surface microfibrils visible. Because the microfibrils are on the primary wall of the fiber structure, they are amorphous microfibrils. Because their cellulose surface is covered by both hemicellulose and lignin components of the fiber at the main wall, which functions as a weak barrier layer between the fiber and the matrix, natural fibers have low fiber compatibility with the matrix [55]. The surface characteristic of treated SSF differs from that of untreated SSF, according to the research. The fibrillose-like structure of the untreated SSF is visible, while the fibrillose surface structure of the treated fibers is extracted [56]. Because of the boundary layer at the fiber–matrix contact, the composite's stress distribution capacity is often limited. Chemical treatment is required to eliminate the weak boundary layer in composites for improved stress transfer performance. Figure 3b depicts SSF that has been alkaline treated. The fiber's surface has become rougher, indicating that some surface material has been removed. Alkaline treatment of natural fibers improves fiber hydrophilicity by removing a portion of hemicellulose, lignin, and other surface contaminants that form the weak boundary layer, exposing the cellulose crystalline microfibrils to the fiber surface [57]. In this case, the treated SSF is thought to be more compatible with the matrix, and the rougher surface improves fiber–matrix adhesion even more than the raw SSF [58].

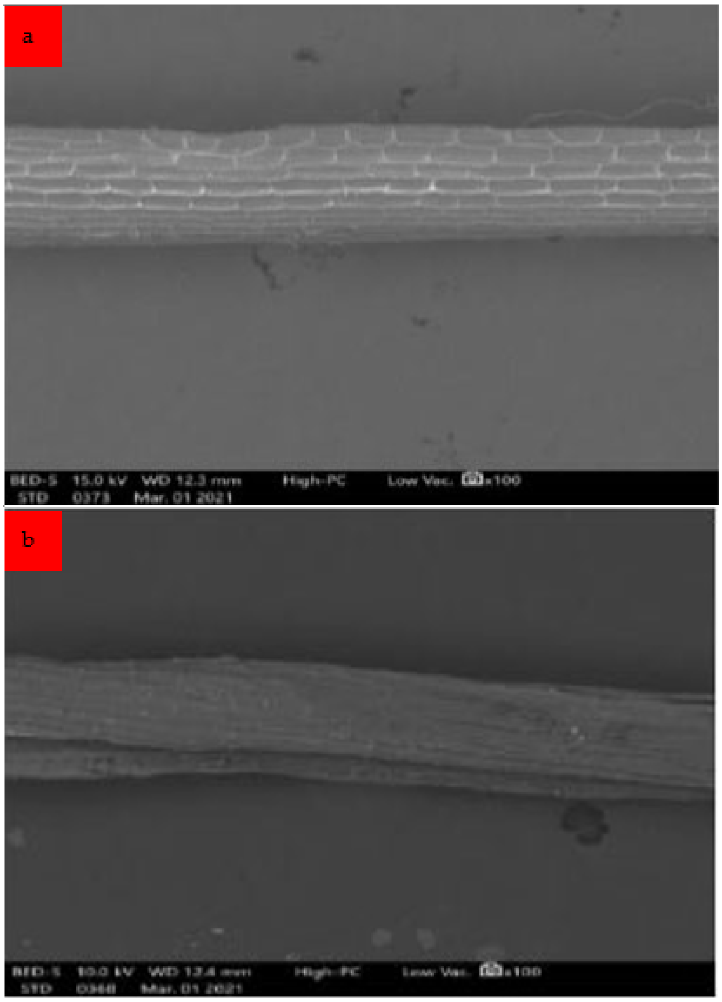

Figure 3. (**a**) Untreated and (**b**) treated SSF [59].

3. Fresh Properties

3.1. Workability

Generally, any kind of fiber decreased the flowability of concrete. Similar trends were seen as demonstrated in Figure 4 [60] and Table 2. The slump value of the concrete mixture was reduced when the SSF content was increased. Fiber additions of 1.0, 2.0, 3.0 and 4.0 percent reduced the decline by 7, 21, 28, and 50 percent, respectively. The viscosity of the concrete mixture rose when the fibers were disseminated into it due to the creation of the binder matrix–fiber network structure; as a result, the mixture's workability and flowability deteriorated [61]. When a greater quantity of fiber is added to the coating surrounding the fiber, more cement paste is used. This increased consumption lowers the workability of concrete. As a consequence, the mixture that includes 1.0 percent SSF gives the least amount of decrease but could still be sufficiently consolidated [62]. Hemp fiber, however, has a somewhat higher slump value. The amount of air in the concrete grew as the fiber length was reduced, and more air in the concrete had a greater negative impact on the slump [63]. Because of the increased surface area of the fibers, extra water may be essential to cover them, leaving less cement paste available for lubrication. The increase in the surface area of fiber may be attributed to the reduction in the fluidity of concrete mixtures when Cesare is added. Furthermore, fiber increased the frictional resistance among the concrete ingredients and the fiber, requiring the use of additional cement paste to alleviate the inner conflict [64]. Although fibers have many benefits in concrete, they reduce the flowability of freshly mixed concrete [65,66]. Water consumption increases owing to the increased surface area of the fibers. Because of the higher resistance among aggregates and fibers in the mixes, the need for greater potential energy for the ingredients to flow is based on mass [67]. The results are still good, and the decreased droop is due to the fibers absorbing a lot of the water in the mix [68]. Hemp fibers cause the concrete to slump, suggesting a loss of workability. This observation is described by the extreme permeability of hemp strands, which attracts a significant quantity of water for blending. The amount of fiber eaten has a direct relationship with porosity [69]. With the addition of fibers, the slump is reduced. Because fibers absorb water, the higher the fiber–cement ratio, the lower the slump. For larger fiber–cement ratios, it is advised to employ an appropriate super plasticizer that does not impact other attributes except workability. Because of the inefficient bonding of components in concrete with increased fibers, the increased fiber–cement ratio tends to void in concrete, even when completely compacted [70].

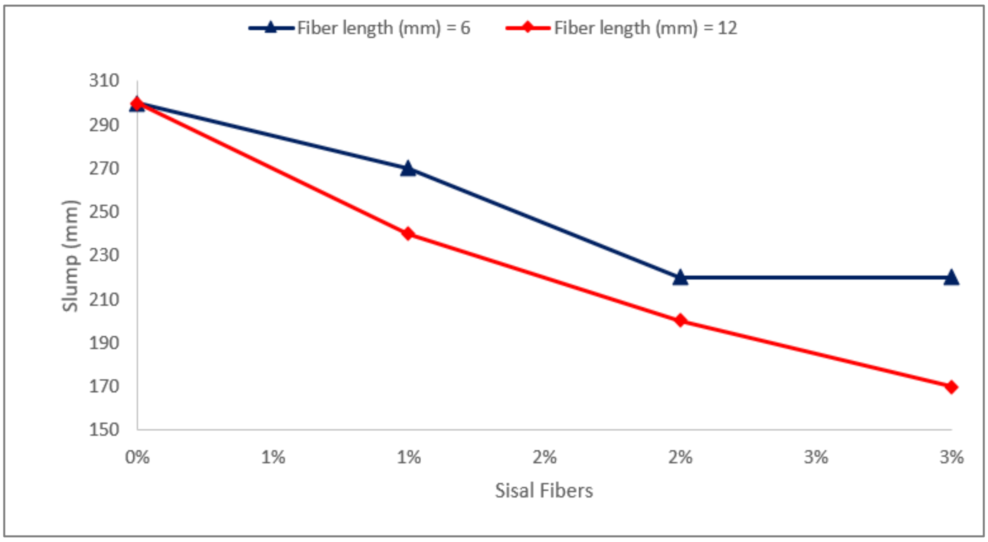

Figure 4. Slump flow: data source [60].

