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Application of Natural Plant Fibres in Development of Sustainable Concrete: A Review

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Concrete is the most prevalent material used for construction purposes. The steel reinforcement is often done to provide tensile strength and ductility to the buildings. There are environmental concerns related to the manufacturing process of reinforced concrete structures, including carbon dioxide emission, alongside the problem of corrosion of the steel reinforcement. Natural plant fibers have gained significant attention in recent years as sustainable alternatives due to renewable, energy-efficient, improved flexural strength, reduced environmental impact, enhanced workability, cost-effectiveness, aesthetic appeal, and compatibility with existing infrastructure. Utilization of natural fibres has limitations, including higher moisture absorption rate and hydrophilicity, which is correlated with a reduction in compressive, tensile, and flexural strength. In addition, long-term durability issues, *viz*., increased shrinkage and swelling, reduce the overall performance compared to the synthetic fiber-reinforced concrete. Despite these constraints, continued research efforts are aimed at overcoming these challenges through improved fiber treatments, modified concrete formulations, and enhanced construction practices to maximize the features of natural fibers in concrete applications. This review aims to present a comprehensive compilation of the utilization of natural fibres in the development of sustainable concrete.

Keywords: Concrete applications, Environmental impact, Fiber-reinforcement, Reinforced concrete, Sustainable concrete

Introduction

Concrete is widely recognized as a building material for having superior Compressive Strength (CS) and less Tensile Strength (TS). The annual worldwide consumption of concrete is approximately 17.50 billion tonnes. The total consumption comprises aggregate (13 billion tonnes) and cement (2.6 billion tonnes).[1] The overuse of mining and quarrying to gather aggregates resulted in the depletion of natural resources and has a direct detrimental effect on the ecological environment, including the destruction of ecosystems and landscapes.[2] Cement is responsible for 74–81% of carbon dioxide (CO_2) emissions from concrete manufacturing.[3] The CO_2 emissions associated with conventional normal-strength concrete mixes, where Portland cement is the sole binder, have been reported to range from 0.29–0.32 tons of CO_2 equivalent per cubic meter.[3] Corrosion of steel reinforcement due to moisture infiltration and carbonation of concrete can lead to the deterioration of structures, increasing maintenance costs, and reducing the lifespan of buildings. Additionally, the emergence of concrete cracks poses a major threat to a building's structural integrity. It is noteworthy that ordinary concrete is fragile, and therefore, an approach for making concrete a ductile material is required.

Natural Fibers (NF) are sustainable with the added advantages of being low-cost, lightweight, recyclable, biodegradable, non-carcinogenic, safe to handle, and process. The inherent flaws in cement-based substances can be resolved with the supplementation of NF as reinforcement. The incorporation of NF into cement can enhance the flexural and bending attributes of concrete, along with a reduction in crack formation.[4] NF *viz*. banana, flax, hemp, bamboo, coir, kenaf, sisal, jute, pineapple, and ramie fibres have been studied extensively for their potential to amplify the mechanical characteristics *viz*. split TS, flexural strength, shear strength, impact resistance, energy absorption, and deflection of concrete. Further, NF improves volumetric stability and internal curing, which both minimize early-age shrinkage in high-performance concrete.[5]

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Commercial entities involved in plant fiber-based concrete production include M/s. Hempcrete Ltd. (using hempcrete for eco-buildings), M/s. Bamboo India (producing bamboo-based concrete products), and M/s. Coir Board (promoting the use of coir fibers in cement for road construction). These processes help produce sustainable, eco-friendly concrete alternatives that can be used in various construction applications while minimizing the environmental impact of traditional concrete manufacturing.

Ramakrishna and Sundararajan[6] stated that there are serious worries about the durable performance of NF in a highly alkaline cement matrix. Additionally, the natural limits of plant fibres, such as water swelling and drying-induced shrinkage negate the fiber-reinforcing effect. To increase compatibility and interfacial binding strength, NF must have its surface modified.[7] Additionally, it's crucial to consider factors like fibre content, fibre length, surface modification, mixture design, mixing method, placing method, and curing method when using NF in concrete.

The research gaps in NF-reinforced concrete include the long-term durability of fibers in the alkaline cement matrix and the optimization of fiber-matrix bonding. Effective surface modification techniques need further exploration to enhance compatibility and mechanical performance. Additionally, the lack of standardized testing procedures for fiber characterization and performance assessment hinders consistency in research and industrial applications. The economic feasibility and lifecycle environmental impact of NF-reinforced concrete, along with its suitability for specialized applications, need to be studied.

This review is a comprehensive analysis of multiple NF in fiber-reinforced concrete, unlike conventional studies that focus on individual fibers. It highlights the mechanical performance, durability challenges, and environmental benefits while addressing key limitations. Novel strategies, including fiber surface modifications, optimized mix designs, and hybrid fiber approaches, are explored to enhance the performance. By identifying critical research gaps, standardization needs, and economic feasibility, it offers a roadmap for advancing NF-reinforced concrete as a mainstream sustainable construction material.

Natural Plant Fibres

The chemical characterization of NFs differed significantly due to the fibre extraction process carried out at different stages, and also the method of extraction. They may be separated from the plant stalk, stem, seed, or leaf. The cellulose content in the fiber is reported to have a positive correlation with the TS, Young's modulus, and stability of the plant fiber.[8] Hemicellulose is accountable for biodegradation, moisture absorption, and thermal degradation, whereas lignin is thermally stable but susceptible to UV degradation.[9] The chemical composition of plant fibres is listed in Table 1.

