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DURABILITY CHARACTERISTICS OF STEEL FIBER REINFORCED CONCRETE UNDER AGGRESSIVE ENVIRONMENTAL CONDITIONS: A COMPREHENSIVE REVIEW

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Abstract
Steel fiber reinforced concrete (SFRC) has emerged as a promising composite material for enhancing structural performance in aggressive environmental conditions. This review synthesizes current knowledge on the durability characteristics of SFRC exposed to chloride, sulfate, acid, and freeze-thaw attack. Comprehensive analysis of laboratory testing methodologies reveals that SFRC exhibits superior durability performance compared to plain concrete through enhanced chloride resistance, improved freeze-thaw cycling durability, and better performance under combined environmental exposures. The review identifies critical factors influencing durability including fiber dosage, fiber type, concrete matrix properties, supplementary cementitious materials, and environmental parameters. Results from 42 peer-reviewed studies demonstrate that well-designed SFRC can extend service life by up to seven-fold in marine environments. However, synergistic interactions between multiple aggressive mechanisms remain insufficiently characterized, particularly regarding coupled sulfate-freeze-thaw and chloride-sulfate attack. Strategic recommendations for advancing SFRC durability design include optimization of nano-reinforcement integration, development of predictive service life models, and enhanced understanding of fiber-matrix interface behavior under combined environmental stresses. This review establishes the foundation for evidence-based design practices and identifies critical research gaps in sustainable SFRC development for infrastructure applications in extreme environments.

1. Introduction

Steel fiber reinforced concrete is exposed to environmental influences such as acid attack, with strength and corrosion resistance dependent on fiber type, dosage, and concrete matrix properties (Kroviakov, Kryzhanovskyi and Hedulian, 2025). Concrete infrastructure in coastal regions, saline soils, and cold climates faces accelerated deterioration from multiple aggressive mechanisms operating simultaneously. The synergistic interaction between freeze-thaw cycles and sulfate attack induces more severe and complex deterioration mechanisms than either factor in isolation (Wu *et al.*, 2025), creating

unprecedented durability challenges for conventional reinforced concrete structures.

Steel fiber reinforced concrete (SFRC) represents an innovative approach to enhance durability through multiscale reinforcement mechanisms. Unlike conventional rebar reinforcement that localizes stress concentration at discrete locations, dispersed steel fibers distribute reinforcement throughout the matrix, providing crack control at multiple scales. The chloride transport properties of steel fiber reinforced concrete coupled with bending load were investigated through bulk diffusion tests, establishing that SFRC had better chloride resistance than plain concrete, especially when specimens were under bending load, with chloride diffusion coefficient of SFRC under tension 30-38% lower than plain concrete (Wang *et al.*, 2017).

The mechanisms by which SFRC enhances durability remain subjects of active investigation. Steel fibers enhance shear strength of self-compacting concrete in different environmental conditions including air, sulfate attack, and acid exposure, with results showing that fiber-reinforced concrete with 0.2% steel fiber demonstrated good durability effects, achieving compressive strength of 52.6 MPa in air, 46.37 MPa in sulfate, and 34.4 MPa in acid conditions (Awrahman *et al.*, 2023). The durability performance varies significantly depending on environmental exposure type, exposure duration, and material composition.

Table 1: Overview of Aggressive Environmental Conditions and SFRC Performance Mechanisms

Environmental Exposure	Primary Mechanism	Typical Duration	SFRC Performance Enhancement	Reference
Chloride ingress (marine)	Ion diffusion; pore network transport	6-24 months	30-40% reduction in diffusion coefficient	Indices 19-1, 18-1
Freeze-thaw cycles	Physical crystallization; expansion	100-300 cycles	38-48% higher strength retention	Indices 27-1, 30-1
Sulfate attack	Chemical reaction; ettringite formation	90-180 days	20-25% better mass retention	Indices 7-1, 16-1
Acid attack	Chemical dissolution; pH reduction	180-365 days	15-20% improved strength retention	Indices 1-1, 7-1
Combined salt-freeze-thaw	Coupled crystallization and expansion	150-200 cycles	29.6-82% differential improvement	Indices 29-1, 37-1

Marine environments represent particularly severe durability challenges due to combined chloride, freeze-thaw, and sulfate attack mechanisms. Slag waste incorporated as cement replacement in steel fiber reinforced concrete showed that GGBS incorporation leads to improved durability attributes as indicated by reduced penetration depth and lower migration coefficient of chloride ions, with probabilistic service life assessment showing that GGBS addition led to significantly higher service life—more than seven times—as set by the criterion of chloride ion penetration up to 50 mm (Kim *et al.*, 2021). This dramatic service life extension illustrates the potential of strategic material design to extend SFRC durability.

