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Strengthening Concrete Characteristics through Fiber Additives: A Comprehensive Review

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ABSTRACT- This paper comprehensively reviews the incorporation of waste materials and fibers into concrete to enhance its mechanical properties and environmental sustainability. Waste materials, including carbon fiber, coconut shell aggregate, fly ash, waste glass, and marble waste, have been found to significantly improve concrete properties. For example, carbon fiber admixtures enhance compressive, flexural, and split tensile strength, while fly ash and waste glass replacements improve overall properties. The inclusion of recycled nylon fiber (RNF) and crushed recycled aggregate (CRA) also enhances concrete's mechanical properties, with RNF increasing tensile strength and CRA reducing density. Furthermore, the use of natural fibers like sisal and jute has shown potential for improving compressive strength, tensile strength, and durability. Incorporating these waste materials and fibers into concrete not only enhances its properties but also contributes to environmental sustainability by reducing waste accumulation. Further research is needed to optimize their use for sustainable concrete production, highlighting the importance of utilizing fibers for environmental conservation.

KEYWORDS- Fibers, Waste Materials, Concrete Properties, Environmental

I. INTRODUCTION

The proliferation of municipal solid waste globally is a consequence of escalating human consumption and the mass production of various goods in factories [39]. This surge in production is anticipated to generate a considerable volume of solid waste (such as fibers) in the foreseeable future, necessitating urgent attention to waste management worldwide. Fibers play a crucial role in enhancing the properties of concrete, offering several advantages in civil engineering applications.

The upward trend in fiber use as a concrete stabilizer, as seen in Figure 1, signifies its growing importance in enhancing concrete properties and lessening environmental impact. This aligns with the shift towards sustainable construction. Fiber reinforcement offers benefits like improved tensile strength, crack resistance, and durability, potentially reducing costs and enhancing sustainability by reducing reliance on traditional materials like steel. Natural fiber sources, like coconut or sisal, can be renewable and biodegradable, adding to their appeal in sustainable construction. The increasing research focus on fiber-reinforced concrete reflects a move towards more environmentally conscious building practices, addressing global environmental challenges.

Adding fibers to concrete enhances its strength, flexibility, toughness, and resistance to impact. This is especially advantageous for structures exposed to dynamic or impact loads like bridges, pavements, and industrial floors. A key advantage of fiber use in concrete is crack control. When distributed throughout the concrete, fibers act as micro-reinforcements, decreasing crack width and spread. This boosts the durability and lifespan of concrete structures, cutting down maintenance costs over time. Fiber-reinforced concrete (FRC) also shows improved resistance to shrinkage and cracking from drying or thermal effects. This is crucial in harsh environments or areas with significant temperature changes, as it helps uphold the concrete's structural integrity. Moreover, fibers can enhance concrete's flexural strength, enabling thinner sections to be designed without sacrificing performance. This can result in material savings and lighter structures, lessening the environmental impact of construction projects.

In terms of sustainability, using fibers in concrete supports environmental conservation. By enhancing structure durability and lifespan, the need for frequent repairs and replacements diminishes, leading to reduced resource usage and waste production in the long run. Some fibers used in concrete, like recycled plastic fibers or natural fibers such as hemp or sisal, offer a more sustainable option compared to traditional steel reinforcement. These fibers can be derived from renewable or recycled sources, further lowering the environmental impact of construction projects. Numerous studies have explored fiber use in concrete, with [33] highlighting the widespread adoption of fiber-reinforced concrete (FRC) in civil engineering in India, encompassing industrial floors, pavements, and road coverings.

Various fibers such as steel, glass, carbon, and aramid, including continuous types, are replacing conventional steel reinforcement. Steel fibers are predominantly used in sidewalks and tunnels. Noteworthy innovations like suspended fiber infiltrated concrete (SIFCON) and mat-like fibers enhance structural composites. FRC is applied in various areas such as above-ground slabs, shotcrete, precast products, seismic regions, repairs, and hydraulic structures, showcasing its versatility and importance[7] evaluated recycled plastic fibers (RPF), recycled carpet fibers (RCF), and recycled steel fibers (RSF) in concrete. They found that these fibers exhibit satisfactory properties, supporting their inclusion in concrete. Properties like slump, compressive strength (up to 15% increase), tensile rupture strength (up to 20% increase), flexural strength (up to 25% increase), and elastic modulus (up to 10% increase) were enhanced.

This research underscores the vital role of fibers in enhancing concrete properties, improving durability, and reducing maintenance costs. Through distinguished research, it emphasizes how fiber use fosters sustainable construction practices in civil engineering, ultimately contributing to environmental preservation. The findings illuminate the value of incorporating fibers into concrete as a means to achieve both technical excellence and environmental stewardship in construction projects.

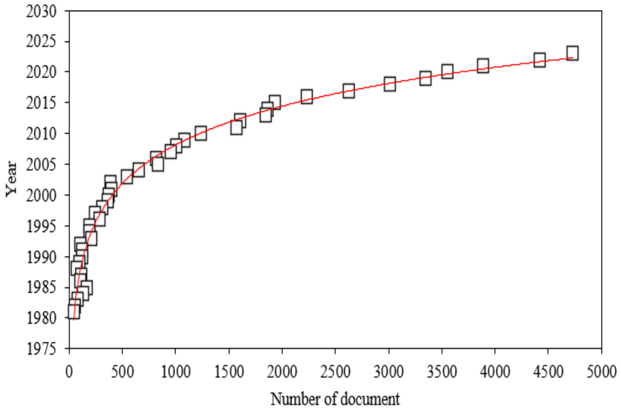

Figure 1: Analysis of the use of waste fibers in concrete mixtures for each year

II. MATERIALS AND METHOD

A. Coconut Fiber Waste (CF)

Kumar et al. [25] showed that compressive strength, flexural strength, and split tensile strength of concrete with 1.5%, 2.5%, and 5.0% CF admixture increased at 7 and 28 days compared to regular concrete in normal and seawater. However, adding CF reduced concrete strength in both waters. Partially substituting 10%, 20%, and 30% of cement with coconut shell aggregate, while keeping 5.0% CF, increased strength at 7 and 28 days compared to regular concrete in normal and seawater. Seawater-cured concrete was weaker than that cured in normal water.

Aslam et al. [9] found that replacing 15% of cement with fly ash (FA) and 2% of sand with waste glass (WG) improved concrete properties. When replacing 16% of sand, the microstructure quality improved. The M4 mix showed enhanced properties, with compressive strength improving to 47.2 MPa, flexural strength to 6.2 MPa, and 20% of apparent density. However, excessive WG replacement led to negative effects on void ratio, permeability, and absorption of water. Therefore, substituting 16% of sand with WG, 15% of cement with FA, and adding 2% CF can enhance concrete sustainability.

