

REVIEW

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An overview of the application of recycled textile fibers in structural concrete

Md Faiyaz Shahriar^{1*}, Rizwanur Rahman² and Takia Kamal³

*Correspondence:

Md Faiyaz Shahriar
g202427140@kfupm.edu.sa

¹Department of Civil and
Environmental Engineering, King
Fahd University of Petroleum and
Minerals, Dhahran, Saudi Arabia

²Department of Civil Engineering,
Bangladesh University of
Engineering and Technology,
Dhaka, Bangladesh

³Department of Apparel
Engineering, Bangladesh University
of Textiles, Dhaka, Bangladesh

Abstract

Global textile production exceeds 110 million tons annually, yet less than 20% of discarded textiles are recycled, leaving enormous quantities in landfills. To address this waste challenge, the present review evaluates the potential of using recycled textile fibers (RTFs) as sustainable reinforcement in concrete, examining their effects on mechanical performance and durability. This study synthesizes experimental and theoretical research on natural, synthetic, and blended RTFs, including their recycling methods, fiber treatments, and strategies for integrating them into cementitious matrices. Results indicate that RTF inclusion generally enhances tensile and flexural strength and ductility, with an optimal fiber dosage around 0.5% by volume maximizing these gains. Beyond this optimum, higher fiber content tends to reduce compressive strength and workability due to fiber agglomeration and void formation. RTFs also improve concrete durability by mitigating shrinkage cracking and refining the pore structure, which decreases water and chloride ingress and thereby enhances freeze–thaw and chemical resistance. Microstructural observations show effective fiber–matrix interactions, as fibers bridge cracks and create a more homogeneous matrix, correlating with improved post-cracking toughness. Overall, incorporating RTFs into concrete offers a promising route toward sustainable construction by valorizing textile waste and improving material performance. Key challenges such as reduced workability and fiber dispersion issues at high fiber dosages, along with the lack of standardized design codes, must be addressed to enable broader application.

Keywords Recycled textile fibers, Fiber-reinforced concrete, Sustainable construction materials, Mechanical properties, Ductility, Toughness

1 Introduction

Worldwide production of textile fibers has increased significantly during the last several decades, led by man-made fibers like polyester, supplemented by natural fibers like cotton. Consequently, production of textile waste has increased significantly, a high proportion of which is going to landfill or incineration, as opposed to recycling [1]. For instance, Fig. 1 on textile waste management indicates that very little of the textile waste is recycled and millions of tons annually are either buried in landfills or incinerated, leading to severe soil and air pollution. Landfills release toxic pollutants into the ground, while incineration leads to poisonous gases and greenhouse gas emissions [2]. These troubling



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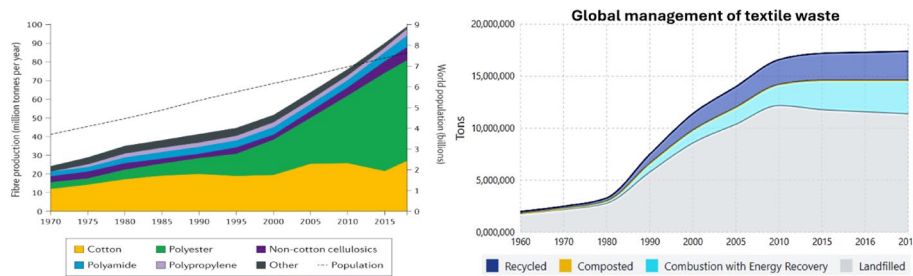


Fig. 1 Global textile waste generation (Left) [3] and global textile waste management (Right) [4]

trends underscore the imperative for sustainable remedies to conventional solutions to textile waste disposal.

Textile waste recycling into concrete is a profitable route towards sustainable waste management, reducing landfill area and reducing reliance on virgin material [4]. Using recycled textile fibers as reinforcement in concrete is in harmony with circular economy philosophies and can minimize the use of cement, thereby limiting associated carbon emissions. Previous work has concentrated on individual categories of fibers or specific concrete properties [5].

Given the pressing textile waste challenge and sustainability imperatives, repurposing discarded textiles as concrete reinforcement has emerged as a promising circular-economy solution. However, previous reviews of recycled textile fibers (RTFs) in concrete remain limited in scope, often focusing narrowly on specific fiber categories or single performance aspects. These studies lack an integrated perspective spanning mechanical and durability outcomes and offer little guidance on optimal fiber dosage. This review overcomes these limitations by comprehensively comparing natural, synthetic, and blended RTFs, mapping how fiber dosage influences both strength and durability, and identifying optimal dosage recommendations for each fiber type. This integrated analysis provides a holistic performance perspective and practical guidelines beyond those of prior studies.

2 Methodology

2.1 Planning phase

Following established systematic review protocol [6], the steps are entailed as Planning, Conducting, and Reporting illustrated in Fig. 2. In Planning, the questions guiding the research were established to explore how recycled textile fibers (RTFs) affect the mechanical performance, durability, and sustainability of concrete. The inclusion criteria were peer-reviewed studies on natural or synthetic RTFs in cementitious composites yielding relevant mechanical or durability details, and non-conforming studies were not included. A systematic search of major databases (Scopus, ScienceDirect, Google Scholar) was undertaken in accordance with PRISMA guidelines for transparent study selection as shown in Fig. 2 [7].