The complexity of environmental degradation in aggressive conditions demands comprehensive understanding of multiple interacting mechanisms. The durability and serviceability of steel-fiber-reinforced concrete tunnel linings in cold regions are significantly challenged by repeated freeze-thaw actions, making accurate prediction of frost resistance critical, and

machine learning models have been developed with R^2 of 0.91 for predicting freeze-thaw resistance based on mixture design parameters, fiber properties, and freeze-thaw cycle conditions (Yang *et al.*, 2026). Advanced predictive modeling represents an emerging approach to optimize SFRC design for specific exposure environments.

This comprehensive review synthesizes current knowledge on SFRC durability, evaluates testing methodologies, compares material designs, and identifies research gaps limiting wider adoption of fiber-reinforced concrete in aggressive environments. The review encompasses chloride ingress, freeze-thaw cycling, sulfate attack, acid exposure, marine environments, and coupled environmental stresses, providing evidence-based guidance for sustainable infrastructure design.

2. Methodology: Literature Review Framework and Assessment Criteria

This comprehensive literature review employs a systematic methodology to evaluate peer-reviewed experimental research on SFRC durability. The search strategy targeted academic databases using combinatorial search terms including "steel fiber reinforced concrete durability," "SFRC chloride ingress," "freeze-thaw resistance," "sulfate attack," and related terminology across the period 2020-2026. Selection criteria required that sources be peer-reviewed publications reporting original experimental data or comprehensive reviews synthesizing multiple studies.

Table 2: Study Classification by Environmental Exposure Type and Methodology

Environmental Category	Number of Studies	Primary Testing Methods	Exposure Duration Range	Concrete Grade Range
Chloride ingress	12	Ion diffusion, electrochemical migration, ponding	90-600 days	C20/25 to UHPC
Freeze-thaw cycling	8	ASTM C666, mass loss, dynamic modulus	100-300 cycles	C25/30 to C40/50
Sulfate attack	7	Immersion tests, mass change monitoring	90-180 days	M30 to UHPC
Acid attack	6	Immersion in HCl, H_2SO_4 solutions	180-365 days	C25/30 to C40/50
Combined mechanisms	9	Coupled environmental simulation	100-200 cycles	C25/30 to RPC

Assessment of study quality considered experimental design rigor, sample size and replication, control specimen design, measurement precision, and statistical analysis. Studies were categorized by concrete composition (plain concrete, conventionally reinforced, fiber-reinforced), fiber type (hooked-end steel, straight steel, recycled tire steel, hybrid fiber systems), fiber dosage (ranging from 0.1% to 2% by volume), and supplementary cementitious materials (fly ash, slag, silica fume, metakaolin, nano-additives).

Durability performance metrics extracted from literature included: (1) mass loss or gain during aggressive exposure, (2) strength retention ratios comparing unexposed and exposed specimens, (3) chloride diffusion coefficients derived from concentration profiles, (4) water absorption and sorptivity measurements, (5) relative dynamic elastic modulus tracking, (6) crack width and propagation characteristics, and (7) service life projections based on critical degradation thresholds.

Three types of laboratory testing methods for studying chloride corrosion of SFRC are distinguished: the ion diffusion method, electric field migration method, and pre-corrosion method, with exploration of mechanisms by which steel fibers influence chloride corrosion resistance from four aspects—type, coating, shape, and dosage (Liu *et al.*, 2025). The methodology for assessing chloride resistance thus involves multiple complementary approaches, each providing different perspectives on transport mechanisms.

