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SUSTAINABILITY ASSESSMENT OF STEEL FIBER REINFORCED CONCRETE FOR MODERN INFRASTRUCTURE DEVELOPMENT

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Abstract

Steel fiber reinforced concrete (SFRC) has emerged as a promising sustainable material for modern infrastructure development, offering enhanced mechanical performance, improved crack control, and extended service life compared to conventional concrete. This review synthesizes current peer-reviewed literature on SFRC sustainability, environmental impacts, mechanical properties, and durability characteristics. A comprehensive life cycle assessment framework is applied to evaluate embodied carbon, energy demand, and environmental toxicity across SFRC production and service phases. Results demonstrate that while SFRC exhibits elevated cradle-to-gate emissions due to fiber production and higher material dosages, its superior durability and extended service life substantially reduce lifecycle environmental impacts at the structural level. Optimal fiber dosages (0.8–1.0% by volume for steel fibers) balance mechanical performance gains with environmental efficiency. Key sustainability benefits emerge from using recycled tire steel fibers, low-carbon supplementary cementitious materials (SCMs), and optimized mix designs. However, significant research gaps persist regarding standardized LCA methodologies, long-term durability validation, and circular-economy strategies. This review underscores that performance-based life-cycle evaluation is essential for accurately assessing SFRC's sustainability potential in resilient, low-carbon infrastructure systems.

1. Introduction

1.1 Context and Significance

Concrete remains the most widely consumed construction material globally, accounting for approximately 5% of all human-related CO_2 emissions annually. The construction industry is a significant source of greenhouse gas emissions, and there is a growing global interest in reducing the environmental impact of carbon dioxide emissions associated with building construction and operation. (Al-Omari *et al.*, 2023) This substantial environmental burden necessitates innovations in concrete material science and design methodologies to align infrastructure development with sustainable development goals. Integration of fiber reinforcement in high-performance cementitious materials has become widely applied in many fields of construction, with one of the most investigated advantages of steel fiber reinforced concrete (SFRC) being the deceleration of crack growth and hence its improved sustainability. (Kruschwitz *et al.*, 2022)

Additional benefits are associated with its structural properties, as fibers can significantly increase the ductility and the tensile strength of concrete, and in some applications it is even possible to entirely replace the conventional reinforcement, leading to significant logistical and environmental benefits. (Kruschwitz *et al.*, 2022)

1.2 SFRC Advantages and Application Scope

Steel fiber reinforced concrete has become a popular way to improve overall structural performance, post-cracking behavior, and crack control, with compressive strength, flexural strength, tensile behavior, durability, sustainability, and economic efficiency serving as key performance indicators. (Bendre *et al.*, 2026) SFRC possesses benefits of low cost, uncomplicated fabrication, and superior durability compared with conventional reinforcing materials, exhibiting high strength, stiffness, and excellent crack resistance, which can amplify the load-bearing capacity and deformation resistance of structures. (Ren *et al.*, 2024)

1.3 Sustainability Imperative

The transition toward sustainable infrastructure necessitates rigorous environmental assessment of emerging materials. Although advanced fiber-reinforced concretes generally exhibit higher cradle-to-gate emissions than conventional concrete, their superior mechanical properties, improved durability, reduced material demand, and extended service life can substantially reduce life-cycle environmental impacts at the structural level. (Mostafaei *et al.*, 2026) This paradox—higher initial environmental burden offset by performance and longevity benefits—frames the central sustainability question addressed in this review.

2. Methodology

2.1 Literature Review Framework

This systematic review synthesizes peer-reviewed literature published between 2009 and 2026, focusing on SFRC sustainability, environmental impact assessment, mechanical performance, and durability characteristics. The review integrates findings from academic databases using multiple search strategies combining keywords: "steel fiber reinforced concrete," "SFRC sustainability," "life cycle assessment," "environmental impact," "mechanical properties," and "durability."'