The mechanical properties of fibres *viz*. CS, TS, flexural property, impact strength, and wear behaviour are the indication of the material's capacity to endure extreme loading and in critical conditions. Microfibrillar angle (MFA) is considered to be responsible for the axial strength properties of a fiber. Various NF's have distinctive morphological

Table 1 — Chemical composition

	Cellulose (%)	Hemicellulose (%)	Pectin (%)	Lignin (%)	Fat and wax (%)	Ash (%)	Moisture (%)
Banana[10,11]	31.27–65	6–19	3–5	5.00–15.07	1.2	2.60–8.65	9.74–13.10
Flax[9,11]	60–85	16–18	1.8–15.0	0.6–5.0	1.0–6.0	—	7
Hemp[9,11,12]	70–92	18–22	3	2–5	0.8–1.7	—	8
Jute[10,13,14]	51–84	12.0–20.0	0.20–0.38	5.00–14.56	0.5	0.5–2.0	7.0–12.6
Kenaf[12,15]	56.4–72.0	20.3–26.2	3–5	9.0–14.7	<1	2.2	—
Ramie[9,10,16]	68–76	13–15	1.0–1.9	0.6–9.3	0.3	2.1	12–17
Abaca[12,17]	56–68	17.5–25.0	<1	5.0–15.1	3.0	—	—
Sisal[17,24]	52.8–76	10–16	10–14	7–13	0.3	—	5
Pineapple[10,17]	55–81	6–20	2–4	4.6–12.0	4–7	2–3	—
Cotton[9,10,18]	82–98	2–6	4–5.7	0.5–1.0	2–3	—	8–25
Kapok[23,24,45]	13–35	23–32	7–23	13–21	<1	—	—
Coir[9,12]	32–43	0.15–0.25	3	40–45	0–6	—	10
Bamboo[12,19]	26.0–54.6	11.4–30.0	<1	21–31	1–4	—	—
Softwood & hardwood[20]	38–47	19–35	0.4–5	16–34	<1	—	—

attributes and therefore considering them into a single ambit is not desirable. The physical, mechanical, and microscopic characterization of the longitudinal and cross-section of different NF are mentioned in Table 2 and Fig. 1.

Important Properties of Concrete Required in Construction

As per the Indian standards[55], the quality of concrete is decided by virtue of size, density, CS, water absorption, and drying shrinkage. The detailed specification is given below:

Dimensions

The concrete block must have the specified dimensions *viz*. length (400, 500 or 600 mm), width (50, 75, 100, 150, 200, 250, or 300 mm), and height (200 or 100 mm). Moreover, the block should be prepared in half length of 200, 250, or 300 mm. The maximum variation allowed should be limited to ± 5 mm (length) and ± 3 mm (width, height).

Block Density

A block's density is determined as the fraction of its mass and volume, which includes any holes, cavities, and end recesses.

Compressive Strength

The concrete's qualities are represented by its CS. The multiple factors that might affect include the quality of coarse aggregates, strength of cement, water: cement, sand quality, and quality control during production (Table 3).

Water Absorption

The water absorption should be ≤10% by mass.

Drying Shrinkage

It is the average of three units, and should not increase by more than 0.1%.

Moisture Movement

Consequent to the immersion in water, the moisture movement of the dried blocks shall not exceed 0.09 %. This measurement may be repeated thrice for clarity.

Process for Preparation of Fibre Reinforced Concrete

The commercial manufacturing process of NF-based concrete involves fiber preparation, concrete mixing, quality control, molding, curing, and strength testing to ensure its structural viability (Fig. 2). Coir, jute, hemp, sisal, flax, and bamboo are used as reinforcements to improve concrete's mechanical properties, crack resistance, and durability. These fibers undergo preprocessing, such as hammering, fibrillation, or chemical treatments, to enhance their bonding with the cement matrix and prevent clumping. The typical composition of fiber-reinforced concrete includes cement (10–20% by volume), fine aggregates (20–30%), coarse aggregates (35–45%), water (12–18%), and NF (0.5–5% fiber volume fraction), depending on fiber type and desired strength characteristics. Once the fibers are mixed with dry cement and aggregates, water is added, and the fresh concrete undergoes a slump cone test to assess workability. The prepared mix is then cast into molds, commonly in cube or beam shapes for testing purposes, and compacted to remove air voids. After