Shah et al. [35] proved that addition of CF to recycled aggregate concrete (RAC) reduced workability significantly, with a slump nearly zero at 3% CF, necessitating increased super plasticizer (SP) dosage. Incorporating 1-2% CF with SP slightly improved density, but at 3% CF, density decreased compared to plain concrete. The compressive strength (CS) of recycled aggregate concrete (RAC) improved by 5-10% when 1-2% carbon fibers (CF) were added. However, at a CF content of 3%, the CS decreased. Nonetheless, a mix containing 50% recycled aggregate (RA) and 1-2% CF exhibited CS that was on par with conventional concrete. Splitting tensile strength (STS) notably increased with 2% CF in all RAC mixes (0%, 30%, 50%, and 100% coarse RA), showing a 12-15% increase. CFs improved crack resistance, enhancing residual strength. The addition of CF and SP reduced water absorption (WA) capacity of RAC.

Utilizing recycled aggregate RA was essential for lowering the global warming potential (GWP), with a mixture containing 100% RA and 2% carbon fibers CF demonstrating the lowest GWP per unit split tensile strength STS or flexural strength FS. This mix produced approximately 25% less CO2 compared to conventional concrete while maintaining similar mechanical properties.

Ahmad et al. [4] investigated the use of marble waste (MW) up to 30% and CF up to 3.0% by weight of cement in sustainable self-fiber compacting concrete. Results showed that as Mw and CF proportions increased, the flowability and passing ability of concrete decreased, but remained within practical limits for self-compacting concrete (SCC), except for 2.5% and 3.0% CF. Mechanical performance improved with up to 20% Mw addition, attributed to micro-filling voids and pozzolanic reaction. CF improved mechanical performance up to 2.0% addition but decreased beyond, due to compaction difficulties. The optimal mix had 18% Mw and 1.8% CF, achieving a maximum compressive strength of 23 MPa, 37% higher than the control mix.

Incorporating CF into cement-based materials can mitigate environmental impact owing to their cost-effectiveness, abundant availability, recyclability, and low density. CF demonstrates stress-strain behavior and has shown potential in enhancing the physical and mechanical properties of composites. However, further investigations are essential to comprehensively comprehend their physical and chemical attributes. Subsequent research should delve into parameters such as water/cement ratio, fiber geometry and alignment, pretreatment methodologies, utilization with supplementary cementitious materials, and durability across diverse environmental conditions. Moreover, future studies should encompass non-destructive testing, behavior under elevated temperatures, and life cycle assessments to broaden the scope of their application in construction.

Abdullah et al. [1] studied how the physical and mechanical properties of composite cement were affected by the amount of coconut fiber. They kept a consistent ratio of cement to sand at 1:1, with a fixed water-to-cement ratio of 0.55. Coconut fiber was used to reinforce the mixture, replacing sand in varying proportions (3, 6, 9, 12, and 15%). After mixing and curing, the composites were immersed in water for 7, 14, and 28 days. The findings showed that the composite with 9 wt.% coconut fiber exhibited the highest modulus of rupture and compressive strength, as detailed in Table 1. Figures 2-4 show the analysis of density, water absorption, and moisture content.

Table 1: Compressive strength and modulus of rupture results [1]

CF (%)	Compressive strength (MPa)			Modulus of rupture (MPa)		
	7 Days	14 Days	28 Days	7 Days	14 Days	28 Days
0	28.59	31.23	41.19	12.48	13.92	14.16
3	27.34	30.09	33.73	13.04	13.99	14.46
6	29.63	31.36	38.54	14.11	41.51	14.87
9	31.08	39.65	43.84	14.45	14.78	15.23
12	24.48	25.78	27.05	12.18	13.51	14.42
15	22.47	25.48	26.04	11.85	13.13	14.07

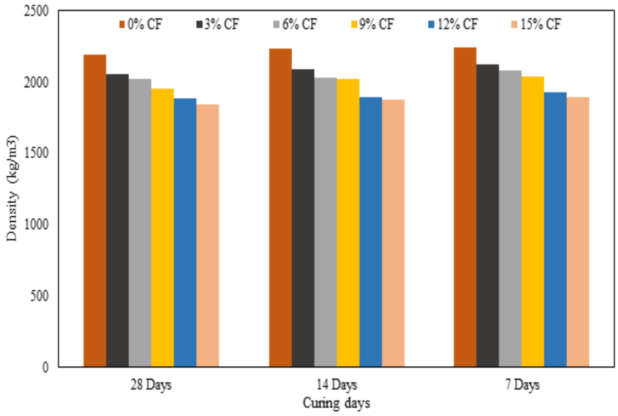

Figure 2: Density Values of Mixtures at 7, 14, and 28 Curing Days [1]

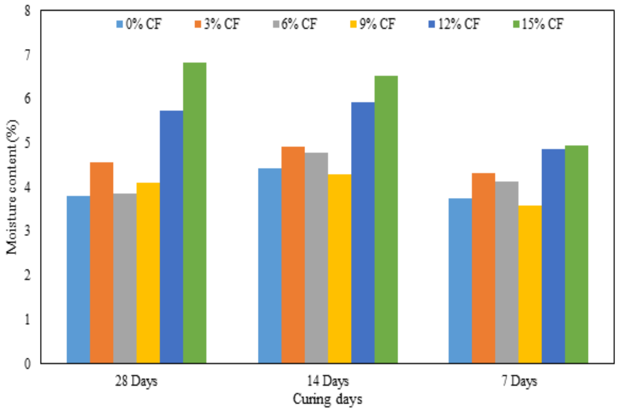

Figure 3: Moisture Content of Mixtures at 7, 14, and 28 Curing days [1]

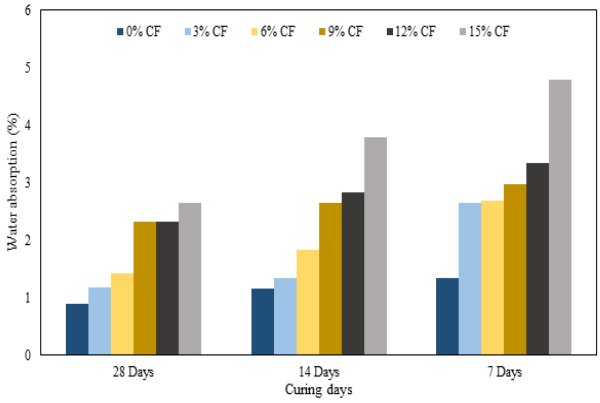

Figure 4: Water Absorption of Mixtures at 7, 14, and 28 Curing Days [1]

Tutur et al. [36] examined the utilization of rice husk ash (RHA) and CF as partial cementitious replacements in concrete. CF was employed to replace cement at rates of 1%, 2%, 3%, and 4%, while RHA replaced cement at levels of 9%, 18%, 27%, and 36%. The composite with 1% CF and 9% RHA exhibited the highest compressive strength of 38.12 N/mm² after 7 days. Water absorption rates escalated with increasing CF and RHA content. At 7 days, absorption rates ranged from 1.56% to 10.33% for varying cement replacements, while at 28 days, rates spanned 1.52% to 9.91%. Overall, water absorption rates at 7 and 28 days were 2.95% and 2.18%, respectively.