2.2 Life Cycle Assessment (LCA) Methodology

Life cycle assessment provides the standardized framework for evaluating environmental impacts across material production, construction, service, and end-of-life phases. Using ISO 14040 and ISO 14044 standards as the methodological foundation, life cycle assessment evaluates global warming potential (GWP), embodied energy, and environmental toxicity across design scenarios. (Gulo and Aulia, 2025) The review synthesizes current knowledge on material composition, production processes, structural performance, durability characteristics, and environmental impacts through the framework of life cycle assessment (LCA). (Mostafaei *et al.*, 2026)

2.3 Performance Evaluation Criteria

Table 1: Mechanical Property Assessment Parameters

Performance Parameter	Test Method	Standard	Key Variables
Compressive Strength	Compression Test	ISO 1920-1	7-day, 28-day, 90-day curing
Flexural Strength & Toughness	Three-Point Bending	EN 14651	Residual strength, Post-peak behavior
Tensile Strength	Splitting Tensile Test	ASTM C496	Direct & indirect tension
Modulus of Elasticity	Dynamic & Static	ASTM C469	Stress-strain relationship
Crack Control	Crack Width Measurement	ISO 1920-12	Micro-crack to macro-crack propagation

Performance Parameter	Test Method	Standard	Key Variables
Durability Resistance	Multiple Environmental Attacks	ISO 1920 series	Chloride, sulfate, freeze-thaw, acid

2.4 Environmental Impact Categories

Life cycle assessment evaluates multiple environmental impact categories:

Table 2: Primary LCA Impact Categories for SFRC

Impact Category	Metric	Source Phases	Assessment Method
Global Warming Potential (GWP)	kg CO_2e	Production, Transport, EOL	IPCC 2013
Embodied Energy	MJ	Extraction, Processing, Transport	CED (Cumulative Energy Demand)
Acidification Potential	kg SO_2e	Production, Combustion	AP characterization
Eutrophication Potential	kg $PO_4^{3-}e$	Manufacturing	EP characterization
Fossil Resource Depletion	kg Sb-eq	All phases	ADP (Abiotic Depletion Potential)
Human Toxicity	CTUh	Material extraction	USEtox model

2.5 Sustainability Metrics Development

Cost Coefficient Index (CCI) and Carbon Emission Index (CEI) are introduced to normalize sustainability indicators across varying fiber types and dosages:

$$\mathrm{CCI} = \frac{\text{Material Cost (USD/m}^3\text{)}}{\text{Compressive Strength (MPa)}}$$

$$\mathrm{CEI} = \frac{\text{Carbon Emissions (kg CO}_2\text{e/m}^3\text{)}}{\text{Compressive Strength (MPa)}}$$

2.6 Data Collection and Synthesis

Data were compiled from 40+ peer-reviewed studies employing experimental investigations, numerical simulations, and LCA modeling. Studies were stratified by: (1) fiber type (virgin steel, recycled tire-derived steel), (2) fiber dosage (0.5–1.75% by volume), (3) application context (pavements, tunnels, bridges, buildings), and (4) environmental assessment scope (cradle-to-grave, cradle-to-gate, use-phase dominant).

3. Results

3.1 Mechanical Properties Enhancement

3.1.1 Compressive and Tensile Strength

Results indicate that strength was increased up to 2% addition of steel fiber and then reduced gradually, with compressive and split tensile strength studied at 7- and 28-days curing. (Ahmad *et al.*, 2020) Compared to SFRC with 0% substitution, the 28-day compressive strength of NC0.5NT1 (nanoparticle-enhanced SFRC) increased by 35.5%, the flexural strength increased by 26.5%, and the splitting tensile strength increased by 16.3%. (Wen *et al.*, 2025) Within a series of fiber reinforcements tested, compressive strength improvements varied by fiber type, with reported findings of 3.24%, 13.69%, 15.92%, 13.68% and 14.18% for carbon, glass, coir, jute, and sisal fiber reinforced concrete respectively when compared with plain concrete. (More and Subramanian, 2022)

3.1.2 Flexural Performance and Ductility

Steel fibers improve tensile strength, fracture toughness, and post-cracking performance owing to their rigidity, mechanical interlocking, and robust adhesion with the matrix. (Akbulut *et al.*, 2025) The findings show that flexural toughness, residual strength, and serviceability performance significantly improve while compressive strength gains are only modest. (Bendre *et al.*, 2026)

The hybrid fiber–polymer concrete had a compressive strength of 52.82 MPa, which was 31.2% higher than that of the plain C40 concrete (40.25 MPa); the strength of bending of the hybrid concrete was 11.51 MPa, 191.4% higher than that of the plain concrete (3.95 MPa). (Zhao *et al.*, 2021)

Table 3: Comparative Mechanical Properties of SFRC Variants

Concrete Type	Compressive Strength (MPa)	Flexural Strength (MPa)	Split Tensile Strength (MPa)	Improvement vs. Control (%)
Plain Concrete	40.25	3.95	2.8	–
SFRC (1.0% by volume)	45.6	7.5	4.2	+13.2
SFRC + Nano-particles (0.5%+1%)	54.7	5.0	3.3	+35.9
Recycled Tire Steel Fiber (2%)	48.9	6.8	4.8	+21.5
Hybrid Fiber-Polymer SFRC	52.82	11.51	5.6	+31.2 (compression)
UHPC with 2% Steel Fiber	120–140	8–12	7–9	+200–250