Table 2 — Physical and mechanical properties

NF	Type	Length (mm)	Diameter (µm)	Apparent density (g/cm^3)	TS (MPa)	Young's modulus (GPa)	Elongation at break (%)	MFA (°)
Blast fibres	Banana[10,21,22]	1000–1500	80–250	1.34–1.95	320–500	25–38	2.40–3.22	11–12
	Flax [23–26]	6–80	12.4–23.9	1.29–1.5	300–2000	15–160	1.2–5	8.3–11
	Hemp [27,28]	5–55	10.9–42	1.4–1.6	285–889	14.4–44.5	0.8–3.3	11
	Jute [14,29–31]	1–120	15–200	1.38–1.49	114–800	10–31.2	1–1.8	7–12
	Kenaf [32–34]	30	100–500	1.2–1.45	129–930	9.02–53	1.26–2.7	9–15
	Ramie [16, 35,36]	9–25	90–155	1.0–1.6	400–1000	24.5–128	3.6–8.95	7.5
Leaf fibres	Abaca [35,37–39]	2–17	150–260	1.5	1760.22	17.1–18.4	6.2–8.8	5–17
	Sisal [30, 40–41]	28–32	20–300	0.9–1.5	343–577	10.94–30.3	2.08–4.08	10–25
	Date Palm [42]	60	100–1000	1.3–1.45	210–270	3–7	10–14	—
	Pineapple [17,43]	3–8	7–18	1.07–1.53	126.60–1627	4.41–82.51	1.41–4.0	8–15
Seed fibres	Cotton [18,23,44]	10–60	—	1.5–1.6	287–800	5.5–13	3–10	20–30
	Kapok [23,24,45]	7–35	8–35	1.3	45–93	1.7–4.0	1.2–4.0	5
Fruit fibres	Coir [30,46,47]	20–30	100–460	1.15–1.3	131–343	4–22.4	3.7–44.7	30–49
Grasses and reed fibres	Bamboo [48–50]	0.5–5	5–40	0.86–1.44	1200–1610	32–43.7	3.8–10.6	8–10.7
Wood fibres	Softwood, Hardwood[51–54]	1–8	10–60	1.44–1.50	553–1300	15.4–27.5	3–7	5–40

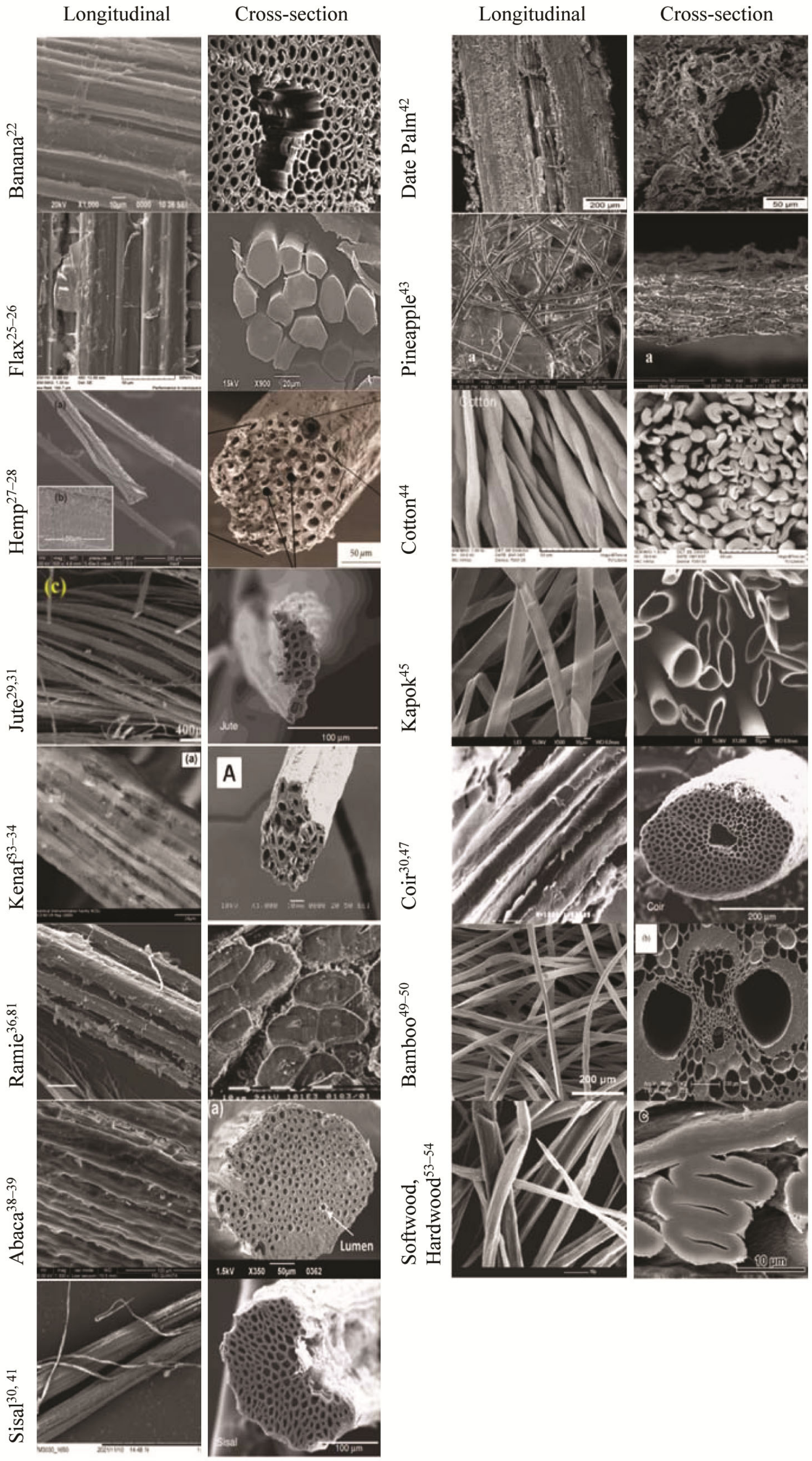

Fig. 1 — Longitudinal and cross-section micrographs of different plant fibers

Table 3 — Physical requirement of concrete (Ref: IS: 2185 (Part I))[55]