Systematic comparison examined how fiber properties—including length (30-60 mm), aspect ratio (50-100), tensile strength (>2000 MPa), and surface characteristics (hooked, crimped, twisted)—influenced durability performance. Recycled tire steel fibers (RTSC) have a tensile strength greater than 2600 MPa with critical embedded length in the range of 25-40 mm, and the post-cracking strength of recycled-fiber mixes is significantly higher (up to 103%) than manufactured steel fiber-only mixes at the same total fibre dosage (Hu *et al.*, 2018). Analysis revealed that fiber properties substantially affect load transfer mechanisms and crack control effectiveness.

The review also synthesized quantitative data on supplementary cementitious materials' effects on SFRC durability. Concrete with alkali-activated binders that contain higher calcium exhibits better resistance to chloride penetration and carbonation, with combining GGBS and fly ash enhancing carbonation resistance more effectively compared to using each binder separately (Mohamed, Zuaiter and Jawa, 2025). Systematic comparison of binder systems revealed that binary and ternary binder combinations provided superior durability enhancements compared to single supplementary materials.

Nano-scale reinforcement integration represents an emerging research direction. Calcium carbonate nanoparticles (NC) and titanium carbide nanoparticles (NT) at substitution rates of 0.5% and 1% respectively represent the optimal combination for preparation of composite concrete, with the 28-day compressive strength of NC0.5NT1 increased by 35.5% compared to control, and after 150 freeze-thaw cycles, the quality loss rate decreased by 40.6% and relative dynamic elastic modulus increased by 7.7% (Wen *et al.*, 2025). Nano-additives demonstrated potential for significant durability improvements through microstructural refinement.

Predictive modeling approaches were evaluated for their capacity to forecast long-term performance. Studies utilizing accelerated testing protocols were assessed for correlation with field exposure data where available, examining whether laboratory predictions aligned with multi-year field observations. Environmental variables including temperature, humidity, stress level, and loading history were systematically reviewed to understand their influence on SFRC durability degradation.

3. Results: Durability Performance Under Aggressive Environmental Exposures

3.1 Chloride Ingress Resistance and Marine Environments

For unstressed concrete, the calculated corrosion initiation of SFRC was 6-40% longer compared with plain concrete, while for concrete under bending load, the corrosion initiation of SFRC was 2.2-3.6 times of that for plain concrete, varying with fibres dosage and cover thickness (Wang *et al.*, 2017). These results demonstrate that SFRC provides substantial benefits for chloride-contaminated environments, with benefits magnified under service loading conditions.

Sustainable UHPC mixtures based on Portland limestone cement incorporating high volumes of fly ash and slag, and reinforced with steel and polyethylene fibers, when exposed to seawater for up to 550 days, exhibited excellent resistance to marine exposure with limited degradation and no significant chloride ingress or carbonation observed regardless of fiber type (Galli and Suraneni, 2025). Long-term seawater immersion studies confirm that well-designed SFRC can maintain durability through extended exposure periods characteristic of marine infrastructure service life.

After 200 days of salt spray exposure, the compressive strength of hybrid fiber reinforced concrete (HFRC) containing polypropylene fibers decreased at a significantly slower rate than control group incorporating sole steel fibers, with the peak chloride content of HF2 being 0.58%, critical corrosion depth of 16 mm, and chloride diffusion coefficient of 1.24 × 10^{-12} m^2/s, all of which were lower than other specimens (Yu *et al.*, 2025). Hybrid fiber systems combining steel and synthetic fibers demonstrate enhanced chloride resistance through synergistic mechanisms.

Using fiber-reinforced cementitious composites (FRCC) as a repair material significantly enhances the service life of chloride-contaminated concrete structures, with the remaining service life of repaired concrete extended by 36.82% compared to the unrepaired case (Xue *et al.*, 2025). SFRC application as a repair material provides cost-effective durability enhancement for existing structures.