Figure 2 illustrates systematic literature review's process according to PRISMA. 293 articles were first identified across leading publishers including Elsevier, MDPI, and Springer. After deduplication, 248 papers were filtered, which reduced the group to 210 for an eligibility test of the full-text. The group was further cut down to 133 articles by a quality assessment. The last check had 117 articles, with sources from IEEE, PubMed,

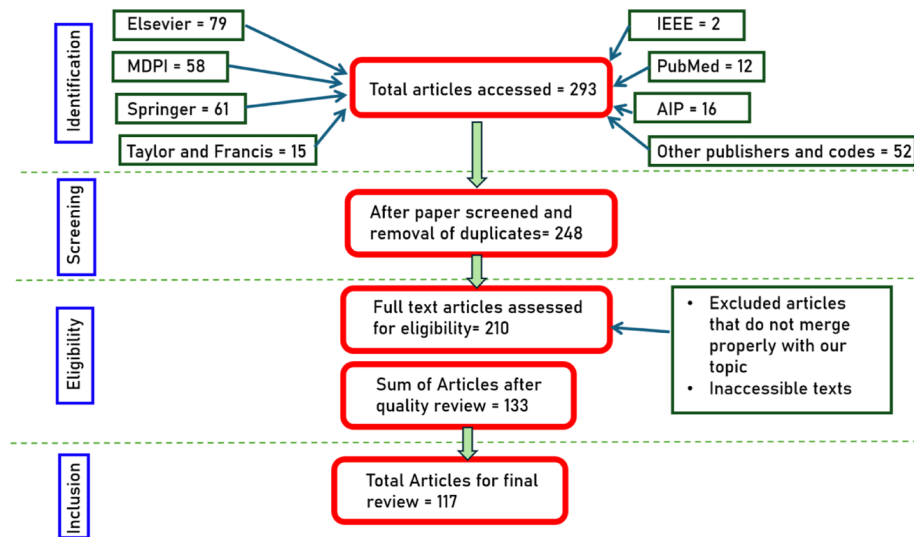


Fig. 2 PRISMA workflow diagram of the current study

AIP, and other publishers. Articles were not considered if they were off-topic or not available. This strict strategy yielded a high-quality, focused dataset to synthesize the review article.

2.2 Conducting stage

Systematic screening of results obtained from the search was conducted at the Conducting stage. After deletion of duplications, titles and abstracts were screened for inclusion criteria, and full-text eligibility assessment of the remaining articles. Data from studies reported were abstracted, such as fiber type, dosages, and salient results on mechanical and durability performance. Relevance and quality of studies were assessed qualitatively, prioritizing high-quality experimental evidence of RTF effects. Experimental publications reporting improvements in concrete properties took priority, whereas non-experimental research was used only for background purposes.

2.3 Reporting stage

In Reporting, the results from the studies included were grouped by theme and synthesized. Results are ordered in sections by mechanical performance, durability, microstructural behavior and environmental sustainability. The narrative synthesis makes use of tables and figures wherever feasible to present principal trends. The open review process and thematic organization follow PRISMA-style best practice, highlighting the rigor and reproducibility of the approach [7] (Fig. 3).

3 Types of recycled textile fibers

3.1 Natural fibers

Plant and animal natural fiber textiles from cotton, flax, hemp, and jute (plants) and wool and silk (animals) dominate sustainable textiles due to biodegradable properties, low thermal conductance, and renewability [8, 9]. Mechanically recycled cotton is torn into short staple fibers, washed, carded, and re-spun, usually requiring blending with virgin fibers due to the reduced fiber length [8, 10]. Wool can be subjected to multiple cycles of recycling without degradation in quality, whereas silk tends to be re-sewn or blended due

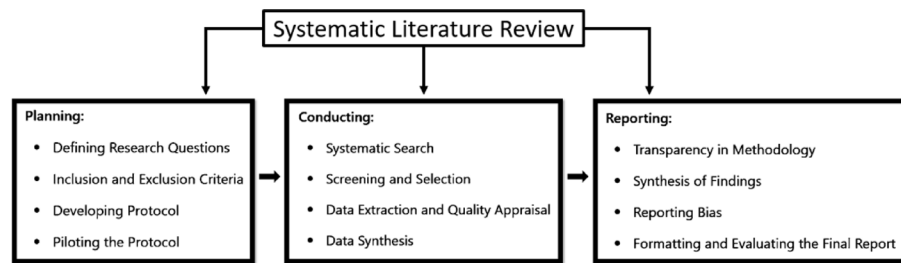


Fig. 3 Systematic approach for reviewing literature

to tensile degradation upon shredding [11]. Novel chemical recycling technologies for hemp and linen involve the solvolysis of lignin, releasing high-purity cellulose for near-indefinite recyclability [12]. Recycling is frustrated by contaminants like finishes, dyes and blends, with fiber separation becoming more difficult [13]. Technological innovations in automatic sorting and enzymatic treatment enhance the effectiveness of recycling, enabling the conversion of cotton waste into hydrophilic insulation materials [8]. Nonetheless, globally, textile recycling is limited to approximately 15%, which indicates the need for enhanced closed-loop systems to facilitate the full potential for a circular economy with natural fibers [12].

3.2 Synthetic fibers

Synthetic fibers, predominantly petrochemical-based, dominate world textiles (around 64%), with polyester (PET) alone contributing 52% [14]. Key fibers include cost-effective PET, high-strength/high-toughness nylon, chemically resistant polypropylene, and acrylic (as a wool substitute) [15]. Synthetic fibers are challenging to recycle because they are non-biodegradable, become mixed (polyester-cotton, nylon-elastane), and have dye contamination, resulting in < 1% fiber-to-fiber recycling [16, 17]. Strategies include mechanical recycling (fiber shredding, reducing quality and length, limiting reuse) [18]; chemical methods like glycolysis of PET and ammonolysis of nylon, depolymerizing fibers to monomers with high-purity products but energy and advanced catalysis demanding [19]; new biological recycling with enzymes for PET depolymerization; solvent-based separation (ionic liquids) [20]; and AI-facilitated sorting technologies. Economic and infrastructural barriers mandate design-for-recycling and policy action for enhancing textile circularity [21, 22].

3.3 Blended fibers

Blended fibers, made up of natural, synthetic, or semi-synthetic fibers, dominate textiles due to added functionality, price factor, and durability. Well-known blends include cotton-polyester (increases wrinkle resistance and flexibility) cotton-elastane, and synthetic pairs like nylon-elastane [23, 24]. Less typical blends such as Kevlar-Nomex or Nomex-Nylon are applied in high-performance uses but complicate recycling [25]. Recycling is limited by fiber incompatibility: mechanical methods like shredding create lower-quality fibers, while chemical methods require precise constituent separation. Cotton-polyester blends, for example, need acidic hydrolysis or enzyme treatment to depolymerize cellulose and recycle polyester [24]. Elastane hinders recycling even in trace amounts by clogging machinery or requiring selective dissolution [26]. Consequently, mixed fabrics

often end up in landfills, recycled only 20% globally [27]. New enzymatic and solvent-based technologies have the potential to improve recycling. (Fig. 4).