Table 2. Slump flow of concrete made with SSF.

Reference	Sisal Fiber (SSF)	Slump (mm)
[37]	0%, 0.5%, 1.0%, 1.5% and 2.0%	92, 69, 52, 40 and 20
[60]	Fiber length (mm) = 6 0%, 1%, 2% and 3% Fiber length (mm) = 12 0%, 1%, 2% and 3%	300, 270, 220 and 220 300, 240, 200 and 170
[62]	0%, 1%, 2%, 3% and 4%	70, 65, 55, 50 and 35
[71]	0%, 0.5%, 1.0% and 1.5%	75, 73, 73 and 72

3.2. Water Retention

The moisture content and the swelling processes take place in wood cells. Water vapor enters and is absorbed into the middle lamella and the cell walls when the relative humidity rises, creating hydrogen bonds that cause considerable cell swelling. The water saturation threshold of plant cells is achieved when the bound water saturates the cell walls and the central lamella, which varies depending on the plant species being investigated (between 20 and 40 percent for wood cells). Pejic et al. [72] studied the impact of non-cellulosic biopolymers such as lignin on the water sorption of natural fiber bundles and found that a reduction in lignin concentration tended to enhance the ability of natural fibers to retain water. According to Figure 5, the plant fiber bundles with the greatest lignin levels also had low overall moisture content.

In contrast, nettle fiber bundles have a high moisture content above 80% relative humidity compared to other bast fibers. This might be due to a poor retting-inducing high pectin concentration and to greater hygroscopic nature. As a result, high microfibrillar angle (MFA) and lignin concentrations, such as those seen in palm fiber bundles, tend to minimize swelling and restrict the ability of water retention. Because of the biochemical, structural, and morphological characteristics of natural fibers, the processes of water sorption and swelling are complicated. These mechanisms are affected in this respect by several variables, including lumen size and microfibrillar angle (MFA) [73]

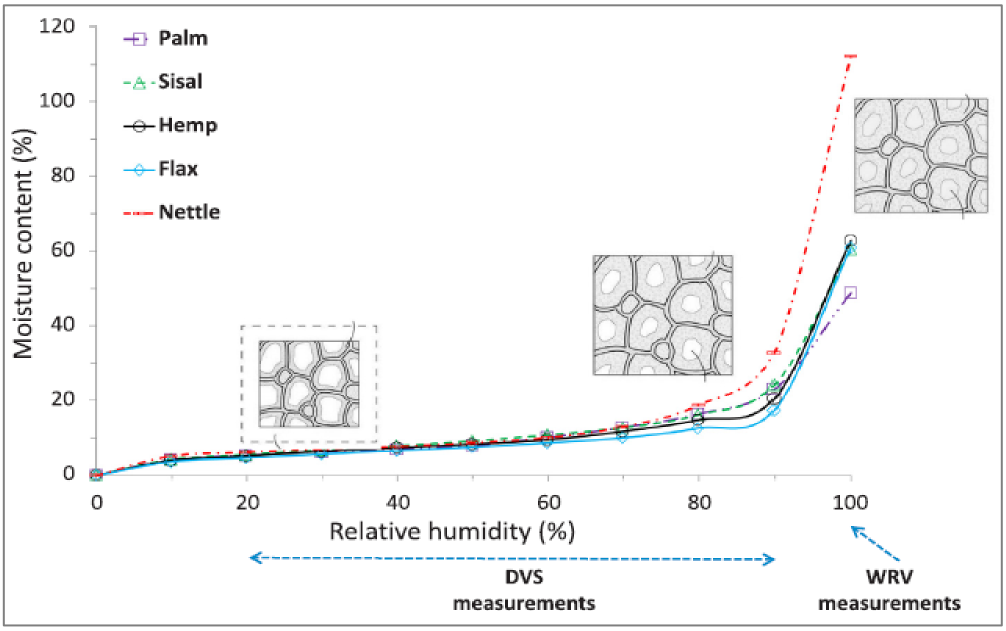

Figure 5. Relationship between relative humidity and moisture content. Reprinted with permission from Ref. [74]. 2022 Elsevier.

4. Mechanical Strength

4.1. Compressive Strength (CS)

Sisal fiber (SSF) improved the compressive strength (CS) of concrete up to a certain limit as shown in Figure 6 and Table 3. Fibers also increased concrete CS up to a point before reducing due to a lack of workability, according to studies [6]. The concrete's CS is lower than the reference concrete even at a higher dose. The restriction (confinement) of the fiber around the cylindrical specimens enhances the CS. Compression produces lateral expansion, which is constrained by the fibers, raising CS. The fibers can withstand strain and shear because of their strength [6]. Basalt fibers in high-performance concrete have been studied to assess their tensile strength, modulus, and CS, among other things. It has been observed that increasing the fiber volume percentage by 2% improves CS. The strength started to decline when the fiber loading reached 2%. Basalt fiber volume percentages did not affect elastic modulus testing [75]. Concrete reinforced with kenaf fibers outperformed standard concrete samples in terms of mechanical performance [76]. CS was diminished when fiber intake was increased above 1.25 percent. This might be because there are more propylene or SSF available at a volume fraction of 1.50 percent, lowering the CS [41]. As a result, the presence of SSF had no discernible effect on CS [77]. Fibers increase the mechanical performance of concrete at both the initial and later stages when used at 1.0 percent by volume. The biggest strength gain after 28 days was determined to be 29.15 percent [49]. According to one research study [78], adding 6.0 percent (by mass of binder) SSF with a length of 40 mm to regular cement concrete reduced CS by 22.0 percent. The increased porosity caused by the inclusion of fibers is responsible for the decrease in CS. However, it was also observed that incorporating 1.5 percent SSF into regular concrete boosted its CS by roughly 5.6 percent [41]. Concrete reinforced with kenaf fibers outperformed standard concrete samples in terms of mechanical performance [76]. As a consequence, there is an appropriate limit for coconut fiber. The optimal dose of fiber for strength, according to the research, is 2.0 percent by weight of the cement [26]. According to the research, the best amount of coir fiber in concrete is 0.25 percent, which leads to a 19% improvement in 28-day CS [39]. The addition of 1.0% to 3.0% SSF by volume had a minor (15%) effect on the CS of UHPC specimens in this investigation. SSF may efficiently stop fractures from spreading [79]. According to one research study, 1.5% of the fibers increased CS by nearly 15% when compared to the control specimens' strength [43]. The addition of SSF to the UHPC mixture, however, enhances the porosity of the matrix [78]. As a result, adding SSF to UHPC has two opposing impacts on CS, and further research is needed to relieve this detrimental impact on UHPC's mechanical strength.