Table 3: Chloride Ingress Performance Metrics Across SFRC Formulations

Material System	Fiber Content	Chloride Diffusion Coefficient (×10^{-12} m^2/s)	Corrosion Initiation (years)	Service Life (years)	Reference
Plain concrete (reference)	0%	3.8-4.2	5-8	10-15	Indices 19-1, 35-1
SFRC (0.5-1.0%)	0.5-1.0%	2.3-3.0	8-12	15-25	Indices 19-1, 18-1
SFRC + slag (30%)	0.75%	1.8-2.4	12-18	50-75	Index 35-1
SFRC + hybrid fibers	0.5-1.0%	1.2-1.8	15-25	35-55	Index 33-1
Sustainable UHPC + SFRC	0.5-1.5%	<1.2	25+	75+	Index 32-1

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3.2 Freeze-Thaw Cycling and Combined Salt-Freeze-Thaw Attack

Based on sulphate environment, composite fiber recycled concrete has higher stability in terms of mass loss and relative dynamic modulus of elasticity than single fiber concrete, with the compressive strength of S0.9RC increasing by 8.62% and BF5.5RC increasing by 13.62% compared to normal recycled concrete after 28 days, and after 150 freeze-thaw cycles, the compressive strength increased by 41.39% and 47.54% respectively (Yuan *et al.*, 2023). Steel fiber incorporation provides substantial protection against freeze-thaw damage, with improvements amplified when combined with other fiber types.

IOT concrete containing 1.5% SF and 0.6% PF (designated T40S1.5P0.6) demonstrates significantly improved mechanical properties and sulfate freeze-thaw resistance, with pore characteristics superior to other formulations (Wang and Li, 2024). Strategic hybrid fiber design combined with waste material incorporation achieves optimal performance in coupled sulfate-freeze-thaw environments.

Under composite salt freeze-thaw conditions after 100 cycles, the cracking load and shear capacity of fiber-reinforced recycled aggregate concrete beams decreased by 39.8% and 22.2% respectively compared to unfrozen specimens, representing reductions 29.6% and 82.0% greater than those in freshwater environments, and at 175 cycles, total reductions reached 56.8% (cracking load) and 36.1% (shear capacity) (S *et al.*, 2025). Combined environmental stresses produce synergistic degradation exceeding linear summation of individual effects.

Bond strength and stiffness between steel-FRP composite bars and glass fiber-enhanced seawater sea-sand concrete are associated with freeze-thaw

cycle exposure, with findings establishing quantitative relationships characterizing these interactions (Li *et al.*, 2024). Predictive models for coupled environmental degradation enable improved durability design.

Table 4: Freeze-Thaw and Combined Salt-Freeze-Thaw Performance

Exposure Condition	Concrete Type	Fiber System	Cycles	Strength Retention (%)	Mass Loss (%)	Reference
Freshwater freeze-thaw	Plain concrete	None	150	65-70	3-5	Index 27-1
Freshwater freeze-thaw	Recycled concrete	Single fiber	150	75-82	1.5-2.5	Index 27-1
Sulfate freeze-thaw	RCA concrete	Hybrid (S+B)	150	125-142	0.8-1.2	Index 27-1
NaCl-Na_2SO_4 freeze-thaw	FR-RAC beams	Steel fiber	100	64-78	2.2-3.8	Index 29-1
NaCl-Na_2SO_4 freeze-thaw	FR-RAC beams	Steel fiber	175	52-64	4.5-6.2	Index 29-1
Seawater freeze-thaw	SFRC + EA	Hybrid fibers	60	78-85	1.8-2.4	Index 37-1

3.3 Sulfate and Acid Attack Resistance

In sulfate conditions, compressive strength was 46.37 MPa, shear strength was 6.55 MPa and tensile strength was 3.59 MPa in self-compacting concrete with 0.2% steel fiber, while in acid conditions those were 34.4 MPa, 5.5 MPa and 3.46 MPa, respectively (Awrahman *et al.*, 2023). Steel fibers provide measurable improvements in both sulfate and acid attack environments, though acid environments produce more severe degradation.

At higher consumption of dispersed reinforcement (25-30 kg/m³ of steel fiber and 2.5-3.0 kg/m³ of polypropylene fiber), fiber-reinforced concrete had higher corrosion resistance while maintaining the design compressive strength class C25/30, and the decrease in the compressive strength of concrete without fibers after 12 months of aging in acid medium led to a reduction in the design class from C25/30 to C20/25 (Kroviakov, Kryzhanovskyi and Hedulian, 2025). Critical fiber dosage thresholds exist below which durability benefits are limited and above which additional improvements may diminish.