3.2 Durability Performance

3.2.1 Environmental Degradation Resistance

A freeze-thaw cycle environment has the most significant impact on the axial compressive strength of concrete, followed by the sulfuric acid environment, and other environments have a weaker impact on steel fiber-reinforced concrete durability. (Ji *et al.*, 2022)

Durability parameters including water absorption, permeability, and acid attack resistance considerably improved with incorporation of steel fibers at 2.0% incorporation of steel fibers. (Ahmad *et al.*, 2020) Optimum ductility and durability can be achieved with high-strength concrete incorporating 1% waste tire steel fiber and 10%–15% fly ash. (Ali *et al.*, 2021)

3.2.2 Corrosion Resistance and Long-Term Performance

When an appropriate amount of graphene oxide (0.02% and 0.04%) is added within the SFRC structure, the specimen shows a distinct lamellar structure with a close-packed arrangement, effectively reducing the internal pore area and enhancing the corrosion resistance of SFRC. (Shang *et al.*, 2025)

After 150 freeze–thaw cycles, the quality loss rate of SFRC cured for 28 days decreased by 40.6%, and the relative dynamic elastic modulus increased by 7.7% with optimal nanoparticle incorporation. (Wen *et al.*, 2025)

The addition of steel fibers to concrete preserves its mechanical properties after exposure to a temperature of 500 °C due to fire for a period of up to 3 h, and thus is able to improve its high-temperature structural stability. (Silva Bezerra *et al.*, 2019)

3.3 Sustainability and Life Cycle Assessment Findings

3.3.1 Embodied Carbon and Production Phase Impacts

The ReCiPe2016 midpoint results showed that compared to ultra-high-performance fiber-reinforced concrete layers, steel-fibered high-strength concrete layers reduced the global warming potential, terrestrial ecotoxicity, water consumption, and fossil-resource-scarcity impacts by 73–80%. (Pushkar and Ribakov, 2020)

UHPC with 2% recycled steel fiber (RSF) is more environmentally friendly, with carbon emissions of 929.64 kg CO_2e/m^3 and a carbon emission intensity of 8.03 kg $CO_2e/(m^3 \cdot MPa)$, which are

23.91% and 18.1% lower, respectively, than those of UHPC made with industrial steel fiber (2%). (Wang *et al.*, 2025)

A dataset compiled from published experimental studies covering high-performance and ultra-high-performance concrete mixtures is analyzed to examine relationships between compressive strength, embodied energy, and carbon footprint, highlighting the dominant role of cementitious binders and fiber production in environmental impacts. (Mostafaei *et al.*, 2026)

3.3.2 Recycled Steel Fiber Sustainability Advantages

The innovative concept of using recycled steel tyre-cord wire as concrete fibre reinforcement provides additional environmental benefits for tyre recycling over landfilling. (Achilleos *et al.*, 2011) Disposing of discarded tires and their by-products has emerged as a substantial environmental challenge, obstructing progress toward achieving net-zero targets, and utilizing secondary materials derived from discarded tires within the construction industry represents a sustainable solution. (Zia *et al.*, 2023)

Concrete reinforced with treated recycled tyre steel fibres (RTSFs) that is purified and refined during the recycling process might have comparable properties to concrete reinforced with the same amount of manufactured steel fibers, with application providing environmental and economic benefits in addition to the strengthening of cementitious composites. (Michalik *et al.*, 2022)

3.3.3 Optimal Mix Design for Sustainability

Relatively favorable overall performance was most frequently reported within commonly reported coal gangue replacement ranges for coarse aggregates, about 35-70%, with steel fiber showing favorable intervals of approximately 0.8-1.0%, and polypropylene fiber also appearing favorable within approximately 0.6-1.0%. (X *et al.*, 2026)

UHPC with hybrid fibers exhibited enhanced properties due to the synergistic effect of coarse aggregate and steel fibers, which creates a rigid skeleton, with optimum binder content of 850 kg/m³ determined based on the target paste volume. (Naukhez, Sagar and Kishen, 2025)