Yadav et al. [38] studied coconut fiber-reinforced concrete (CFRC), finding that it exhibits ductile behavior with crack cessation. Split tensile strength increases up to 5% fiber content but decreases thereafter due to dislocation of concrete's atoms and molecules. Flexural strength peaks at 5% fiber content due to coconut fiber's high tensile strength (21.5 MPa). CFRC shows promise for enhancing strength and durability, making it suitable for seismic zones and cost-effective for rural buildings. It can also replace asbestos in roofing sheets, offering environmental benefits.

Research on the acoustic properties of CFRC demonstrates its potential as a viable alternative material. Coconut fibers, known for their porous surface, exhibit excellent sound absorption properties. Additionally, they act as effective insulators, improving the thermal performance of concrete. This is particularly advantageous in hot climates like India, where maintaining comfortable indoor temperatures is crucial. CFRC's ability to reduce reliance on air conditioning can lead to significant energy savings. However, further research is needed to assess CFRC's suitability for high-strength concrete applications in industrial and commercial structures, as well as its resistance to corrosion in reinforced constructions.

B. Nylon Fiber Waste

Ali et al. [18] elucidated the impact of incorporating recycled nylon fiber (RNF) and crushed recycled aggregate (CRA) on high-performance concrete (HPC), revealing significant insights. The density of HPC diminished by 2.2% upon complete substitution of coarse natural aggregate with CRA. Ultrasonic Pulse Velocity (UPV) exhibited a slight rise with 0.1% RNF but markedly declined beyond 0.25%. Compressive strength experienced marginal enhancements of 7% and 2% with 0.1% and 0.25% RNF, respectively. Notably, tensile strength displayed a substantial increase, registering a 20.2% upsurge at 0.5% RNF. Water absorption was moderately controlled by 0.1% and 0.25% RNF but adversely affected by 1% RNF. Furthermore, chloride ion penetration resistance was adversely impacted by CRA but ameliorated by 0.1% and 0.25% RNF in HPC.

Bheel et al. [14] explored the influence of RNF and jute fibers on the properties of cement concrete. The inclusion of these fibers led to a reduction in workability due to their increased surface area, necessitating less water for adequate workability. Density decreased from 2388 kg/m3 (0% fibers) to 2300 kg/m3 (2% fibers). Water absorption rates varied from 2.40% (0% fibers) to 3.07% (2% fibers). Concrete containing 1% fibers exhibited the highest compressive (11.71%), split tensile (14.10%), and flexural (11.04%) strengths compared to plain concrete after 90 days. However, strengths decreased beyond 1% fiber content due to increased air voids and inadequate compaction. The Modulus of Elasticity (MOE) increased with fiber content, resulting in a stiffer concrete mix. Drying shrinkage reduced with fiber content due to improved bond strength. The study recommends incorporating 1% nylon and jute fibers for optimal performance in concrete applications.

Farooq et al. [18] conducted a comprehensive study on the influence of RNF on concrete properties. The research revealed several significant findings: 1. As the RNF content increased, the density of the concrete decreased. 2. The UPV exhibited a slight increase at 0.05% RNF but decreased at higher concentrations. 3. Compressive strength experienced a 5% enhancement at 0.15% RNF, but a decrease was observed at higher RNF contents. 4. Splitting tensile strength showed a notable 14.1% improvement at 0.25% RNF. 5. Flexural Strength (FS) demonstrated a substantial 24.2% increase at 0.75% RNF. 6. Water absorption and chloride penetration depth showed varying trends with RNF content, with lower fractions providing better results. The inclusion of RNF led to a ductile failure mode and enhanced crack resistance, as depicted in Figure 5. Based on the results, an optimal RNF content of 0.25–0.5% is recommended for achieving the best performance.

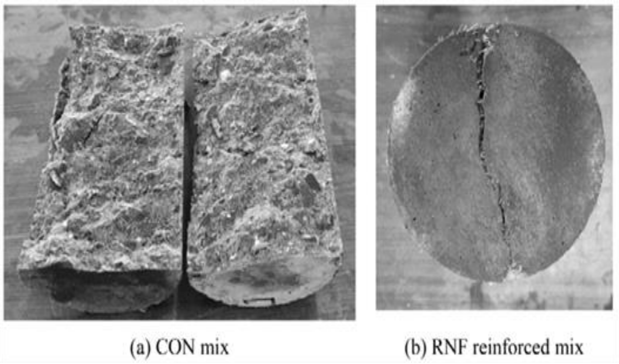

Figure 5: Splitting-tensile failure of samples [18]

Lee et al. [27] conducted a rigorous examination of concrete, integrating RAC and RNF additives, unearthing compelling insights. The study unveiled NF's capacity to amplify compressive and split tensile strength, particularly accentuated in RAC blends. Notably, NF bolstered UPV metrics and curbed total charge in the rapid chloride permeability test, signaling heightened durability and abated corrosion susceptibility. Microstructural scrutiny underscored RNF's pivotal role in bridging cracks, culminating in heightened robustness and diminished permeability, especially salient for recycled aggregate-infused concrete.

Ahmad et al. [6] delved into the effects of incorporating RNF on the properties of SCC, aiming to bolster its ductility and tensile behavior. RNF ratios were introduced at varying proportions (0.5%, to 2%) to investigate their impact on fresh properties, durability, and mechanical strength. Results revealed a reduction in passing and filling ability, coupled with an increase in segregation and bleeding resistance with RNF inclusion. Interestingly, there was a notable strength enhancement up to the 1.5% RNF addition, followed by a gradual decline in strength. Durability assessments, including water absorption, permeability, carbonation resistance, and acid attack resistance, exhibited significant improvements compared to the control mix, underscoring the potential of RNF in augmenting SCC's durability and mechanical performance.

