



REVIEW ARTICLE

Innovative eco-development of recycled scrap-tire steel fibers (STSF)-based concrete composite for Saudi construction industry: a review of properties, performance, and applications

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Abstract: The growing demand for sustainable construction materials is critical to reduce environmental burdens, especially in rapidly urbanizing Saudi Arabia. This review advanced the eco-development of recycled scrap-tire steel fiber (STSF) concrete by linking STSF recovery and processing routes, fiber geometry, cleanliness, and tensile quality to interfacial micromechanics and composite performance. It proposed a unified STSF classification, supported by effect-size synthesis, to standardize reporting, reconcile disparate test methods, and enable performance based specifications. The review systematically evaluated how STSF length, diameter, and dosage influence strength, toughness, crack control, and structural response, while also assessing sustainability and structural efficiency gains through waste diversion and reduced carbon intensity. Evidence across the literature is synthesized to identify effective reinforcement strategies, key dispersion and bonding mechanisms, and practical mix optimization pathways aligned with Saudi supply chains and exposure conditions. The findings underscore the potential of STSF-based composites to contribute to eco-efficient construction, enhancing the mechanical resilience and lifespan of concrete structures. Moreover, this research provided a critical foundation for future studies and practical implementations, positioning STSF as a strategic component in advancing green construction practices within Saudi Arabia and globally. The study reinforced circular-economy principles with sustainable materials for global construction. Besides, it outlined a practical, micromechanics-guided route from waste-tire recovery to field-deployable high-performance concrete in the Kingdom of Saudi Arabia.

Keywords: waste management, tire wastes, recycled scrap tire steel fiber, properties, performance, applications

1 Introduction

The use of waste materials, particularly discarded tires, has gained increasing attention in the civil engineering sector for potential use in construction [1]. Recycling practices within the construction industry have evolved from being a mere trend to a fundamental necessity [2]. A significant advancement involves the reuse of materials from demolition processes or the incorporation of waste products from other sectors into new construction applications [3]. In particular, the integration of recycled waste, such as tire-derived fibers, into fiber-reinforced concrete has attracted substantial

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interest due to its beneficial properties [4]. The recycling of car tires, in particular, represents an environmentally sustainable solution within the broader context of the circular economy, prompting the development of advanced tire recycling methods [5]. Techniques like cryogenic grinding and pyrolysis have facilitated the recovery of reusable materials from tires, making them applicable in various industries [6]. Recent improvements in recycling technologies have not only enhanced the efficiency of tire processing but also reduced the environmental burden associated with tire waste [7].

Industry is the major contributor to global greenhouse-gas emissions, with carbon dioxide from this sector accounting for roughly one quarter of the total, driven especially by energy-intensive branches such as steelmaking, non-ferrous metallurgy, chemicals, non-metallic minerals, and pulp-and-paper production [8]. Against this backdrop, the world generates about 1.5 billion end-of-life tires each year (**Fig. 1a,b**); waste rubber is highly persistent, and tire fires are difficult to extinguish, releasing substantial CO₂ as their voided structure facilitates oxygen availability [9], while combustion residues contaminate soils and waterways [10]. These hazards make the management of scrap tires a pressing global challenge. One valorization route has been to integrate rubber into concrete as a partial replacement for natural aggregates [11], thereby conserving river sand and lowering the associated carbon footprint [12]. However, extensive studies also show that substituting rubber for either fine or coarse aggregates can adversely affect concrete strength, necessitating careful mix design and performance optimization [13]. However, the expanding amount of waste generated by the vulcanization industry presents a considerable environmentally friendly issue.

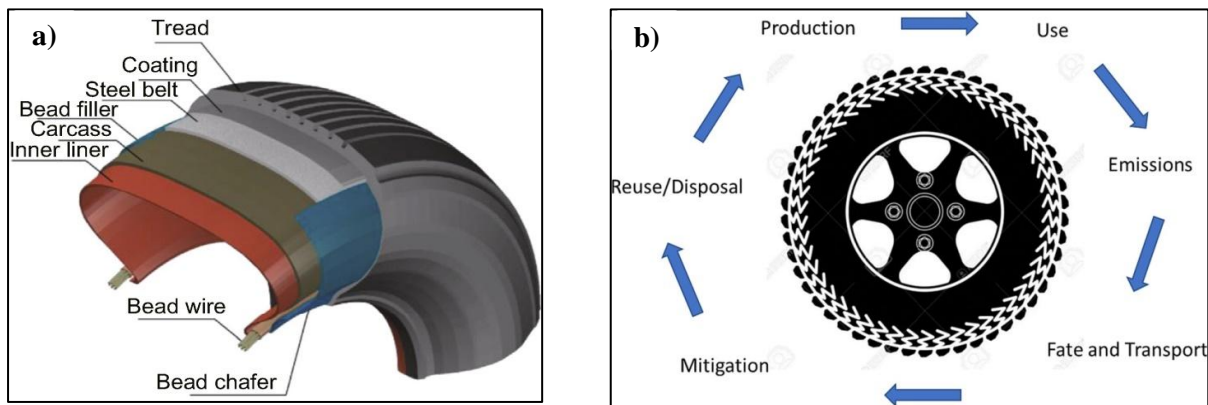


Fig. 1. a) A cross-section of a tire (Adapted with permission [3]), and b) Entire life-cycle of tire (Adapted with permission [14])

To address this, incorporating steel from used tires as dispersed reinforcement in novel construction materials aligns with objectives for sustainable development [15]. Tire recycling encompasses the treatment of tires that are no longer usable due to damage or wear, repurposing them for alternative applications [16]. The utilization of steel fibers retrieved from these tires in concrete offers an economical approach to waste management while also benefiting the environment and enhancing the structural properties of concrete [17]. Recycled scrap tire steel fibers (STSF) have emerged as a promising material for various concrete applications, including slabs, precast elements, and road barriers, presenting a sustainable replacement to traditional reinforcement approaches [18].

In the domain of sustainable construction materials, research has increasingly focused on the utilization of recycled steel fibers and rubber from recycled tires as reinforcing agents in concrete [19–21]. Concrete reinforced with steel fibers obtained from waste tires has shown marked improvements in toughness and post-crack behavior, characteristics typical of fiber-reinforced concrete [22]. These steel fibers have also been found to substantially increase the dynamic resistance, performance of fatigue, durability, and shear strength of concrete after cracking [23]. The improved post-cracking strength is largely due to the fibers' ability to control crack development, which rely on few factors for example fiber properties, adhering with the concrete, and distribution within the concrete matrix [24]. Markedly, steel fiber-reinforced concrete slabs have demonstrated their capacity to effectively replace conventional steel wire mesh layers, contributing a superior structural integrity, faster construction times, and greater cost efficiency [25]. **Fig. 2** shows international overview of scrap tire waste recycling

practices [26,27]. It is exhibited stark contrasts in end-of-life tire management: Saudi Arabia landfills the majority (65%), while Germany, England, Italy, and France emphasize energy recovery (35–56%) and rubber-crumb production (27–40%), with only modest retreading and export [26,27]. Overall, European countries divert far more tires from landfills than Saudi Arabia.

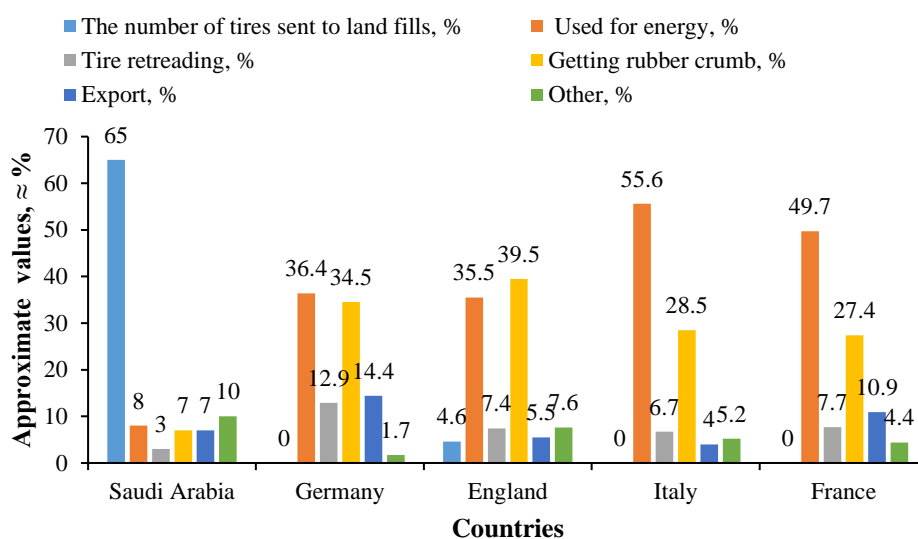


Fig. 2. International overview of scrap tire waste recycling practices (Data obtained from [26,27])

The accelerating accumulation of end-of-life tires (ELTs) presents a persistent environmental and logistical burden, underscoring the need for circular solutions that valorize this waste stream within high-value construction materials [15]. Reclaimed STSF have emerged as a technically and economically credible alternative to virgin steel or proprietary fibres, with multiple studies showing that they can wholly or partially replace commercial fibres without loss and often with notable gains, in key material properties [28–30]. Reported benefits include cost efficiency and improved mechanical response when STSF are used alone or in hybrid blends with commercial fibres [31–33]. At the microstructural level, shorter and finer tire-derived fibres have been shown to increase composite stiffness, thereby refining the stress–strain behaviour of fibre-reinforced concrete [34]. In practice, STSF offer a compelling pathway to reduce or replace traditional steel mesh in pavements, a proposition supported by encouraging industrial demonstrations [23]. Parallel research on polymeric alternatives (e.g., high-density polyethylene) indicates consistent improvements in post-cracking performance [24] and shrinkage control, with recycled and virgin polymer fibres yielding broadly comparable mechanical enhancements [35–37]. While steel fibres tend to provide only modest gains in compressive strength [21,25], increases in fibre dosage reliably elevate tensile capacity and crack resistance, albeit with greater performance variability at higher reinforcement ratios [38].

Despite rapid advances in tire-to-fiber processing, the literature on recycled STSFs remains fragmented, with limited field-scale evidence and inconsistent reporting on fiber morphology, cleanliness, and surface condition variables that critically govern interfacial bond, crack-bridging efficiency, durability, and structural response. This review addressed that gap by offering a rigorous, end-to-end synthesis spanning STSF extraction routes and post-processing, property control (geometry, aspect ratio, contamination, and surface roughness), and the consequent microstructure–bond–performance linkages in cementitious composites. The main objective is to establish a design-relevant evidence base: it benchmarks mechanical behavior such as compressive, tensile and flexural strengths, and durability performance, and it situates these results within comparative assessments against industrial steel fibers and life cycle/techno-economic considerations. The novelty of this review lies in: a unifying taxonomy for STSF processing and fiber quality control; a mechanism-based mapping from fiber attributes to interfacial micromechanics and their efficiency in enhancing strength, structural response, and composite-level performance; and a synthesis of prior results into application-oriented guidance for practitioners, designers, scientists, and researchers. By integrating performance metrics with sustainability and cost perspectives, it delineated practical mix-design envelopes, testing protocols,

and quality-assurance checkpoints, and it articulated a targeted research agenda to close code/standardization gaps. Collectively, the contribution positions STSF-based concrete as a credible, circular-economy solution for the construction industry; regionally (e.g., Saudi Arabia) and globally; advancing both waste valorization and structural reliability.

2 Waste management of recycled scrap tire steel fibers

The global surge in waste production, particularly from discarded automotive tires, has posed significant environmental challenges [39]. Tires, composed of resilient and non-biodegradable materials, are notoriously difficult to dispose of, leading to mounting stockpiles of waste in landfills and incineration facilities [17]. As sustainability becomes a critical focus in both waste management and construction industries, innovative strategies for repurposing tire-derived materials are gaining traction [6,29,40]. One promising approach involves the recovery and recycling of steel fibers embedded in tires, transforming them into valuable reinforcing agents for concrete composites [30,32,41]. This process not only offers a solution to the growing issue of scrap tire waste but also provides a resource-efficient alternative to traditional steel fibers used in construction, contributing to the development of greener and more durable materials [10,42]. By integrating recycled fibers into concrete, this dual-purpose solution addresses both waste management concerns and the mandate for green construction materials, marking a pivotal step in circular economy practices [43,44]. However, despite this potential, critical challenges and targeted innovations are still required to optimize the recycling process and fully realize its life-cycle and techno-functional returns. Further, **Fig. 3** displays vehicle tire waste management from 1960 to 2018. It is exhibited that a long-term shift in U.S. tire waste management from heavy reliance on landfilling (peaking 6 Mt around 2000) toward recycling and energy recovery [45]. By ~2010, recycling (5.5–6 Mt) surpasses landfilling that is declining to 4–5 Mt, while combustion with energy recovery steadily rises to 3–3.5 Mt; composting remains negligible throughout. Overall, the data indicates progressive diversion from landfills toward higher-value recovery pathways after 2000 [45].

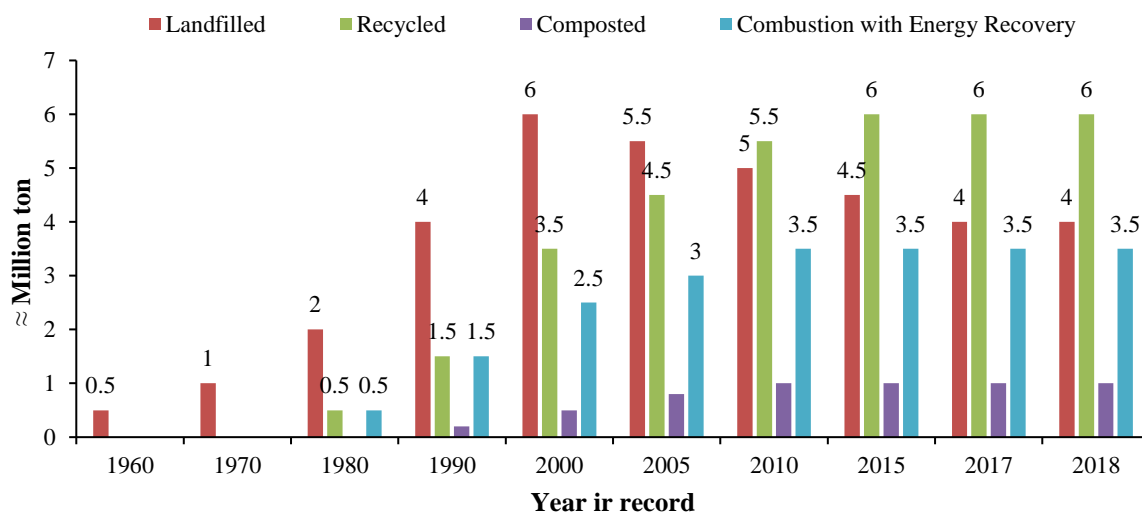


Fig. 3. Vehicle tire waste management from 1960 to 2018 (Adapted with permission from [45])

The abundant supply of discarded tires, around 17 million tons annually, presents an opportunity to extract steel fibers for sustainable development. The potential use of steel in these tires varies based on the type of vehicle [46]. For example, tires from light-transport vehicles typically contain nearly 15% steel, while those from heavy-transport vehicles have approximately 25% steel [29]. The extraction process of steel from these waste tires includes an initial shredding phase, where used tires are broken down into smaller fragments. Following this, the fragments undergo milling to separate tiny particles of rubber, known as crumb rubber. In this stage, steel is separated from rubber using magnetic techniques. It has been reported that up to one-third of a tire's composition can be steel, which is suitable for recycling and potentially useful in applications such as concrete reinforcement [20]. The primary

outputs of tire recycling are textile fibers, rubber fibers, and steel fibers, each with its own potential applications [28].