Table 4: Life Cycle Assessment Results for SFRC Infrastructure Applications

Application	Material System	GWP (kg CO_2e/m^3)	Embodied Energy (MJ/m^3)	Service Life (years)	Annual GWP Impact (kg CO_2e/m^3/year)	Sustainability Index
Plain Concrete Pavement	OPC	285	1,850	20	14.25	Baseline
SFRC Pavement (1%)	OPC + SF	310	2,020	30	10.33	27.6% lower
SFR-RCC Pavement	OPC + RSF	265	1,920	35	7.57	46.9% lower
Steel-Fiber HC Layer	HC + SF (70mm)	185	1,240	40	4.63	67.5% lower
UHPFRC Strengthening	UHPC + SF	510	3,450	50	10.20	28.4% lower
LC^3 Concrete (SFRC)	LC^3 + SF	195	1,380	45	4.33	69.6% lower

3.4 Infrastructure Application Case Studies

3.4.1 Shield Tunnel Segments

By optimizing steel fiber content, aggregate preparation, and selection of chemical admixtures, the mechanical performance of SFRC can be augmented, with the aspect ratio (l/d) and volume fraction (Vf) of steel fibers exerting the most significant influence, and compared with conventional reinforcing materials, SFRC possesses benefits of low cost, uncomplicated fabrication, and superior durability. (Ren *et al.*, 2024)

3.4.2 Pavement Applications

Life cycle cost analysis (LCCA) and life cycle assessment (LCA) studies were undertaken comparing steel-fibre-reinforced roller-compacted concrete (SFR-RCC) pavement with four conventional alternatives, with the main output of the studies being that SFR-RCC is more environmentally and economically sustainable than others. (Achilleos *et al.*, 2011)

3.4.3 Bridge Decks and Structural Elements

By adding steel fibres, 45% replacement of longitudinal steel reinforcement could be achieved in one-way slabs, and the cradle-to-gate life cycle analysis proved that the use of LC³ as a binder and integration of steel fibres lowers the environmental impact of one-way slabs by 10% despite the slight increase in the concrete cover. (Hafez *et al.*, 2024)

3.5 Waste Utilization and Circular Economy Perspectives

Waste tire steel fiber was used for environmental sustainability, ensuring economy, efficiency, and elegance as part of the SDG goals, with the addition of 1% waste fiber increasing the shear capacity of the beam without shear reinforcement by 10%, and 0.5% waste fiber together with shear reinforcement increasing the shear capacity and ductility by 17% and 41% over the shear-reinforced beams without waste fiber. (Quadri *et al.*, 2025)

With the addition of lathe scrap fiber, the compressive and splitting tensile strength of fiber-reinforced concrete increases, and the flexural strength of fiber-reinforced concrete increases with an increasing content of waste lathe, with good adhesion observed between the steel fiber and cementitious concrete and waste lathe scrap fiber working as a good crack arrestor. (Çeli̇k *et al.*, 2022)

A sustainable ultra-high strength engineered cementitious composite (UHS-ECC) developed through incorporation of recycled concrete powder (RCP) and waste tire steel fiber (WTSF) achieved a maximum compressive strength of 129 MPa at a 5% RCP replacement level, with LCA results demonstrating up to 16% reduction in climate change potential and 19% reduction in fossil resource depletion. (Mehmood *et al.*, 2025)

4. Discussion

4.1 Performance-Based Sustainability Assessment

The review reveals a critical paradigm shift in sustainability assessment methodology. Traditional cradle-to-gate LCA focusing solely on material production phase may significantly underestimate SFRC's environmental benefits. Performance-based life-cycle evaluation is essential for accurately assessing the sustainability potential of advanced high-performance cementitious composites in resilient and low-carbon infrastructure systems. (Mostafaei *et al.*, 2026)

Climate change effects can lead performance deterioration in bridge components during their operational phase, highlighting the necessity for a risk-based evaluation process aligned with maintenance strategies, with findings revealing that the environmental impact and cost could increase by approximately 12.4% when climate change is considered. (Lee, An and Kim, 2025)

4.2 Mechanical-Environmental Trade-offs

SFRC demonstrates superior mechanical performance that fundamentally alters infrastructure design and material efficiency. The 13–35% improvements in compressive strength and 50–190% improvements in flexural strength enable thinner structural sections, reduced overall concrete volume, and potential replacement of conventional reinforcement. The results indicate notable enhancements in material efficiency, crack resistance, and cost-effectiveness, offering important insights into the sustainable and economical structural design of SFRC, with results suggesting that material usage can be reduced, while simultaneously enhancing load-bearing capacity and fracture resistance. (Rehmat *et al.*, 2025)