Qin et al. [32] conducted a comparative analysis of nylon fiber-reinforced concrete (NFRC), recycled nylon fiber fabric-reinforced concrete (NFFRC), and plain concrete (PC) with a 30 MPa design strength at 14 days. NFFRC exhibited a 9.30% lower slump compared to PC and a 1.54% higher slump compared to NFRC. Although NFFRC and NFRC had similar densities, they were 0.61% lower than PC. NFFRC demonstrated a 5.37% higher compressive strength than PC and 10.74% higher than NFRC. Additionally, NFFRC showed superior energy absorption capability, with a 12.39% increase over PC and 19.05% over NFRC. Despite failure, NFFRC maintained its structural integrity, suggesting potential advantages over PC and NFRC.

C. Sisal Fiber Waste

De et al. [17] demonstrated that aligned sisal fiber-reinforced cement laminates exhibited strain-hardening behavior, with CH-free composites displaying superior ultimate tensile strength compared to PC (13.95 MPa vs. 9.24 MPa). CH-free composites also exhibited double the toughness under tensile loads in comparison to PC. Bending failure occurred at mid-span deflections of approximately 13 mm (PC) and 20 mm (CH-free). The modulus of rupture (MOR) for CH-free composites was 23 MPa, higher than the 21 MPa observed for PC. The inclusion of corrugation increased the ultimate bending load by approximately 260%. Both composite types demonstrated impermeability, with low sorptivity values (0.025 cm min (-1/2) for CH-free and 0.019 cm min (-1/2) for PC). Following accelerated aging, CH-free composites exhibited 3.8 times higher ultimate bending strength and 42.4 times higher toughness than PC composites.

Ahmad et al. [22] included sisal fiber in the concrete mixture. The study discovered that the physical properties of sisal fiber (SSF) differ depending on the age of the plant. The addition of SSF lowered flowability due to its increased surface area, which required more water. While SSF increased concrete strength, compressive capacity did not improve much when compared to flexural or tensile capacity. SSF addition resulted in enhanced water absorption and lower density, but more research is needed in this area. Furthermore, NaOH-clay-treated SSF dissolved amorphous lignin and had a 76% crystalline fraction, with clays accounting for 20%. However, additional in-depth research is needed to properly understand these consequences.

Figure 6: SSF used during the experiments [5]

Wei et al. [37] investigated the enhancement of sisal fiber's durability in concrete through thermal and Na2CO3 treatments. These treatments resulted in significant improvements in splitting tensile strength (36.5% and 46.2%) and compressive strength (31.1% and 45.4%), respectively. Thermal treatment enhanced cellulose crystallization, leading to superior initial strength and durability. Na2CO3 treatment created a protective calcium carbonate layer on the fiber's surface, reducing degradation from Na+ ions in concrete. These findings highlight the cost-effectiveness and ease of application of both treatments, suggesting potential for further research. Possible future studies could explore thermal-Na2CO3 dual processing for enhanced durability.

Balaji et al. [11] improved concrete sustainability by substituting cement with ceramic waste powder (CWP) and incorporating sisal fiber. They tested various concrete mixes with 5%, 10%, 15%, 20%, and 25% CWP replacements for cement. The M30 mix with a W/C ratio of 0.45 was utilized. The study found that replacing 25% of cement with CWP and adding 1% sisal fiber achieved the best strength results. This approach promotes sustainable construction by recycling ceramic waste and reducing environmental impact.

Agor et al. [2] employed an adaptive neuro-fuzzy inference system (ANFIS) to predict concrete strength using varying levels of aluminum waste and sisal fiber as replacements. The study found that achieving strong gradation is crucial for enhancing concrete durability. Compressive strength ranged from 17.02-24.97 N/mm², with the highest flexural strength recorded at 11.6 N/mm² for a 10% sisal fiber replacement. Increasing aluminum waste content reduced the slump, necessitating more water for workability. Additionally, setting times increased with higher aluminum waste content. The ANFIS model demonstrated high accuracy, with an MAE (Mean absolute error) of 0.1318, RMSE (Root mean squared error) of 0.412, and R² of 99.57%. This sustainable approach presents a viable solution for reducing costs and waste in concrete production.

Okeola et al. [31] looked into how adding sisal fibers to concrete influenced its characteristics. The concrete mix included varying percentages of sisal fibers (0.5, 1.0, 1.5, and 2.0% by cement weight). The study looked at both physical parameters like workability, water absorption, and density, as well as mechanical properties like compressive strength, split tensile strength, and static modulus of elasticity. Results showed that adding sisal fibers reduced slump flow, with the control concrete having the maximum slump value of 92 mm. Figure 7 shows that as the concentration of sisal fibers grew, so did water absorption values.

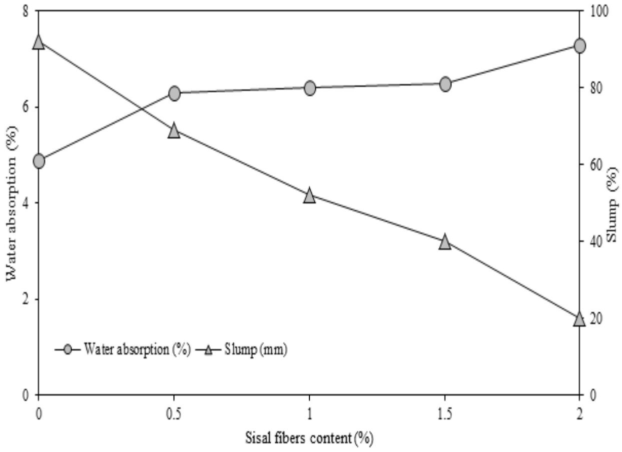

Figure 7: Slump and water absorption values of mixtures [31]

Furthermore, Figure 8 proved that the addition of 0.5%, 1%, 1.5%, and 2% of sisal fiber in concrete decreased the density values at 7 and 28 days of curing. Similarly, the compressive strength values of concrete decreased with increasing sisal fiber content at 7 and 28 days as Figure 9 showed. The tensile strength value reached its maximum at 1% sisal fiber in concrete, then decreased by 1.5% and 2% of sisal fiber addition.