It is reported that when ELTs undergo thermochemical decomposition in controlled settings, they produce substances such as pyrolytic gas and pyrolysis oil. These by-products can undergo additional processing to serve as valuable inputs for the production of new goods [40]. Shredded tires are being employed in civil engineering, particularly as lightweight fillers and for thermal insulation [47]. The grinding process plays a crucial role in removing additional materials from rubber [48], and it impacts the dimensions, form, and characteristics of the surface of the resulting powders or crumb rubber [47]. These rubbers are being employed as fillers in composite materials, reducing the reliance on newly sourced materials [10]. Techniques such as water jets and wet grinding have proven effective in extracting rubber from waste tires [49]. Moreover, crumb rubber is added in small amounts to new tire rubber and other rubber-based products [10]. The removal of extra components such as steel wires and fibers is conducted using tools such as fans, electromagnets, and pneumatic separators in recycling plants [42]. Ambient grinding is often preferred because of its simplicity and the high surface area of the rubber crumbs produced, although it is noted that the strength characteristics of these materials may diminish at elevated concentrations. Future developments in physical surface treatment of crumb rubber could improve the compatibility of these materials for various uses, especially in the construction industry, for applications such as asphalt and rubberized concrete [49].

3 Technological recycling mechanism



Fig. 4. Sketch of the scrap tire recycling processes (Adapted from an open access source [50])

The recycling mechanism of scrap tire waste into recycled steel fibers for reinforcing concrete composites involves a multi-step process aimed at extracting and processing the steel fibers embedded in tires (**Fig. 4**) [50]. Initially, scrap tires are collected and sorted, ensuring that they are free from contaminants such as oils, dirt, and other debris [15]. The collected tires undergo a shredding process, where they are reduced into smaller chunks or chips. This shredding step is followed by mechanical

separation, which utilizes magnets and other techniques to segregate steel wires from rubber particles [47]. The recovered fibers are then extracted and cleaned, ensuring the removal of any residual rubber or impurities that may affect their bonding with concrete [29]. Also, there is a critical consideration which is the dimensional processing of the recovered fibers [21]. Achieving uniformity in fiber size and aspect ratio is essential for ensuring consistent reinforcement performance across concrete batches [39]. However, the recycled nature of these fibers makes it difficult to achieve the same level of precision as with virgin steel fibers [32]. The current processes of cutting and stretching, while effective, may introduce variability in the fiber dimensions, which may influence the overall performance and integrity of the composite material [48].

This raises the need for more advanced techniques, such as laser cutting or controlled drawing, to ensure that the recycled fibers meet stricter specifications. Once the steel fibers are separated, they are processed to meet specific size and dimensional requirements suitable for reinforcing concrete composites [19]. This often involves cutting, stretching, or shaping the fibers to achieve desired lengths, diameters, and aspect ratios [51]. Depending on the required end-use, the fibers may undergo additional surface treatments to enhance their adhesion properties when incorporated into the concrete matrix [33]. The STSFs are then mixed into the concrete during the batching process [51]. The fibers are typically included in specific proportions to guarantee uniform distribution throughout the mix, increasing the strength of concrete properties [24]. Furthermore, the study of hybrid fiber utilization in concrete boosts has been a focal point for several researchers, especially those investigating how different fiber materials and geometries, recovered via either shredding or pyrolysis process, can effectively improve the properties of concrete, as shown in **Fig. 5**.

It is reported that, particularly when rubber fibers used in combination with steel or in the form of chipped tire rubber, are increasingly being incorporated into concrete mixtures, as various studies highlight [47]. Compared to normal concrete, the addition of rubber could result in concrete that exhibits enhanced post-crack strength without significantly affecting workability [48]. The STSFs have proven to be particularly advantageous for practical applications for instance road barriers, precast components, and concrete slabs, presenting a viable alternative to traditional methods [18].

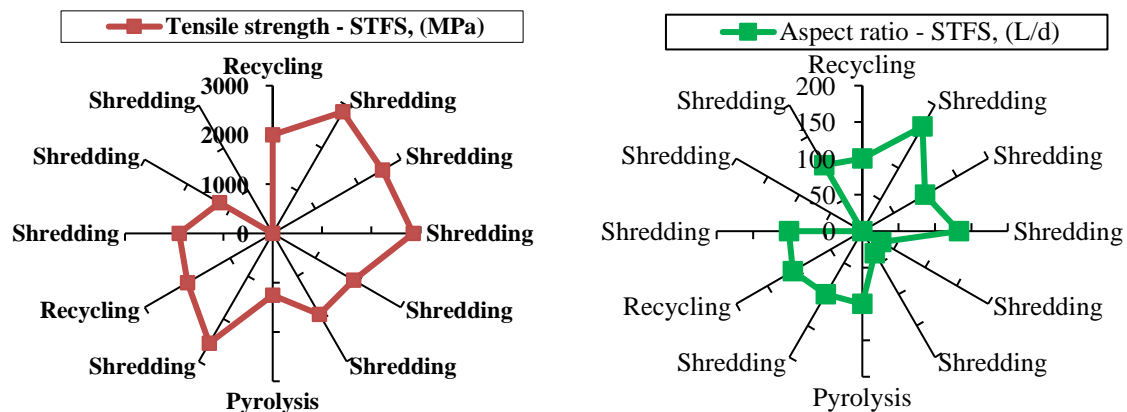


Fig. 5. Effect of aspect ratio on the tensile strength of concrete admixtures reinforced with STSFs, as reported by previous researchers (Data obtained from [21,32,52–60])

Several reports suggest that steel fibers retrieved from wasted tires can partially or entirely replace commercial fibers in concrete, without sacrificing performance and sometimes even enhancing certain aspects of the concrete [28–30]. These fibers contribute to cost savings and bolster the mechanical performance of the concrete, either in isolation or when combined with commercial fibers [32]. Moreover, finer and shorter tire fibers have been observed to improve the stiffness of fiber-reinforced concrete, thereby enhancing its mechanical properties [34]. Advancing and refining recycling techniques for ELTs are essential for environmental protection and the sustainable use of tire resources (**Fig. 6**) [28,41,61].

The STSFs increase the tensile strength, crack resistance, and durability of concrete by forming a network within the material that helps control crack propagation and increases toughness [38]. This

method not only offers a sustainable solution to tire waste but also reduces the consumption of traditional steel fibers, contributing to the manufacturing of more sustainable and cost-effective building materials [62]. In conclusion, while the recycling of scrap tires into STSFs for concrete reinforcement offers clear environmental and mechanical advantages, there are several technological and methodological challenges that need to be addressed to optimize the process [16,39,41,48,63]. Improvements in fiber extraction, dimensional control, surface treatments, and sustainability metrics are critical to fully realizing the potential of STSFs as an eco-friendly alternative in construction materials.

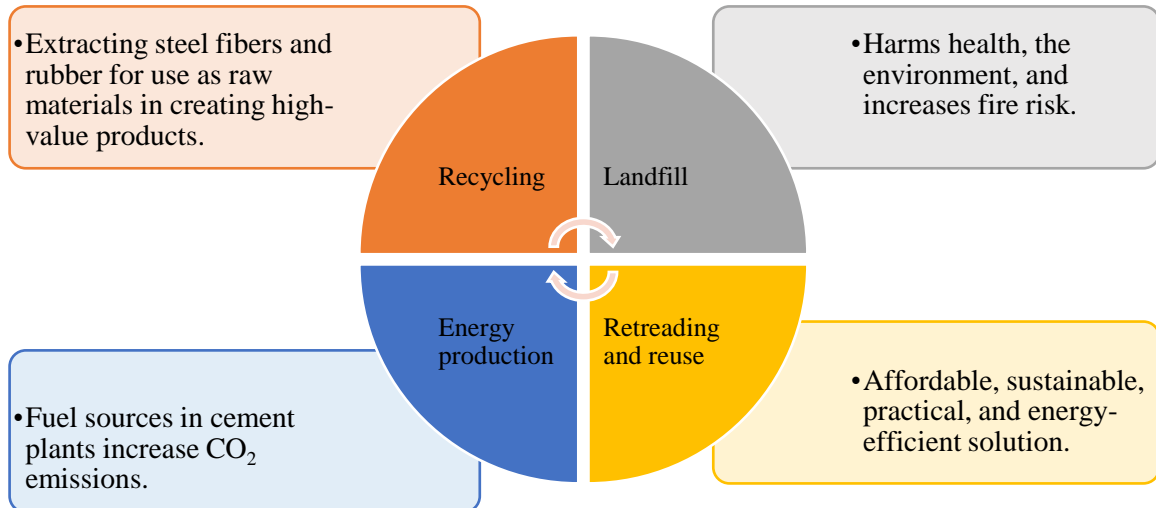


Fig. 6. Numerous management alternatives for ELTs (Adapted with permission [41])

4 Challenges of variability and quality control of STFS

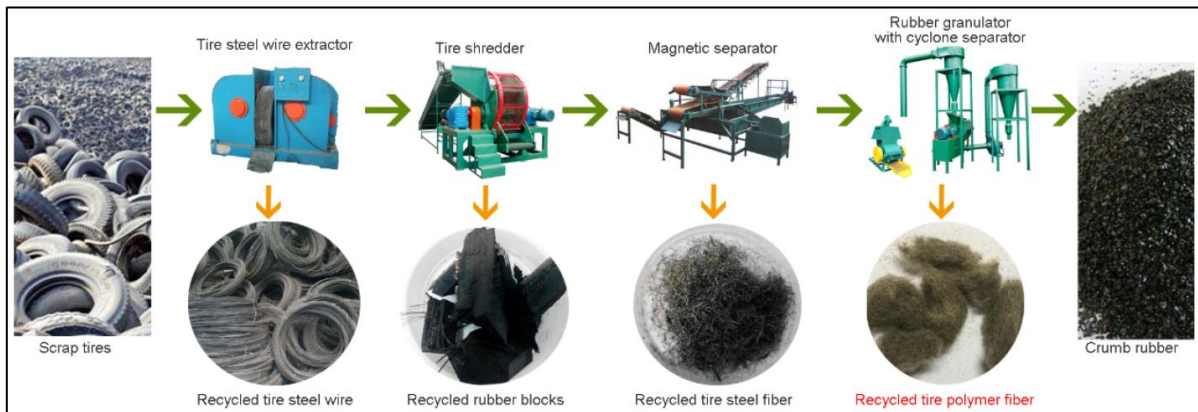


Fig. 7. Tire shredder and wire-liberation processes (Adapted with permission from [61])

A central obstacle to reliable performance in STSF-reinforced concretes is the variability introduced by the recycling stream itself. Shredding and wire-liberation (**Fig. 7** [61]) yield heterogeneous fiber geometries broad spreads in length, diameter, aspect ratio, curvature, and surface roughness, producing nonuniform crack-bridging, erratic pull-out response, and inconsistent fiber networks (orientation, spacing, and percolation). The geometry and cleanliness of STFSs are governed by both the tire source and the recovery route [64]. Two extraction pathways dominate: 1) mechanical recovery, typically tire shredding followed by electromagnetic separation because of its lower cost, which yields irregular, corrugated fibers with a broad size distribution [21]; and 2) pyrolysis, in which shredded or whole tires are heated to ~600 °C in an oxygen-free reactor so that nonmetallic constituents volatilize or fragment, enabling magnetic separation of the steel and co-producing carbon black,

activated carbon, and fuel gas [58]. Fibers from pyrolysis are generally more uniform and largely free of rubber or textile residues [65].

Mechanical properties are likewise uneven: prior service loading, cyclic bending during tire use [15], localized corrosion, and mechanical liberation can induce work-hardening, residual stresses, micro-cracks, and surface pitting, lowering tensile strength and fatigue resistance for a fraction of fibers while others remain near virgin quality [14]. Purity is an additional constraint [66]. Residual rubber, brass coatings, textile traces, and process oils impede wetting and bond development in the interfacial transition zone (ITZ), increase entrapped air, and act as weak interphases that trigger premature debonding under cyclic moisture or chloride ingress [17,18]. Rubber residues also complicate mixing and dispersion, promoting fiber balling and elevating plastic viscosity at practical dosages [20]. Reportedly, it is revealed that impurity levels reflect this contrast: it is reported that found 9% impurities for pyrolytically recovered fibers, and it is also observed 17% for mechanically recovered STFSs [66]. Consequently, many studies recommend pre-use screening to eliminate enormously short or overly long lengths, loose crumb rubber, and rubber-adhered fibers before incorporation into concrete [67]. Several investigations have proposed post-processing treatments, most notably surface polishing and high-temperature thermal conditioning, improving the cleanliness and overall purity of the recovered fibers [49,68]. Collectively, these uncertainties undermine mix design transferability, inflate inter-laboratory scatter, and weaken the link between laboratory metrics and field durability. Mitigation requires pre-processing (sieving/grading by aspect ratio, de-rubberization and de-oiling) [53], statistical quality control on batches (geometry and strength distributions rather than single means), and performance-based specifications that tolerate variance while safeguarding workability, bond, and corrosion resistance [62,67].

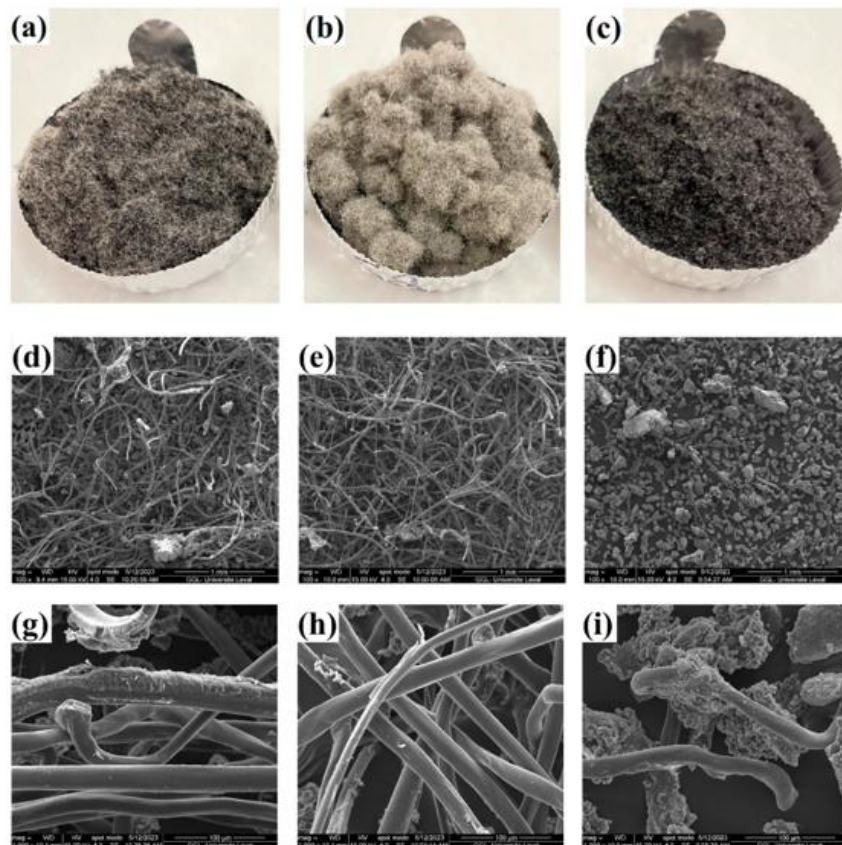


Fig. 8. Overview photographs and SEM micrographs of the STFSs: (a, d, g) show tire fibers before sieving; (b, e, h) display the parted clean STFS; and (c, f, i) present the parted crumb rubbers (Adapted with permission from [69])

Regarding, variability in STSF geometry, purity, and mechanical properties, it propagated into unstable fresh and hardened performance [66,69]: broad length/diameter spreads and residual rubber elevate viscosity, promote balling and entrained air, distort orientation, and widen scatter in residual

strengths and fatigue response, while brass/oil residues weaken the ITZ and heighten corrosion susceptibility under chlorides or carbonation. **Fig. 8a-i** shows that the second-pass sieving at 46 mesh (0–355 μm) produced clean STFS, the clean STFS fiber, now visibly lighter after removing rubber fines. In contrast, GR is black and rubber rich. SEM/ImageJ (**Fig. 8**) sizes [69]: CF $20 \pm 5 \mu\text{m}$; GR $70 \pm 20 \mu\text{m}$. Closing this variability requires moving beyond bulk recovery toward engineered feedstocks [70]. Multi-stage screening with optimized magnetic circuits and machine-vision sorting can narrow aspect-ratio distributions and reject kinked or undersized wires; cryogenic liberation, wet washing, and controlled pyrolysis or abrasive tumbling reduce rubber and oils without over-oxidizing steel; plasma/ozone activation and selective de-brassing with subsequent passivation improve wetting and interfacial electrochemistry [6]. Critically, these steps must be coupled to inline quality control that certifies distributions such as length, cleanliness indices, pull-out percentiles; and to performance-linked acceptance, for example: rheology rise, single-fiber pull-out, mortar prism residuals [21]. Only with such closed-loop sorting–purification, specification can STSF evolve from a heterogeneous waste stream to a predictable reinforcement that supports transferable mix designs [22].