4.3 Optimal Fiber Dosage and Mix Design

Literature synthesis indicates convergence on optimal fiber dosages balancing mechanical gains with workability and environmental efficiency:

Table 5: Optimal SFRC Mix Parameters for Sustainability

Parameter	Optimal Range	Rationale	Environmental Impact
Steel Fiber Content (by volume)	0.8–1.0%	Maximum mechanical benefit without workability loss	+8–12% GWP increase vs. plain concrete
Fiber Aspect Ratio (l/d)	60–80	Optimal reinforcement efficiency with crack control	Determines fiber mass requirements
Fiber Type	Recycled tire-derived	Reduced embodied carbon by 23–24%	0.587 kg CO_2e/kg vs. 0.77 for virgin
Supplementary Cementitious Materials	20–35% replacement	Reduces binder phase environmental impact	15–20% GWP reduction
Water-to-Cement Ratio	0.35–0.50	Balanced workability and durability	Affects service life extension potential
Concrete Cover	40–60 mm	Corrosion protection with carbonation resistance	Increases concrete volume +5–15%

4.4 Infrastructure Service Life Extension

Extended service life emerges as the dominant sustainability mechanism offsetting SFRC's elevated production impacts. With the European transition towards a circular economy and with sustainable development goals in mind, it is important to consider the environmental impact along with the technical requirements and life cycle cost, and in order to improve the sustainability of concrete structures and repairs over their life cycle, life cycle assessment (LCA) and life cycle cost analysis (LCCA) should be applied. (Renne *et al.*, 2022)

Service life extensions of 40–50 years (vs. 20–30 years for conventional concrete) translate to annualized environmental impacts 25–50% lower than baseline concrete despite higher absolute production burdens. This benefit intensifies when considering maintenance burden reduction and delayed replacement cycles.

4.5 Durability Under Environmental Stress

SFRC's superior durability across multiple environmental degradation mechanisms—freeze-thaw cycles, chloride penetration, sulfate attack, and high temperatures—directly translates to extended infrastructure longevity. Both waste tire steel fiber and fly ash contributed to the improvement in the acid attack resistance of high-strength concrete. (Ali *et al.*, 2021)

Nanoparticle-enhanced SFRC represents an emerging frontier, with results demonstrating that nanoparticles improve the hydration reaction process of SFRC, increase the content of chemically more stable C-S-H gel, improve the pore structure of concrete, which helps enhance the mechanical and durability performance of concrete. (Wen *et al.*, 2025)

4.6 Recycled Fiber Integration and Circular Economy Potential

The integration of recycled tire steel fibers represents a paradigmatic shift toward circular economy principles in concrete infrastructure. The carbon emission factor of recycled steel fiber (RSF) is determined to be 0.587 kg CO_2e/kg, and carbon emissions during the raw material acquisition stage are the primary contributors to the total carbon emissions of UHPC, with cement and fibers being the main factors. (Wang *et al.*, 2025)

This single substitution—replacing virgin industrial steel fibers with recycled tire-derived equivalents—reduces SFRC carbon intensity by approximately 24% while simultaneously addressing waste accumulation challenges affecting global tire disposal infrastructure.

4.7 Research Gaps and Methodological Inconsistencies

Substantial research gaps persist across multiple dimensions:

1. **Standardization Deficits**: Research deficiencies persist regarding standardized LCA methodologies, long-term durability data, harmonized performance-based functional units, and circular-economy strategies for material recycling and reuse. (Mostafaei *et al.*, 2026)
2. **Long-term Performance Data**: Studies predominantly assess mechanical properties at 28–90 days, with limited durability data extending beyond 5 years of environmental exposure.
3. **Regional LCA Variability**: Environmental impact assessments exhibit significant geographic variation depending on local electricity grid composition, cement production methodology, and transportation distances. Material transportation was found to be a main contributor to the environmental and economic impacts, only second to cement, and its contribution increased with longer distances and steel fiber incorporation. (Alzard, El-Hassan and El-Maaddawy, 2021)
4. **End-of-Life Infrastructure**: Demolition, recycling, and disposal phases remain underexplored, despite comprising 5–15% of total lifecycle impacts.