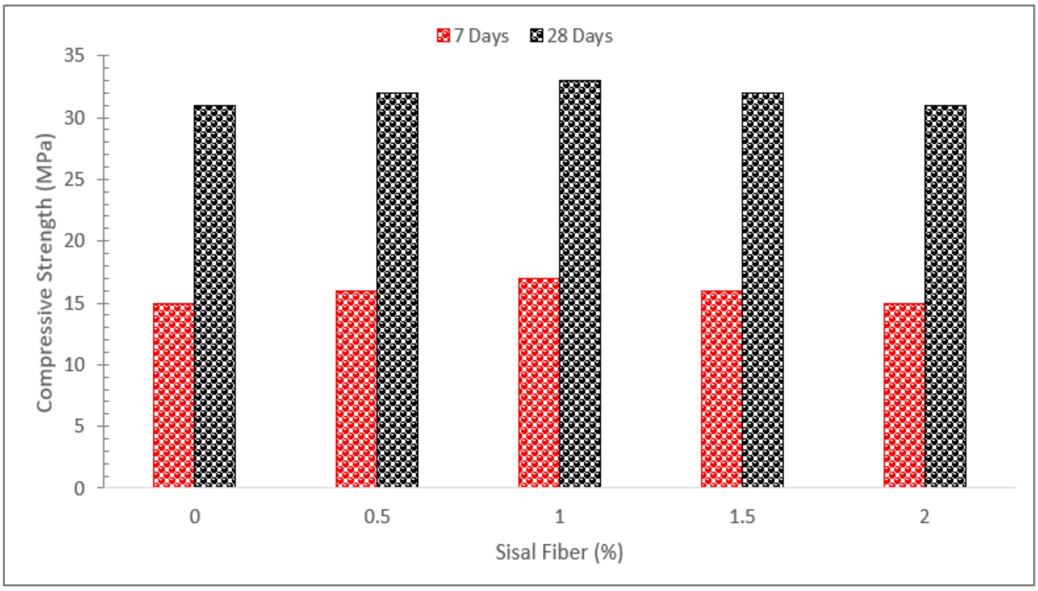

Figure 6. Compressive strength (CS); data source: [80].

Table 3. Compressive strength of concrete made with SSF.

Reference	Sisal Fibers (SSF)	Compressive Strength (MPa)
[37]	0%, 0.5%, 1.0%, 1.5% and 2.0%	7 Days 28.49, 25.11, 24.32, 23.68 and 21.68 28 Days 36.37, 35.62, 33.55, 31.00 and 30.42
[60]	Fiber length (mm) = 6 0%, 1%, 2% and 3% Fiber length (mm) = 12 0%, 1%, 2% and 3%	118, 120, 110 and 114 118, 125, 112 and 120
[81]	0%, 4%, 4% and 4%	7 Days 24, 17, 18 and 18 28 Days 34, 28, 24 and 24 90 Days 54, 37, 34 and 35
[82]	MCC + Sisal 0%+0%, 0.1%+ 0%, 0% + 0.25%, 0% + 0.50% 0.1%+0.25%, 1% + 0.25%, 1.5% + 0.25%, 1% + 0.50% and 1.5% + 0.50%	43.0, 51.0, 40.8, 39.4, 51.9, 41.2, 40.4, 41.8 and 39.5
[40]	0%, 0.5%, 1.0%, 1.5% and 2.0%	7 Days 13.5, 9.8, 9.8, 8.2 and 8.2 28 Days 21, 18, 16, 19 and 18

Table 3. *Cont.*

Reference	Sisal Fibers (SSF)	Compressive Strength (MPa)
[41]	0%, 0.50%, 1.00%, 1.25% and 1.50%	7 Days 26.31, 36.93, 37.31, 37.85 and 38.32 28 Days 40.62, 40.76, 41.68, 42.49 and 42.96 90 Days 42.54, 42.80, 43.62, 44.26 and 44.91
[83,84]	0%, 1.0%, 1.5% and 2.0%	7 Days 31, 36 and 34 14 Days 33, 41 and 39 21 Days 34, 45 and 41
[62]	0%, 1%, 2%, 3% and 4%	28 Days 35.6, 36.2, 36.9, 37.6 and 34.6 56 Days 41.2, 41.88, 42.69, 43.50 and 40.03 90 Days 44.5, 45.25, 46.13, 47.00 and 43.25
[85]	0%, 2%, 3%, 4.5% and 6%	3 Days 20, 28, 30, 35 and 36 7 Days 40, 42, 43, 44 and 45 28 Days 40, 41, 43, 45 and 50
[71]	0%, 0.5%, 1.0% and 1.5%	7 Days 26.95, 25.6, 25.21 and 24.62 28 Days 38.87, 35.31, 36.82 and 34.42 90 Days 47.51, 45, 46.11 and 44.51
[86]	0%, 0.2%, 0.4%, 0.6%, 0.8% and 1.0%	5mm 3.6, 3.7, 3.8, 4.0, 4.5 and 4.4 10 mm 3.6, 3.5, 3.4, 3.3, 4.0 and 3.6
[70]	0%, 1%, 2% and 3%	28 Days 91, 92, 93.5 and 91.5
[80]	0%, 0.5%, 1.0%, 1.5% and 2.0%	7 Days 15, 16, 17, 16 and 15. 28 Days 31, 32, 33, 33 and 31
[87]	0%, 1.5%, 2.0% and 2.6%	7 Days 12.5, 8.5, 8.0 and 8.0 28 Days 21, 16, 19 and 19
[88]	0%, 0.5%, 1.0%, 1.5% and 2.0%	M20 29.62, 37.26, 40.38, 35.44 and 32.26 M30 36.45, 41.22, 47.56, 45.12and 38.67 M40 42.65, 45.77, 53.82, 50.94 and 43.32

4.2. Flexural Strength (FL)

General flexural strength (FL) improved with SSF as shown in Figure 7 and Table 4. Although SSF did not influence CS, an increase in SSF content in hierarchical composites from 0.25 to 0.5 percent enhanced FL, mostly owing to cracking [82]. The FL of UHPC specimens was reduced by 5.2 to 8.4 percent when a volume content of 1.0 to 3.0 percent SSF with a length of 6 mm was added. The addition of 1.0 percent SSF lowered FL marginally, whereas the addition of 2.0 and 3.0 percent fibers enhanced the FL of UHPC specimens by 5.5 and 8.3 percent, respectively. When the length of the SSF was raised to 18 mm, the content of 1.0%, 2.0%, and 16.7% rose. The presence of 3.0% fibers with a length of 18 mm, however, reduced FL. This is owing to the mixture's poorer flowability, which causes inhomogeneous fiber distribution in the matrix [89]. As a result, the excessive inclusion of long fibers reduces the FL of UHPC [60]. The findings demonstrated that sisal fiber, particularly when used at a sisal fiber content of 0.15 percent, may enhance the flexural strength and reduce the flexural stiffness of foam concrete under static loading [90].