In brief, STFSs encountered in practice span roughly 0.6–208 mm in length and curvature index in the 15–20 range [21,23,32,54,55,64,65,71–88]. Fiber diameter is determined as the arithmetic mean of three readings, one at each end and one at mid-span, and, across typical datasets, diameters display a multimodal distribution whereas lengths generally exhibit a single dominant mode [73]. Fiber curvature is characterized by a curvature index defined as the proportion by which the development length, as the path measured along the fiber’s axis, exceeding the straight-line chord length; a value of 0 denotes a perfectly straight fiber and 100% denotes a fully curved fiber [64]. The aspect ratio, as length divided by diameter, for STFSs is commonly, though only slightly, higher than that reported for other recycled fiber types [62].

5 Mechanical properties and structural performance

5.1 Compressive behavior

Compressive strength in STSF-modified concrete is largely governed by the competition between fibre-induced microcrack restraint and processing-induced porosity [89]. At low–moderate dosages (about 0.5–1.0% by volume), clean, well-dispersed tire-derived steel filaments can marginally raise or preserve f_c by bridging wing cracks and delaying coalescence around aggregate contacts; the principal benefit, however, is a tougher, less brittle stress–strain response with higher peak strain and a flatter post-peak softening branch [90]. Strength losses reported at higher volumes usually trace to workability penalties, air entrapment, fibre balling, and weakened ITZs from residual rubber, problems mitigated by rigorous fibre cleaning/separation, high-range water reducers, optimized low w/b, SCMs such as silica fume or slag, and careful vibration [91]. Reportedly, the compressive response of cementitious composites incorporating STFSs showed a clear dependence on fiber type and content, with divergent trends at low versus high contents [92–96]. Several investigations document strength penalties at elevated dosages: one study reported reductions of 1.93%, 13.5%, and 18.3% when STFS were added at 2%, 4%, and 6% by volume, respectively, and a larger 26.5% decline when whole STFS were used at 8% [29]. comparable reductions for WRTSF concretes are echoed elsewhere [97], and further reports also note decreased compressive strength in WRTSF-reinforced mixes [22]. By contrast, performance gains are frequently observed at lower contents and in carefully configured systems. Using STFS with nominal dimensions of 1 mm thickness, 50 mm length, and 2 mm width, incremental increases in the fiber volume fraction from 0.5% to 2.0% produced compressive-strength improvements from 6.1% to 9.4% over the control concrete, respectively [98], rapid-hardening mortars similarly showed enhanced compressive capacity when reinforced with STFS [99]. Not all intermediate dosages are beneficial, for instance, a $\approx 5\%$ decrease was measured at 1.25% STFS relative to the reference mix [64], yet several studies still identify a low-content window with net gains, including rises of about 5% at 0.5% STFS and 13% at 1.0% STFS compared with the corresponding controls [32]. In another dataset, specimens containing 0.23% STFS sustained 23.3% higher compressive stress than plain counterparts, and those with 0.46% STFS withstood 25.4% more, indicating substantial improvements within that sub-percent range [62]. **Fig. 9** exhibited that relative strength was taken as the strength of an RTSF-reinforced mix

at a given fibre content, normalized by that of the companion plain (no-fibre) concrete [100,101]. The results showed distinct maxima at 0.23%, 0.46%, and 0.75% fibre contents, indicating that the benefit of STSF is dosage-dependent and governed by the fibre-length distribution and the strength of the concrete matrix [62,76,90,102]. Mechanistically, these favorable outcomes are attributed to the irregular geometry and random orientation of STSFs, which restrain tensile strains, delay microcrack initiation and propagation, and thus improve the compressive stress–strain response up to an optimum dosage [99]; beyond that mixture-specific threshold, packing disruption, fiber interaction, and agglomeration effects dominate, leading to the decreases recorded at higher fiber volumes, a behavior pattern that aligns with stress–strain observations reported across multiple independent studies [103].

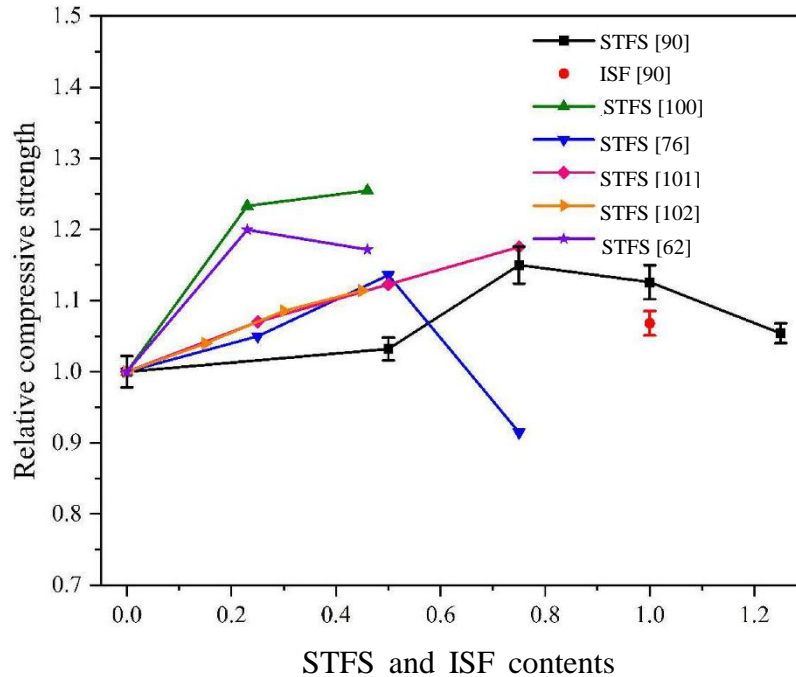


Fig. 9. Relative strength of concrete as a role of STSF content (Data obtained from [62,76,90,100–102]), Annotation: Industrial steel fibers (ISFs)

Across comparable volume fractions, these STSFs can elevate compressive capacity, with 0.5% additions yielding at around 10% and 15.6% strength gains, respectively [104]. The superior response typically seen with ISFs at the same dosage is commonly attributed to their greater fiber count and more uniform dispersion, a factor identifies as the dominant driver of compressive performance [105]. Owing to the irregular geometry, tensile properties, and length variability of STSFs, reported outcomes span a wide envelope from 23% reductions to 25% improvements, depending on mixture design and placement quality. Consistent with this spread, it is observed beneficial effects of STSFs on cubic compressive strength [62], whereas low-dosage incorporations produced decreases a similar study [106]. In the present work, a 0.5% STSF dosage delivered the largest measured improvement of 36%, an outcome plausibly linked to the lower w/c ratio and the achieved uniform distribution of the fibers within the concrete matrix. A variety of related studies, such as that of [80], have explored how STSFs affect concrete compressive strength, focusing on different mix designs [21,31,33,80,89,100,107]. Studies have shown a significant 11% increase in compressive strength when concrete includes 0.50% of STSFs measuring ~94 mm. In addition, the use of 0.75% and 1% of 7.30 mm STSFs contributed to an 11% and 13% increase in compressive strength, respectively [89]. An increase of 3% in strength was also observed with the incorporation of 0.13% of 26 mm STSFs [21]. In terms of structural stability, a notable 43% enhancement was detected in concrete with 0.50% of 26 mm STSFs, while a 14% decrease was noted with the same percentage of 93.60 mm STSFs [89]. A slight 3% reduction in stability was recorded with 0.46% of ~14 mm STSFs [33]. Further, it is revealed that the length of fibers significantly enhances the mechanical properties of concrete, leading to improvements of over 10% in compressive strength, more than 50% in flexural strength, and over 30% in split-tensile strength as revealed in **Table**

1. The application of STFS not only bolsters performance but also aligns with sustainable practices, offering a viable pathway for advancing environmental responsibility within the construction sector.

Table 1. Summary of key findings of strength properties various STSF-based concrete strengths at 28 days as reported by previous researchers (Data obtained from [92–96])

Strength properties	SF diameter (mm)	SF (%)	Fiber tensile	w/c	SF length (mm)	Reported strength (MPa)	Refs
Compressive strength (MPa)	0.2–1.39	0.4	–	0.52	20–99	59.17	[93]
	0.15	0.75	2000	0.44		66	[94]
	1.15	1.2	1054.7	0.5	40	35.25	[95]
Flexural strength (MPa)	0.72–0.89	1.5	970.2	0.42	60	43.94	[96]
	0.15	0.75	2000	0.44		5.60	[94]
Tensile strength (MPa)	0.72–0.89	1.5	970.2	0.42	60	14.79	[96]
	0.2–1.39	0.4	–	0.52	20–99	7.49	[93]
Impact resistance (blows)		1.0	–			4.44	[93]
	1.15	1.2	1054.7	0.5	60	3.10	[95]
	0.15	0.75	2000	0.44	40	4.60	[94]
Fracture toughness: Energy absorption (Joule)	1.15	1.2	1054.7	0.5	60	143	[95]
	0.72–0.89	1.5	970.2	0.42	60	1248	[96]
Fracture toughness: Energy absorption (Joule)	0.15	0.75	2000	0.44	40	81	[94]
	0.72–0.89	1.5	970.2	0.42	60	1.616	[94]
Fracture toughness: Energy absorption (Joule)	1.15	1.2	1054.7	0.5	60	36.51	[96]
	0.15	0.75	2000	0.44	40	77.60	[95]

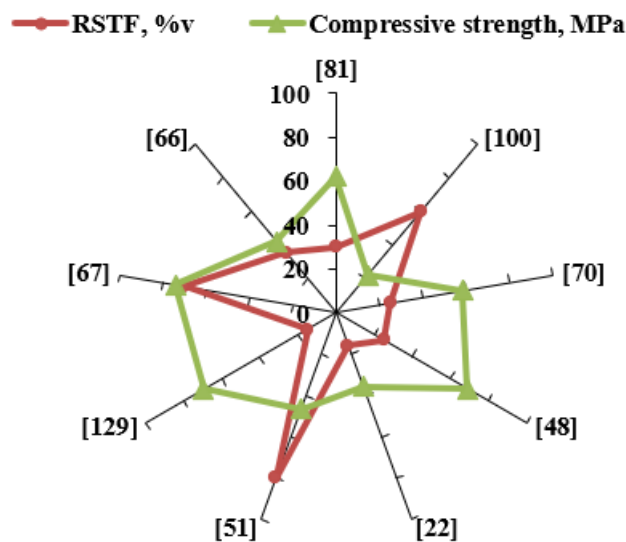


Fig. 10. Impact of RSTF content on the compressive strength of different concrete admixtures, as reported in previous research (Data obtained from [22,48,51,66,67,70,81,100,101,129])

The lead of research in this domain has focused on evaluating strength properties, which are crucial for construction purposes [108]. Incorporating 3% STSF into concrete has been found to increase its splitting strength by approximately 51% associated with conventional concrete. However, this improvement comes with a reduction in compressive strength, which drops to 11 MPa, representing a 22.4% decrease [109]. The optimal steel bead fiber content in lightweight concrete for strength enhancement is around 1%, achieving an approximate 6% increase, with compressive strength reaching 52 MPa [110]. Utilizing steel fibers derived from waste tires as reinforcing in materials of construction not merely contributes to ecological conservation but also supports sustainable development initiatives.

Fig. 10 exhibits the development trends of compressive strength property with different content of STSFs. It is also reported that an investigation studied how the STSF affects the axial compressive characteristics and fracture patterns of ultra-high performance concrete (UHPC) [60]. The findings indicated that UHPC reinforced with STSF fibers exhibited superior resistance to pull-out forces than did those reinforced with recycled steel fibers. However, the use of excessive STSFs was found to

diminish the enhancement in strength properties and lessen the cost-effectiveness of UHPC [22]. The study of hybrid fiber utilization in concrete boosts has been a focal point for several researchers, especially those investigating how different fiber materials and geometries can synergistically improve the mechanical properties of concrete [22,106,111].

Although many mixes show gains in compressive strength, several studies document strength losses when STFSs are added (**Fig. 10**). It is found that fiber volume fractions between 0.5% and 1.5% reduced compressive strength relative to the control between 1.9% and 9.4%, respectively [112]; likewise, it is reported declines of 11% and 92% at dosages of 2% and 4% [113]. These reductions are commonly attributed to fiber clustering and cross-linked fiber networks at higher contents, which enlarge pore volume and weaken the RTSF–paste interfacial bond [59]. The interplay between increased porosity and the crack-bridging system thus governs the net response of RTSF-reinforced concrete [83]. Consistent with this interpretation, prior work warns that exceeding a mixture-specific threshold fiber dose leads to compressive strength deterioration [64]; for example, it is identified a threshold near 0.5% when varying the fiber content from 0.1% to 1% and the elevated fiber contents also multiply ITZs, impairing stress transfer through the matrix [47, 114].

The introduction of uniformly distributed steel fibers in concrete can address issues such as crack formation caused by temperature changes, thereby enhancing the engineering qualities of the material [117]. The key function of the inclusion of fibers is not to increase strength alone but rather to enhance the compressive, toughness, ductility, and dynamic properties of concrete [118,119]. The environmentally responsible disposal of waste tires is also a significant concern [120]. Processing waste tires to recover their basic components is one method of disposal [51]. Remarkably, tires contain almost 13–27% steel. Research indicated that concrete strengthened with STFSs from waste tires can perform comparably to traditional fiber-reinforced concrete [62,64]. Moreover, the effectiveness of tire fibers in concrete composites has been evaluated based on several factors, including their mechanical properties [121], the bond between the concrete matrix [23,122] and the fiber [30], the method of producing STSF-reinforced concrete [123] and the proportion of fiber in the mix [124]. These fibers primarily function to bridge cracks that may form within the concrete, allowing for plastic deformation and increased resistance to crack growth [91,113].