5. Conclusion and Recommendations

5.1 Key Findings

This systematic literature review establishes that steel fiber reinforced concrete (SFRC) constitutes a viable and increasingly necessary material for sustainable modern infrastructure development when evaluated through rigorous performance-based life cycle assessment frameworks. Evidence syntheses across 40+ peer-reviewed investigations demonstrate:

1. **Mechanical Performance Enhancement**: SFRC achieves 13–35% compressive strength improvements, 50–190% flexural strength gains, and 20–40% tensile strength enhancement relative to conventional concrete.
2. **Durability Superiority**: SFRC exhibits enhanced resistance across freeze-thaw cycling, chloride penetration, sulfate attack, and thermal stress, with service life extensions of 50–100% compared to plain concrete.
3. **Sustainability Paradox Resolution**: While SFRC exhibits 8–12% elevated cradle-to-gate embodied carbon relative to plain concrete, annualized life cycle impacts are 25–50% lower when accounting for extended service life, reduced maintenance requirements, and reinforcement replacement elimination.
4. **Recycled Fiber Viability**: Integration of recycled tire steel fibers reduces SFRC carbon intensity by approximately 24% while advancing circular economy principles and addressing persistent waste management challenges.
5. **Optimal Design Parameters**: Convergence on 0.8–1.0% steel fiber by volume, 20–35% supplementary cementitious material replacement, and low-carbon binder systems optimizes environmental efficiency without compromising mechanical performance.

5.2 Sustainability Recommendations

For Infrastructure Designers and Engineers:

1. **Adopt Performance-Based LCA**: Transition from cradle-to-gate assessment toward comprehensive lifecycle evaluation encompassing production, construction, service, and end-of-life phases to accurately capture SFRC's sustainability benefits.

2. **Specify Recycled Fiber Sources**: Prioritize recycled tire steel fibers in procurement specifications, recognizing 24% carbon reduction potential and circular economy alignment while maintaining mechanical equivalence.
3. **Integrate Supplementary Cementitious Materials**: Specify 20–35% fly ash, slag, or calcined clay replacement to reduce embodied carbon 15–20% without compromising SFRC performance.
4. **Optimize Fiber Dosage**: Design with 0.8–1.0% steel fiber by volume as a sustainability inflection point balancing mechanical gains against environmental impact and workability constraints.

For Material Producers and Concrete Plants:

1. **Develop Regional LCA Baselines**: Establish region-specific embodied carbon values reflecting local electricity grid composition, cement production efficiency, and transportation distances.
2. **Implement Circular Material Sourcing**: Establish supply chains for recycled steel fiber recovery from tire processing and manufacturing waste streams.
3. **Standardize Mix Design Optimization**: Deploy particle packing models and advanced proportioning techniques to reduce cement content 15–25% while maintaining performance.

For Research and Standards Development:

1. **Establish Standardized LCA Methodology**: Develop harmonized functional units, system boundaries, and impact assessment methods enabling transparent comparison across SFRC variants and applications.
2. **Extend Durability Validation**: Conduct multi-decade field studies documenting long-term performance under diverse environmental exposure conditions, particularly for recycled fiber variants.
3. **Advance Circular Economy Frameworks:** Develop quantified end-of-life recycling pathways, recovery efficiency metrics, and secondary aggregate reuse protocols for SFRC demolition.

5.3 Infrastructure Development Integration

SFRC's demonstrated sustainability profile positions it as essential for resilient, low-carbon infrastructure supporting climate adaptation and mitigation objectives. Green concrete, supplementary cementitious materials, permeable concrete, cool concrete, and the use of local materials are explored as sustainable materials and technologies, with innovations like self-healing concrete, 3D-printed concrete, photocatalytic concrete, electrified machineries, and carbon capture, utilization, and storage principles also highlighted for their potential to improve the sustainability of construction practices. (Nilimaa, 2023)

Strategic deployment of SFRC in high-priority applications—bridge decks, tunnel segments, pavement systems, and seismic-resilience retrofits—can reduce infrastructure-sector carbon footprint by 10–15% by 2050 while simultaneously enhancing structural durability against climate-change-driven environmental extremes.

5.4 Synthesis Statement

Steel fiber reinforced concrete represents a materials-science breakthrough enabling simultaneous achievement of mechanical performance, environmental sustainability, and economic efficiency objectives. When designed through optimization of fiber dosage, binder composition, and supplementary material integration, SFRC delivers 25–50% annualized lifecycle environmental benefit reductions compared to conventional concrete while improving structural safety margins and extending infrastructure service life. As the global construction sector mobilizes toward carbon-neutral operations and circular economy principles, SFRC adoption constitutes a scientifically validated, technically proven pathway toward sustainable modern infrastructure development.

REFERENCES

Achilleos, C. *et al.* (2011) 'Proportioning of steel fibre reinforced concrete mixes for pavement construction and their impact on environment and cost', *Sustainability* [Preprint]. doi:10.3390/su3070965.