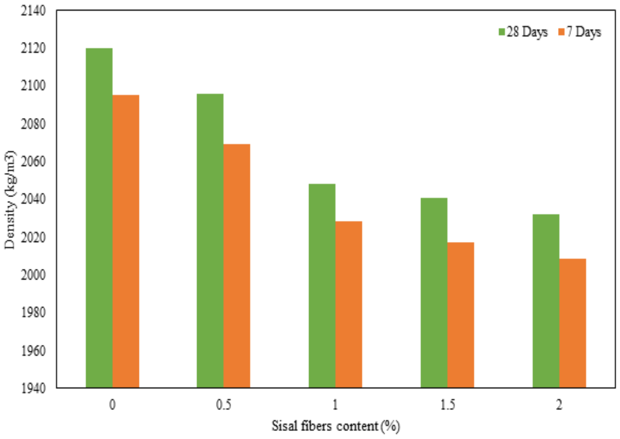

Figure 8: Density values of mixtures [31]

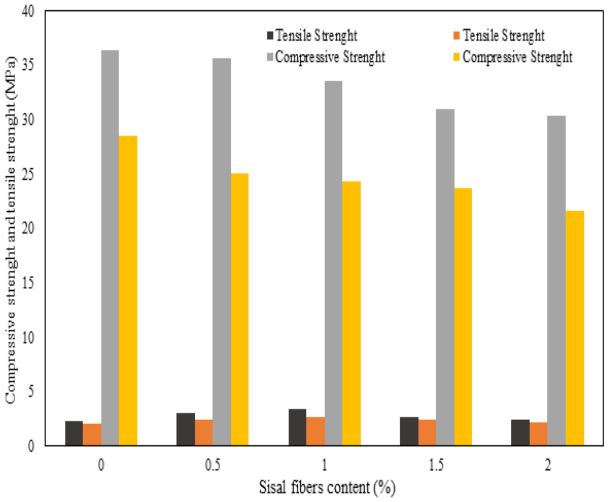

Figure 9: Compressive and Tensile Strength Values of Mixtures [31]

Liu et al. [28] found that treating sisal fiber with NaOH solution (10-30%) for 10-60 minutes effectively removes lignin, improving its compatibility with cement. Mass loss initially increases with time and concentration, reaching a plateau as lignin is removed, then decreasing due to structural damage. Microscopic analysis showed in Figure 10 that fibers treated for 30 minutes (10% NaOH) had smoother surfaces and better integrity, while prolonged treatment (60 minutes, 30% NaOH) led to internal damage and branching, which can cause cement slurry issues. A 30-minute soak was deemed optimal. In terms of concrete strength, with 5mm fiber length, the 28-day compressive strength increases with fiber content, plateauing at 0.75%. For 10mm fibers, strength initially increases then decreases, peaking at 0.75% content. With 15mm fibers, compressive strength decreases, with a slower decline after 0.75%. Flexural strength follows a similar trend, peaking at 0.75% fiber content for 5mm and 10mm lengths. Incorporating fibers reduces small cracks, improving concrete integrity and flexural strength. Sisal fiber enhances foamed concrete shrinkage performance, with longer fibers leading to smaller shrinkage values at the same content.

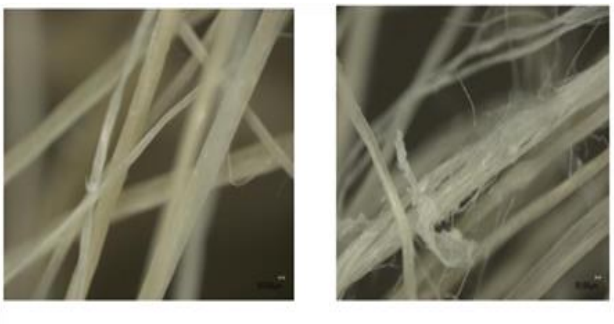
(a)10% NaOH for 30 minutes (b) 30% NaOH for 60 minutes

Figure 10: 3D Ultra-Deep Micrograph Analysis of Sisal Fibers [28]

Iniya et al. [21] found that increasing sisal fiber content beyond 2% and reducing fiber length by 30-50mm in concrete resulted in a notable decrease in mechanical properties, exceeding 1.5%. Water absorption significantly enhanced physical and mechanical properties, leading to higher tensile and compressive strength. Introducing natural sisal fibers improved flexural and fracture strength, with greater ductility in fracturing. Mechanical characteristics of sisal fiber depended on manufacturing conditions, fiber size, length, strain rate, and environment. Despite reaching maximum flexural strength, fibers continued to maintain sample cohesion, enhancing crack resistance.

Beskopylny et al. [12] focused on enhancing concrete properties using natural sisal fibers, which do not require extensive production processes, making them cost-effective and environmentally friendly. Concrete samples with 0.25%, 0.5%, 0.75%, 1.0%, 1.25%, and 1.5% sisal fiber content were tested at 15 days of age, with a compressive strength of 48 MPa. Optimal reinforcement was found at 1% sisal fiber, resulting in a 22% increase in compressive strength, 27% in axial compressive strength, 33% in bending tensile strength, and 29% in axial tensile strength. Deformation characteristics also improved, with 25% increase in axial compression strain, 42% in axial tension strain, and 15% in elastic modulus.

Sabarish at al. [34] explored the potential of sisal fiber in strengthening concrete, conducting tests to assess its impact on compressive and flexural strength. Their findings revealed that concrete reinforced with sisal fiber exhibited higher compressive and flexural strength compared to traditional concrete. The addition of sisal fiber resulted in a notable increase in compressive strength, with the reinforced beam supporting a load of 420.04 N/mm², significantly higher than the 336.032 N/mm² of conventional concrete. Furthermore, the tensile strength of the reinforced concrete beams, fully enveloped by sisal fiber, peaked at 38.5 N/mm². Even under substantial loads, the sisal fiber maintained its structural integrity, contributing to a significant enhancement in the ultimate flexural strength of the beams.

Research on chemically treated sisal fiber composites should focus on crack durability and rupture processes for future material development. Current studies lack detailed analysis, especially regarding interface strength and failure mechanisms. Understanding these aspects is crucial for accurately describing material strength.

D. Jute Fiber Waste (JF)

Burrola et al. [15] illustrated the extensive genetic diversity of JF, boasting over 81 distinct genotypes. Thriving in the humid climates of Asia and South America, it serves primarily for domestic consumption while finding versatile applications in packaging, textiles, and accessories. Its microfibrillar angle is a critical determinant of tensile strength, with lower angles associated with superior mechanical properties. Unlike cotton, jute's higher cellulose content and lower microfibrillar angle contribute to its inherent stiffness. With an original length spanning 1 to 4 meters, it can be tailored to suit diverse manufacturing processes. The main properties of JF are summarized in Table 2.