Type	Grade	Block density (kg/m^3)	Minimum CS of units (N/mm^2)	Minimum strength of individual units (N/mm^2)
Hollow (Open and closed cavity) load bearing unit	A (3.5)	≮1500	3.5	2.8
	A (4.5)		4.5	3.6
	A (5.5)		5.5	4.4
	A (7.0)		7.0	5.6
	B (2.0)	<1500 but ≮1000	2.0	1.6
	B (3.0)		3.0	2.4
	B (5.0)		5.0	4.0
Hollow (Open and closed cavity) non-load-bearing unit	C (1.5)	<1500 but ≮1000	1.5	1.2
Solid load bearing	D (5.0)	≮1800	5.0	4.0

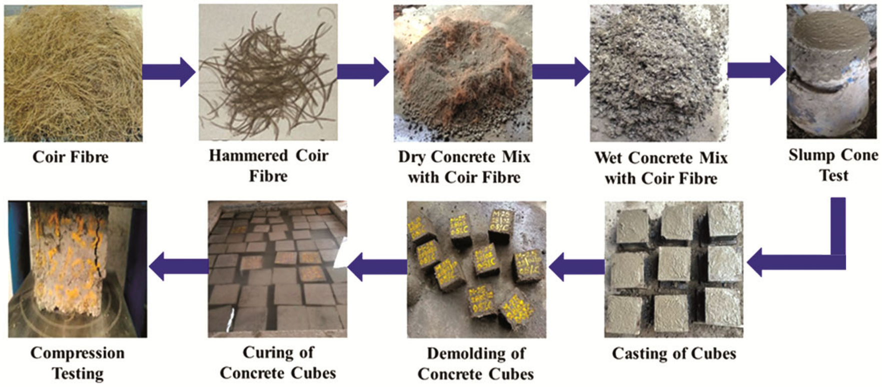

Fig. 2 — Process for preparation of coir fibre reinforced concrete cubes[80]

the initial setting, the specimens were carefully demolded and subjected to a controlled curing process (28 days). Finally, compression and flexural strength tests are performed to evaluate the mechanical performance of the fiber-reinforced concrete. The proportion and type of fiber are optimized based on application requirements, ensuring enhanced durability, impact resistance, and eco-friendliness.

Natural Fibers as Construction Materials

Banana Fibres

Banana fibers (BF) are lignocellulosic with helically woven cellulose microfibrils, high cellulose content, and low microfibril angle, giving them excellent mechanical strength and resistance to impact, heat, and corrosion. These properties make them effective for enhancing concrete performance.

Mugume *et al.*[21] evaluated the concrete mixtures having BF (40-60 mm), fibre content (0.1-2.5%), and reported that length had a non-significant effect on CS at less fibre content ≤0.25%. Simultaneously, it was also seen that the shorter fibres were superior as compared to the longer ones at high dosages of ≥0.25%. Shorter fibres at lower dosages have a significant influence on the flexural strength of concrete. By enhancing the microstructure of the concrete and strengthening the bonds between the fibres and matrix, the incorporation of BF increased the mechanical qualities of the concrete. Addition of BF should be kept to a maximum of 1% of the total fibre content, ideally utilizing shorter fibre lengths, for best results.

The incorporation of 0.5% BF to reinforced concrete, according to Kesavraman[56], resulted in an 18.62% improvement in CS after 28 days. The reported increase in flexural strength and split TS was 17.64% and 15.18%, respectively. However, the impact energy of the concrete having 2% BF was 36.9% higher than control, highlighting the fact that BF resists the concrete break.

The flexural toughness index of BF-reinforced concrete (5% weight and 50 mm length) improved while the modulus of rupture was reduced by 39%. However, compared to regular Portland cement, the hardness index and total energy absorption were 580% and 404% higher, respectively. Owing to the enhanced bridging effect and binding strength between the fibres and concrete matrix, the availability of less dense and lighter fibres decreases the strength of fibre-reinforced concrete.[57]

In overall, BF improves strength and toughness of concrete when used at low dosages with shorter lengths. However, excessive dosage and long fibers may reduce performance due to clustering and low density.

Flax Fiber

Flax fibres (FF) have the highest specific tensile characteristic.[27] FF is a cellulose polymer with a higher crystalline structure, making it tougher and stronger, simultaneously extra brittle and wrinkle-prone. Lai *et al.*[58] showed that alkali treatment enhanced the crystallinity and roughened the surface of FF, which improved adhesion between the cementitious matrix and fibre by eliminating amorphous portions. The key factor causing the decline of CS in FF-reinforced cement composites is that FF improved the quantum of macropores, voids, and microcracks. The surface treatment of FF with EDTA (5 g/L for 4 h) improved TS (by 82.7%) and elastic modulus (by 13.6%). Treating FF with stearic acid (1% for 4 h) resulted in a 200% rise in TS and a 31.3% rise in elastic modulus. Lower thermal conductivity (4%), lower elastic modulus (49%), increased residual TS, and fracture energy (88%) were the results of concrete mixes reinforced with treated FF (0.5%).

It was observed that a 0.25% addition of FF resulted in similar results to the control mix. It indicated that the cement paste would be able to coat the fibres, making it impossible for the water to infiltrate the matrix.[25] In contrast to the control specimens without fibre, Fernandez[17] found that adding 5% FF (30 mm) to concrete increased the compressive and flexural strengths of the mortar specimens by 10% and 28%, respectively.

Due to the flexible nature of FF, adding it to cementitious matrices causes fibre clumping, which lowers the characteristics of both fresh and cured concrete.[59] Page *et al.*[60] observed that adding 0.1-0.3% FF significantly decreased the workability of concrete and suggested utilizing FF with a shorter length as a solution to curtail the workability loss. However, when the fibre length decreased, FF's effectiveness in enhancing the mixture's mechanical qualities decreased.