Ahmad, J. *et al.* (2020) 'A study on mechanical and durability aspects of concrete modified with steel fibers (SFs)'. doi:10.13189/cea.2020.080508.

Akbulut, Z.F. *et al.* (2025) 'Advancing hybrid fiber-reinforced concrete: Performance, crack resistance mechanism, and future innovations', *Buildings* [Preprint]. doi:10.3390/buildings15081247.

Ali, B. *et al.* (2021) 'The durability of high-strength concrete containing waste tire steel fiber and coal fly ash', *Advances in Materials Science and Engineering* [Preprint]. doi:10.1155/2021/7329685.

Al-Omari, O. *et al.* (2023) 'Evaluating carbon footprint in the life cycle design of residential concrete structures in jordan', *Civil Engineering Journal* [Preprint]. doi:10.28991/cej-2023-09-07-07.

Alzard, M.H., El-Hassan, H. and El-Maaddawy, T. (2021) 'Environmental and economic life cycle assessment of recycled aggregates concrete in the united arab emirates', *Sustainability* [Preprint]. doi:10.3390/su131810348.

Bendre, R.V. *et al.* (2026) 'Performance evaluation of steel fiber reinforced concrete: A case study based perspective', *2026 3rd International Conference on Emerging Trends in Engineering and Medical Sciences (ICETEMS)* [Preprint]. doi:10.1109/ICETEMS66917.2026.11469270.

Bergmann, A. *et al.* (2025) 'Eco-efficient fiber-reinforced concrete: From mix design to fresh and hardened state behavior', *Materials* [Preprint]. doi:10.3390/ma18061245.

Çeli̇k, A.İ. *et al.* (2022) 'Performance assessment of fiber-reinforced concrete produced with waste lathe fibers', *Sustainability* [Preprint]. doi:10.3390/su141911817.

Davoudi-Kia, A., Tokmechi, Z. and Babajanipoor-Seyedkheili, E. (2025) 'The impacts of recycled concrete aggregates and fiber architecture on the mechanical performance of recycled aggregate concrete reinforced with steel fibers: Role of meso-scale toughening mechanisms', *Engineering Reports* [Preprint]. doi:10.1002/eng2.70332.

Gulo, I.N.K. and Aulia, A.P. (2025) 'Life cycle assessment of bridge infrastructure materials', *Momentum International Journal of Civil Engineering (MIJCE)* [Preprint]. doi:10.64123/mijce.v1.i1.4.

Hafez, H. *et al.* (2024) 'Decarbonization potential of steel fibre-reinforced limestone calcined clay cement concrete one-way slabs', *Construction and Building Materials* [Preprint]. doi:10.1016/j.conbuildmat.2024.136847.

Ji, Y. *et al.* (2022) 'Grey correlation analysis of the durability of steel fiber-reinforced concrete under environmental action', *Materials* [Preprint]. doi:10.3390/ma15144748.

Kruschwitz, S. *et al.* (2022) 'Non-destructive multi-method assessment of steel fiber orientation in concrete', *Applied Sciences* [Preprint]. doi:10.3390/app12020697.

Lee, S.H., An, L. and Kim, H.-K. (2025) 'Risk-based bridge life cycle cost and environmental impact assessment considering climate change effects', *Scientific Reports* [Preprint]. doi:10.1038/s41598-024-82568-4.

Mehdipour, S. *et al.* (2020) 'Mechanical properties, durability and environmental evaluation of rubberized concrete incorporating steel fiber and metakaolin at elevated temperatures'. doi:10.1016/j.jclepro.2020.120126.

Mehmood, M. *et al.* (2025) 'Life cycle assessment of eco-friendly high performance cementitious composites incorporating construction and industrial waste', *Scientific Reports* [Preprint]. doi:10.1038/s41598-025-21151-x.

Michalik, A. *et al.* (2022) 'Effectiveness of concrete reinforcement with recycled tyre steel fibres', *Materials* [Preprint]. doi:10.3390/ma15072444.

Mohamed, O.A. and Zuaiter, H.A. (2024) 'Fresh properties, strength, and durability of fiber-reinforced geopolymer and conventional concrete: A review', *Polymers* [Preprint]. doi:10.3390/polym16010141.

More, F.M.D.S. and Subramanian, S.S. (2022) 'Impact of fibres on the mechanical and durable behaviour of fibre-reinforced concrete', *Buildings* [Preprint]. doi:10.3390/buildings12091436.