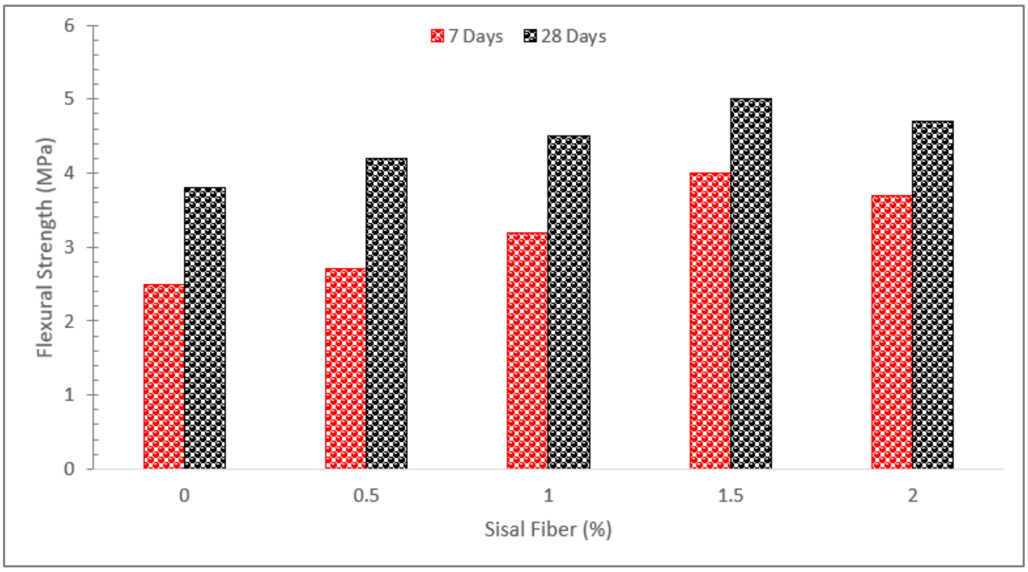

Figure 7. Flexural strength (FL): data source [80].

Table 4. Flexural strength of concrete made with SSF.

Reference	Sisal Fibers (SSF)	Flexure Strength (MPa)
[60]	Fiber length (mm) = 6 0%, 1%, 2% and 3% Fiber length (mm) = 12 0%, 1%, 2% and 3%	10.0, 9.00, 9.50 and 11.0 10.0, 9.00, 11.0 and 11.5
[81]	0%, 4%, 4% and 4%	7 Days 5.4, 4.2, 4.2 and 4.6 28 Days 7.5, 6.1, 5.2 and 5.6 90 Days 9.0, 7.3, 6.2 and 6.8
[82]	MCC + Sisal 0%+0%, 0.1%+ 0%, 0% + 0.25%, 0% + 0.50%0.1%+0.25%, 1% + 0.25%, 1.5% + 0.25%, 1% + 0.50% and 1.5% + 0.50%	6.7, 6.5, 6.3, 6.1, 6.8, 6.5, 6.5, 6.1 and 6.0
[83]	jute fiber + Sisal fiber 0% + 35%, 10% + 25%, 20% + 15%, 25% + 10% and 35% + 0%	32.17, 40.95, 29.65, 34.49 and 56
[62]	0%, 1%, 2%, 3% and 4%	5.17, 5.29, 5.59, 5.76 and 5.07

Table 4. *Cont.*

Reference	Sisal Fibers (SSF)	Flexure Strength (MPa)
[85]	0%, 2%, 3%, 4.5% and 6%	3 Days 3.0, 4.2, 5.0, 4.7 and 4.4 7 Days 5.0, 6.0, 6.2, 6.0 and 5.7 28 Days 6.0, 6.4, 7.0, 6.0 and 5.9
[71]	0%, 0.5%, 1.0% and 1.5%	7 Days 2.69, 3.15, 3.36 and 3.00 28 Days 4.21, 4.56, 4.87 and 4.63 90 Days 4.94, 5.83, 5.88 and 5.21
[86]	0%, 0.2%, 0.4%, 0.6%, 0.8% and 1.0%	5 mm 0.65, 0.68, 0.73, 0.78, 0.92 and 0.90 10mm 0.65, 0.70, 0.80, 0.85, 0.90 and 0.65
[80]	0%, 0.5%, 1.0%, 1.5% and 2.0%	7 Days 2.5, 2.7, 3.2, 4.0 and 3.7 28 Days 3.8, 4.2, 4.5, 5.0 and 4.7
[88]	0%, 0.5%, 1.0%, 1.5% and 2.0%	M20 3.06, 4.22, 5.87, 6.41 and 7.13 M30 3.80, 5.48, 6.43, 6.95 and 7.44 M40 4.38, 6.43, 7.27, 7.26 and 7.97

Fibers improve flexural capacity by preventing fractures from forming. The load is immediately transferred to the fibers due to the interface between the concrete components and the fibers. Fibers prevent fractures from breaking by allowing the crack to propagate across the fibers and transmit the load. The fibers and concrete matrix withstand the force as a whole, giving the structure more FL [49]. Banana fibers improved the microstructure of concrete by enhancing fiber-to-matrix bonding, as well as lowering the size of ITZ and, as a result, the permeability of the concrete by sealing voids, which improved the composite's mechanical properties [91]. The use of SSF with a length of 6 mm for matrix reinforcement results in a greater increase in porosity than bridging effects. Li et al. observed similar findings [92]. The addition of short fibers (10 mm) reduced the FL of cement concrete marginally. The larger bonding area between the longer fibers and the matrix results in a greater pull-out load, allowing the fractures to be bridged more efficiently [93]. As the fiber length rises, the FL increases at the same fiber volume percent. Furthermore, when the SSF volume percentage rises, the FL increases. This is because when the SSF volume content rises, more SSF appears on the crack surface, enhancing the fibers' bridging strength [94]. As reported by Andiç-Çakir [93], long fibers with a length of 20 mm were added at 0.4 and 0.75 percent (by total weight of mixture) to enhance the FL of cement concrete by roughly 5.25 and 14.35 percent, respectively.

4.3. Tensile Strength (TS)

Tensile strength (TS) of concrete improved with SSF, as shown in Figure 8 and Table 5. SSF has a high cellulose content, which accounts for its improved TS and resistance to water absorption. Because of its cost-effectiveness, exceptional acoustic and thermal properties, adequate TS, high toughness, abrasion resistance, and plentifulness, SSF is the most widely used natural fiber in the construction industry [62]. In terms of strength and durability, fiber-reinforced concrete outperforms regular concrete. Fiber stops cracks rather than prevents them. Notably, CF has a larger impact on TS than CS. Fibers have been demonstrated to help post-cracked concrete behave better [53]. Furthermore, fibers with a volume of 0.5 to 2.0 percent have a far bigger impact on concrete TS than fibers with a volume of less than 0.5 percent [54].

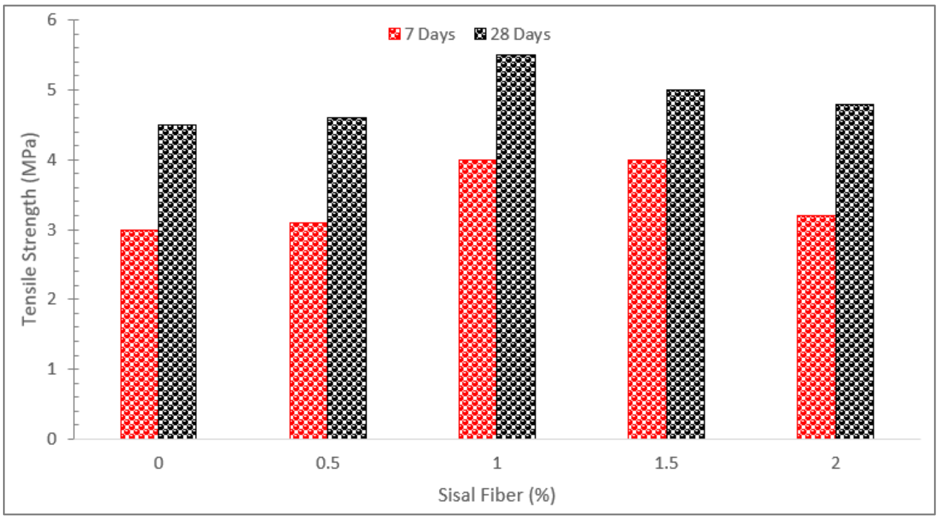

Figure 8. Tensile strength (TS): data source [80].