From a cement-matrix point of view, hydrophobic synthetic fibers such as polypropylene, polyester, and nylon are the most promising; at around 0.5–1.0% by volume they enhance post-crack toughness, impact and freeze–thaw resistance, and reduce transport properties such as chloride ingress, while achieving workable mixes. Natural cellulosic fibers like jute, coir, and sisal are effective in crack control and drying-shrinkage reduction at about 1–2% by volume but are benefited by surface treatments or pozzolan-rich binders to avoid alkali-induced degradation and stabilize the interfacial transition zone [33]. Blended or hybrid systems, i.e., cotton–polyester wastes or basalt–polypropylene blends, can balance strength and ductility, enhance pore structure, and further cut down ion transport when optimized in dosage and length of fibers. Overall, synthetics are favored where durability and post-crack performance are critical; naturals are suited to shrinkage and crack control through appropriate conditioning; and hybrids are used when toughness and durability are to be combined [34].

4 Fiber treatment and processing methods

Textile fiber recycling processes find a balance of mechanical performance, cleanliness, and energy efficiency, mechanical processing is low-energy but shortens fiber length, while chemical and biological processes offer selectivity but at high cost or complexity. Hybrid processes and surface treatments enhance concrete adhesion and durability, optimizing fiber performance. The stages of recycling processes are summarized in Table 1.

While mechanical recycling is low-energy, it downsizes fibers (5–50 mm) and therefore restricts performance. For concrete applications, surface treatments are found to be very effective. Alkali treatment increases fiber tensile strength by 15–20% and creates surface roughness for improved interfacial bonding. Similarly, pozzolanic coating reduces hydrophilicity, eliminating degradation in the alkaline concrete environment. Hybrid methods involving thermomechanical processing also yield benefits, with improved fiber liberation at less damage than mechanical alone. Lastly, surface treatments and hybrid processes are best in optimizing the performance of fibers in concrete composites.



Fig. 4 Different types of textile fibers [27–32]

Table 1 Treatment phases of textile fiber recycling

Treatment Phase	Processes	Mechanism	Changes in fibers	References
Mechanical Recycling	Fragmentation: Shredding, cutting, or milling of textile waste.	Physical force breaks down fabrics into shorter fibers or granules.	Reduced fiber length (5–50 mm); increased aspect ratio; surface roughening; partial delamination of coatings.	[4, 16, 17]
	Fiber Opening: Carding, air-jet separation.	Separation of entangled fibers using mechanical agitation or aerodynamic forces.	Improved fiber dispersion; reduced clumping; length heterogeneity (retains 40–60% of original length).	[35]
Chemical Recycling	Solvent-Based Separation: Use of ionic liquids or alkaline hydrolysis.	Selective dissolution of synthetic polymers or degradation of natural polymers.	Purification of target fibers ($\geq 90\%$ cellulose/polyester recovery); removal of dyes/sizing agents; minimal strength loss.	[35, 36]
	Hydrothermal Depolymerization: High-pressure steam/acid treatment.	Hydrolysis breaks polymer chains into monomers (e.g., PET $\rightarrow$ terephthalic acid).	Fiber disintegration; monomer recovery; residue-free output suitable for repolymerization.	[36, 37]
Biological Treatment	Enzymatic Degradation: Cellulases (for cotton) or proteases (for wool).	Enzyme-targeted cleavage of specific bonds (e.g., β -1,4-glycosidic in cellulose).	Selective removal of natural fibers from blends; preserved synthetic fiber integrity; reduced contaminants.	[35]
Hybrid Methods	Thermomechanical: Thermal pre-treatment (200–300 °C) + shredding.	Heat softens polymer matrices (e.g., elastane), easing mechanical separation.	Enhanced fiber liberation; reduced fiber damage; lower energy consumption vs. stand-alone mechanical processes.	[37]
	Chemo mechanical: Mild acid wash + carding.	Chemical pre-treatment weakens adhesives/coatings; mechanical processing separates fibers.	Improved fiber cleanliness; higher length retention; minimized micro fibrillation.	[17, 38]
Surface Modification	Alkali Treatment (Mercerization): NaOH (2–10% w/v) immersion.	Swelling of cellulose fibers removes surface impurities; enhances roughness.	Increased surface area; improved interfacial bonding with cement; higher tensile strength ($\uparrow 15$ –20%).	[36, 39]
	Pozzolanic Coating: Slurry immersion (e.g., diatomaceous earth + cement).	Formation of C-S-H phases on fiber surfaces during curing.	Reduced hydrophilicity; strengthened fiber-matrix interface; mitigated mineralization in alkaline concrete.	[17]

5 Concrete mix design with recycled textile fibers

5.1 Code considerations and limitations

Despite the proven mechanical benefits of recycled textile fibers (RTFs) in concrete, such as improved crack control, ductility, and spalling resistance, international design codes offer limited guidance for their application. Codes like ACI 544R-18 and the DAFStb Guidelines address synthetic fibers such as polypropylene and steel but lack special consideration for heterogeneous RTFs from textile wastes [4, 40, 41]. ACI 544R-18 classifies fibers by tensile strength and modulus, but not the variability in geometry, adhesion, or degradation typical of mechanically recycled RTFs [42]. Similarly, ACI 549.4R-13 is aimed at fabric-reinforced cementitious systems and does not address dispersed RTFs as reinforcement [43]. The European Model Code 2010 welcomes sustainability but does not have RTF-specific mix design parameters like aspect ratios or optimum dosages for blended fibers. The most critical regulatory shortcomings include the absence of standard classification by fiber type or source, insufficient durability test procedures for alkali and UV resistance, and the prescriptive dosage requirements. Empirical testing thus

remains a necessity [44]. Bidabadi et al. (2020) [45] and Lav Varma & Sharma (2011) [46] emphasize the need for standard classifications and test procedures in order to attain structural reliability and long-term performance of RTF-reinforced concrete systems.