In brief, Unlike conventional steel fibers, STSF brings the added advantage of eco-efficiency, reducing both the environmental footprint and the reliance on virgin materials [125,126]. These fibers not only contribute to improved mechanical performance but also exhibit unique behaviors under various loading conditions, making STSF-based concrete an attractive solution for sustainable construction practices [19,25]. Understanding the specific properties of this composite material is essential for optimizing its use in real-world applications, as it holds the potential to redefine the performance standards of concrete in modern construction [127]. The compressive response of concrete reinforced with STFSs is governed primarily by the fiber aspect ratio and the w/c ratio. Strength–dose trends vary with these parameters: fibers that are too stubby (low aspect ratio) or excessively slender (very high aspect ratio) provide little net benefit, mixes formulated with lower w/c ratios reliably attain higher compressive strengths, and progressive increases in w/c produce gradual strength losses. At any fixed w/c, strength typically rises as fiber content increases to a mixture-specific optimum and then falls beyond that point. Hence, maximizing compressive strength in RTSF-reinforced concrete requires coordinated optimization of both the fiber aspect ratio and the w/c ratio. Also, compressive strength discrepancies in STSF-reinforced concrete chiefly arise from interacting fiber-matrix variables. Geometry controls load transfer: higher aspect ratios and deformed ends improve pull-out resistance yet raise clustering risk if dispersion is poor. Purity matters, residual rubber/corrosion weakens the ITZ, while cleaned or textured fibers recover bond. Dosage shows an optimum; excess fibers impair workability and entrap air. Matrix design (low w/b, adequate paste, graded aggregates) and processing (superplasticizer, addition sequence) further modulate outcomes, demanding co-reporting of morphology, cleanliness, volume fraction, and rheology.

5.2 Flexural behavior

Flexural performance in STSF-reinforced concretes is governed by a multi-scale interplay between matrix brittleness, interfacial bond, and the stochastic geometry of recycled tire, derived filaments

[85,107]. Compared with commercial hooked or crimped fibres, STSF typically exhibit irregular cross-sections, residual brass plating, and mixed lengths; these features increase mechanical anchorage and frictional pull-out, promoting crack bridging and higher post-cracking residuals, provided dispersion and orientation are controlled during casting or pumping [97,116]. Reported gains in first-crack modulus of rupture are modest when matrix strength dominates, but the decisive advantage of STSF emerges beyond cracking. It is basically known that toughness factors at fibre volumes of about 0.5–1.5%, especially when fibers are graded or surface-conditioned to stabilize the ITZ [56,101]. Performance is sensitive to processing: rubber contamination or twisted cord bundles can reduce effective aspect ratio and bond efficiency, whereas mild sand-coating, lime or polymer emulsions, and magnetic separation tighten pull-out distributions and narrow variability [66]. The blending STSF with short micro-fibres suppresses microcrack coalescence, delays localization, and enhances fatigue and impact flexural resistance without penalizing workability if paired with SCC rheology control [129]. Emerging test-analysis links inverse identification of tensile softening from beam tests, size-effect corrections, and probabilistic orientation factors are clarifying how STSF translate into design-level parameters for serviceability and moment capacity [66,130]. It is found that raising the RTSF volume fraction beyond about 0.75% produced no meaningful gains in flexural behavior, whereas other investigations have documented outright reductions after RTSF addition [66]. For example, it is measured lower flexural strength in RTSF-reinforced mixes than in plain concrete [66]. The principal causes repeatedly cited include difficulties achieving a uniform fiber dispersion, linked to inadequate compaction and fiber agglomeration, together with greater randomness of fiber orientation along the failure plane and a high proportion of short fibers, all of which undermine crack-bridging efficiency [66,130].

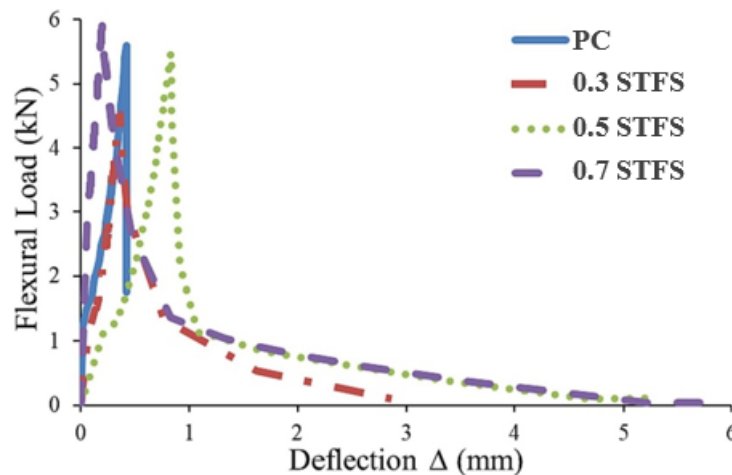


Fig. 11. Flexural load versus deflection profiles of STSF-reinforced concrete composite at different content levels ((Adapted with permission [80])

Mechanical damage imparted during tire shredding can also depress the intrinsic tensile capacity of STFSs, further weakening their bridging action [131]. In addition, residual rubber on the steel attenuates bond quality at the fiber–cement interface and diminishes flexural resistance, whereas clean, rubber-free STFSs can develop a comparatively strong interfacial adhesion [67]. It is reported that using 1% 45 mm STSFs led to a 16% increase in stability, and a 2% to 157% improvement in flexural strength was observed; in particular, a 40% increase was observed with 0.4% 62 mm STSFs [80]. It is exhibited that first cracking in flexure (**Fig. 11**) occurred at 100% of peak load for PC and at 99.56%, 99.45%, and 99.32% for 0.3STFS, 0.5 STFS, and 0.7 STFS. Post-failure surfaces show diameter-dependent behavior: thin fibers (<0.10 mm) mostly fractured with little pull-out, whereas thicker fibers (>0.10 mm) tended to pull out, consistent with split-tensile mechanisms where the bond–capacity balance governs pull-out versus rupture. A 3% decrease in stability was also documented with 0.50% of 21 mm STSFs [31]. Similarly, a 16% boost in split tensile strength was observed with 0.2% of 26 mm STSFs [100]. A remarkable 33% increase in flexural strength was observed with 0.50% of the 60 mm STSFs. In addition, a reduction in water absorption was noted when less than 0.25% STSFs were used, and a further decrease of less than 0.50% STSFs was observed [107].

A volumetric content of roughly 0.5% STSFs per cubic meter is commonly recommended to promote uniform dispersion and maximize flexural capacity [132]. In hybrid configurations, the mean peak load is on the order of 10 kN, and the post-cracking response evidence superior crack-bridging owing to the complementary action of micro- and macro-scale fibers [133]. Mirroring tensile-test outcomes, combining STSF with end-hooked steel fibers (ESF) produces a synergistic uplift in the residual strength of fiber-reinforced concrete [128]. The flexural metrics from the present program compare favorably with prior studies, particularly at serviceability and ultimate load levels—as summarized against the literature in [59]. The notably higher peak reported is plausibly attributable to differences in loading rate [134]. Morphologically, the STSFs displayed a deformed profile and rough surface texture, whereas ESFs featured hooked ends with a comparatively smooth finish. Tests on $100 \times 100 \times 400$ mm prisms, 150×300 mm cylinders, and 150 mm cubes showed softening at the modest fiber dosages employed, consistent with earlier observations [111]. Mechanistically, STSFs act primarily as micro-reinforcement; as macrocracks open, their efficacy diminishes because the shorter, thinner, hook-free fibers tend to pull out, limiting post-peak toughness [59]. To conclude, achieving adequate compaction in mixes containing STSFs can be challenging even at low contents, underscoring the importance of mix rheology control and placement practice to realize the intended flexural benefits.

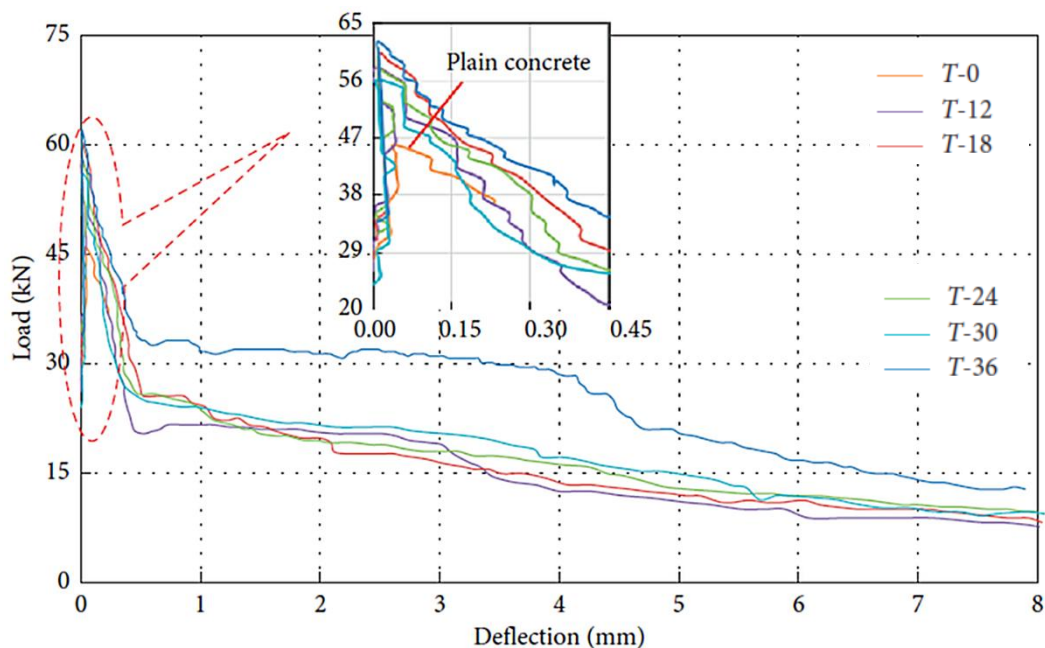


Fig. 12. The load-deflection profiles of STSFs-reinforced plain concrete (Adapted with permission [85])

From **Fig. 12**, it is reported that when cracks form at the base of plain concrete specimens, they propagate rapidly upward, causing a complete loss of load-bearing capacity [85]. Introducing STSFs significantly increases the load at initial cracking and enhances post-cracking performance through STSFs-concrete bonding. STSFs improve ductility [106] and toughness, shifting failure behavior from brittle to elastoplastic. It is highlighted that plain concrete loses load abruptly (brittle failure within < 0.5 mm), whereas the modified mixes unload more gradually; one mix sustains 25–35 kN up to 5–6 mm, indicating markedly higher residual capacity, ductility, and energy absorption (toughness) [85]. However, the load-deflection curves show no strain-hardening behavior, differing from prior research, likely due to fiber properties. Increased STSFs content raises maximum deflection and residual load capacity, with fuller load-deflection curves and higher secondary load peaks observed as fiber volume increases [85]. In response to specimen- and method-sensitivity, alternative testing standards have been applied to whole STSFs concretes [132]. At low dosages, measurable flexural strength gains have been documented: increases of roughly 15.9% at 0.23% STSFs and 9% at 0.46% relative to reference mixes [21]. At substantially higher contents, pronounced enhancements are possible; for example, using pyrolytically recovered fibers 0.8–1.55 mm in diameter and 50 mm long, flexural strength improvements up to about 150% were achieved at 6% by volume [97]. Dose–response benefits have also been observed on a mass basis, with flexural strength rising by approximately 21.4%, 19.6%, and

19.6% at 20, 40, and 60 kg·m⁻³ STFSs, respectively [76], and similar positive trends reported across different fiber sizes and volume fractions [111]. It is also converge on an optimal content near 0.5% by volume for maximizing flexural strength under comparable conditions [135].

The diminished bonding between the rubber particles and cement paste is a contributing factor to the reduced concrete strength. Studies, particularly those focusing on RS2-R5, indicate that the predominant failure mechanism in concrete includes the separation of particles of rubber from the surrounding matrix, supplemented by thin interfacial cracking [13]. Similar behavior has been observed in RS2-R35 samples [13]. Furthermore, an increase in rubber content within the concrete mix leads to the development and propagation of cracks surrounding the particles of rubber. These cracking patterns contribute to energy dissipation at the time of failure, thus, to improve the material's ductility. Moreover, STSF significantly aids in absorbing energy within the crack regions, delaying total specimen failure. This energy dissipation mechanism is a fundamental for increasing the post-cracking toughness of the concrete [136]. Figs. 9-10 exhibited that the integration of STSFs into concrete significantly improves the strength properties as well as the stiffness and ductility, facilitating the stress transfer across cracks, thereby enhancing the diagonal post-cracking stiffness of reinforced concrete beams. Also, this incorporation strengthens resistance to cracking, limits crack width and boosts hardness and shear strength. [137]. It is also revealed that flexural strength increases with RTSF only up to a threshold, beyond which additional fiber lowers strength; for instance, raising RTSF from 0.23% to 0.46% reduces strength by ~15% relative to the control [50]. **Fig. 13** shows that the study with the highest RSTF fraction (0.02 %) reports the top flexural strength (6.9–7.0 MPa), while mixes with ≤0.007 %) cluster near 4–5 MPa, indicating a clear dosage–response up to this low-volume regime. Mechanistically, this reflects the transition from insufficient fiber density (limited crack bridging) to a threshold where fiber–matrix pull-out and bridging meaningfully delay crack propagation; beyond 0.02 %v, further gains would be expected to plateau or even decline due to workability loss and fiber clustering, warranting optimization for each mix design.

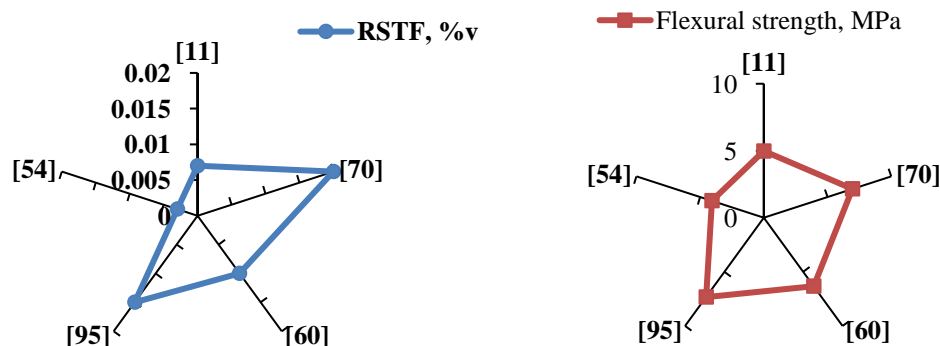


Fig. 13. Impact of the content of RSTF on the flexural strength of different concrete mixes, as documented in previous research (Data obtained from [11,54,60,70,93–95])

One approach involved combining STSFs with plastic fibers to remove the need for steel stirrups in structural concrete [140]. Plastic fibers were found to be effective at preventing early plastic shrinkage cracks and enhancing concrete cohesiveness because their Young's modulus is similar to that of concrete during early hydration stages [140]. In addition, the integration of synthetic fibers with STSFs has been shown to boost the fracture energy and toughness of concrete once it hardens [117]. Moreover, the STSFs act as essential elements for enhancing the shear strength of beams, allowing for the configuration of stirrup-free concrete structures [141]. The impact of hybrid fibers, including various types of long or geometrically distinct steel macro-fibers and a kind of steel microfiber, on the tensile strength of concrete has also been explored. The macro-fibers were found to be the primary factor affecting the overall tensile strength of concrete [142]. Moreover, the microfibers in these hybrid systems contributed positively to the occurrence of multiple cracks, leading to strain hardening in the concrete [34]. Recent study has delved into the properties of concrete augmented with a blend of hybrid STSFs at a rate of up to 0.9% by volume and PP fibers, with a maximum addition of 0.5% by volume

[83]. The results of these studies revealed that the dual integration of STSFs and PPFs efficiently mitigates the extension of cracks and fosters better post-cracking performance in concrete structures [117]. Besides, it has been observed that integrating PPFs increases the toughness of concrete. This suggests that the functionality of concrete reinforced with STSF could be significantly improved by including PPFs up to 66.7% of the total fiber composition [125]. However, the proportion of PPFs used is crucial in developing hybrid STSF/PPF reinforced concrete, as exceeding 0.3% of the PPFs in a total fiber content of 1.0% can diminish the strength properties of the material [143]. **Fig. 14** highlights the impact of incorporating STSFs into concrete on its strength properties. The findings discovered a marginal reduction in splitting strength with the addition of STSFs, though this decline remains minimal, not exceeding 5% when compared to concrete containing 100% STSF. The inclusion of STSF at a 5% concentration results in a substantial improvement of tensile strength, with an impressive increase of 213% reported [58]. Conversely, research suggests that combining STSFs does not produce a synergistic effect on splitting strength when all the content of STSF remains at 1.5% [70]. To mitigate the challenges posed by high fiber volumes, modern concrete technologies, such as self-compacting concrete and the use of advanced high-performance superplasticizers in which are essential for minimizing reductions in compressive strength [144].