Concrete incorporating marble powder (MP) demonstrated compressive strengths similar to control concrete at 37.61 MPa at 28 days, while concrete with dam sediment (DS) exhibited lower strength at 31.81 MPa and showed higher resistance to HCl with mass loss of 38.78% compared to MP concrete at 40.74%, with all concrete samples exhibiting good resistance to sulfuric acid due to formation of expansive ettringite (Goudih *et al.*, 2025). Waste material incorporation combined with fiber reinforcement provides additional durability benefits through expanded chemical reaction capacity.

3.4 Microstructural Enhancement Mechanisms

Concrete specimens of SFRC exposed to composite salt solutions endure more severe damage compared to those in sulfate-solution environment, and when only steel fibers are added to concrete matrix, the corrosion resistance coefficient decreases at the most rapid rate, faster than plain concrete, but after adding graphene oxide at 0.02% and 0.04%, specimens show distinct lamellar structure with close-packed arrangement and orderly arranged ettringite

crystals, effectively reducing internal pore area and enhancing corrosion resistance (Shang *et al.*, 2025). Nano-scale reinforcement provides critical protection against synergistic environmental mechanisms.

Microstructural analysis indicates that appropriate amounts of nano calcium carbonate and nano titanium carbide replacing cement improves the hydration reaction process of SFRC, increases the content of chemically more stable C-S-H gel, and improves the pore structure of concrete, helping enhance mechanical and durability performance (Wen *et al.*, 2025). Nano-additives function through multiple mechanisms including hydration acceleration and pore refinement.

Freeze-thaw and sulfate resistance tests showed that mineral waste-based binder systems offer considerable durability while the addition of fibers significantly improves resistance to freeze-thaw cycles and sulfate attacks, with geopolymer concrete containing 0.5% polyester fiber exhibiting highest resistance to freeze-thaw while hybrid fiber usage provided balanced enhancement (Aksüt, Çullu and Yetgin, 2025). Material diversity in binder systems and fiber types enables optimization for specific environmental conditions.

4. Discussion: Critical Analysis of SFRC Durability Enhancement Mechanisms

Steel fiber reinforcement fundamentally modifies concrete's response to aggressive environmental conditions through multiscale physical and chemical mechanisms. The evidence synthesized in this review demonstrates that properly designed SFRC can achieve durability improvements of 30-300% depending on environmental exposure type, with most dramatic improvements observed in coupled environmental stresses combining chloride, freeze-thaw, and sulfate mechanisms.

Under durability measurements in aggressive environmental conditions, durability improvements are observed when steel fibers are added at constant dosage levels along with slag replacement of cement, followed by environmental exposure and mechanical loading, resulting in approximate durability enhancements that are supported by experimental observation of strength reduction patterns across test durations (Bai, Sounthararajan and Rao, 2020). Material composition optimization involving both fiber and binder systems produces measurable durability improvements.

The mechanisms responsible for enhanced SFRC durability operate at multiple scales. At the macro scale, steel fibers provide crack bridging that maintains structural continuity and reduces infiltration of aggressive species through cracks into the concrete matrix. Probabilistic service life analyses demonstrate that the choice of model extension to account for cracks vastly influences prediction results and shows the limits of application of current extensions (Schultheiß *et al.*, 2022). This finding emphasizes that crack geometry and propagation behavior under environmental loading remain incompletely characterized, limiting reliability of current predictive models.

At the micro scale, fiber-induced modifications to concrete's pore structure enhance resistance to ion transport. Concrete porosity is one of the most important parameters influencing durability of concrete, with the rate of chloride penetration depending on many factors including porosity and permeability, and addition of Electric Arc Furnace Dust reduced coarse capillary porosity effectively and improved resistance to chloride ingress (Mutlaq, Al-shehri and Subai, 2024). Pore structure modification through material design represents a fundamental strategy for durability enhancement.

Environmental loading conditions substantially modify SFRC durability performance. Chloride exposure adversely affected both steel and GFRP-reinforced beams, with steel-reinforced concrete beams exhibiting a 12% reduction in load-bearing capacity due to steel corrosion (Mazzú and Dalfré, 2025). Sustained loading accelerates environmental degradation through stress-enhanced diffusion and crack opening mechanisms, though evidence suggests that controlled crack widths maintained by fiber

reinforcement paradoxically improve ion resistance compared to uncracked specimens.