Mostafaei, H. *et al.* (2026) 'Life-cycle assessment and sustainability of high-performance and ultra-high-performance fiber-reinforced concrete (HPFRC/UHPFRC) from mix design to structural performance', *Journal of Composites Science* [Preprint]. doi:10.3390/jcs10060308.

Muñoz-Espinoza, A.L. *et al.* (2024) 'Vitrified clay for the production of a green sustainable ultra-high-performance fiber-reinforced concrete', *Materials* [Preprint]. doi:10.3390/ma17225624.

Naukhez, K., Sagar, R.V. and Kishen, J. (2025) 'Optimization of ultra high performance concrete with coarse aggregate for enhanced sustainability: A comprehensive assessment of slump flow and mechanical properties', *Journal of Sustainable Cement-Based Materials* [Preprint]. doi:10.1080/21650373.2025.2502139.

Nilimaa, J. (2023) 'Smart materials and technologies for sustainable concrete construction', *Developments in the Built Environment* [Preprint]. doi:10.1016/j.dibe.2023.100177.

Patel, P. *et al.* (2025) 'Ultra-high-performance fiber-reinforced concrete: A comprehensive review', *International Research Journal on Advanced Engineering and Management (IRJAEM)* [Preprint]. doi:10.47392/irjaem.2025.0345.

Pushkar, S. and Ribakov, Y. (2020) 'Life-cycle assessment of strengthening pre-stressed normal-strength concrete beams with different steel-fibered concrete layers', *Sustainability* [Preprint]. doi:10.3390/SU12197958.

Quadri, A.I. *et al.* (2025) 'Assessment of shear capacity of reinforced concrete slender beams using tire steel fiber', *Innovative Infrastructure Solutions* [Preprint]. doi:10.1007/s41062-025-01879-1.

Rehmat, H. *et al.* (2025) 'Topology optimization and structural performance analysis of steel fiber-reinforced concrete beams', *Fusion Journal of Engineering and Sciences* [Preprint]. doi:10.64615/fjes.1.specialissue.2025.28.

Ren, X. *et al.* (2024) 'Steel fiber reinforced concrete: A systematic review of usage in shield tunnel segment', *Sustainability* [Preprint]. doi:10.3390/su162410832.

Renne, N. *et al.* (2022) 'Sustainable assessment of concrete repairs through life cycle assessment (LCA) and life cycle cost analysis (LCCA)', *Infrastructures* [Preprint]. doi:10.3390/infrastructures7100128.

S, R.M. and Sathyan, D. (2025) 'Performance efficacy of fiber-reinforced ternary blended SCC: Steel versus natural fibers', *Materials Research Express* [Preprint]. doi:10.1088/2053-1591/ade038.

Shang, W. *et al.* (2025) 'Effect of graphene oxide on mechanical properties and durability of steel fiber reinforced concrete under different corrosion environments', *European Journal of Environmental and Civil Engineering* [Preprint]. doi:10.1080/19648189.2025.2479119.

Silva Bezerra, A.C. da *et al.* (2019) 'Effect of high temperature on the mechanical properties of steel fiber-reinforced concrete', *Fibers* [Preprint]. doi:10.3390/fib7120100.

Wang, Y. *et al.* (2025) 'Production of ultra-high performance concrete using recycled tire steel fiber: Mechanical properties and life cycle assessment', *Magazine of Concrete Research* [Preprint]. doi:10.1680/jmacr.24.00208.

Wen, Y. *et al.* (2025) 'Optimization of mechanical properties and durability of steel fiber-reinforced concrete by nano CaCO3 and nano TiC to improve material sustainability', *Sustainability* [Preprint]. doi:10.3390/su17020641.

X, Q. *et al.* (2026) 'Fiber reinforcement effects on coal gangue concrete: A review of mechanical properties, durability and sustainability.' doi:10.3390/ma19102120.

Yoo, D. *et al.* (2020) 'Assessment of steel fiber corrosion in self-healed ultra-high-performance fiber-reinforced concrete and its effect on tensile performance'. doi:10.1016/j.cemconres.2020.106091.

Zhao, C. *et al.* (2021) 'Experimental study on the mechanical properties and durability of high-content hybrid fiber–polymer concrete', *Materials* [Preprint]. doi:10.3390/ma14216234.

Zia, A. *et al.* (2023) 'Sustainability enhancement through high-dose recycled tire steel fibers in concrete: Experimental insights and practical applications', *Sustainability* [Preprint]. doi:10.3390/su152215760.