5.2 Fiber content optimization

Optimizing RTF content demands balancing mechanical performance enhancements against workability reductions, leveraging advanced analytical and experimental strategies. Key methodologies include:

- *Fiber Factor Theory*: This approach quantifies reinforcement potential using the dimensionless parameter $F_f = V_f \times (l_f/d_f)$, where V_f = volume fraction, l_f = length, d_f = diameter. For cotton-polyester blends, $F_f = 0.3$ to 0.6 maximizes crack bridging; exceeding $F_f=0.8$ raises water demand, cutting strength by 12–18%. Hybrid blends like elastane-cotton require segmented F_f due to modulus divergence [4, 47].
- *Rheology-Driven Optimization*: The Particle Flow Model (PFM) simulates RTF interactions in fresh concrete by modeling fibers as rigid cylinders within a Bingham fluid. Inputs include fiber aspect ratio, volumetric concentration and matrix viscosity. Simulations reveal that 0.3–0.5% RTF by volume maintains slump more than 100 mm, while increase up to 0.7% causes yield stress to surge by 150–300%, necessitating superplasticizers. Experimental validation via rheometers shows that surface-treated RTFs like alkali-mercerized cotton reduce viscosity by 20% compared to untreated fibers, enabling higher dosages [45, 48].
- *Response Surface Methodology (RSM)*: Multi-variable RSM designs identify synergistic interactions between RTF properties and mix components. For instance, a Central Composite Design by Dissanayake et al. (2021) [17] modeled compressive strength (f'_c) and slump (S) as functions of RTF dosage (V_f), water-cement ratio (w/c) and recycled aggregate content (R_a):

$$f'_c = 68.7 - 22.4V_f - 18.6(w/c) - 0.3R_a + 9.2V_f \times (w/c) \quad (1)$$

$$S = 185 - 210V_f - 120(w/c) - 0.7R_a \quad (2)$$

This model confirmed that 0.4% RTF maximizes f'_c at $w/c = 0.45$ and $R_a=30\%$ [4, 21].

- *Recycling-Process Calibration*: Chemically separated RTFs like ionic liquid-treated polyester exhibit higher tensile strength, allowing 20–30% lower V_f . Enzymatically separated fibers need + 0.1% V_f to offset bond loss from micro-pitting [40].

5.3 Mix proportions

In the absence of formal code specifications, elaborate best practices have evolved for incorporating recycled textile fibers (RTFs) into concrete mixtures. The fundamental challenge is RTFs' high water absorption (5–20% by mass), which strongly impacts

workability and requires systematic adjustment of all mix components. Cementitious System Optimization is the foundation of effective RTF concrete design. Additional cementitious paste content is required to compensate for workability loss caused by fibers and to enable fiber coating [49, 50].

The equivalent paste volume (EPV) principle guides the adjustment: $V_p = V_{\text{voids}} + V_{f, \text{abs}} + V_{\text{excess}}$, where $V_{f, \text{abs}}$ = water absorbed by RTFs, and V_{excess} = workability buffer (5–15% of V_{voids}) [45, 47]. Supplementary cementitious materials play a key role, with wheat straw ash having more than 100% pozzolanic activity indices and enhancing 28-day compressive strength by 24.75% at 10% cement replacement by secondary C-S-H gel formation. Silica fume (8–12%) provides nano-filler effects, reducing RTF-induced shrinkage by 30–40%, whereas fly ash (20–25%) provides spherical particle lubrication to restore workability [4, 51]. Aggregate system optimization solves both the RTF integration and recycled aggregate issue simultaneously. Modified packing density design takes advantage of fully recycled fine aggregates (CRFA) with retained powder content, reducing voids by 5–8%. The optimum mass fraction of fines (40–45%) minimizes specific surface area while making packing density feasible >0.75 . Pre-wetting of CRFA to 40–60% saturation prevents uncontrolled water release, stabilizing water-cement ratio [48]. Chemical admixture integration is indispensable for RTF concrete performance. Polycarboxylate ether-based superplasticizers (0.8–1.2% by cement mass) provide steric hindrance for fiber dispersion, while hydrophobic admixtures reduce RTF moisture sorption by 15–30%. This integrated approach successfully produces C55-grade RTF concrete with 12.7% cost reduction and complete recycled aggregate utilization [45, 47].

Existing design codes do not have precise guidance for recycled textile fibers (RTFs), leading to dependence on empirical testing. Fiber content is maximized by using models such as the Fiber Factor and Response Surface Methodology, with 0.4% volume being typical. Dosages above optimal levels greatly diminish workability, necessitating the addition of superplasticizers. Mix design has to factor in high fiber water absorption by modifying the paste volume through supplementary cementitious materials. Silica fume retards shrinkage, while fly ash increases workability. Mixing pre-wetted recycled aggregates with chemical admixtures offers high-quality, cost-effective RTF concrete with C55-grade properties at a 12.7% cost reduction.

6 Effects of using textile fibers in concrete

Natural and synthetic fibers enhance concrete properties in different ways; their effects are summarized in Table 2.

At mesoscale, textile fibers have various impacts in concrete elements which further enhances different concrete properties. Some of the mechanisms are:

6.1 Stress transfer

Fibers carry stress in concrete, improving load distribution and minimizing localized stress concentrations to avert premature failure [64]. Their reinforcement improves flexural strength via resistance to bending forces, improving load-carrying capacity for demanding applications. Fibers also significantly improve impact resistance shown in Fig. 5 (Left) by absorbing and distributing impact energy to reduce the formation and propagation of cracks. This is especially important for structures that are exposed to dynamic loading like industrial floors, pavements, and seismic-resistant structures.