Given the constraints of the literature, the meta-analysis was confined to rubberized concretes reinforced with STSFs drawn from studies that held the water–cement ratio and superplasticizer dosage constant. Within this controlled subset, the data indicates that flexural capacity can be recovered even at relatively high rubber replacement levels; in particular, substitutions up to about 25% restore flexural strength to values comparable with conventional concrete, whereas replacements beyond this threshold produce marked declines.

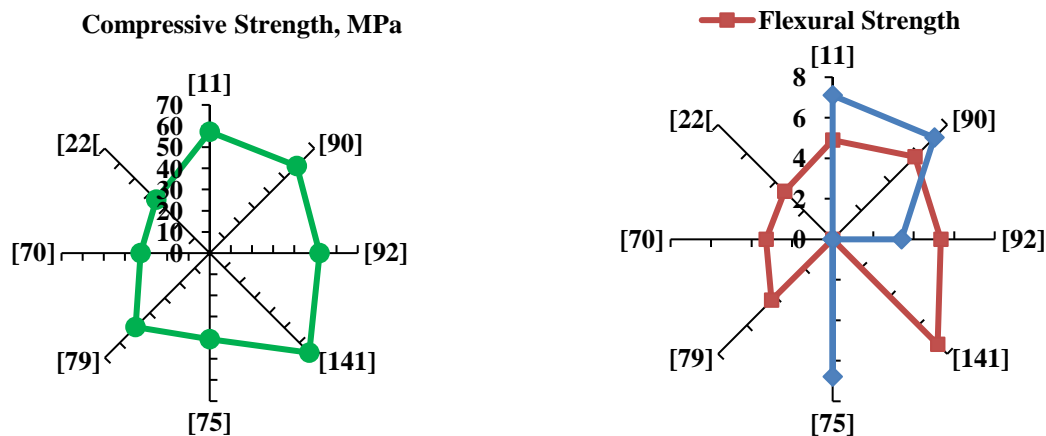


Fig. 14. Development trends of strength properties with different content of STSFs (Data obtained from [11,22,70,75,79,90,92,108,141])

Enhancing the rubber–cement interface, most effectively by surface-treating the rubber particles, mitigating the loss of strength at elevated rubber contents and yields measurable gains in flexural response. In parallel, STSFs show strong promises to boost flexural performance. Accordingly, combining treated rubber particles with STSFs is expected to deliver a synergistic improvement in flexural strength relative to mixes employing either strategy alone. Also, flexural-strength scatter in STSF-reinforced concrete primarily reflects differences in crack-bridging efficiency driven by fiber geometry, cleanliness, dosage, and matrix design. Higher aspect ratios, hooked/deformed ends, and favorable orientation raise pull-out work and post-crack toughness, whereas oversized or poorly dispersed fibers promote balling and weak fiber alignment. Surface impurities such as rubber, oils, corrosion, degrading ITZ bond; mechanical/chemical cleaning restores anchorage. Dosage exhibits an optimum beyond it, workability loss and voids offset bridging gains. Matrix rheology and quality, for example: low w/b, adequate paste viscosity, governing fiber dispersion/orientation and ITZ densification. Future studies should co-report orientation factors, cleanliness index, aggregate size, and rheology to enable fair comparisons.

5.3 Tensile behavior

The tensile responses of STSF-reinforced concretes are dominated by crack-bridging and pull-out mechanics rather than increases in the pre-cracking tensile strength of the cementitious matrix [146]. Tire-derived filaments-irregular, brass-plated, and aspect-ratio-rich mobilize higher interfacial friction and mechanical anchorage, elevating splitting tensile strength modestly at about 0.5–1.0% while transforming the post-crack behavior into a ductile [147], energy-absorbing softening with markedly increased fracture energy and residual tensile capacity [81]. Orientation and dispersion factors are decisive: clustered cords or rubber contamination suppress effective bonds and shorten pull-out slips, whereas cleaning, grading by length, and surface conditioning and stabilizing residual indices [66,130]. Hybridization with micro-fibres further delays microcrack coalescence, enabling tension-stiffening and tighter service crack widths even when the peak direct tensile strength changes little [105]. It is scientifically approved that Tensile strength generally increases with the fiber aspect ratio l/d (Fig. 15) [21,23,32,54]: longer and/or thinner STFSs bridge more cracks and develop higher pull-out resistance, raising peak tensile (or splitting) strength and post-crack toughness. However, beyond an optimum l/d (mix-dependent), workability and fiber dispersion deteriorate (balling, poor orientation), so gains plateau or reverse; improving surface deformation and bond can partly offset the need for very high l/d :

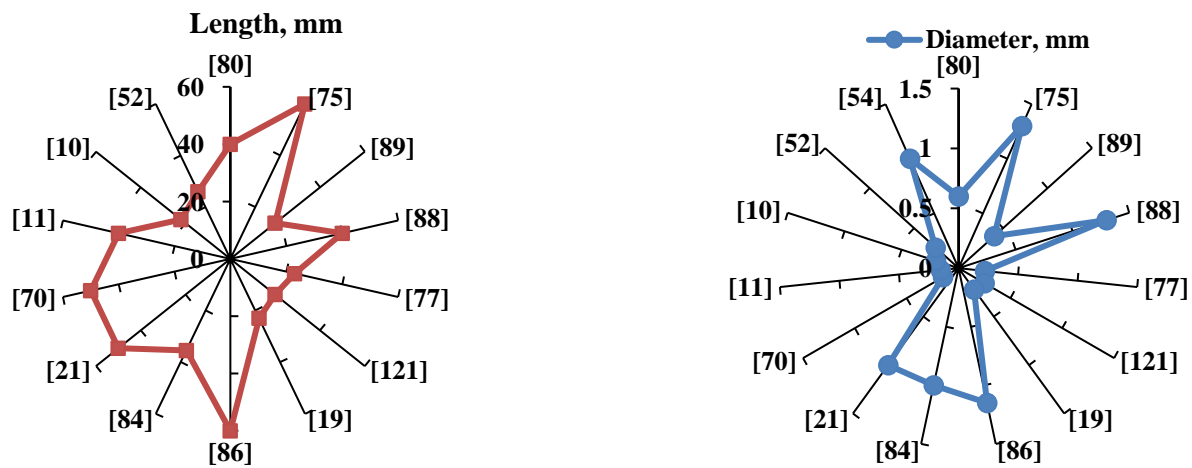


Fig. 15. Representative lengths and diameters of STSF used in various concrete mixtures, as reported by previous studies (Data obtained from [21,23,32,54,55,64,65,72–89, 121])

Like industrial steel fibers, STSFs are produced from high-grade tire cord and therefore exhibited strong weathering resistance together with high tensile strength and toughness [148]. Numerous studies show that adding STSFs enhances both tensile capacity and flexural response of concrete [104], and in self-compacting matrices their inclusion improves mechanical performance and impact toughness; at 1.5% by volume, the ultimate crack roughness of non-fibred concrete fostered by not less than 450% [149]. When benchmarked against new steel fibers, STSFs have demonstrated 50–76% effectiveness in upgrading compressive and tensile properties, depending on mixture design and dosage [150]. Because they are repurposed from waste, STSFs also offer performance gains with comparatively modest cost and environmental burdens [151]. Mechanistically, the STFSs possess irregular, corrugated morphologies that develop bonds along their full embedment length often yielding stronger interfacial engagement than ESFs, whose mechanical anchorage is concentrated at the hooks while RTSFs as a class can be treated as short, high-modulus, high-tensile reinforcements that effectively bridge microcracks within the cementitious matrix [152]. Crack bridging is the principal mechanism by which fibers transmit stresses across an emerging failure plane [76]. Even so, several investigations report that raising the RTSF dosage can depress splitting tensile strength: it is noted as the volume fraction rose from 1% to 5%, and measured a 4% reduction when increasing STFSs from 0.5% to 1.0% [32]. By contrast, it is observed no meaningful change with higher contents [153]. These outcomes are commonly linked to fiber agglomeration and the attendant growth of pore volume, which weaken the matrix and limits effective stress transfer [130]. Notwithstanding such dosage-related penalties, RTSF mixtures typically outperform plain concrete in splitting tension. Moreover, substituting another

recycled fiber with STFSs generally produces no significant difference in tensile capacity, underscoring the practical suitability of STFSs [70]. The favorable performance is frequently attributed to the fibers' rough, tortuous surfaces, which enhance frictional interlock and bonding at the fiber–cement interface [13].

At matched volume fractions, both STFSs and conventional steel fibers can raise tensile strength at 0.75% by volume, gains of about 28% and 26.33% over plain concrete were reported, respectively [154]. Incorporating whole STFSs also shifts the material response from brittle to more ductile, a change attributed to the heterogeneous fiber geometry that promotes mechanical interlock throughout the matrix. In particular, the variability in STFS diameter and length enhances load transfer along the embedment, with one study noting 50% higher tensile strength at 0.75% STFS relative to the reference mix [102]. Hybridization with conventional steel fibers frequently delivers the largest improvements because hooked ends provide strong anchorage while STFS contribute pervasive bridging, together yielding a more effective crack-arrest system [111]; even at modest contents, increases on the order of 14% were observed at 0.6% STFS [146]. Literature syntheses further document percentage differences in tensile strength for STFS-reinforced mixes relative to their companion controls across a wide range of dosages and test setups [155]. Multi-objective optimization has echoed these trends: a hybrid of 0.15% virgin steel fibers with 1.35% STFS achieved a suitability function value of 0.620 when global-warming potential was included among the criteria [70], while a separate desirability analysis indicated that a combination of 1.0% conventional fibers and 0.5% STFS offers superior mechanical performance in terms of tensile strength under the studied conditions [156].

Furthermore, recent study has centered on the mechanical characteristics of STSF-reinforced concrete [33], which exhibit superior tensile strength and ductility, as well as satisfactory shear performance [106]. The concrete reinforced with 1% STSF exhibited a tensile strength improvement of 49–68% compared to plain concrete [104]. Regarding durability, STSF-reinforced concrete shows a marginal increase in corrosion susceptibility relative to that of ISF-reinforced concrete; however, this increase does not significantly impact post-cracking resistance [54]. These observations demonstrated that STSF addition notably diminishes concrete brittleness and offers post-cracking behavior comparable to that of ISF-reinforced concrete [62,64]. Moreover, the specific attributes of STSF, such as geometrical dimensions and pull-out behavior, were examined. The results revealed that STSF could create a stronger bond between the fiber and the matrix, enhancing the overall performance [21]. In general, it is evident that the efficiency of stress transfer within a material is significantly impacted by fiber length, with longer fibers demonstrating superior performance in facilitating stress distribution compared to shorter fibers.

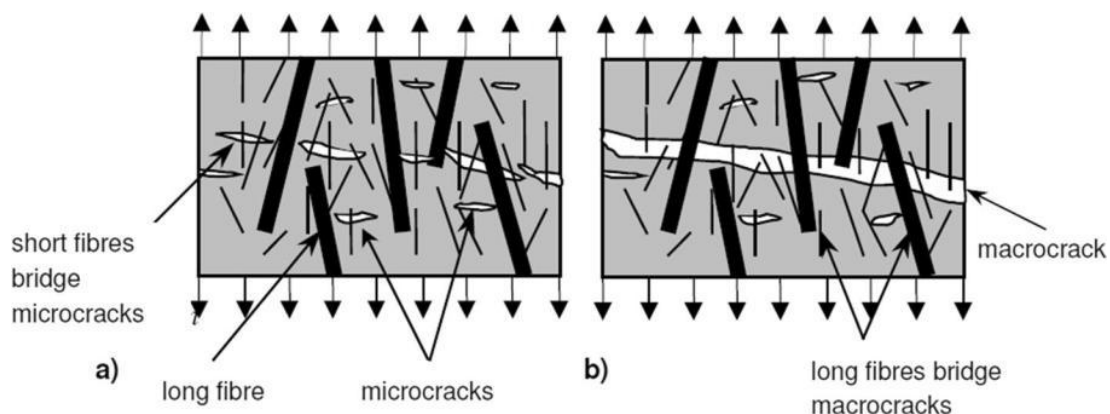


Fig. 16. Contribution of different fiber types in minimizing crack widths under tensile stress (Adapted from [158])

Compared to synthetic fibers, STFS, whether industrially produced or recycled, offers a superior mechanical benefit to concrete. STFS shares similar properties with industrial steel fibers, such as resistance to environmental fluctuations [15], high tensile strength, and exceptional toughness, as these fibers originate from premium-grade steel used in tire production. Incorporating STFS has been revealed to improve concrete's flexural and tensile performance [157]. The activation of fibers typically commences once the concrete matrix starts forming microcracks that are initially invisible [38]. The

integration of a hybrid system comprising short and long steel fibers has been exhibited to significantly improve the toughness of concrete. This enhancement is particularly evident at smaller crack opening translations, where fibers of discrete lengths effectively engage at various stages of crack development and propagation (**Fig. 16**) [158]. Moreover, shorter fibers play a critical role in reducing permeability by controlling crack growth more effectively. This hybrid fiber-reinforced concrete presents a promising solution for industrial applications requiring resilience under extreme environmental conditions [159]. Traditionally, steel rebars are used to reinforce concrete and are strategically placed to counter shear and tensile stresses [160]. Recent research, however, has discovered the utilization of dispersed, discontinuous fibers to mitigate the inherent brittleness of concrete [161].

The research emphasizes that splitting tensile strength serves as a reliable predictor of concrete's flexural strength, with STSF contributing significantly to its enhancement. STSFs, referred to as RSTF fibers [137], are key recycled materials sourced from waste tires. Studies comparing the performance of STSFs with virgin steel fibers have highlighted the distinct characteristics of these materials [62,106]. At specific dosages, concrete reinforced with STSFs demonstrated post-cracking behavior, toughness, and shear performance comparable to mixtures reinforced with virgin steel fibers. Also, the inclusion of STSFs has been shown to effectively counteract the reduction in flexural strength commonly associated with the addition of recycled tire rubber in rubberized concrete. This improvement underlines the viability of STSFs to enhance the strength properties of rubberized concrete composites, particularly by mitigating the negative effects of rubber incorporation on flexural strength [162]. However, challenges such as the complex storage of STSFs have spurred numerous experimental investigations into their use in cementitious materials [163]. These studies generally indicate that STSFs enhance several properties, including early-age shrinkage resistance and spalling resistance in concrete and mortar [164]. Furthermore, it has been reported that STSFs enhance mechanical performance under high strain rates and cyclic loading conditions [129]. A higher exposure level was utilized during the microscope imaging process to enhance the visibility of the fibers, resulting in increased brightness [137]. **Fig. 17** illustrates that splitting tensile strength clusters around 3–4 MPa and peaks only modestly (4.2 MPa) at intermediate RSTF contents, while very low or very high contents show limited benefit, indicating no simple monotonic dosage–response [21,22,48,66]. The scatter suggests an optimum low-volume addition where crack-bridging is effective; beyond that, workability, fiber clustering/orientation, and mix-design differences dominate the response across studies.