Rahimi *et al.*[59] reported that mixing FF to the cementitious matrix (at 183 rpm for 6 min) was sufficient to increase fibre homogeneity, enhance flowability, and improve mechanical characteristics. The addition of FF (1.2%) in dry form has a detrimental influence on flowability (by 30%). However, soaking (24 h in distilled water) or hydrothermal (5 min boiling in distilled water followed by rinsing and ambient drying) or alkali treatments (48 h immersion in 6% wt NaOH) can increase flowability and provide outcomes that are comparable to those combinations that do not contain absorbent PVA.

Flax fibers enhance the mechanical properties of concrete when properly treated. Surface treatments improve FF's bonding and mechanical performance in cement composites. Optimal fibre content and mixing techniques can enhance strength and flowability, though excessive or untreated FF may hinder performance.

Hemp Fiber

Hemp fibre (HF) has supreme TS and good tolerance for an alkaline environment, which makes it an excellent reinforcing material.[61] Regardless of the mixing technique utilized, Li *et al.*[61] observed that fibre weight is responsible for compressive and flexural characteristics of HF reinforced concrete. Arnaud and Gourlay[62] observed that curing conditions (relative humidity) have a significant impact on the mechanical behaviour of hemp concretes. To create a concrete mix, Awwad *et al.*[63] reduced the coarse aggregate in the concrete by 20–30% and added 0.75–1.0% HF. The newly designed concrete mix was more malleable and exhibited ductile behaviour, but also exhibited a 25% drop in CS, a 20–30% reduction in elasticity modulus, and a 25–35% reduction in heat conductivity without impacting splitting TS. Workability-wise, the slump in 0.75% hemp mixes ranged from 100 to 150 mm, which was adequate; however, with 1% hemp mixes, the droop reached the lowest permissible level (70 mm), and a greater volumetric ratio is not advised. Hemp fibre did not affect the concrete's ability to withstand fire. After being exposed to 400°C, HF begins to partially dissolve within the concrete; hence, the incomplete disintegration of HF might minimize fracture propagation at high temperatures, enhancing the fire resistance of concrete.[64] Hemp fibre enhances ductility and fire resistance in concrete but may reduce CS and workability at higher dosages.

Jute Fiber

Jute is the most affordable, useful, and readily available natural plant fibre used for commercial applications. Jute fibre (JF) surface is abrasive, and it tightly binds with the cement slurry. Therefore, compared to chemically generated fibres, the tensile and toughening properties of JF are superior.[14] Islam and Ahmed[65] illustrated that fresh characteristics of concrete were negatively impacted by a 0.50% addition of JF. However, a lower concentration (0.25% JF) had a positive effect on the toughened attribute of concrete. Flexural TS was influenced by fibre length, fibre volume, and their interactions to varying degrees. As observed, the JF-prepared concrete cylinders collapsed in longitudinal fractures, whereas the untreated concrete cylinders failed in axial splits (Fig. 3a). While the JF-prepared cylinders were partially separated, the ordinary concrete cylinders split into two equal pieces (Fig. 3b). JF, when added to concrete, enhanced its ability to withstand flexural stress by bridging cracks. (Fig. 3c).

Kundu *et al.*[66] reported the cost of a JF (3–5 mm length) reinforced concrete paver block treated with tannin and polymer was INR 46.2. The authors suggested that the JF surface alteration resulted in a ₹1.20 rise for paver blocks. For the control paver blocks, the cost increase would be offset by improvements in CS (30%), flexural strength (49%), and flexural toughness (166%). It was also claimed that surface-modified JF was more resilient in concrete than untreated JF. Jute fiber offers a cost-effective and widely available reinforcement that enhances concrete's flexural strength, toughness, and crack resistance, especially when surface-treated.

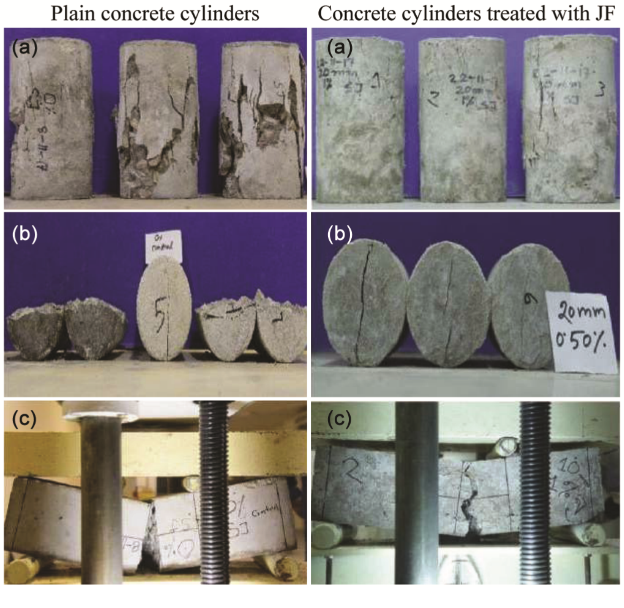

Fig. 3 — Failure pattern of the concrete cylinders observed under (a) compressive strength test (b) split tensile test (c) flexural tensile test[65]

Kenaf Fiber

Kenaf fibre (KF) has the issue of higher moisture absorption capacity to be used in cementitious composites. Therefore, pre-treatment of KF before using it for such applications is the best way to address this. According to Ahmad *et al.*[67], heat and alkali treatment of the fibres enhances the interfacial connection between fibre and matrix. When KF was treated with $NaHCO_3$ (6% w/w) for 72 h of immersion, followed by washing, 24 h ambient drying, and 24 h oven drying (70±5°C), TS was raised by almost 160% in comparison to untreated fibres. The KF-reinforced blended cementitious composite showed the best mechanical qualities, with a 42.1% increase in CS when compared to the control. It was blended with 50% activated alum sludge ash and 4% nano silica.