Table 2 Advantages of using fibers in concrete

Advantage	Natural	Synthetic	Reason behind advantage
Improved crack control in concrete [52]	✓	✓	Both bridge micro-cracks
Acoustic insulation due to thermal properties [53]	✓		Natural — porous/low λ fibers
Strength and durability for high-level structural reinforcement [54]		✓	Synthetic — higher tensile & toughness
Uniformity in mixing and placement within concrete [55]		✓	Synthetic — uniform, low water uptake
Better resistance to chemical exposure like alkalis and chlorides [56]		✓	Synthetic — inert & hydrophobic
Reduced environmental impact from renewable sources [57]	✓		Natural — renewable, lower footprint
Cost-effective compared to expensive synthetic fibers [58]	✓		Natural — often locally cheaper
Improved impact resistance against loads [59]	✓	✓	Synthetic — higher post-crack energy
Less moisture sensitivity and water absorption [60]		✓	Synthetic — hydrophobic, low sorption
Consistency and stability in fiber properties [61]		✓	Synthetic — industrially consistent
Enhanced workability reducing segregation and bleeding [62]		✓	Synthetic — reduces bleeding; less slump loss
Good sustainability for reinforcement and waste use [63]	✓	✓	Natural = renewable; synthetic = upcycled PET
Natural fibers have lower carbon emissions [33]	✓		Natural — many LCAs favor natural
Compatibility and bonding with cement matrix [62]		✓	Synthetic — engineered surfaces, no swelling
More biodegradable and prone to degradation [33]		✓	Natural — biodegradable

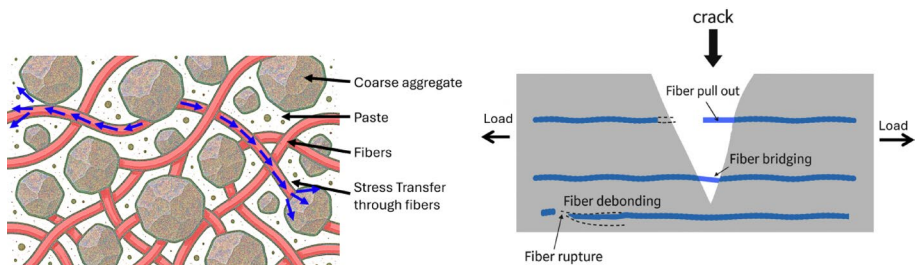


Fig. 5 Stress transfer through fibers in Textile fiber reinforced concrete (Left) [65] and Crack reducing mechanism of fibers (Right) [67]

L.Bian et al. [65] noted that the heightened elastic modulus in the matrix-fiber interfacial layer imposes additional stress on the fibers and indicated its significant role of stress transfer. Aktham H. Alani et al. [66] noted that the addition of PET fibers in ternary blended binder increased the stress values and strain capacity of concrete compared to non-fiberized mixtures.

6.2 Cracking control and bond strength

Selection of fiber type, amount, and distribution in concrete highly influences its mechanical properties, such as flexural strength and cracking. Optimal fiber dosage is dependent on the strength requirement, properties of fibers, and mix design, where dispersal guarantees good strengthening. Fibers regulate the formation of cracks by

spanning the cracks, hindering transfer of stress, and inhibiting crack growth, thereby adding toughness and ductility. Ming Li and coworkers mentioned that recycled nylon fibers increased the roughness of crack surfaces and reduced water permeability at higher dosages [68]. J. Shen and Y. Zhang (2022) [69] mentioned that composite fibers (polyacrylonitrile-based carbon, basalt, and glass) increased the toughness index of FRC by over 30%, with the formation of a mesh structure that improved stability and mechanical properties. Fibers also promote bond strength by anchoring the cementitious matrix and reinforcement bars or overlays, anchoring the interfacial surfaces and distributing load [71]. They also dissipate energy in the pull-out, debonding, and bridging mechanisms, slowing down crack extension and enhancing ductility. Fibers also limit shrinkage, reducing cracking and enhancing durability shown in Fig. 5 (Right). Raymond J. Connolly [67] demonstrated that bond and flexural strength are fiber orientation dependent. Wenchen Shan et al. [72] stated that hybrid fiber-reinforced engineered cementitious composites (ECC) had exhibited more ductile bond-slip behavior than ordinary concrete due to fiber bridging, maintaining stable bond stress through redistribution of stress.

6.3 Thermal and spalling resistance

Spalling, or flaking or chipping of concrete surfaces [73], occurs due to high temperature, freeze-thaw action, chemical attack, corrosion of reinforcement or overloading of structures, compromising structural strength. Fibers enhance thermal resistance by reducing heat transfer through thermal bridges and enhance spalling resistance by bridging thermal cracks. Certain fibers are melted with fire temperatures (steel ~ 1500 °C, polypropylene ~ 165 °C) and create voids in which steam pressure is released, reducing the risk of spalling. H.Wu et al. [74] found steel and polypropylene fibers improved thermal resistance and reduced spalling to a lesser extent. Other studies found unsaturated polyester resin inhibited micro-defects in freeze-thaw cycles [75]. Zhang and Tan demonstrated that some polymer fibers like low-density polyethylene, polypropylene and polyamide prevented spalling in ultra-high-performance concrete by increasing permeability below 200 °C by thermal expansion-induced microcracks before the melting, while ultra-high-molecular-weight polyethylene and polyester fibers did not [76].

6.4 Creep-shrinkage, freeze thaw and corrosion resistance

Fibers reduce shrinkage (plastic and drying) and creep in concrete by bridging microcracks and distributing loads, enhancing dimensional stability and long-term durability for resistance to cracking and time-dependent deformation under sustained loading [71]. They also improve durability to freeze-thaw cycling by forming a network barrier that is resistant to water infiltration, preventing scaling and crack growth [77]. Moreover, some fibers, like coated steel fibers, enhance corrosion resistance by acting as sacrificial anodes or barriers to corrosive substances and chloride ions, enhancing service life in aggressive environments such as in marine exposure or deicing salt regions [78].

In short, textile fibers enhance concrete by controlling cracks and improving strength, toughness, and durability. Synthetic fibers provide superior chemical resistance and spalling protection, whereas natural fibers offer sustainability benefits. Key mechanisms like fiber bridging and stress transfer increase impact and shrinkage resistance. These

improvements boost ductility and longevity, making fiber-reinforced concrete ideal for dynamic loads and harsh environments.