Table 5. Tensile strength of concrete made with SSF.

Reference	Sisal Fibers (SSF)	Split Tensile Strength (MPa)
[37]	0%, 0.5%, 1.0%, 1.5% and 2.0%	7 Days 2.07, 2.47, 2.68, 2.42 and 2.18 28 Days 2.35, 3.05, 3.46, 2.74 and 2.51
[40]	0%, 0.5%, 1.0%, 1.5% and 2.0%	7 Days 1.5, 1.8, 2.0, 1.6 and 1.4 28 Days 2.3, 2.8, 2.6, 2.2 and 1.9
[25]	MMC 0%, 10%, 20% and 30% SMC 0%, 10%, 20% and 30%	MMC 9.2, 9.65, 11.25 and 10.2 SMC 9.2, 10.8, 12.5 and 14.7
[83]	jute fiber + Sisal fiber 0% + 35%, 10% + 25%, 20% + 15%, 25% + 10% and 35% + 0%	17.99, 14.84, 9.72, 5.37 and 12.91
[62]	0%, 1%, 2%, 3% and 4%	3.01, 3.15, 3.26, 3.42 and 2.98
[71]	0%, 0.5%, 1.0% and 1.5%	7 Days 1.73, 2.17, 2.54 and 2.36 28 Days 2.42, 2.69, 3.21 and 2.95 90 Days 2.97, 3.2, 3.56 and 3.32
[80]	0%, 0.5%, 1.0%, 1.5% and 2.0%	7 Days 3.0, 3.1, 4.0, 4.0 and 4.2 28 Days 4.5, 4.6, 5.5, 5.0 and 4.8
[87]	0%, 1.5%, 2.0% and 2.6%	7 Days 1.5, 2.0, 1.6 and 1.4 28 Days 2.3, 2.5, 2.3 and 1.7

According to the test findings [95], the addition of sisal fibers may increase the compressive strength by around 6% and the tensile strength by about 4% when compared to the reference concrete. This was because the sisal strands store moisture that is gradually released after hydration, aiding in the development of strength. It was determined that raising the fiber content from 0% to 20% by weight increased TS almost three times [55]. Studies stated that fibers enhanced tensile capacity more successfully than CS [6,64]. The CS of the mortars improved with the addition of coir fibers up to 0.5 percent as compared to the control mortar, but it decreased with a higher content of coir fiber [96]. Coconut fibers are the strongest natural fibers, having a TS of 21.51 MPa. They can withstand stresses that are four to six times greater than those encountered by other natural fibers. Various research has investigated the use of coconut fibers for a variety of purposes. The diameter of the fibers is virtually the same, and the levels of TS are similar. The fibroblasts of different individual cells, for example, were affected by kind of plant, its location, and puberty, among other things [56]. The use of fibers in concrete may increase the flexural strength of the concrete [97]. Fiber improves concrete strength by bridging and bearing a portion of the stress [98]. The coaxial TS of jute/epoxy and SSF/epoxy composites was raised by 32% as compared to sisal epoxy. The TS of a hybrid composite was reduced [83]. The tensile and flexural characteristics of ionomer-treated SSF improved as a consequence of uniform stress distribution and the changing of the matrix to scattered fibers, according to certain research [99]. At relatively low fiber dosages of up to 1%, increased fiber content has only a positive influence on concrete TS. Similarly, a significant impact of fiber length on concrete TS was identified for lower fiber levels of up to 1%, with longer fibers being more effective than shorter ones. However, an inverse trend was noted above 1% fiber content. This phenomenon is more noticeable at the extremes of fiber dosages (i.e., 0.1 and 2.5 percent) [91]. Superior impact strength with moderate tensile and flexural qualities are produced by SSF-reinforced composites. When the 2.0 percent dosage was surpassed, however, the strength was reduced [64]. Fibers are employed in concrete to enhance flexibility by delaying the emergence of tension fractures or by preventing the formation of cracks, resulting in a TS of fiber-reinforced concrete that is higher than conventional concrete. Crack stopping rather than crack prevention is derived from the impact of fibers. When compared to other materials, fiber has a bigger influence on TS than compressive strength. The prevention of cracks (bridging effect) of SSF is shown in Figure 9. Fibers have been proven in many studies to boost the TS of post-cracking behavior [100]. At volume fractions ranging from 0.5 to 2.0 percent, which were used in this research, fibers were shown to have a greater effect on TS [101]. Overall, the SSF has the credibility to improve the tensile capacity of concrete in a similar way to the other types of fibers such as steel or carbon fibers.

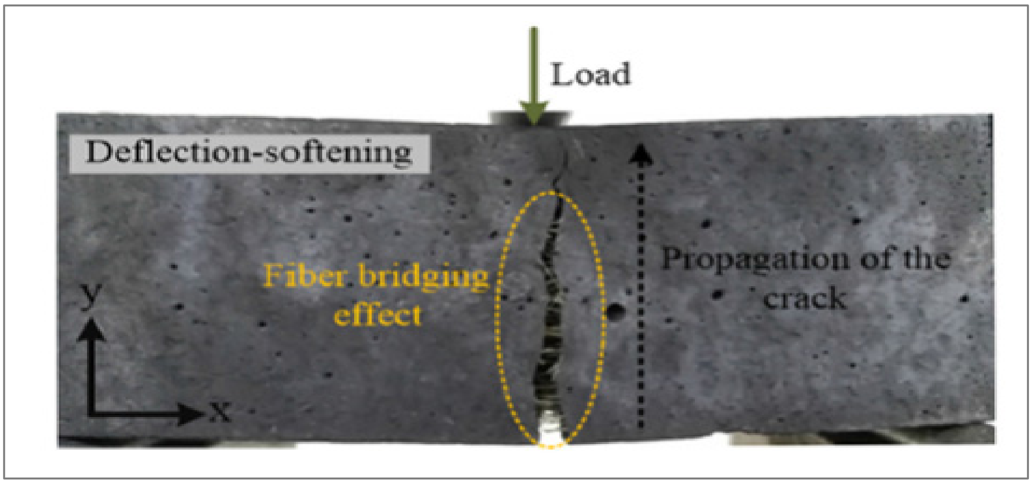

Figure 9. Crack prevention of SSF [60].

4.4. Fatigue Behaviors

Most concrete or FRC fatigue testing has been carried out under bending loads [102]. Damage to the fatigue type results in permanent, regional, and gradual structural alteration [103]. In a static test, loads that are less than the material ultimate tensile cause cyclic stresses. Fatigue affects every known engineering material that is exposed to cyclic stresses that are repeated. Machine vibration, maritime constructions, wind action, and vehicle traffic are a few examples of these cyclic loads [104]. When loads lower than the design load are applied for many stress cycles, the structure may collapse [105]. The structure rigidity gradually decreases because of repetitive stress, which might ultimately result in fatigue failure. With the creation of concrete railroad bridges that were subjected to millions of cycles throughout their lifetime, interest in concrete fatigue first emerged [106].