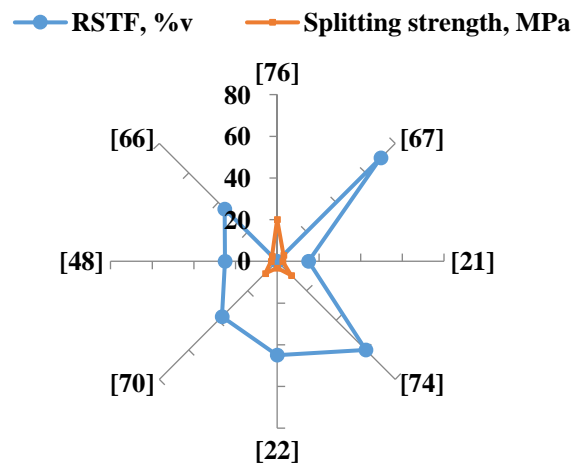


Fig. 17. Impact of the content of RSTF on the tensile strength of different concrete mixes, as documented in previous research (Data obtained from [21,22,48,66,66,70,74,76])

Moreover, recent research has focused on the mechanical properties of STSF-reinforced concrete [33], which exhibit superior tensile strength and ductility, as well as satisfactory shear performance [106]. The concrete's tensile strength strengthened with 1% STSF was found to increase by 49–68% compared to that of plain concrete [104]. Regarding durability, STSF-reinforced concrete shows a marginal increase in corrosion susceptibility relative to that of ISF-reinforced concrete; however, this increase does not significantly impact post-cracking resistance [54]. These observations exhibited that STSF addition notably diminishes concrete brittleness and offers post-cracking behavior comparable to

that of ISF-reinforced concrete [62,64]. Moreover, the specific attributes of STSF, such as geometrical dimensions and pull-out behavior, were examined. The results revealed that STSF could create a stronger bond between the fiber and the matrix, enhancing the overall performance [21]. In addition, research has demonstrated that STSFs, portrayed by their superior tensile strength and stiffness, exhibit a remarkable ability to resist shear stresses, thereby postponing the onset and progression of cracking. This performance is attributed to the fiber bridging mechanism, where the tensile stresses induced by bending moments during flexural loading are transmitted as shear stresses at the fiber-matrix interface. The interaction at this interface, facilitated by the contact surfaces between the fiber and the surrounding matrix, effectively counters these shear stresses, enhancing the overall structural integrity [165]. Incorporating recycled STSFs not only enhances material performance but also supports eco-construction uses by reducing the eco-impact of waste tires and alleviating the demand for non-renewable resources. **Fig. 18** shows the actual distributions of various STSFs in the concrete networks as reported by previous researchers worldwide [166,167]. It is presented key micromechanical actions by STSF that strengthen the concrete matrix. Across panels, STSFs span crack faces (crack-bridging), with many fibres showing partial debonding and pull-out, and others failing by rupture at the crack plane [130]. Pull-out evidence interfacial slip that dissipates fractured energy and restrains crack opening, while fibre rupture indicates high bond efficiency and effective stress transfer to the steel; the coexistence of both mechanisms is consistent with improved post-cracking toughness and residual tensile capacity [137].

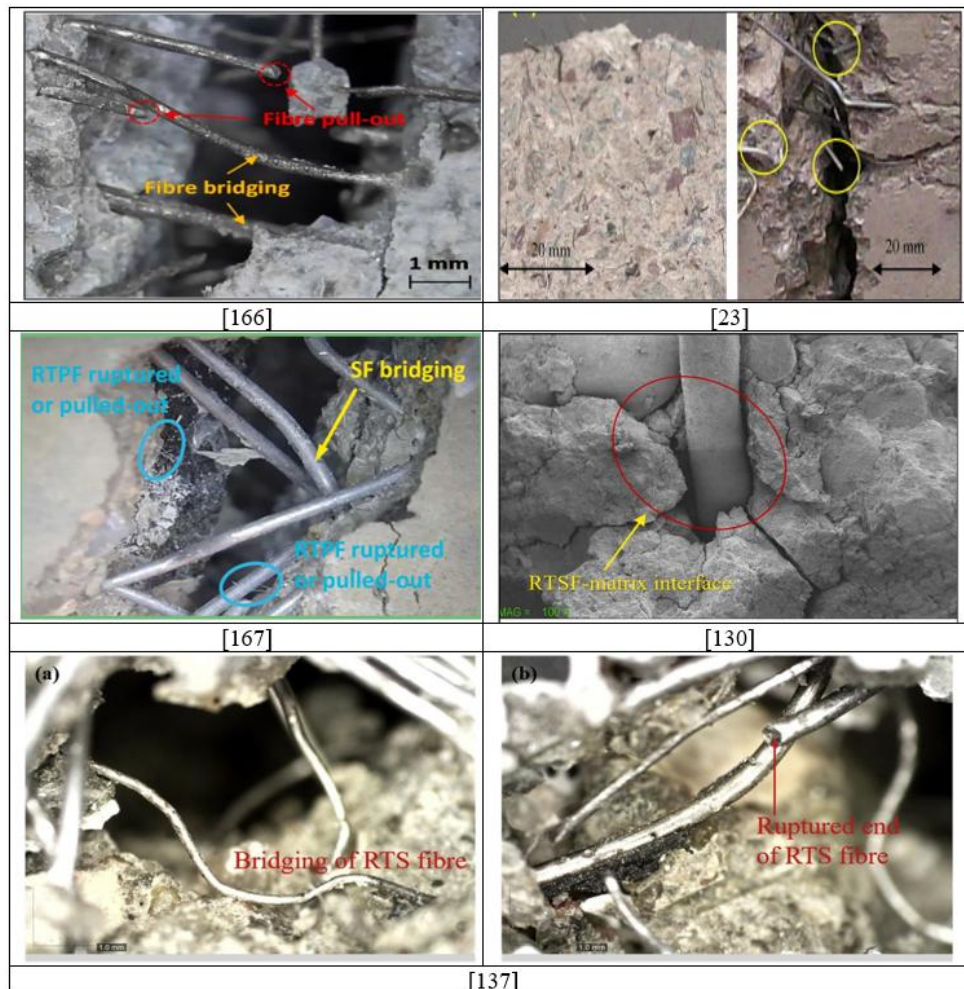


Fig. 18. Representative fibre–matrix interactions and failure modes in STSF-reinforced concrete-bridging, pull-out, rupture, and STSF–matrix interface

The images also revealed the STSF–matrix interface and local aggregate interlock, suggesting that the irregular geometry/surface roughness typical of recycled wires enhances mechanical anchorage compared with smooth industrial fibres [137]. At the same time, the micrographs highlight practical

constraints: occasional fibre clustering, curved/entangled morphologies, and possible residual rubber or weak paste pockets near interfaces, all of which can cause heterogeneous stress transfer and variable pull-out responses [166]. Overall, the observed bridging, pull-out, and rupture events explain how STSFs arrest crack propagation and elevate energy absorption, while the noted dispersion and interface variability underscore the need for careful mixing, dosage, and surface cleanliness to fully realise STSF's toughening potential [167].

In conclusion, in STFS-reinforced concrete, crack bridging depended sensitively on fiber dosage and spatial distribution: increasing content and achieving a uniform dispersion generally intensifies bridging action and toughness, whereas excessive additions promote clustering, degrade workability, and can erode mechanical performance [166]. The governing response arises from a coupled balance among fiber orientation, geometry, dispersion quality, and interfacial bond strength; careful control of these variables is essential to tailor mixtures for specific applications and to realize the targeted strength and durability. Consistent with this framework, multiple studies from different settings report that modest whole STFSs contents, around 0.5% by volume, enhancing the mixture's flexibility and post-cracking behavior. Trends in splitting tensile strength across a range of steel-fiber dosages further underscore the favorable role of STFSs in tension, with gains in tensile capacity typically exceeding those in compression at higher fiber contents, reflecting the fibers' principal contribution to bridging and restraining crack opening. Correspondingly, specimens containing STFSs tend to exhibit partially ruptured, ductile failure modes, whereas control concretes without fibers commonly fail in a brittle manner with complete splitting. Also, variations in tensile strength of STSF-reinforced concrete largely reflect differences in crack-bridging mechanics governed by fiber geometry, cleanliness, dosage, and matrix quality. Higher aspect ratios, hooked/deformed ends, and favorable orientation increase pull-out work and delay crack localization, whereas oversized or poorly dispersed fibers reduce effective alignment and create stress concentration. Surface impurities from tire processing degrade ITZ adhesion; cleaned or roughened fibers restore bond and raise effective stress transfer. Dosage is non-monotonic: an optimum enhances bridging, but excess fibers impair workability, entrap air, and weaken the paste-aggregate skeleton.

6 Durability performance

It is well-known that the STFS has gained attention as a valuable resource derived from discarded tires, addressing the critical issue of waste tire accumulation in landfills worldwide [17]. This innovation emerged as part of efforts to recover and utilize the functional materials embedded in waste tires, transforming what was previously considered an underutilized byproduct into a sustainable solution [39]. STFS, a cost-effective and sustainable alternative, is made from steel cords or wires reclaimed from used tires [3,14]. Durability evidence for STSF concretes remains comparatively sparse, yet the available studies suggest several favorable long-term behaviors. For chloride ingress, one investigation measured chloride contents of 0.7% and 0.8% by binder mass in mixes with 1% RTSF and in companion plain concretes, respectively, indicating no penalty from fiber addition [54]; likewise, the critical chloride threshold for corrosion initiation on RTSF surfaces appears comparable to that of industrial ESFs. Permeability indicators also trend positively: water-absorption tests showed lower uptake in a mix containing $40 \text{ kg} \cdot \text{m}^{-3}$ RTSFs than in an otherwise identical ESF mixture at the same dosage, with still lower absorption when RTSFs and ESFs were used in hybrid form [168]. Mechanistically, the random, volumetric dispersion of steel fibers reduces the effective cathodic area compared with reinforcement provided solely by a rebar cage, thereby moderating corrosion processes [133]. Consistent with this, naturally corroded RC beams exposed for three years to a 10% NaCl environment exhibited lower gravimetrically measured corrosion rates, a more diffuse corrosion pattern, and less severe pitting when the rebars were embedded in steel fiber-reinforced concrete rather than plain RC [169]. Moreover, rebars in SFRC generally require a higher chloride concentration to trigger corrosion than those in fiber-free members [30], an outcome aligned with the crack-arresting action of steel fibers that limits penetrability to aggressive agents such as chlorides [170].

A microstructural examination of the recycled steel wire-containing samples was conducted using scanning electron microscopy (SEM). The SEM was used to examine samples containing recycled steel wire, with images in **Fig. 19** captured at 500x magnification [103]. The right-hand image enlarges

regions highlighted in the left, and key findings are annotated. **Fig. 19a–d** details interactions between waste steel fibers and concrete. Ettringite, formed from calcium sulfoaluminate in sulfate-rich environments, enhances concrete compressive strength by filling pores [103]. **Fig. 19a** shows aggregate distribution and voids, indicating poor hydration in high-void areas. **Fig. 19b** reveals well-hydrated cement-aggregate regions. **Fig. 19c** illustrates the steel fiber-concrete interface, noting occasional gaps, while **Fig. 10d** confirms strong fiber-cement adhesion.

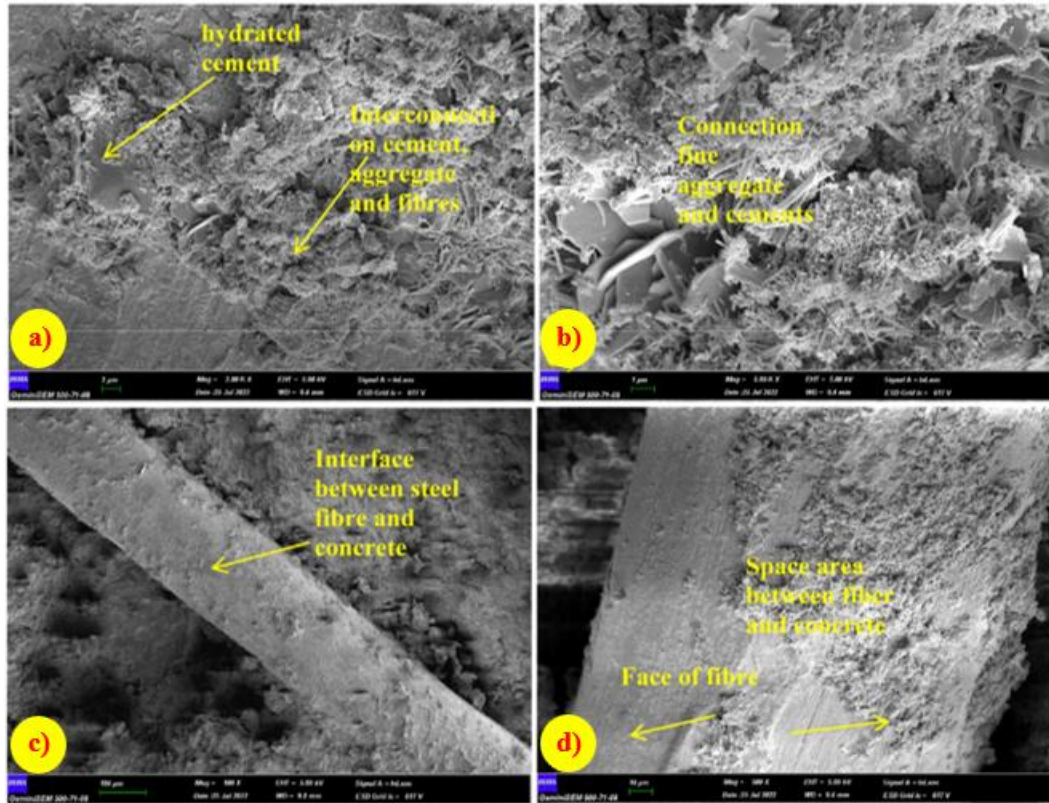


Fig. 19. Microstructure of the test samples of STFS-based concrete (Adapted with permission [103])

Reportedly, it is revealed that steel fibers inhibit crack propagation, limit crack widths, and improve aggregate interlock, thereby increasing the shear capacity and stiffness of reinforced-concrete (RC) members [171]. Beyond mechanical benefits, recent studies indicate that STFS-reinforced concrete (SFRC) exhibits superior durability relative to conventional RC in corrosive environments [172]. A key factor is the random dispersion of fibers throughout the matrix, which as opposed to a discrete rebar cage alone, reducing the effective cathodic area for corrosion processes [173]. In long-term exposure trials, it is reported that RC beams cast with SFRC and subjected for three years to 10% NaCl demonstrated lower rebar corrosion rates by gravimetric assessment, alongside more diffuse corrosion patterns and less severe pitting than in plain RC [169]. Furthermore, rebars embedded in SFRC generally require a higher chloride concentration to initiate corrosion compared with those in fiber-free concrete, a result consistent with the crack-arresting action of steel fibers that restricts ingress of aggressive agents, for example, chloride ions [168]. At the microstructural level, short microfibers better control pastes cracking and reduce water permeability [32], while macrofibers primarily restrain cracks at the aggregate–paste interface. Building on these insights, the present study evaluates how combined micro- and macro-reinforcement influences both corrosion development in rebars and the flexural response of RC beams under accelerated corrosion, employing STFSs from tire-recycling plants as microfibers and end-hooked steel fibers ESFs as macrofibers [174].