7 Mechanical properties of textile fiber reinforced concrete

7.1 Compressive strength

Compressive strength of textile fiber-reinforced concrete is highly dependent on dosage and quality of fibers. Natural fibers enhance ductility and crack bridging; e.g., 0.5% coir fibers add 6–7% strength, and 1.5% weight alkali-treated bamboo enhances strength by approximately 9% [79, 80]. Optimal natural fiber dosages are in the range 1–2% by volume, beyond which fiber clumping limits performance [81, 82]. Synthetic fibers primarily improve post-cracking behavior and residual strength; polyester increases strength by 10–20% at ~ 0.25%, and nylon experiences ~ 22% improvement at 0.5% [5, 83]. Polypropylene in room conditions brings about modest gains (~ 6%) but is very effective in minimizing loss of strength upon exposure to heat. Best synthetic dosage is between 0.5 and 1% by volume, and increased percentages result in workability issues and reductions in strength [4]. Hybrid fiber composites combining natural and synthetic fibers utilize synergistic benefits, e.g., coir-PP-jute (7% strength gain) and wheat straw-bamboo (~ 9% increase) [79, 84]. Optimal hybrid levels are 0.1–0.5% natural and 0.5–1% synthetic by volume, compromising better ductility and strength without excessive porosity or fiber clumping [5]. Figure 6 indicates steel and glass fibers have the highest optimum dosage around 1.5% while polypropylene has the lowest (~ 0.4%). Notably, jute fibers yield the highest compressive strength peaking around 2% dosage, with sugarcane, coconut, and sisal fibers following closely [85–88].

7.2 Flexural and tensile strength

Natural and man-made fibers contribute to concrete's tensile and flexural strengths significantly, with optimum dosages commonly between 0.5 and 2.0% by volume [90]. Natural jute, coir, and sisal fibers provide considerable improvement at relatively low dosages; 0.25% by weight of jute fiber, for instance, improved direct tensile strength by 35%, while 0.4% jute fiber improved splitting tensile and flexural strengths by 18.7% and 29.1%, respectively. 1.5–2.0% by volume coir fibers improved splitting tensile strength by around 20–40%, although over 3% compromised performance due to clumping of the fibers and inadequate dispersion [91–93]. Around 1% by weight sisal fibers improved splitting tensile strength by nearly 47%. Synthetic fibers also improve concrete toughness

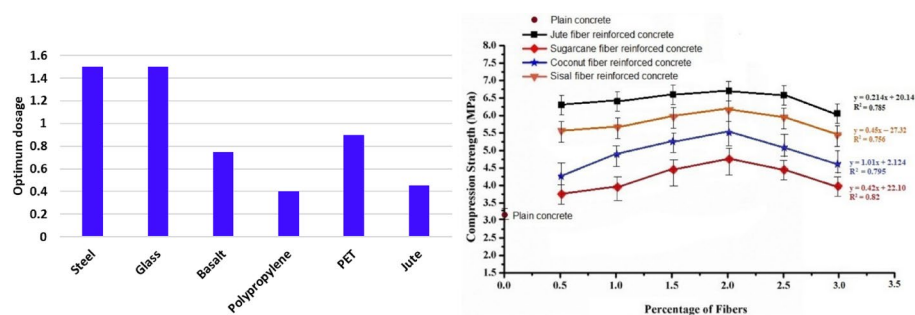
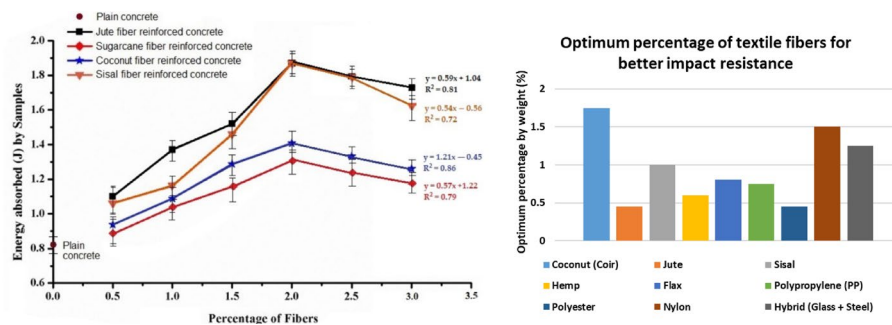


Fig. 6 Optimum dosage for different fibers (Left) [85–88] and Variation of compressive strength with the dosage of fibers (Right) [89]

Table 3 Effect of textile fibers in flexural and tensile strength of concrete

Fiber Type	Dosage Range	Tensile Strength Change	Flexural Strength Change	Optimal Dosage	Remarks
Polypropylene	0.08–1.0%	8–12%	5.5–18%	1.0%	Good bonding with concrete matrix
Cotton	0.1–0.5%	–8% to –15%	–2% to –8%	0.25%	Poor performance, reduces strength
Jute	0.25–2.0%	8–35%	10–40%	1.0%	Maximum 35% tensile strength increase
Nylon	0.5–1.5%	10–20%	15–25%	1.0%	Decline after 1.5% due to balling effect
Sisal	0.25–2.0%	7–20%	11.6–30%	1.0%	Good natural fiber alternative

**Fig. 7** Effect of percentage of natural fibers in concrete impact energy absorbance (Left) [89] and Optimum dosage for different fibers (Right) [57–107]

and strength; polypropylene fibers at 1–1.5% increased flexural and splitting tensile strengths by about 26–34%, while polyester fibers at 0.42% increased these strengths by 37% and 27%, respectively [94–96]. Nylon fibers at 1.5% increased the tensile strength by up to 47%. Both types of fibers improve ductility, crack bridging, and post-cracking toughness. Optimal dosages of fibers around 0.5–1.5% best balance strength gain, durability, and workability [97]. Table 3 summarizes the effect of these fibers in concrete [81, 94, 97–102].

7.3 Impact resistance

Textile fiber-reinforced concrete (FRC) employs natural, synthetic, or hybrid fibers to enhance impact resistance through bridging of microcracks, absorption of energy, and postponement of crack propagation, which converts brittle concrete into a ductile composite [103, 104]. Natural fibers at low dosages can double the impact resistance of concrete in drop-weight tests (with some research reporting up to six-fold improvement) and enhance tensile and flexural strengths by 20–50% [4, 105]. Synthetic fibers give higher improvements: at ~ 0.5–1.0% vol, polypropylene or polyester can improve fracture energy and post-crack strength by ~ 25–50%, and polypropylene has given several-fold improvements in the absorption of impact energy in drop-weight tests [104]. Hybrid fiber systems yield synergistic toughness enhancements higher than single-fiber blends like mixing micro- and macro-fibers more than doubles crack resistance [88]. Beyond an optimum fiber content (~ 0.5–2.0% vol), fiber clustering and workability loss cause diminishing returns [105]. Figure 7 shows natural fibers enhanced concrete's impact strength significantly up to 138% at optimum 2% fiber loading, with reduced performance beyond this threshold [89] and optimum fiber percentages.