The addition of KF to reinforced concrete slabs increased their flexural strength and ductility. Owing to this and with a reduction in the slab thickness, the failure mode of the slab altered from brittle to ductile (Fig. 4) as reported by Syed Mohsin *et al.*[32]. Zhou *et al.*[68] reported that consequent upon the addition of 1% KF, the CS of KF reinforced high strength cement composites diminished by 12.2–46.2%, but the flexural strength increased by 30.7–66.9%. KF, when pre-treated, effectively enhances the flexural behaviour and ductility of concrete, transforming failure modes from brittle to ductile, though its impact on CS remains a limiting factor.

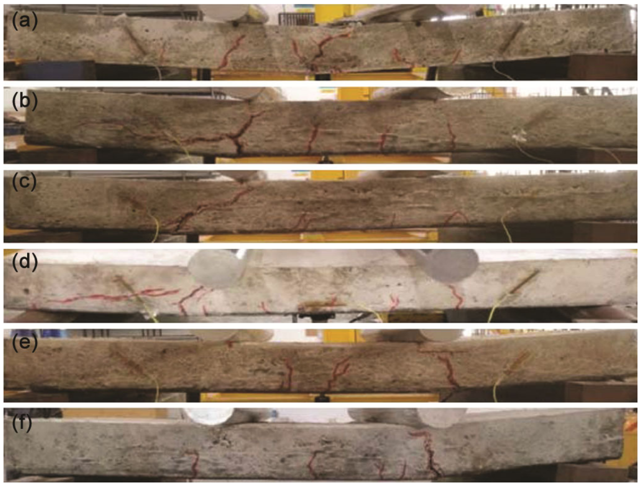

Fig. 4 — Cracking pattern and failure mode of slab (a) KF: 0%, Slab thickness: 120 mm, Failure mode: Bending (b) KF: 1%, Slab thickness: 120 mm, Failure mode: Bending-Shear (c) KF: 2%, Slab thickness: 120 mm, Failure mode: Shear- Bending (d) KF: 0%, Slab thickness: 100 mm, Failure mode: Shear (e) KF: 1%, Slab thickness: 100 mm, Failure mode: Bending (f) KF: 2%, Slab thickness: 100 mm, Failure mode: Bending[32]

Ramie Fibers

The inclusion of ramie fiber (RF) (19 mm length and 0.09 mm diameter) has improved the mixture's TS by 8%, CS by 27%, and water absorption by 3.5% without changing the mixture's consistency.[41] Mydin[16] has also reported that when a load was applied to lightweight foamed concrete (LFC), the addition of RF to the cementitious matrix helped to stop the microcrack from spreading. The high failure strain posed by RF might result in enhanced compatibility between the fibres and the cement matrix of the LFC. The density of the microstructure is created by the aggregate reaction of RF, which also results in smaller voids and a more precise arrangement of pores. Hasan *et al.*[35] reported that the inclusion of RF (9 mm length, 0.09 mm diameter), the CS, splitting TS, and flexural strength increased by 18%, 17.3%, and 31.8%, respectively.

Abaca Fibers

Abaca fibre (AF), owing to its high TS, folding resistance, buoyancy, porosity, and resistance to deterioration from saltwater, is frequently used for producing fiber-reinforced polymer composites. Its incorporation has a significant impact on fire resistance, water absorption, and biodegradability. Anthony *et al.*[39] reported that the addition of 0.5% AF (40 mm length) increased CS by 17.8% when compared to conventional concrete. The other characteristics, like split tensile, flexural, and impact strength, showed higher values of 6.5, 11.9, and 28.5%, respectively. Upon further addition of AF, i.e., at 1.0 and 1.5%, a decrease in the strength was observed. Tampi *et al.*[37] added AF (0–0.25%) to the concrete mixture where the fibre length by 25, 37.5, and 50 mm. Compression, tensile, and flexural tests of the AF concrete mixture (0.15%) and fibre length (50 mm) resulted in optimal increases of 12.61, 72.64, and 98.08%, respectively.