As illustrated in **Fig. 20**, a pronounced phase dominated by $\text{Ca}(\text{OH})_2$ is evident within the temperature range of 400–475 °C [131]. Decomposition in the WS 0.8 sample begins at 401.71 °C, followed by sequential degradation in the PL (plain) and WS 0.4 samples (where RTFS is denoted as WS in **Fig. 20**). Thermogravimetric analysis (TGA) of the powder particles indicates that the breakdown of hydration products in concrete initiates at temperatures exceeding 400 °C. The decline in strength

correlates with the dehydration process triggered by elevated temperatures, linking strength loss to specimen mass reduction [175]. A clear trend emerges as temperature-induced mass loss increases; strength diminishes significantly. For instance, at approximately 600 °C, a 10% mass loss corresponds to a 50% reduction in strength. It is reported that when mass loss exceeds 20% at around 800 °C, nearly 70% of the concrete's strength is compromised [131]. The incorporation of both STSF and STSF has been observed to reduce tensile strength [176]. This reduction is likely credited to the non-uniform dispersion of fibers within the matrix of concrete, which may promote the initiation and spread of cracks.

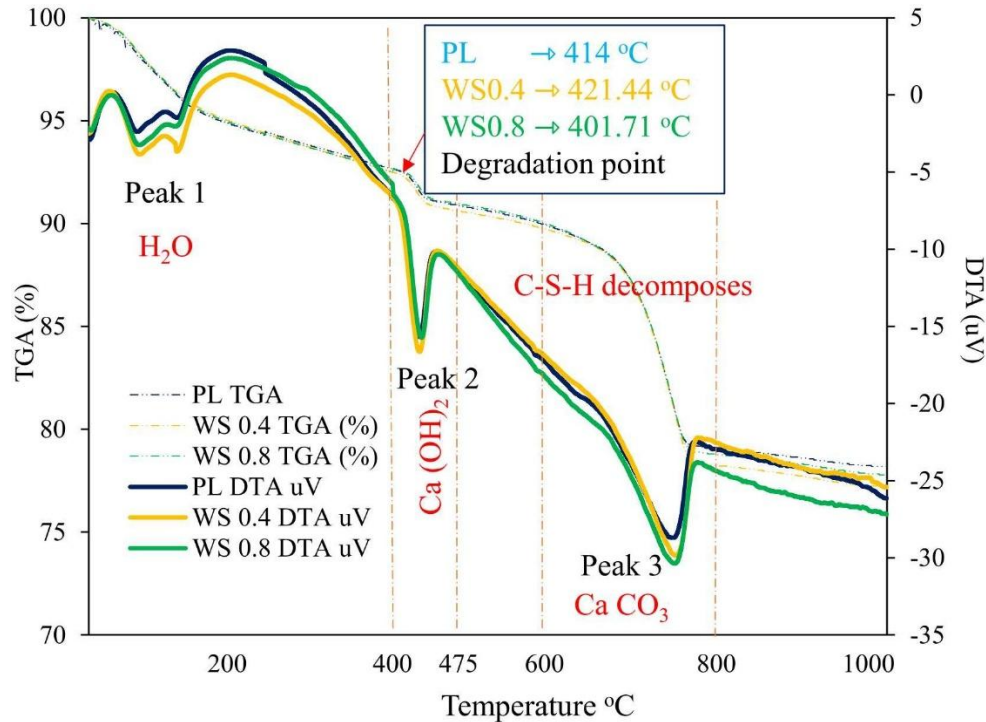


Fig. 20. Thermogravimetric (TGA) and differential thermal analysis (DTA) of specimens subjected to varying temperatures (Adapted with permission [131])

In brief, durability outcomes for STSF-reinforced concrete are encouraging but contingent on fiber quality, cleanliness, and dispersion. Studies show refined crack networks and reduced transport (water, air, chlorides), especially when STSF is paired with cementitious materials matrices that densify the ITZ; yet corrosion risks can rise with untreated brass/rubber residues or poor grading. Progress now hinges on standardized, exposure-relevant testing and microstructural diagnostics to link fiber surface condition, ITZ chemistry, and transport tortuosity to service-life predictions. With targeted surface treatments and synergistic binders, STSF composites can credibly evolve from waste valorization to reliable, durable solutions for structural and repair use.

7 Environmental effects, economic development, and applications

7.1 Environmental impacts and economic development

Deploying STSF in cementitious composites advances circular-economy goals by transforming an enduring waste liability into a high-value reinforcement that can displace virgin steel fibers and reduce cradle-to-gate embodied impacts [129]. Life-cycle assessments consistently indicate a “double dividend”: avoided burdens from diverting tires from landfills and stockpiles, and substitution credits relative to primary steelmaking, provided functional performance is held constant at the element level (e.g., residual flexural strengths at energy-absorption property [126]). Because STSF improves crack control, post-cracking ductility, and impact/fatigue resistance, reimbursements extend into the use phase through longer maintenance intervals, fewer overlays, and extended service life, that frequently outweigh material-stage savings in whole-life carbon models [23,24]. Realizing these gains hinges on quality assurance in tire-steel recovery (cleaning, sizing, de-rubberization), robust mix design to

manage workability and dispersion, and end-of-life strategies that recover steel via magnetic separation during concrete recycling [15]. As datasets mature, product-specific environmental product declarations and performance-based specifications allow STSF concretes to compete transparently with industrial steel or synthetic fibers, aligning procurement with verifiable outcomes rather than prescriptive inputs [62,76,90,100–102].

Fig. 21 consolidates prior multi-criteria evaluations of STSFs in concrete by plotting normalized indicators for RTSF mixtures against those with another recycled fibers [67,151,177]. The radar profile indicates that RTSF-reinforced concrete generally underperforms in mechanical efficiency relative to ISF counterparts, yet it exhibits marked advantages in environmental and economic dimensions, yielding a superior overall (total) efficiency envelope [177]. Because multiple studies have documented this mechanical shortfall for RTSF-based mixes, targeted strategies to improve strength-related metrics are essential to facilitate broader field adoption [67,151]. Furthermore, life-cycle assessment of steel-fiber-reinforced concrete incorporating STSFs remains comparatively sparse, underscoring the need for systematic LCA studies to substantiate the observed sustainability benefits and guide performance-optimized mix design.

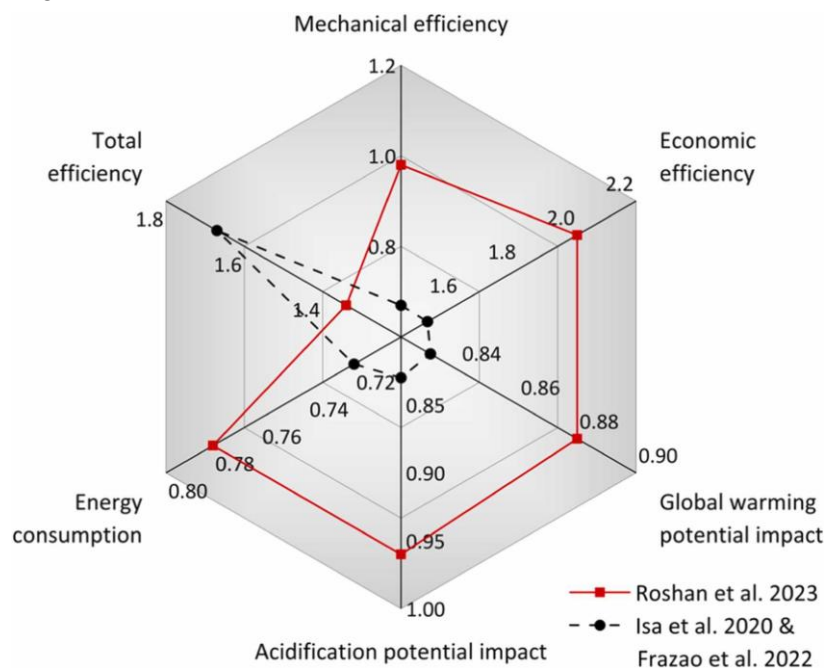


Fig. 21. Multi-criteria evaluations of STSFs in concrete by plotting normalized indicators for RTSF mixtures against those with another recycled fibers (Data obtained from [67,151,177])

The economic development case is equally strong [123]. Industrial symbiosis between tire-recycling facilities and ready-mix or precast plants stabilizes demand for recovered steel, supports small and medium enterprises that invest in metrology and certification, and creates local jobs in collection, sorting, processing, and testing [125]. Policy levers, extended producer responsibility for tires, landfill restrictions, recycled-content targets in public works, carbon pricing, and green public procurement, can tip markets in favor of STSF by internalizing externalities and rewarding documented life-cycle value [126]. When owners adopt performance-based tendering for common concrete applications, contractors can realize whole-life cost reductions from durability dividends, while regions with large tire stockpiles convert a ubiquitous waste stream into a nearby infrastructure input, retaining value locally [127]. In sum, with standardized material descriptors and contamination limits, and third-party verification of concrete performance, STSF transitions from niche waste valorization to a scalable lever for decarbonizing the concrete supply chain, de-risking maintenance budgets, and catalyzing inclusive, place-based industrial growth [119,123].

This underscores the importance of evaluating the environmental impact of automobile tires [2]. Research across various studies on the life cycle and ecological influence of products such as car tires highlights the need to identify specific impact categories and their relative importance [49,68,178]. It is

also critical to consider both the costs already incurred and those anticipated in the future [20]. The environmental footprint of an object is linked to its design, exemplified by the difference between traditional car tires and those made from natural rubber [41]. Recycled tires have multiple uses in industry and commerce, with notable applications in construction engineering and as a fuel source [137]. One prominent application involves the making of crumpled rubber, which is used in the paper and cement industries for furnace heating [179].

Furthermore, Chen et al. [166] clearly present a contribution evaluating the economic and environmental impacts of STSF (referred to as WF in **Fig. 22**) on UHPC. A detailed sustainability analysis is included, encompassing assessments of embodied carbon per m^3 and material costs, using the data provided in **Table 2**. The cost analysis highlights the economic advantages of replacing industrial fibers (IF) with STSF in UHPC production. It should be observed that material costs can vary significantly based on manufacturer, production year, and geographic location. As depicted in **Fig. 22** [166], the incorporation of WF2.0 results in a reduction of approximately 26.9% in total material costs and a 52.5% reduce in omitted carbon in comparison with the UHPC containing 2.0% STSF.

Table 2. Embodied CO₂ and cost of material for each constituent in UHPC (Data obtained from [67,70,71,166,180–185])

Type of material	Embodied COs (kgCO ₂ eq/kg)	Cost (USD/kg)	Refs.
Silica fume	0.014	0.12	[180,181]
Cement	0.93	0.18	[70,182]
Superplasticizer	0.60	0.92	[180,181]
Quartz sand	0.010	0.046	[181,183]
WF = STSF	0.083	0.11	[67,184]
Industrial fibres (IF)	2.68	0.90	[71,185]

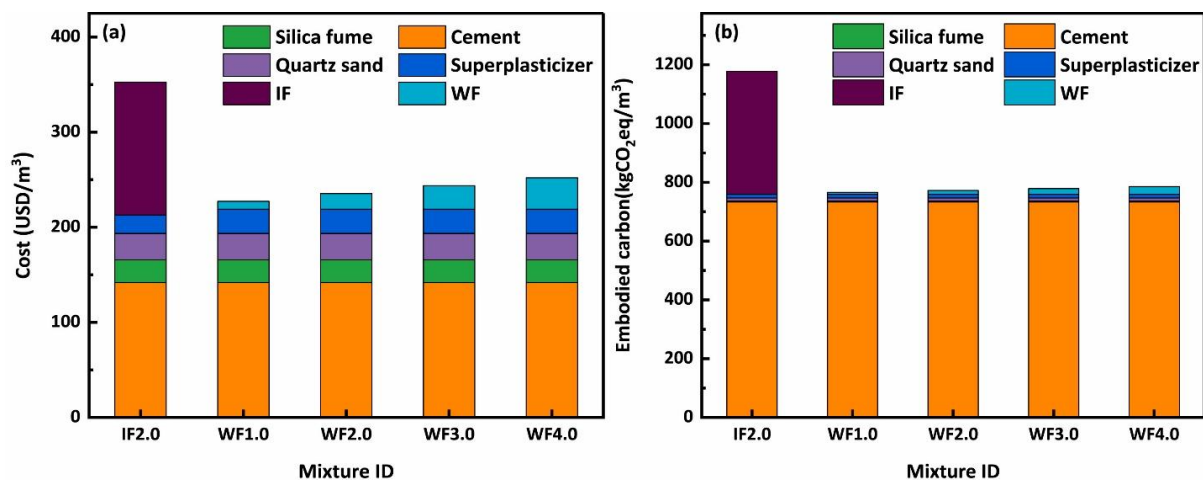


Fig. 22. (a) Cost of material and (b) embodied CO₂ of the STSFs and other mixtures of UHPC (Annotation: WF = STSF) (Adapted with permission [166])

In recent years, as reported by Valentini et al. [186], the application of life cycle assessment (LCA) to recycled tires has significantly improved. This tool is particularly adept at navigating the complexities and interdependencies inherent in contemporary integrated waste management systems. LCA has been instrumental in quantifying energy savings across various applications, such as reducing primary energy consumption from 74 to 43 GJ in concrete mixtures [187]. This assessment was conducted to facilitate a comparative analysis of environmental impacts across different categories. In brief, a research has shown that STSFs are significantly more cost-effective than their counterparts, with prices up to ten times lower [188]. On average, the cost of STSF is almost one-fifth that of its alternative [4]. Typically, the dosage for STSF in various applications ranges from 20 to 50 kg/m^3 . Replacing other materials with STSFs can lead to substantial cost savings, ranging from 15.2€ to 38€ per cubic meter [4].

8 Applications

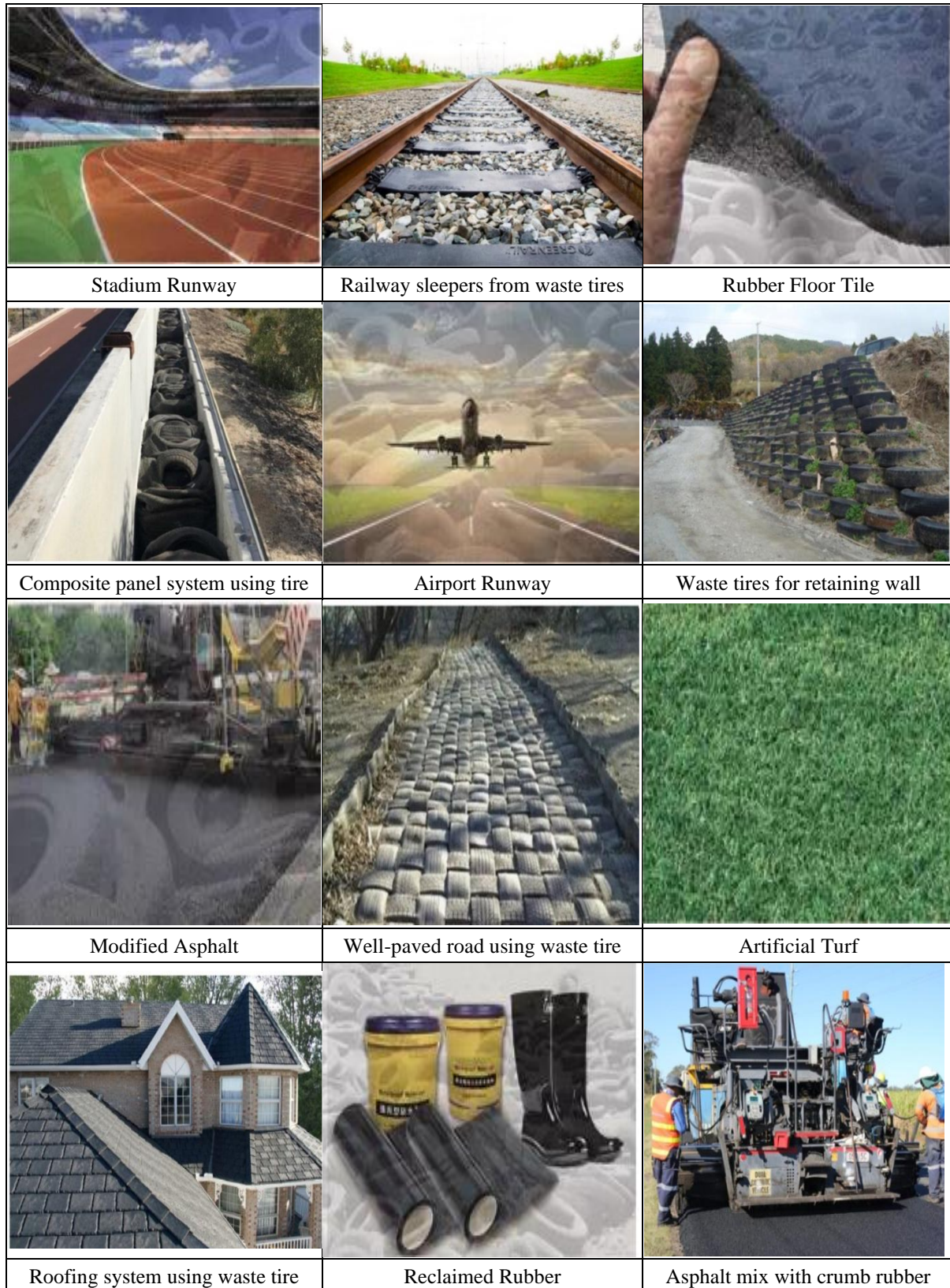


Fig. 23. Representative uses of tire-derived materials in construction and transport applications (Actual depictions obtained from [1,50])

Across the built environment, STSF-reinforced concretes are best viewed as performance-tailored materials rather than mere waste-derived substitutions, with application domains emerging wherever crack-width control, impact/fatigue resistance, and post-cracking toughness govern serviceability or

whole-life cost [127]. In slabs-on-grade for logistics platforms, industrial floors, and container yards, STSF dosages calibrated to residual flexural strength, enabling joint-spacing extension and, in many cases, partial or full substitution of light mesh, thereby shortening placement cycles and reducing restraint-induced cracking [151]. For pavements and rigid overlays, particularly in ports, heavy-haul corridors, and airside hardstands; STSF confers enhanced aggregate interlock and fatigue endurance at joints and cracks, supporting thinner sections or longer repair intervals under repeated wheel loads [72].