Fiber dosage is important since both synthetic and natural fibers enhance the compressive, tensile, and flexural strength of concrete, as well as impact resistance. Natural fibers improve ductility and crack control, while synthetics exhibit improved post-cracking behavior and energy absorption. Hybrid blends capitalize on both strengths. Dosages optimal and in excess of which fiber clumping, compromised workability, and diminishing returns occur are exceeded. The most significant practical conclusion is the selection of appropriate fiber type and content to strike a balance between significant mechanical improvements and appropriate practical workability of the concrete, without compromising constructability.

8 Durability of textile fiber reinforced concrete

Textiles fibers have various effects in concrete durability. The following Table 4 concisely summarizes findings from research papers investigating the impact of natural and synthetic textile fibers on key durability properties of concrete.

Polypropylene (PP) is the most reliable durability fiber: at low levels it inhibits freeze–thaw scaling, limits sulfate expansion, and reduces chloride permeability. Contextual benefits derive from natural plant fibers: hemp/flax add freeze–thaw resistance; coir adds acid resistance; high jute contents are acid-sensitive. Optimized resistance to carbonation is achieved with medium PVA contents. Creep and drying shrinkage can be best avoided by micro-synthetic fibers and by low-dosage waste-PP, and early-age shrinkage is regulated by cellulose fibers. Hybrids like highly diluted basalt and PP also minimize ion ingress. In practice, PP can be placed first for sea/deicing and freeze–thaw; coir can be used where mild acids are expected, PVA can be selected to limit carbonation; and micro-synthetics or cellulose can be used with good paste/admixture control, to manage shrinkage and long-term deformation.

9 Microstructural analysis

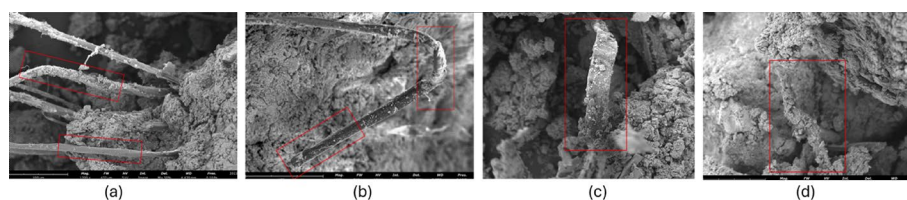
Natural fiber like kraft fibers, being natural cellulose, exhibit significant microstructural vulnerability to cement alkalinity, particularly calcium hydroxide which penetrates the outer lumen causing damage shown in Fig. 8 (c, d). Additives like gypsum or metakaolin mitigate this: gypsum creates a homogeneous matrix, improving fiber bonding and reducing $\text{Ca}(\text{OH})_2$ attack shown in Fig. 8 (c) while metakaolin consumes $\text{Ca}(\text{OH})_2$ early, reducing degradation and promoting denser C-S-H gel formation that enhances bonding Fig. 8 (d).

However, cement products still attach heavily to kraft fiber walls, potentially weakening them under load. Conversely, polyester fibers show superior alkali resistance, with gypsum integration effectively preventing $\text{Ca}(\text{OH})_2$ attack, leaving their smooth surface intact and promoting strong petrification bonds which can be observed in Fig. 8 (a). Metakaolin reduces but does not eliminate minor polyester wall damage shown in Fig. 8 (b), as cement products still attach, improving bond strength. Both fibers rely critically on additive-modified matrices for durability and effective interfacial bonding [121].

SEM comparisons show that natural cellulosic fibers like jute/cotton have lumen-filled, rough, alkali-sensitive surfaces that can debond in cement; mild alkali or silane treatment removes extractives, increases crystallinity/roughness, and gives a denser ITZ with higher C-S-H adhesion and reduced fiber degradation [122, 123]. Synthetic fibers are hydrophobic and smooth; unmodified, the ITZ will be weaker and more porous but