According to Naaman and Hammoud [107], combinations of fiber-reinforced concrete that include 2% of hooked steel fibers may withstand bending fatigue forces that are more than twice as great as those of ordinary concrete. Average fatigue lifetimes of precracked FRC specimens were in the order of 10 cycles for loads between 10% and 90% of static strength, 8000 cycles for a load range between 10% and 80%, and more than 2.7 × l06 cycles or a load range between 10% and 70% [107]. According to the findings of fatigue tests [108], sisal fiber may lengthen the fatigue life of foamed concrete. When the sisal fiber percentage is less than 0.15 percent, the stronger the concrete is when the sisal fiber content is greater. The fatigue life of the foamed concrete will decrease with an increase in sisal fiber content if it is larger than 0.15 percent. A study [109] investigated the fracture spacing of cement composites reinforced with sisal fibers under tensile and bending responses. The results showed that the sisal fibers can arrest and bridge cracks even when the composite is subjected to 106 cycles at 50% of ultimate tensile strength. The authors then conducted additional research on the pull-out behavior of sisal fiber from a cement matrix and investigated the tensile fatigue behavior of long-aligned sisal fiber-reinforced cement composites. Parant et al. [110] evaluated multi-scale steel fiber cement composites under bending fatigue and found that specimens could withstand up to 2 million load cycles below a loading ratio of 0.88 (maximum fatigue stress range from 35.9 to 40.8 MPa for a modulus with a rapture of 61.5 MPa). Only a few articles [111,112] and tension loads [113] discuss fatigue under uniaxial compression.

5. Physical Properties

5.1. Water Absorption (WA) of Concrete

There is an indirect way of determining concrete durability. In general, water contains hazardous substances. These components react with cement ingredients, resulting in differences in concrete performance. Owing to temperature changes, more water in the pore of the cement concrete freezes and thaws, causing the concrete structure to fracture due to expansion and contraction [114].

The immersion WA of concrete is a significant feature that provides an indirect indicator of the concrete's pore structure and endurance in corrosive environments [115]. Figure 10 shows the WA of concrete in the current investigation. The findings show that reinforcing concrete with sisal threads increases concrete's WA significantly. When 0.5 percent SSF was added to concrete, the absorption rate increased by 28.99 percent after 28 days. Following that, successive additions of 0.5 percent SSF resulted in minimal change until 2 percent SSF was added to the mix, resulting in a 49.176 percent increase in WA above the control concrete. In conclusion, increasing the proportion of SSF in the mix increased the WA of concrete cubes. A similar conclusion was reached by the authors in [116].

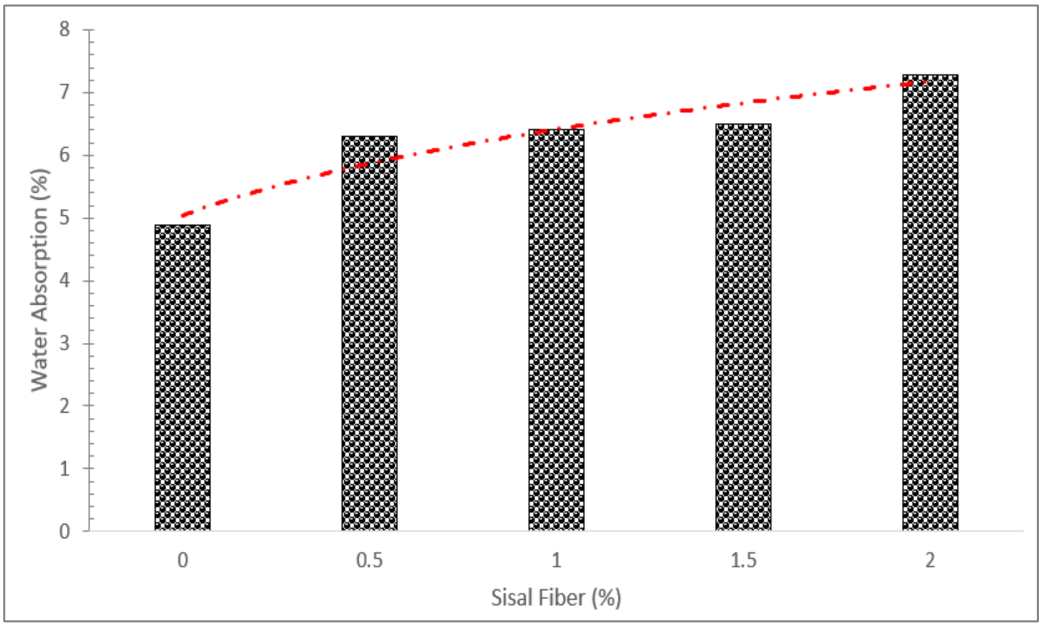

Figure 10. Water absorption: data source [37].

Although the research in [117] suggested that adding additives such as silica fume to concrete might help reduce FRC's WA, reduced workability caused poor compaction and enlarged pores, resulting in a direct link between WA and SSF percentage. WA decreases as the amount of fibers substituted rises to 2.0 percent substitution and then steadily decreases, with a maximum WA at 0% replacement and lowest WA at 2.0 percent addition of fibers [20]. It was also discovered that a 2.0 percent replacement of fibers resulted in the lowest WA [6]. This is because ordinary concrete's elastic modulus is lower than fiber-reinforced concretes. As a consequence, the insertion of fibers strengthens the tensile characteristics of concrete, limiting the creation and propagation of early fractures [118]. In other words, the density of concrete is raised, resulting in a reduction in concrete WA. WA increased at larger dosages (above 2.0 percent) owing to a lack of workability and resulting in less dense concrete. Fibers serve as a link for the pores in concrete, improving permeability and porosity, and allowing the concrete to absorb more water [117]. Furthermore, fiber inclusion leads to greater capillary activity. Fibers may operate as a water-conducting route, allowing concrete to absorb more water [119]. As a consequence, when exposed to a corrosive environment, concrete becomes more prone to deterioration, making it less resilient. The rate of water absorption of sisal fibers was reduced when it was surface treated with cellulose acetate polymer. The greatest absorption of treated sisal was 88 percent after 10 days of immersion, whereas raw sisal showed values of 200 percent [120].

5.2. Density

Compressive strength and long-term durability are required in concrete. The mechanical properties of concrete are influenced by its density. Denser concrete is stronger and has less voids and porosity. Water and liquid chemicals are less permeable to concrete and have fewer voids. As a consequence, the penetration of WA or other dangerous chemicals will be minimized, and this kind of concrete will endure longer.

Because of the increasing hydration, the density rose from 7 to 28 days, although the densities at each curing age tend to decrease when the amount of SSF increases, as shown in Figure 11. The results reveal that 0% fiber has the greatest density (2120 kg/m^3) and 2% fiber has the lowest density (2032 kg/m^3), both of which are beyond the range of structural lightweight concrete and hence may be categorized as normal weight concrete. At 7 days of curing, the density of 0.5%, 1.0%, 1.5% and 2.0% addition of fiber-reinforced concrete was lowered by 1.14%, 3.41%t, 3.74%, and 4.18%, respectively, when compared to control concrete. The percentage reductions in density for SSF additions of 0.5%, 1.0%, 1.5%, and 2.0% were 1.24%, 3.18%, 3.71%, and 4.13%, respectively, after 28 days of curing. Because of the decreased bulk, the density and proportion of SSF have an inverse relationship. Sisal density replaces denser elements such as coarse and fine particles [121].