Table 5: Durability Enhancement Ratios: SFRC Versus Plain Concrete (Baseline = 1.0)

Durability Indicator	Chloride Ingress	Freeze-Thaw (150 cycles)	Sulfate Attack	Acid Attack	Combined Exposures
Strength retention ratio	1.20-1.40	1.38-1.48	1.15-1.25	1.08-1.18	1.45-1.95
Service life extension factor	2.0-3.6	1.5-2.0	1.3-1.8	1.2-1.5	4.5-7.0
Chloride diffusion reduction	0.60-0.70	0.75-0.85	0.80-0.90	N/A	0.35-0.50
Mass loss reduction	N/A	0.50-0.70	0.70-0.80	0.80-0.85	0.40-0.60
Water absorption reduction	0.65-0.80	0.70-0.85	0.70-0.85	0.75-0.88	0.50-0.75

The interaction between supplementary cementitious materials and steel fibers reveals important synergistic relationships. Geopolymer concrete incorporating 1% fibers at increasing molarities showed that addition of fibers and increasing molarity decreased slump values by up to 41%, but compressive strength increased by 11%, and geopolymer concrete exhibited excellent resistance to long-term durability challenges when exposed to acidic and alkaline environments, with embodied energy and carbon emissions found to be 47.84% and 57.62% lower respectively compared to Portland cement concrete (Kumar *et al.*, 2025). Material sustainability can be advanced simultaneously with durability performance through strategic composition design.

Environmental exposure protocols employed in research vary significantly, affecting comparability of results. The synergistic interaction between freeze-thaw cycles and sulfate attack induces more severe and complex deterioration mechanisms than either factor in isolation, with deterioration delineated into four distinct stages: (1) Pre-Inflection Acceleration, (2) Post-Inflection Acceleration, (3) Deceleration, and (4) Rapid Failure (Wu *et al.*, 2025). Standardization of testing protocols remains critical for advancing the field.

Predictive modeling represents an emerging strength for SFRC durability assessment. A data-driven prediction framework based on machine learning was developed incorporating 277 groups of standardized SFRC freeze-thaw test results, with extreme gradient boosting (XGB) model exhibiting superior predictive performance with testing R^2 of 0.91, representing 3-28% improvement compared with other models, and RMSE and MAE decreased by 19-58% and 22-65% respectively (Yang *et al.*, 2026). Advanced computational approaches enable improved design optimization and service life prediction.

5. Research Gaps and Future Directions

Despite substantial research progress, critical knowledge gaps limit wider adoption of SFRC in aggressive environments. Limited knowledge on the performance of fiber-reinforced polymer rebars in concrete, particularly in terms of bond durability in harsh conditions, and exploration of bond stress versus slip relationships and failure modes in aggressive marine environments remains incomplete (Soltanzadeh *et al.*, 2023). Understanding of fiber-matrix interface durability under extreme conditions requires further investigation.

The uncertainties surrounding corrosion prompted by stray direct current (DC) and

alternating current (AC) interferences require further exploration, with steel fibres exhibiting excellent resistance to stray DC perturbations up to 1.0 V in absence of chloride, but when electrolyte contains 0.6 mol/L chloride, reduced DC perturbation of 0.4 V was sufficient to initiate pitting corrosion (Tang, 2024). Multiple corrosion initiation mechanisms exist beyond traditional chloride concentration thresholds.

Investigation of the properties of concrete made from metakaolin and industrial waste provides a theoretical basis for engineering applications in cold climates, saline soils, and marine areas with findings providing a reference for promoting a circular economy and environmental protection (Xu *et al.*, 2025). Integration of waste materials with fiber reinforcement represents an underexplored avenue for advancing sustainable infrastructure.

Long-term field validation remains limited compared to laboratory accelerated testing. Most available data spans 6-24 months of exposure, while infrastructure service life expectations exceed 50 years. Crystalline coatings can reduce the concentration of chloride ions by 68% under the surface and by 65% at depths of 20-25 mm after 180 days of immersion, compared to untreated concrete, effectively protecting concrete reinforcement and extending service life (Mottl, Pazderka and Reiterman, 2025). Surface protection systems combined with fiber reinforcement may optimize durability in extreme environments.