Table 4 Effect of textile fibers in concrete durability

Source	Property Tested	Test Performed	Fiber Type & Sample Details	Key Findings
[109]	Freeze–Thaw Resistance	Freeze–thaw (100 cycles)	Synthetic fiber mortar	Fibers prevented scaling and preserved surface integrity
[110]	Freeze–Thaw Resistance	Freeze–thaw (56 cycles, salt)	Hemp/flax mortar (1% vol.)	Fibers significantly reduced scaling and retained flexural strength
[111]	Freeze–Thaw Resistance	Freeze–thaw until failure	Polypropylene (0–1%, concrete M30)	1% PP optimal; improved durability up to ~100 cycles
[112]	Freeze–Thaw Resistance	Pavement freeze–thaw cycling	Jute fiber concrete (1%, pavement)	Jute fibers reduced freeze–thaw damage and maintained strength
[113]	Freeze–Thaw Resistance	Freeze–thaw (92 days)	Macro PP fiber SCC (0–1.5%)	Macro-PP fibers strongly reduced freeze–thaw damage
[114]	Chemical Resistance (Acid)	Acid immersion (H_2SO_4 , floors)	PP fiber concrete (2.5 kg/m ³)	PP fibers reduced mass loss and acid-induced damage
[115]	Chemical Resistance (Acid)	Acid attack (ASTM C267)	Jute fiber concrete (0–2%)	High jute content (2%) increased acid susceptibility
[116]	Chemical Resistance (Acid)	Acid immersion (ASTM C267)	Coir fiber concrete (1–3%)	1% coir fiber greatly enhanced acid resistance
[117]	Chemical Resistance (Acid)	Literature review	Rice husk fibers in concrete	Agricultural fibers like rice husk improved acid resistance
[115]	Chemical Resistance (Sulfate)	Sulfate immersion (ASTM C1012)	PP fiber concrete (0.4%)	PP fibers reduced sulfate-induced expansion effectively
[118]	Chemical Resistance (Sulfate)	Wet–dry sulfate cycles (Na_2SO_4)	Hemp fiber concrete (0.25–1%)	0.25% hemp fiber optimal for maximum sulfate resistance
[119]	Chemical Resistance (Chloride)	Chloride permeability (ASTM C1202)	PP fiber HPC (0.15–0.3%)	0.15% PP fiber notably reduced chloride permeability
[34]	Chemical Resistance (Chloride)	Chloride–sulfate wet–dry cycles	Hybrid BF + PP fiber concrete (0.1–0.2%)	0.1% hybrid fibers effectively reduced chloride ingress
[120]	Carbonation Resistance	Accelerated carbonation test	PVA fiber concrete (0–1.5%)	0.75% (6 mm) PVA fiber optimal for carbonation resistance
[118]	Shrinkage Behavior	Review (multiple standards)	Synthetic & natural fibers	Fibers significantly reduced drying shrinkage cracks
[121]	Shrinkage Behavior	Drying shrinkage (ASTM C157)	Waste textile fibers (6–10%)	8% waste fibers substantially reduced drying shrinkage
[29]	Shrinkage & Creep Behavior	Review (drying shrinkage & creep)	Micro-synthetic fibers	Microfibers reduced both drying shrinkage and creep strain
[27]	Shrinkage Behavior	Autogenous & drying shrinkage	Cellulose fiber cement composites	Cellulose fibers reduced early-age shrinkage effectively
[121]	Shrinkage Behavior	Drying shrinkage (90 days)	Waste carpet PP fibers (0.3%)	Waste carpet fibers reduced drying shrinkage (~30%)
[122]	Shrinkage & Creep Behavior	Long-term creep (360 days)	Cotton/PP fibers with pozzolan	Fibers notably reduced long-term creep deformation

**Fig. 8** Microstructure of Polyester **a, b** and Kraft **c, d** in gypsum **a, c** and metakaolin concrete **b, d**

mineral or polymeric coatings and specially formulated binders improve C-S-H precipitation on the fiber and reduce interfacial porosity [124]. or recycled nylon, microscopic observation shows increased tortuosity of cracks and smaller crack apertures, lowering seepage in the matrix–crack network [125]. Mortars containing mixed textile

wastes show porosity refinement and more regular matrices when fiber lengths/dosages are optimized; X-ray micro-CT confirms fiber networks that bridge and deflect cracks rather than present void clusters [25, 68].

10 Conclusion

The use of recycled textile fibers (RTFs) in concrete is a potential strategy for the optimization of material performance with sustainability. In this review, information on maximum utilization of RTFs to generate enhanced mechanical properties and longevity is consolidated. Key findings are discussed below:

- *Performance & dosage*: RTFs increase tensile/flexural strength, ductility, and post-cracking toughness with minimal impact on compressive strength/workability at natural around 1–2% volume and synthetic around 0.5–1.0% volume; over-dosage leads to fiber balling and slump loss, with diminishing returns.
- *Durability mechanisms*: RTFs limit drying shrinkage and creep, and suppress freeze–thaw deterioration by bridging/sealing microcracks and limiting crack growth.
- *Microstructure*: Fibers compact the matrix and strengthen the ITZ; synthetics are alkali-resistant, but natural cellulose need protective binders/additives like gypsum, metakaolin to avoid alkaline degradation.
- *Implementation & selection*: For post-crack capacity and freeze–thaw durability, use synthetic 0.5–1%; for crack control and shrinkage reduction, use natural 1–2%. Hybrids around 0.5% synthetic and 0.1–0.5% natural synergistically enhance toughness/ductility. Maintain workability by uniform dispersion and superplasticizer.
- *Applications & sustainability*: RTFs save fabric scraps and can reduce the use of cement and emissions; they are used in structural repair mortars, precast elements/structures, and tunnel linings when there is a requirement for high toughness and durability.

11 Future recommendations

Despite the promising benefits of textile fiber reinforced concrete, there are certain important gaps that hinder its structural use. Firstly, the absence of standard design codes or material specifications for recycled textile fibers in concrete is a major barrier. Clear guidelines on fiber properties, mix design, and test methods are needed to assure consistent quality and long-term performance [4, 126]. Second, the long-term durability and bond performance of TFRC under severe environments and long-term service are not clear; long-term field data on the performance of fiber–matrix under cyclic weathering, chemical attack, and sustained loading are largely unavailable. Third, most tests to date have been at the material or small-element level, with relatively few structural-scale or field tests. Prior work on recycled-fiber concrete has also focused on material-level behavior often in pavements or slabs rather than full-scale load-carrying members, and therefore a knowledge gap exists for TFRC behavior in steel-reinforced beams, columns, and other structural members [127].

To address these gaps, future research needs to integrate experimental, computational, and field investigations. Structural-scale tests on steel-reinforced TFRC beams, columns, and slabs are recommended to ensure that ductility and crack control afforded by fibers translate into load-carrying capacity without detriment to rebar bond or section capacity. Seismic-resistance applications of TFRC are particularly deserving of study. The

crack-bridging and energy absorption of the dispersed fibers can improve post-cracking ductility and damping, which suggests that TFRC can potentially toughen earthquake-resistant members such as coupling beams, shear walls, and bridge piers. Cyclic loading tests and nonlinear dynamic analysis need to quantify the degree to which fiber additions improve hysteretic behavior, delay stiffness degradation, and dissipate seismic energy [128–131]. Coupled experimental–FEA studies are also required to upscale laboratory findings, as advanced numerical models calibrated against small-scale tests can reliably predict FRC behavior in full-scale girders, paving the way for virtual prototyping of TFRC structures [126]. Pilot applications and durability monitoring of TFRC in real structures, especially in harsh environments, are also suggested in order to evaluate durability, fiber-matrix bond retention, and lifecycle performance in the field. Such holistic efforts will facilitate the development of code provisions and best-practice guidelines, enabling safe implementation of recycled TFRC in load-bearing infrastructure [4].

Author contributions

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