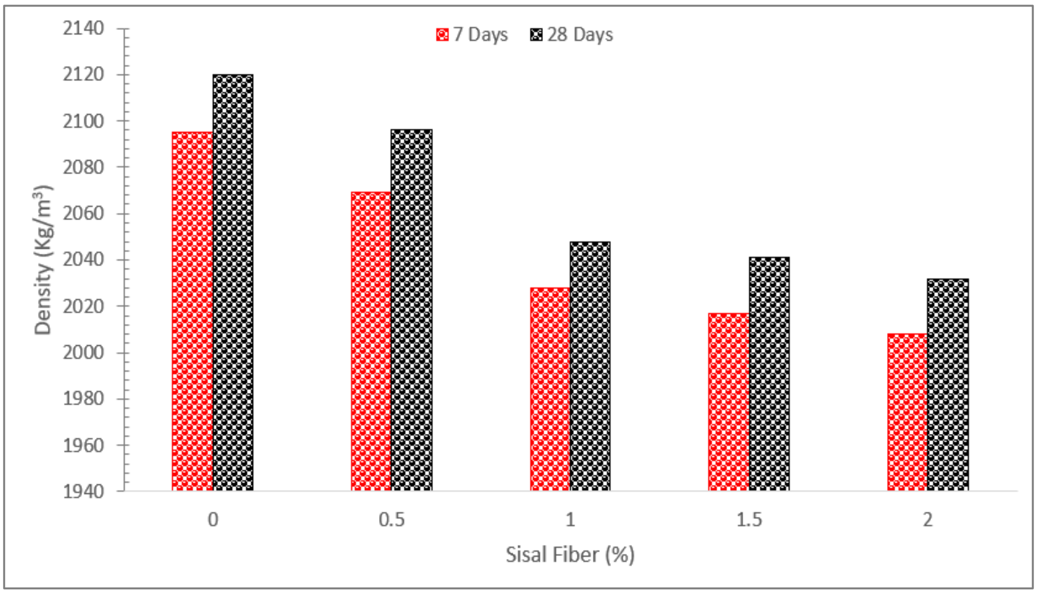

Figure 11. Density: data source [37].

When compared to the reference concrete, coconut fiber with a 2.0 percent dose had the highest density. When compared to other coconut fiber-reinforced concrete, density was lowered with the addition of fibers, with a minimum fresh density at 3.0% addition of coconut fibers [20]. Because coconut fiber-reinforced concrete has less and produces more dense concrete, the density of concrete blends with fibers decreases. As a consequence, fresh-density concrete improves. However, at greater doses, such as 4.0 percent fiber replacement, the compaction process becomes more difficult, resulting in porous concrete and a lower fresh concrete density. If 1.5 percent of fibers by volume are added to the concrete, the fresh density is enhanced by around 15% [122]. Overall, less studies were conducted regarding the density of concrete with the addition of SSF and more in-detail investigations are suggested.

6. Microstructure Analysis

6.1. Scan Electronic Microscopy (SEM)

Scanning electron microscopy (SEM) may be used to investigate sample surfaces (EDS). These techniques are used in applications such as material surface analysis, product failure investigation, reverse engineering, contaminant detection, solder joint evaluation, and others. Figure 12 shows SEM images of the composite. As demonstrated in Figure 12a,b,d, the microstructure of SSF has been revealed to be mineralized. An energy-dispersive X-ray indicated a substantial Ca concentration within the sisal strand as shown in Figure 12c,d. Ca EDS mapping was conducted at the fiber–matrix contact, and the findings indicated a high Ca intensity, as shown in Figure 12e,f. This micro-structure investigation demonstrates that the fiber cells are mineralized owing to greater Ca intensity. In the CH-free composite, there were no indications of fiber breakdown, and there was a much-decreased Ca level inside the fiber cells. The substitution of metakaolin and calcined waste-crushed clay brick to the CH-free composite successfully maintained its energy absorption capacity, improved its primary crack formation, and preserved its final capacity over rapid aging, demonstrating that natural fiber-reinforced concrete has durability issues. The findings found that utilizing the quicker aging method is similar to that which was found by researcher in a past study, with the same materials utilized for wetting- and drying-accelerated aging [123].

The improved packing of the mineral particles with refined sisal pulp was the cause of the more compact microstructure [124].

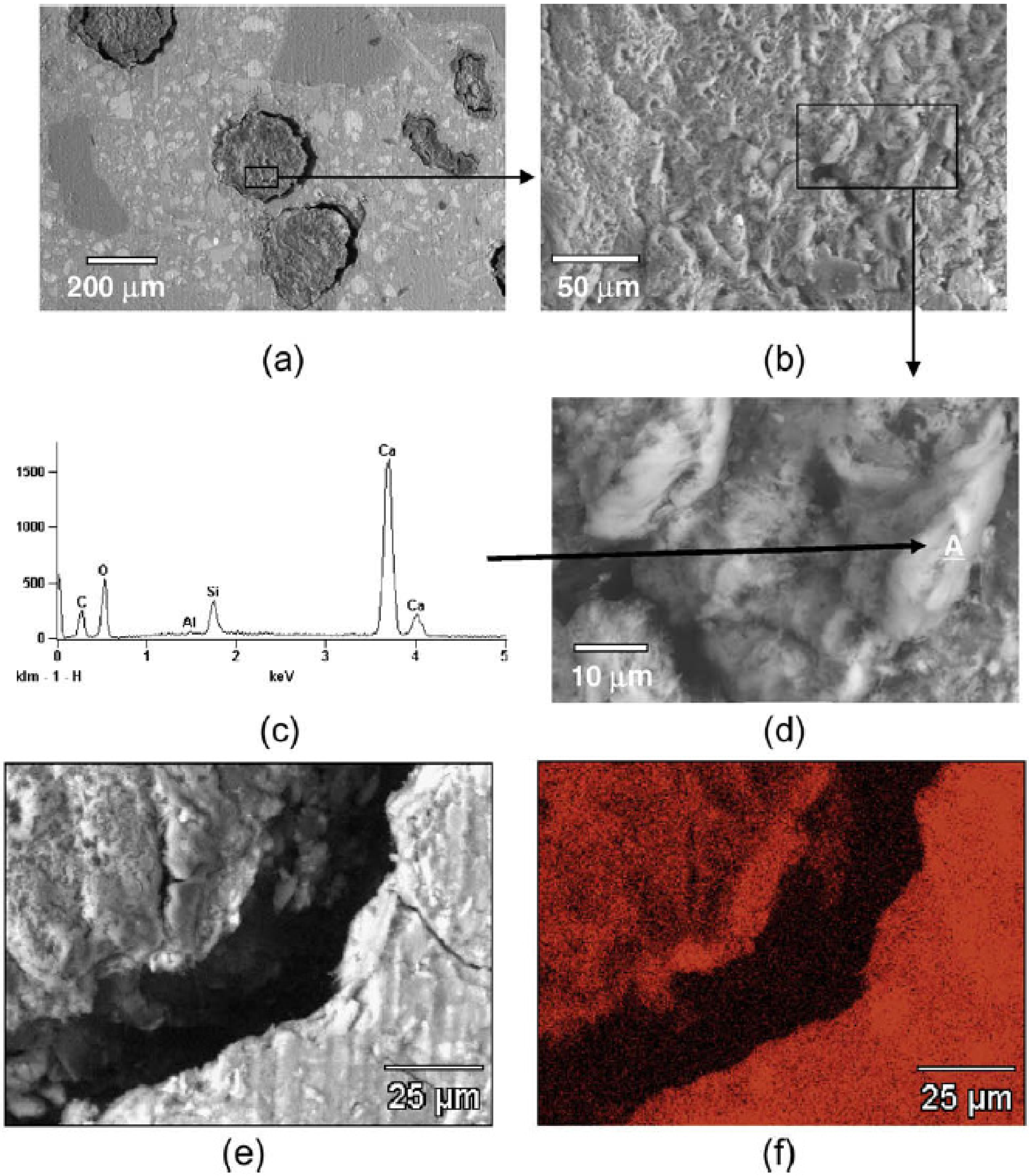

Figure 12. SEM results: (**a**) view of the composite as a whole; (**b**) SSF; (**c**) EDS point A; (**d**) region for EDS; (**e**) EDS mapped; (**f**) EDS mapping for Ca interface. Reprinted with permission from Ref. [125]. 2022 Elsevier.