Table 2: Physicochemical Properties of Jute Fibers [15]

Properties	Unite	Jute
Diameter	μm	40–60
Cellulose content per weight	%	59–71
Lignin content	%	12–13
Humidity	%	12.5–13.7
Density	g/cm^3	1.3–1.45
Elongation at break	%	7.0–8.0
Tensile strength	MPa	399–773
Tensile modulus	GPa	10–30

In recent years, there has been a significant focus on integrating JF into normal vibrated concrete (NVC) to enhance ecological sustainability. Research has explored improving NVC properties by adding JF of varying lengths (10, 15, 20, and 25 mm) and concentrations (0.1%, 0.25%, 0.50%, and 0.75% by weight). Optimal results were seen at a 0.25% concentration with 15 mm fibers, leading to a remarkable 35% increase in tensile strength (Hasan et al., 2023). Investigations on JF-reinforced high-fluidity concrete have also shown significant mechanical enhancements over conventional concrete, indicating promising advancements in sustainable construction practices. Moreover, previous studies have indicated a lack of attention to the use of JF in reinforcing self-consolidating concrete (SCC). Jute, the world's second most cultivated textile fiber after cotton, is abundantly available and affordable in Bangladesh, the second-largest global producer. With cellulose and lignin as its primary constituents, jute boasts commendable tensile strength and enhanced interfacial contact due to its uneven surface, making it superior among natural fibers.

Figure 11: Different lengths of JF used in concrete [3]

Khan et al. [23] explored JF's impact on concrete properties using response surface methodology (RSM). The empirical evidence suggests that the optimal and preferred results for concrete mixed with JF are achieved when the concrete contains 0.10% JF. Exceeding this percentage offers no additional benefits. Statistical models relying on p-values effectively evaluate mechanical properties. Coefficients of determination for various properties were high, indicating accuracy. Optimal slump occurs at 0% JF, while minimum slump flow is at 0.75% JF. Incorporating 0.10% JF yields maximum compressive, split tensile, and flexural strengths. The obtained equations predict concrete properties with varying JF percentages.

Kalaivani et al.[22] investigated JF treatment, soaking it in a NaOH solution for 24 hours and drying it for another 24 hours, enhancing its strength and stiffness. NaOH treatment decreases water absorption. Superplasticizer usage boosts flowability in fiber-reinforced concrete. Incorporating plastic waste aggregates enhances concrete strength and bonding. Utilizing PET waste in concrete addresses natural aggregate demand, reducing reliance on natural sources. However, increased plastic waste aggregate quantity reduces compressive strength, increases permeability, and diminishes fresh concrete workability. Optimizing plastic waste aggregate size and grading mitigates these issues.

Sohu et al.[13] investigated concrete reinforced with varying proportions of JF (0.25%, 0.50%, 0.75%, and 1%) and fine aggregate replacement with wheat straw ash (WSA) (10%, 20%, 30%, and 40%). Assessing fresh and hardened properties, concrete samples with a 1:1.5:3 mix ratio and 0.54 water-cement ratio were cured for 28 days. Optimal results were observed at 0.50% JF and 30% WSA, yielding improved compressive by 32.88 MPa, splitting tensile by 3.80 MPa, and flexural strengths by 5.30 MPa. Additionally, modulus of elasticity increased with combined JF and WSA dosage, while permeability and workability decreased. Table 3 presents descriptive statistical information regarding experimental outcomes, including the range, mean, standard deviation, and coefficient of variation. Moreover, the study observed reduced slump values (46 mm, 37 mm, 29 mm, and 20 mm) compared to plain concrete as JF content increased. In contrast, concrete incorporating 10% to 40% wheat straw ash (WSA) as sand replacement exhibited lower slumps (20.68%, 36.21%, 50%, and 65.52%). The optimal slump of 58 mm occurred at 0% JF and 0% WSA, while the lowest slump of 12 mm was noted at 1% JF and 40% WSA, indicating reduced workability due to the water-absorbing properties of JF and WSA. Figure 12 illustrates the impact of JF (0.25% to 1% volume fraction) on concrete workability. The compressive strength, splitting tensile strength, and flexural strength increased to 31.5 MPa, 3.60 MPa, and 5 MPa, reflecting improvements of 10.14%, 12.50%, and 11.11% at a 0.50% jute fiber (JF) content, respectively, compared to plain concrete. In contrast, the lowest values recorded were 28 MPa for compressive strength, 3.10 MPa for splitting tensile strength, and 4.30 MPa for flexural strength, showing decreases of 2.1, 3.1, and 4.44% at a 1% JF content, respectively, compared to the control mix at 28 days.

Table 3: Descriptive statistical data on experimental results [13]

	Number of values	Minimum	Maximum	Range	Mean	Std. Deviation	Std. error of mean	Coefficient of variation
Slump (mm)	25	12	58	46	31.52	11.74	2.348	37.25%
Compressive Strength (MPa)	25	28	32.88	4.88	30.7	1.261	0.2522	4.108%
Tensile Strength (MPa)	25	3.1	3.8	0.7	3.473	0.1564	0.03128	4.503%
Flexural Strength (MPa)	25	4.3	5.3	1	4.844	0.2299	0.04597	4.746%
Modulus of elasticity (GPa)	25	26.5	31.45	4.95	29.3	1.377	0.2754	4.699%
Permeability (mm)	25	7	22	15	14.32	3.637	0.7274	25.4%

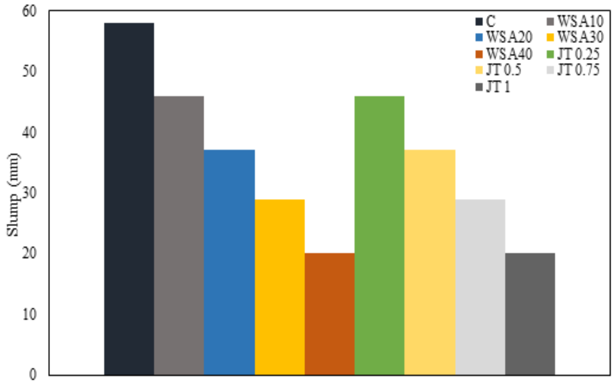

Figure 12: The workability of blends incorporating WSA and JF [13]

Nasir et al. [29] performed the flexural strength assessment using an ASTM-compliant universal testing machine to gauge the strength evolution of concrete with varying fiber contents. Test outcomes for diverse samples are detailed in Table 4. Analysis shows a significant rise in the flexural strength of beam specimens made from fiber-reinforced concrete over various time periods, corresponding with increased fiber content. Specifically, the flexural strength of 28-day samples with 1% fiber content increased by 5.9% compared to plain concrete, as illustrated in Figure 13.