In precast products such as pavers, interlocking blocks, culverts, pipes, and small retaining-wall units (**Fig. 23**), the characteristic thin, twisted morphology of tire-derived wires promotes efficient crack bridging at low fibre mass, improving dimensional stability and edge integrity during demoulding, handling, and service [1,50]. Sprayed concretes for tunnel and cavern linings constitute another high-value use: STSF provides energy absorption and ductility essential for convergence control in early ages, while the recovered-steel surface texture enhances bond and pull-out resistance, allowing designers to meet performance classes specified by contemporary shotcrete guidelines [189]. Because tire processing co-generates rubber fractions, hybrid mixes that combine STSF with fine crumb rubber are increasingly explored for vibration- and noise-attenuating applications, stadia sub-bases, track slabs, and barrier elements, leveraging the damping of rubber and the toughness of steel to meet functional targets in impact, abrasion, and acoustic response [190,191].

Table 3. Summary of the different impacts of ELT as reported by previous researchers (Data obtained from [126,186,187,189–191,195–197])

Type of process or evaluation technique	Descriptions/Footnotes	Reduction in CO ₂ emission	Refs.
The process of retreading tires leads to the release of emissions. Top of Form	A truck tire's weight reduced from 60 kg to 236 kg for a new tire.	The decrease observed was 74%.	[191]
Pulverizing ELTs into fine particles for cement kiln fuel has notable uses.	Incorporating one ton of GTR into civil engineering applications translates to an effective weight reduction ranging between 500 and 300 kg.	Compared to using sand, gravel, or rock, this method reduces CO ₂ by 20–80 kg. Top of Form	[189,190]
Reversing vulcanization allows full recovery of rubber from tires.	It leads to a decrease in primary energy demand by almost 3000 MJ.	A 94% reduction in energy use compared to the production of new rubber.	[195]
Producing and twice replacing a tire over 660 k km generates roughly 552 kg of CO ₂ .	Using oil-based production, switching processes cuts CO ₂ by about 5,000 kg for a tire retreaded twice.	An approximate 80% decrease in carbon CO ₂ .	[196]
Producing and replacing a tire twice over 660 k km results in 552 kg of CO ₂ emissions.	This is notable when considering a new tire that is retreaded twice.	Reduced to 313 kg of CO ₂ , marking a 43% decrease.	[186]
Repurposing shredded rubber from ELTs reduces carbon dioxide emissions by 3217 kg per ton, enhancing environmental sustainability.	The CO ₂ emission is nearly 2703 kg.	There's a CO ₂ emission of 1466 kg.	[187]
The material requirement for a new tire, expected to be replaced after every 220 k km, is roughly 210 kg.	For a tire that is required to travel 660 k km, a new tire that is retreaded twice is considered.	The material quantity is lowered to 96 kg, translating to a reduction of about 54%.	[197]
The utilization of one ton of ELTs as a substitute fuel source in the production of cement.	The use of recycled tires for rubber modified asphalt production, leading to 1110 kg reduction in CO ₂ .	This procedure leads to adverse ecological effects, releasing of 667 kg of CO ₂ .	[126]

Field deployments mirror these mechanics-driven opportunities and illustrate the breadth of end-of-life tire valorization in civil works and construction applications (**Fig. 23**) [1,50]. Rail infrastructure has adopted tire-derived components in sleepers and ballast mats for resilience and vibration control; where rigid concrete elements are required, STSF can deliver the residual load-carry and spall resistance demanded by cyclic wheel loading and tamping operations [1]. In transportation corridors and airfields, STSF-concrete is suited to rigid pavement panels, joint-repair materials, precast thresholds, and blast-resistant hardstands, offering improved post-crack capacity relative to plain concrete [102]. Coastal and riverine works benefit through precast armor units, revetment blocks, and modular retaining-wall elements whose toughness mitigates impact and hydraulic-induced edge damage [50].

Building applications include thin roofing tiles, façade panels, stair treads, and high-traffic floor toppings, where distributed reinforcement controls shrinkage cracking and enhances chip resistance without congesting formwork [192]. Across these settings, successful practice hinges on two enablers: (i) materials prequalification that constrain fibre length/diameter distributions, contamination limits [92–96], and tensile properties to ensure predictable residual strengths in the intended mix, and (ii) performance-based specifications (residual flexural strengths, energy-absorption indices, impact/fatigue benchmarks) that let STSF compete directly with industrial steel or synthetic fibres [11,129,166]. When these conditions are met, STSF composites transition from niche sustainability exemplars to specification-grade solutions for heavy-duty pavements, precast systems, tunnel shotcrete, rail-adjacent slabs, and vibration-managed platforms, applications where toughness, durability, and constructability deliver measurable value [127,151].

Utilizing waste tires in civil construction not only is environmentally friendly but also enhances the cleanliness and longevity of buildings [193]. Conversely, incinerating or burying waste tires can cause irreversible damage to water resources and then may effect human health [39]. The societal values of using STSFs are significant and should not be overlooked [188]. It helps reduce deforestation, decrease land usage in the natural rubber industry, lower particulate air pollution and CO₂ emissions, and minimize waste production [44]. Europe is anticipated to dominate the worldwide market for tire retreading, closely followed by North America, from 2018 to 2028 [194]. According to the authors, retreading stands out as both an environmentally sustainable and an economically viable option, delivering superior quality at a reduced expense. This process has dual advantages, both economically and ecologically, for the community and the tire sector. **Table 4** shows a summary of the different impacts of ELT.

9 Future direction and prospects

The next phase of research on STSF-reinforced concretes should move beyond “proof of concept” sustainability narratives toward rigorously standardized, performance-assured systems that are designable, bankable, and scalable. The manufacturing process of tires involves sourcing various materials, for instance, carbon black, steel, and synthetic rubber. Tires are produced in a diverse range to cater to different customer needs and specific uses [3]. In 2019, the global tire industry was on track to produce approximately 19.25 million tons of tires, with a forecasted increase to 22.75 million tons by 2024 due to an annual growth rate of 3.4% [198]. In the same year, the tire industry's global expenditure was around 15 billion dollars, aligning with a 3.3% yearly increase in production [198]. Factors such as enhanced productivity and diversity in size and design drive the market's ability to offer a wide range of tires [126]. Technically, the distinctive morphology and surface chemistry of tire-derived wires often brass-coated, work-hardened, and accompanied by trace elastomer [1,50]. This makes the ITZ is not identical to that of industrial steel fibers; understanding and engineering this ITZ is central to unlocking reliable residual strengths, impact resistance, and fatigue endurance at practical dosages [17,18]. Progress will hinge on three linked advances: 1) precise control and certification of fibre geometry/strength distributions and cleanliness at industrial scale [92–96]; 2) mechanistic multiscale models that relate those distributions and surface states to pull-out, crack-bridging laws, and structural response [115,124]; and 3) performance-based life-cycle metrics that couple durability gains with cradle-to-gate credits in a transparent functional unit [72,191]. Parallel efforts should adapt STSF to emerging low-clinker binders, alkali-activated systems, and 3D-printed concretes, while addressing corrosion and alkali–silica/chemical exposures typical of transport and marine infrastructure [199]. In

addition, market confidence will depend on harmonized testing, environmental product declarations, and code-ready design methods that allow STSF mixes to compete on verified outcomes rather than prescriptive inputs [127,177,200].

The continuous rise in vehicle manufacturing has resulted in a significant accumulation of discarded tires, creating substantial environmental challenges and posing serious risks to public health. [201]. Inefficient recycling of these tires results in lost economic potential and excessive land consumption [43]. In addition, disposing of these tires often comes with extra costs [29]. It is important to enhance recycling standards, especially with the increasing need for concrete reinforcement in construction industries. Tires can provide a solution in this area [28]. Employing waste rubber as aggregate in concrete mitigates landfill usage and lessens ecological impact [200]. The construction industry can gain profitability improvements through this practice, as it involves recycling materials that might otherwise be discarded in landfills [48]. Using rubber from tires in construction not only promotes recycling but also offers a more sustainable option than other materials [58]. The tire recycling industry supports the circular economy, creating techno-economic advantages [43]. By forming a sustainable recycling chain, revenue can be generated from the sale of recycled materials and recycling services [139]. The development of new products and applications from recycled tire material opens up markets in construction, manufacturing, and renewable energy, fostering economic development [202]. In Saudi Arabia, managing waste is a critical issue, as waste is expected to be handled by more than 106 million tons of waste by 2035 due to rapid industrialization and urbanization [203]. The country's 2022 budget for municipal services was set at \$50 billion, mirroring its 2021 expenditure [127]. However, valuable future directions and prospects have been outlined to guide further investigation by researchers.

- Establish graded product standards for STSF (length/diameter/tensile distributions, contamination limits, brass residue) with third-party certification and traceability.
- Develop surface-conditioning routes (mechanical abrasion, acid pickling, plasma, silane/mineral coatings) tailored to remove elastomeric residues and optimize steel–cement chemistry.
- Quantify durability mechanisms under chlorides, sulphates, carbonational pH drop, freeze–thaw, fire, and combined fatigue–corrosion; establish accelerated protocols specific to STSF.
- Integrate STSF with low-carbon binders and alkali-activated concretes, map interactions between pore solution chemistry and fibre stability.
- Develop high-fidelity orientation/dispersion characterization (fresh-state rheology, X-ray CT, image-based stereology) and link to constitutive crack-bridging models.
- Tailor STSF mixes for shotcrete and 3D-printed concrete (pumpability/extrudability windows, early-age toughness, buildability) supported by process-aware testing.
- Formulate hybrid reinforcements (STSF and microsteel/synthetic fibres or crumb rubber) to co-optimize damping, abrasion resistance, and impact energy absorption.
- Advance performance-based structural design methods (residual flexural strength, and fracture energy, fatigue).
- Produce verified environmental product declarations and consequential LCAs with functional units tied to structural performance and service-life scenarios, not fibre mass alone.
- Demonstrate whole-life cost and carbon reduction in pilot corridors (heavy-duty pavements, tunnel linings, precast marine units) with instrumented long-term monitoring.
- Align policy and procurement, EPR for tires, recycled-content targets, green public procurement, to reward documented performance and verified environmental value.

10 Conclusion

This research presents a novel and commendable effort of great significance for promoting environmentally sustainable recycling practices by converting discarded tire wires into advanced STSFs, tailored for the utilization in eco-efficient concrete. It highlights the exceptional tensile strength of STSFs as a promising material for structural engineering, positioning them as a key component in the development of high-performance, environmentally responsible concrete. By exploring methods for integrating STSFs into concrete, the research evaluates both the mechanical strength, performance,

application and environmental sustainability of these fibers, marking an important step forward in sustainable construction practices. The investigation delved into the dual gains of STSFs, combining enhanced structural integrity with a reduced environmental footprint, thereby urging the construction industry to adopt more eco-friendly and practical techniques. This work not only assesses the practicality of using tire waste as reinforcing fibers but also proposes standards to enhance the structural performance of concrete. Furthermore, it outlines the need for further studies and the establishment of long-term protocols for STSF-enhanced concrete composites, ensuring their viability as a sustainable alternative.

This research resides at the intersection of technological advancement and environmental sustainability, addressing the critical issue of tire waste, which poses substantial risks to bionetworks and public health due to improper disposal and the potential for hazardous fires. Although global tire recycling efforts have intensified, driven by the rapid expansion of the automotive sector, challenges persist in ensuring safe disposal and efficient recycling processes. Grounded in the principles of a circular economy, the study emphasizes tire material recycling as a cornerstone for advancing sustainable development goals. Also, it advocates for increased energy recovery efforts and greater participation from the private sector to enhance waste management systems. The research also highlights the need for future investigations into standardized evaluation frameworks for emerging recycling technologies and a thorough analysis of reclaimed STSFs, particularly for applications in innovative construction methodologies. By presenting these forward-looking strategies, the study lays the groundwork for transforming tire waste management into an engine of sustainable growth, with far-reaching implications for both the environment and the construction industry. Based on this study, several key topics are recommended for further exploration by researchers in civil engineering and construction industries:

- To investigate the optimal mix proportions of STSF in concrete to maximize mechanical properties, durability, and sustainability for different structural applications within the Saudi construction industry.
- To conduct studies on the long-term performance of STSF-based concrete composites under Saudi Arabia’s extreme climate conditions, including high temperatures and exposure to saline or sulfate-rich environments, to assess durability and lifecycle values.
- To perform comprehensive LCAs and carbon footprint analyses to quantify the cost-effectiveness of using STSF in concrete, comparing it to traditional concrete materials and recycling processes.
- To examine the interface bonding characteristics between STSF and cementitious matrices to improve the mechanical interlock, improving the overall tensile strength, ductility, and toughness of STSF-based concrete composites.
- To explore the resistant fire and thermal insulation properties of STSF concrete to understand its behavior under fire exposure and high-temperature conditions, supporting safe and resilient structural design in the construction sector.
- To feasibility and Scalability Studies for Saudi Market: Analyze the economic and logistical feasibility of producing and incorporating STSF at scale, assessing potential challenges in sourcing, production, and application to provide guidelines for commercial adoption within Saudi Arabia’s construction industry.

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CRedit authorship contribution statement

Khaled Mahmoud Abdelaziz: Conceptualization, Investigation, Collection of data, Formal analysis, Supervision, Visualization, Writing – original draft, and review, editing & approving. **M. Amran:** Conceptualization, Investigation, Collection of data, Formal analysis, Supervision, Visualization, Writing – original draft, and review, editing & approving.

Conflicts of Interest

The authors declare that they have no conflicts of interest to report regarding the present study

Data Availability Statement

Data sharing is not applicable.

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