Sisal Fiber

Sisal fibres (SF) have better tensile qualities than other fibres in a variety of environmental conditions[6], and therefore have significant applications in improving the performance of concrete. Frazao *et al.*[69], revealed that the long SF (700 mm) was more efficient in providing the panel with a larger flexural capacity than the short SF (50 mm). Short SF encouraged a softening reaction following cracking, but long fibres enabled the development of a deflection hardening behavior, followed by the production of numerous fractures (Fig. 5). The addition of 2% aligned short fibres and 1% aligned continuous fibre reinforced concrete performed better in terms of mechanical qualities than randomly arranged SF-reinforced concrete.[40]

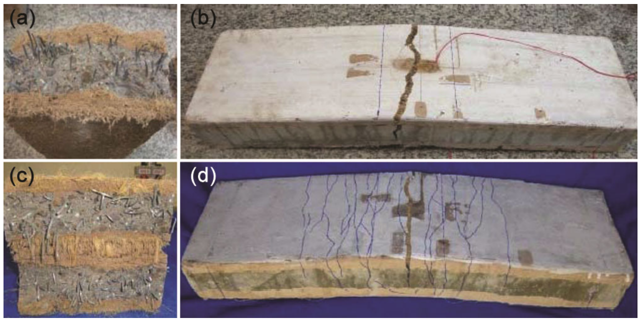

Fig. 5 — Failure mode of: (a) & (b) Short SF-cement composites; (c) & (d) Long SF-cement composites[69]

Fig. 6 — CKFW (a) prior to mixing (b) in hardened samples[71]

Pineapple Fiber

Pineapple fiber (PAF) exhibits a superior strength-to-weight ratio and good fire-retardancy due to the presence of higher crystallinity cellulose. Due to their hydrophilic nature, fibre addition to cementitious material requires surface treatment. The strongest TS parallel to the surface and flexural strength were achieved by adding PAF (1% w/w) that had been treated with 4% NaOH and immersed for 6 h at room temperature.[70]

Cotton Fiber

Addition of cotton knitted fabric manufacturing waste (CKFW) (1.7 and 3.5%) on concrete characteristics was studied by Bartulovic *et al.*[71] (Fig. 6). The flexural strength improved by up to 38%, while the CS decreased by up to 20%. Concrete density was impacted by the CKFW percentages in the range of 0–2%. The ductility and gas permeability of the CKFW mixes were greater i.e., only dry, enclosed areas may be used for such concrete mixtures.

Liu and others[72] reported that after the addition of cotton stalk fibre (CSF) at 0–2 kg/m^3, concrete's compressive and split tensile reached their maximum values i.e., 39.56 and 2.73 MPa, respectively.

Cotton-based fibers enhance concrete's flexural strength, toughness, and integrity at optimal dosages, but excessive amount can reduce CS and limit application to dry environments due to increased permeability.

Coir Fiber

Coir fibers (CCF) are obtained from the coconut husk and are the toughest among all the natural fibers. According to Ali *et al.*[73], the conditions that lead to the strongest link between CCF and concrete are (i) 30 mm embedment length, (ii) thick fibres, (iii) boiling water treatment (iv) 1:3:3 ratio of concrete mix design. Similarly, CCF reinforced high-strength concrete with 50 mm long fibres, and 1.5% cement produced the best performance in binding the components.[74] The addition of CCF increased the compressive and flexural strengths of the construction by 13% and 9%, respectively.[46] However, with a rise in fibre content from 0.6, 1.2, 1.8, and 2.4%, the chloride penetration, intrinsic permeability, and carbonation depth improved in terms of durability. However, due to the disadvantage of its natural degradation, the dose of CCF should be limited, not exceeding 1.2% of the volume of the binder. The research suggested either treating the CCF to prevent deterioration before using it in concrete or substituting it with a non-corrosive fibre.[46]

Coir fibers offer superior toughness and improved bonding within the concrete matrix but are more prone to natural degradation, requiring careful treatment and limited dosage to maintain durability and long-term performance.

Bamboo Fiber

Bamboo fiber (BBF), owing to its inherent longitudinal orientation, is also known as natural glass fibre. The ultimate TS of some bamboo species is equivalent to the yield strength of mild steel.[75] Also, the strength-to-specific weight ratio is 6-fold higher than that of steel. In contrast to many other natural reinforcing materials, bamboo can withstand compression loading better than steel bars.

According to Agarwal *et al.*[75], the glue chosen determines how well-treated bamboo bonds. The results of a two-point load test, adding just 1.49% by area of treated bamboo (with Sikadur 32 gel) as reinforcement boosted the beam's load bearing capability by up to 29.41%.

In comparison to unreinforced concrete block masonry, Moroz *et al.*[76] found that bamboo reinforcement has increased shear capacity and ductility. However, bamboo in a cementitious matrix must be protected against moisture absorption with extra care. Most of the surface area of the horizontal reinforcement still had some bond despite the existence of a longitudinal fracture in the grout over a large portion of the length of the bamboo and a few vertical cracks.

According to Akinyemi *et al.*[77], microwave-assisted alkali treatment produces better results for split TS, modulus of rupture, and modulus of elasticity of BBF reinforced concrete than alkali treatment alone. The quantity of fibre affects the quality and workability of concrete. However, BBF can stop fractures from spreading and growing. Bamboo reinforcement was used in place of steel reinforcement by Nayak *et al.*[78]. The cost of bamboo reinforcement was three times less than that of steel, especially for one-story buildings. Sharma *et al.*[79] analyzed that bamboo has a limited range of applications due to its rapid degeneration when in contact with wet ground. Since bamboo is sturdy, robust, and lightweight, it can be utilized as an excellent roofing material. BBF offers a strong, lightweight, and cost-effective alternative to steel in concrete, especially for low-rise structures. Proper treatment and moisture protection are key to ensuring durability.

Comparative Analysis of Techno-Economics

The detailed comparative analysis of steel reinforcement versus NF reinforcement is listed in Table 4. For a better understanding, a comparative account different resistances (Impact, thermal and corrosion) for steel reinforced and NF reinforced concrete is given in Table 5.