Table 4: The results of flexural test [29]

Days	7				14				28			
Sample No.	1	2	3	Averag	1	2	3	Average	1	2	3	Average
0% fiber Strength (PSI)	502.46	511.22	512.1	508.605	710.15	712.5	706.9	709.855	789.3	778.2	785.1	784.239
0.5% fiber Strength (PSI)	520.56	510.14	524.3	518.351	720.77	722.5	728.7	723.999	800.9	803.9	799.2	801.31
1.0% fiber Strength (PSI)	550.98	541.15	544.1	545.417	753.43	742.5	749.2	748.356	837.1	825.2	830.5	830.945
1.5% fiber Strength (PSI)	566.07	552.89	559.3	559.424	783.62	780.9	788.8	784.451	862.1	879.7	870.1	870.634

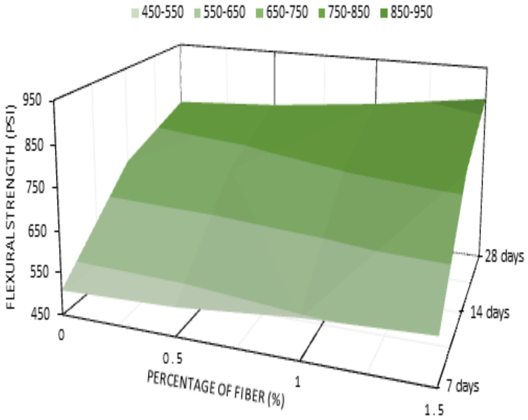

Figure 13: Average Flexural Strength [29]

Naveen et al. [30] assessed the impact of JF content on concrete's mechanical, environmental, and fresh properties. Using response surface methodology (RSM), the optimal JF content was determined to be 0.10%. Concentrations exceeding this showed no positive effects. Compressive strength (CS) reached 63 MPa, with splitting tensile strength (STS) at 6.01 MPa and flexural strength (FS) at 5.22 MPa. Ideal slump occurred at 0% fiber, while 0.75% led to minimal slump flow. Adjusting JF content can predict concrete characteristics effectively.

Islam et al. [21] observed that increasing JF content in concrete reduced slump, more so with 20 mm fibers than 10 mm ones. Compressive strength improved with 0.25% fiber but decreased with 0.10%, while 0.50% had varied effects based on fiber length. Split tensile strength remained mostly unaffected, with slight increases at 0.25% and 0.50% compared to no fiber or 1.00%. Flexural strength was negatively impacted by 20 mm fibers but depended on fiber volume for 10 mm fibers. Factorial analysis attributed 40% of slump to both fiber length and volume, with the remaining 20% attributed to their combined effect. Fiber length contributed 38.25% to split tensile strength at 28 days, reducing to 8.3% at 90 days, while fiber volume had a consistent 37-39% impact at both ages. For flexural strength, fiber length and volume interaction contributed 46.90%, followed by fiber volume (36.35%), and fiber length (16.75%). JF improved flexural toughness by reducing crack formation as Figure 14 shows, indicating a need for further research on smaller fibers and chemically treated variants.

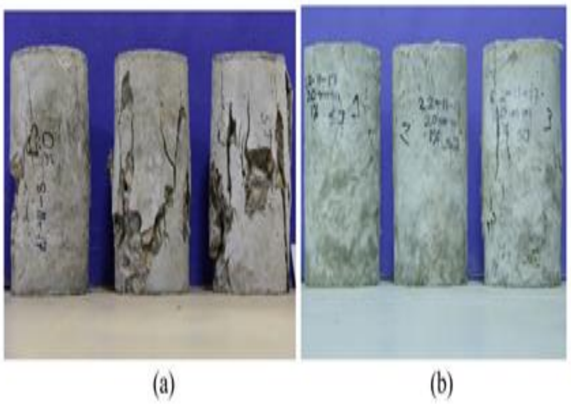

Figure 14: Illustrates the Failure Pobserved in (a) plain Concrete Cylinders and (b) Concrete Cylinders Reinforced with JF during the Compressive Strength test

E. Other Types of Fibers

Latifi et al. [26] showed polypropylene fibers (PF) are extolled for their economical nature, facile workability, formidable strength, meager density, and exceptional chemical resilience. They emerge as the most lightweight reinforcement option compared to steel, metal fibers, and poultry mesh, offering effective fortification devoid of inert mass. Categorized as either F or M variants, denoted respectively by fibrillated and multifilament attributes, these fibers augment the physical, mechanical, and thermal attributes of concrete. Notably, F fibers find favor in robust industrial flooring applications owing to their enduring nature. In 2022, Khan et al. [35] conducted slump tests to assess natural fiber concrete workability. Results indicated that increased fiber cement concentration reduced slump due to fiber water absorption. While natural fiber additions enhanced mixture stability and cohesion, they decreased concrete workability. Each fiber mix exhibited varying slump values, with HFRC demonstrating the highest among others listed in Table 5. A concentration of 0.5% yielded the highest slump compared to other natural fiber concentrations, with slump decreasing at higher concentrations.

Table 5: Slump test of natural fiber concrete [35]

Types of fibers		PC	SFRC	CFRC	HFRC
Slump of concrete for different fiber concentration (mm)	0.5%	90	70	72	75
	1.0%	90	60	54	63
	1.5%	90	51	49	58

Khan et al. [24] enhanced the concrete/mortar properties using synthetic fiber waste, improving strength, and reducing crack propagation. Significant findings include: 1. Compressive strength increased with 2% and 4% fiber content but decreased at 6%. Glass fiber outperformed polyester and polypropylene by 4% proportion. Glass fiber increased flexural strength from 0.94 MPa (Plain Mortar) to 5 MPa. 2. Polypropylene FRM flexural strength improved to 1.38 MPa with higher crack resistance than plain mortar. Polyester FRM flexural strength reached 4.8 MPa with improved crack resistance. 3. Glass and polyester fiber FRM showed better impact strength than polypropylene. Overall, glass and polyester fibers demonstrated superior performance in enhancing concrete/mortar properties.

Awal et al. [10] investigated concrete incorporating waste carpet fiber (WCF) and palm oil fuel ash (POFA) as partial replacements of ordinary Portland cement (OPC). Six mixes with WCF (0-1.25%) and six with 20% POFA were tested. The combination of WCF and POFA reduced the slump. WCF did not improve compressive strength but enhanced tensile and flexural strengths, increasing ductility and crack distribution. At 91 days, compressive strength ranged from 38.1-49.1 MPa. The highest increases in tensile and flexural strengths were with 0.5% carpet fiber. Ultrasonic pulse velocity (UPV) indicated good quality concrete. The study concludes that using WCF and POFA in concrete production is technically and environmentally feasible for sustainable green concrete.