6.2. Fourier Transform Infrared Spectroscopy (FITR)

The C-O stretching groups of lignin in untreated SSF produce distinctive peaks at 1730 and 1245 cm^{-1}, respectively [126]. The distinctive axial vibration of the hydroxyl group of cellulose causes a wide peak in the range of 3300–3500 cm^{-1} and a peak at 1630 cm^{-1} (preferably from the 2, 3 and 6 carbons of glucose). The related hydrogen group is responsible for the peak at roughly 1080 cm^{-1} [127]. Because of Si-O plane stretching vibrations, Na+ clay displays a peak at 1030 cm^{-1} [128]. At 3600 and 1630 cm^{-1}, there are also a few moisture groups owing to OH. Clay phase (Si-O) and SSF (cellulose) phases may be seen in the NaOH-clay-treated SSF. The breakdown of the lignin phase is evident in the NaOH and NaOH-clay-treated SSF owing to the lack of their typical peak at 1727 and 1245 cm^{-1} and similar results have been found elsewhere due to alkaline treatment [129]. In addition, in NaOH-clay-treated SSF, there is no related hydrogen group. In the NaOH-clay-treated SSF, the hydroxyl group of untreated SSF was eliminated at 1630 cm^{-1} (due to cellulose). It was also shown that the chemical treatment of SSF increased the C-H bending vibration of cellulose at roughly 1380 cm^{-1}, owing to cellulose structure. This hydroxyl peak broadens much more in the NaOH and NaOH-clay-treated SSF, forming a shoulder at 2945 cm^{-1}. The frequency of polysaccharides may have moved to 2945 cm^{-1} due to inter- or intramolecular hydroxyl group interaction. One study [130] indicated that alkaline treatment broadens the hydroxyl peak, and increasing peak broadness as a function of NaOH concentration (5 and 10 percent) was found. Because the highest quantity of NaOH (40 percent in water) was utilized in this experiment, the peak was further widened.

EDX was used to determine the concentration of elements contained in the treated and untreated SSF, and the elemental results are reported in Table 6. The presence of C and O components in untreated SSF is attributable to the organic phase of the cellulose polymer. The occurrence of Al, Si and Na phases in SSF treated with NaOH-clay is shown in Table 6. The carbon and oxygen content of NaOH and NaOH-clay-treated SSF has likewise been shown to be lower than that of untreated SSF. The decrease in C and O elements indicates that the alkaline treatment dissolves the lignin phase, which is predominantly composed of C and O components.

Table 6. EDS results. Reprinted with permission from Ref. [56]. 2022 Elsevier.

Chemical	Untreated	NaOH Treated	Clay Treated
C	51.7%	48.2%	47.1%
O	47.9%	42.3%	40.5%
Na	-	9.2%	8.3%
Al	-	-	1.8%
Si	-	-	2.1%
Remaining	0.4%	0.3%	0.4%
Overall	100%	100%	100%

7. Application of SSF in Construction

Traditionally, cement has been utilized for structural purposes for decades. There is a need for alternate materials or a technique to minimize the price of housing functions due to the rising need and cost of the raw material. Roofing tiles, dividing boards, flat and corrugated sheets, and other sisal–cement composites have long been investigated in underdeveloped nations for use in the construction of low-cost dwellings and structures [131]. Because of its high thermal and acoustic insulation capabilities, as well as exceptional tensile strength and toughness, SSF takes the lead among plant fibers in the building sector. Surprisingly, research on cement composites reinforced with SSF has also revealed the material's possibility to be employed in buildings, owing to its greater water permeability resistance [125] and mechanical qualities that are suitable for structural applications [132]. The deterioration of natural fiber-reinforced concrete over time is the biggest stumbling block to their use in the building. This constraint may be circumvented by using low alkali cement, which significantly minimizes fiber deterioration, making natural fiber-reinforced cement a viable option [133].

For fibers made from natural sources, in a variety of industries, including automotive, aerospace, marine, sports goods, and electronics, reinforced composites are quickly gaining popularity as a viable substitute for metal- or ceramic-based materials [134]. Natural fibers are used in a variety of goods, including building materials, particle boards, insulation boards, human and animal feed, cosmetics, medicines, and other biopolymers and fine chemicals [135]. As a consequence, monolithic materials are being phased out in favor of fibers and materials such as carbon, glass, and aramid fibers, which are extensively used in industries such as aerospace, automotive, construction, and sports [136]. Natural fibers are utilized as reinforcement in composites (such as cement paste, mortar, and concrete) in the construction industry because they are cost-effective in increasing tensile strength, shear strength, toughness, and energy absorption capacity [137]. Natural fiber composites provide a number of benefits over synthetic fiber composites, including cheap cost, being lightweight, high specific mechanical characteristics, nonhazardous nature, eco-friendliness, renewability, and so on. As a consequence, its use in a variety of fields, including aeronautical engineering, seems to be promising [136]. Natural fiber parts for interior components are widely produced in the automobile and aerospace industries [138]. Natural fibers are also utilized to manufacture a variety of insulation materials, such as blowing insulation, pouring insulation, impact sound insulation materials, and ceiling panels for thermal and acoustic soundproofing [139].

8. Conclusions

The objective of this assessment is to give useful and complete information on current research and advancements in the mechanical characteristics of SSF-based concrete. This review article also gives a database for the choice of SSF in the construction and building sectors. The following is a summary of the important findings from the current research on SSF-based reinforced concrete:

- The physical characteristics of SSF vary depending on the age of the plants.
- Flowability decreased with the addition of SSF because of the additional surface area of SSF, which needed additional water.
- The strength properties of concrete increased up to a certain limit with the addition of SSF in a similar manner to other types of fiber. It was also observed that SSF does not have much improved compressive capacity as compared to flexural or tensile capacity.
- Water absorption increased and density was reduced with the addition of SSF. However, less information is available in this regard.
- The FTIR and EDX results of NaOH-clay-treated sisal fiber shows dissolution of the amorphous lignin phase and a crystalline fraction of 76%. About 20 wt.% of clays were presented in the NaOH-clay-treated SSF. However, the information is less, and more detailed studies are required.

9. Future Work

- There are no or few studies conducted on the durability of concrete, particularly acid attacks, dry shrinkage and creep properties with the addition of SSF. Therefore, this review also recommends a detailed investigation of the acid attacks, dry shrinkage, and creep properties with the addition of SSF
- Thermal properties were not studied in the past available research. Therefore, this review recommends the conduction of thermal characteristics for SSF-based composites.
- No or little improvement in CS of concrete made with SSF was observed. Therefore, this review recommends adding pozzolanic materials into SSF-based concrete to achieve better concrete.

- The higher doses of SSF cause decreased mechanics and durability due to a lack of flowability. Therefore, this review recommends a detailed investigation of different dose plasticizers at a higher dose of SSF.

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