Scientific Analysis of Natural Fibers for Concrete Reinforcement

Based on the reported findings, hemp, flax and sisal fibers have the required potential for research and application. The distinct properties are described below:

1. Hemp Fiber: Offers high TS, flexibility, and enhances flexural and impact resistance. Its low energy production makes it eco-friendly and suitable for durable, energy-efficient structures.
2. Flax Fiber: Improves TS, ductility, workability, and toughness. It supports dynamic load-bearing applications and has a low environmental footprint.
3. Sisal Fiber: Exhibits superior moisture resistance, enhancing its bond with concrete. It offers good

Table 4 — Comparative analysis of steel vs natural fibre reinforcement

Factor	Steel Reinforcement	NF Reinforcement
Material cost	Higher initial cost	Lower cost
Material availability	Widely available but subject to global market fluctuations	Region-specific availability based on crops like jute, hemp, bamboo
Production cost	Energy-intensive production	Lower production cost
Mechanical properties	High TS, excellent load-bearing capacity	Lower TS, suitable for lightweight applications
Durability	High durability, susceptible to corrosion	Limited durability; requires treatment for increased lifespan
Environmental impact	High carbon footprint	Eco-friendly and renewable
Recyclability	Highly recyclable, though energy-intensive	Biodegradable, but fibers may need treatment for reuse
Performance in concrete	Excellent in high-strength concrete	Effective in lightweight concrete
Corrosion resistance	Vulnerable to corrosion unless treated	Naturally resistant to corrosion, may degrade over time without treatment.
Weight	Heavy	Lighter
Sustainability	Less sustainable due to mining and energy-intensive processes.	Highly sustainable, renewably sourced, eco-friendly
Strength-to-Weight Ratio	High	Low
Maintenance	More	Less
Applications	Best suited for high-load, heavy-duty construction (bridges, buildings)	Suitable for low-load applications, eco-friendly projects, lightweight structures
Processing/Handling	Easy to handle and integrate into construction	Requires specialized handling and treatment processes
Lifespan	Long	Shorter

Table 5 — Comparative Impact, thermal and corrosion resistance

	NF	NF reinforced concrete
Impact resistance	10–40 J	25–50 J
Maximum temperature	150–250°C	300–800°C
Thermal conductivity	0.04–0.1 W/m.K	1.2–1.6 W/m.K
Durability in humid environment	3–5 years	10–20 years
Moisture absorption	10–15%	10–15%

mechanical properties and supports sustainable construction practices.

Continued R&D in fiber treatment and durability will further boost their effectiveness in sustainable concrete applications.

SWOT Analysis of Natural Plant Fibers in Concrete Reinforcement

NF in concrete reinforcement offers sustainability, cost-effectiveness, and improved mechanical properties like enhanced flexural strength and impact resistance, making them a valuable eco-friendly alternative to traditional materials. However, their weaknesses include moisture absorption, which can weaken the fiber-matrix bond and potentially degrade performance over time, and the need for surface modification to improve durability. Despite these challenges, opportunities exist in the growing demand for sustainable construction, with advancements in fiber treatment and the potential for hybrid fiber combinations to optimize concrete properties. The main threats include competition with synthetic fibers, inconsistent fiber quality, and potential long-term durability concerns, which may limit its widespread adoption.

Limitations and Strategies to Overcome for Real-World Applications

Using NF for concrete reinforcement faces challenges like durability and water absorption. Feasible solutions include fiber treatments (alkali, silane, and polymer coatings) to enhance adhesion and longevity, and modified concrete formulations (pozzolans, superplasticizers, and low-alkalinity cements) to improve bonding and performance. These methods are cost-effective, sustainable, and compatible with existing construction practices. Modified mixes can be prepared using standard equipment. With proper selection, natural fiber-reinforced concrete is viable for sustainable, low-cost, and eco-friendly applications in both structural and non-structural construction.

Future Research Directions

Addressing the areas mentioned below will support the advancement and widespread use of NF in sustainable concrete solutions:

1. Investigation for ensuring long-term performance and durability under various environmental conditions.

2. Exploring advanced surface treatments (chemical, thermal, plasma) to enhance fiber-matrix bonding.
3. Developing hybrid combinations of natural and synthetic fibers to improve impact resistance, TS, and durability.
4. Establishing testing protocols and quality control measures to ensure consistent fiber performance in concrete.
5. Evaluating cost-effectiveness and environmental impact to support adoption over conventional materials.
6. Optimization of concrete mix formulations based on fiber type, length, and content for better mechanical performance and workability.
7. Improving fiber sourcing, harvesting, and processing for reliable, sustainable, and large-scale application.

Conclusions

This review highlights the significant benefits of incorporating NF into concrete, particularly in improving compressive strength, split tensile strength, and flexural strength. The positive environmental and economic impacts of NF have led to their growing use in concrete composites. Ongoing research has substantially enhanced the performance of NF-reinforced concrete, and high-performance composites are already being used in the construction industry. Over the past decade, the market for NF has expanded, and future trends indicate continued growth. Surface modification of natural fibers plays a crucial role in improving the bond between fibers and the concrete matrix, further enhancing the mechanical properties of the composite material. Natural plant fibers have demonstrated strong potential for use in construction due to their availability, cost-effectiveness, low density, high strength, and biodegradability. However, fibers like pineapple, date palm, and cotton require further research to improve their performance and make them more viable for construction applications. Continued development in fiber treatment and optimization of concrete mixes will ensure that natural fiber-reinforced concrete can play a key role in the future of sustainable construction.

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