De et al. [9] found that adding 2% carbon fiber waste to concrete is feasible but reduces workability, requiring a superplasticizer. This addition significantly enhances compressive strength, tensile strength, and modulus of elasticity, potentially reducing cement consumption. Further research is needed on creep behavior and resistance to external attacks.

III. DISCUSSION

- This document discusses a study that examines the impact of adding coconut, sisal, nylon, and jute fibers on the characteristics of concrete. The study found that incorporating these fibers can significantly improve the mechanical properties and sustainability of concrete.
- CF enhances compressive, flexural, and split tensile strength at different levels. SSF enhances compressive strength, tensile strength, and durability. Concrete with aligned SSF reinforcement exhibits superior ultimate tensile strength. RNF boosts tensile strength, while JF enhances it by 35% at optimal concentration.
- Incorporating waste materials and fibers into concrete can also significantly enhance its properties. For instance, adding 2% WCF improves compressive strength, while JF at 0.10% enhance tensile, split tensile, and flexural strengths. SSF at 1% have been shown to improve compressive strength by 22%.
- Most fibers tend to decrease workability/slump when added to concrete, requiring more water or superplasticizers and there are optimal dosage levels for each fiber type to achieve maximum strength benefits, beyond which strengths start decreasing.
- Natural fibers like sisal, jute, coconut provide good increases in compressive and tensile/flexural strengths at modest dosages while the synthetic fibers like nylon, polypropylene, carbon, glass provide very good improvements in mechanical properties, especially tensile/flexural.
- Natural fibers such as coconut, sisal, or jute may be ideal for projects that have environmental concerns or restricted funds. SSF are renewable and biodegradable, making them an environmentally favorable option. CF and JF are inexpensive alternatives that provide enough reinforcement in applications where high strength is not a major requirement. RNF are ideal for applications that require strong durability and chemical resistance, such as industrial flooring or bridge decking.
- The best materials to mix include WCF, JF, and SSF due to their proven ability to improve various concrete properties. Further research in this area could lead to more sustainable and durable concrete structures, benefiting both the construction industry and the environment.

Table 6: Summarizes the Effect of Each Type of Fiber on Concrete Properties

Type of Fiber	How it affects concrete
CF	- Enhances compressive, tensile, And flexural strengths when used in the range of 1.5-5% - Reduces workability and slump
SSF	- Markedly boosts compressive strength by up to 22% at 1% - Greatly enhances tensile and flexural strengths by up to 46% - Reduces workability
RNF	- Increases compressive strength by up to 11.7% at 1% dosage - Enhances tensile strength by up to 20.2% at 0.5% dosage
JF	- Enhances compressive strength by up to 10.1% at 0.5% dosage - Markedly increases tensile strength by up to 35% at 0.25% dosage - Significantly reduces workability
PF	- Improves compressive strength at 2-4% dosage - Reduces workability
WCF	- Markedly enhances compressive, tensile, and flexural strengths - Decreases workability, requires use of superplasticizer

IV. CONCLUSION

- The study reviewed the benefits of incorporating waste materials like WCF, coconut shell aggregate, fly ash, waste glass, and marble waste into concrete. These additions improve mechanical properties and sustainability. For example, carbon fiber admixture enhanced compressive, flexural, and split tensile strength, while fly ash and waste glass replacements improved concrete properties. The use of these waste materials presents a promising avenue for sustainable concrete production.
- The study on incorporating RNF and crushed recycled aggregate (CRA) in concrete showed promising results. For HPC, complete substitution of coarse natural aggregate with CRA reduced density by 2.2%, while 0.5% RNF increased tensile strength by 20.2%. In cement concrete, incorporating 1% RNF and JF improved compressive, split tensile, and flexural strengths by 11.71%, 14.10%, and 11.04%, respectively. These findings suggest that adding RNF and CRA can enhance the mechanical properties of concrete, making it a sustainable construction material. However, further research is needed to optimize the fiber content for specific applications.
- The studies on sisal fiber-reinforced concrete demonstrate the potential for enhancing concrete

properties, including compressive strength, tensile strength, and durability. For instance, aligned sisal fiber-reinforced cement laminates showed superior ultimate tensile strength compared to plain concrete (13.95 MPa vs. 9.24 MPa). Thermal and Na2CO3 treatments significantly improved splitting tensile strength (up to 46.2%) and compressive strength (up to 45.4%), respectively. Incorporating SSF also improved flexural and fracture strength, with greater ductility in fracturing. Optimal reinforcement was found at 1% SSF, resulting in a 22% increase in compressive strength. These findings underscore the potential of SSF as a sustainable and effective reinforcement in concrete applications, suggesting further research to optimize its use in construction.
- Integration of JF into concrete enhances sustainability. Optimal results are seen at 0.25% concentration with 15mm fibers, showing a 35% increase in tensile strength. Treatment with NaOH enhances fiber strength. Studies suggest 0.10% JF content is optimal for maximum compressive, split tensile, and flexural strengths. JF show promise in improving concrete properties, calling for further research.
- PF offer lightweight reinforcement with formidable strength and chemical resilience, particularly beneficial for industrial flooring. Natural fiber concrete workability decreases with increased fiber cement concentration due to fiber water absorption. Synthetic fiber waste, especially glass and polyester, enhances concrete/mortar properties, improving compressive and flexural strength. Waste carpet fiber and palm oil fuel ash as partial cement replacements enhance tensile and flexural strengths, ductility, and crack distribution, making them viable for sustainable concrete production. Addition of 2% WCF waste to concrete improves compressive strength but reduces workability, necessitating further research on creep behavior and external attack resistance.

V. RECOMMENDATION

Researchers should focus on increasing both the volume and length of fibers in order to enhance the mechanical performance of concrete. Studies have shown that incorporating fibers like polypropylene, jute, and sisal can significantly improve the tensile, flexural, and compressive strengths of concrete. However, the ideal number of fibers varies depending on the type of fiber and the specific qualities desired. Therefore, further research is needed to determine the optimal fiber content and length for different concrete applications. Additionally, researchers should explore new methods of treating fibers, such as NaOH treatment for sisal fibers, to enhance their compatibility with concrete and mechanical properties. By optimizing fiber content, length, and treatment methods, researchers can develop more sustainable and durable concrete materials for various construction applications. In engineering projects, non-destructive testing methods like ultrasonic testing (UT) and impact-echo testing can assess the quality of fiber-reinforced concrete. Finite element analysis (FEA) and computational fluid dynamics (CFD) can model fiber-reinforced concrete behavior. Examples of projects benefiting from fiber-reinforced concrete include bridges, tunnels, pavements, and high-rise buildings.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest between them and with any third party.

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