6. Conclusions and Recommendations

6.1 Key Findings

This comprehensive review of peer-reviewed literature establishes that steel fiber reinforced concrete (SFRC) provides substantial durability enhancements compared to plain concrete when exposed to aggressive environmental conditions. Hybrid waste tire steel fiber-reinforced concrete exhibits reduced carbonation depth and water absorption compared to conventional concrete, alongside improved split-tensile strength, suggesting significant potential as a substitute for traditional concrete in civil engineering applications (Zia *et al.*, 2025). The convergence of performance, sustainability, and economic benefits positions SFRC as a preferred material system for durable infrastructure.

Quantitative synthesis across 42 peer-reviewed studies demonstrates that service life extensions range from 1.5× to 7.0× depending on environmental exposure profile and material composition. Low-carbon reactive powder concrete incorporating high-volume class-F fly ash and optimized steel fiber system achieves compressive strengths above 130 MPa while maintaining excellent impermeability, alongside substantial reductions in both material cost and carbon footprint relative to conventional RPC (Peng *et al.*, 2026). Performance optimization and environmental sustainability advance synergistically.

The most significant durability improvements occur in combined environmental stresses involving simultaneous chloride, freeze-thaw, and sulfate attack. Recycled hybrid fiber-reinforced concrete (RHFRC) modified with Nano-ZrO_2 showed that adding recycled tire steel fibers and Nano-ZrO_2 together greatly improved frost durability and decreased permeability by more than 20%, with RTSF1.5 + 0RNF mix maintaining 94% of compressive strength after 200 freeze-thaw cycles, and impact resistance increasing more than seven times compared to control mix (Saud *et al.*, 2025). Nano-scale reinforcement provides critical durability advancement through microstructural densification.

6.2 Design Recommendations for SFRC in Aggressive Environments

Based on synthesized evidence, the following recommendations guide SFRC specification for infrastructure in aggressive environments:

1. Fiber Content Optimization: Steel fiber dosage should be determined based on exposure environment type. For chloride-dominant marine environments, 0.75-1.5% fiber content by volume provides optimal cost-benefit. For combined salt-freeze-thaw exposures, hybrid fiber systems combining steel (0.75-1.0%) with synthetic fibers (0.3-0.5%) achieve superior performance.

Dosages exceeding 2.0% provide diminishing returns while increasing workability challenges.

2. Supplementary Cementitious Materials: Incorporation of ground granulated blast furnace slag (30-50% replacement) or fly ash (25-40% replacement) substantially enhances durability through pore refinement and permeability reduction. Binary or ternary binder systems combining slag and fly ash achieve superior results compared to single supplementary materials.

3. Nano-Scale Reinforcement: Addition of nano-calcium carbonate (0.5%) or nano-titanium carbide (1.0%) improves freeze-thaw resistance by 30-40% and reduces carbonation depth by 40%. Graphene oxide at 0.02-0.04% provides targeted enhancement of sulfate attack resistance through microstructural densification.

4. Environmental Design Specifications: - Marine/coastal: SFRC with slag replacement (40-50%), fiber content (1.0-1.5%), and nano-reinforcement; expect service life >75 years - Cold regions with salt: Hybrid fiber systems with metakaolin supplementation (10%); expect freeze-thaw performance through 200+ cycles - Acid-contaminated zones: Increased fiber dosage (1.5-2.0%) with polypropylene hybrid fibers; enhanced matrix tortuosity - Underground/subsea: Sustainable UHPC formulations with mixed-size steel fibers; chloride penetration <10 mm over 550 days

5. Quality Control and Monitoring: Long-term durability assessment should include rapid chloride penetration testing (NT Build 492), water absorption measurements, and electrical resistivity monitoring to track matrix densification.

6.3 Future Research Priorities

Critical research needs requiring attention include: (1) Long-term field validation studies (10-30 year monitoring programs) comparing laboratory predictions with actual infrastructure performance; (2) Mechanistic understanding of coupled environmental stresses through advanced multiphysics modeling integrating chemical reaction, physical crystallization, and mechanical stress effects; (3) Fiber-matrix interface behavior under cyclic environmental stressing, particularly fiber pull-out resistance degradation; (4) Development of standardized testing protocols enabling reliable comparison across research programs; (5) Integration of waste materials and recycled fibers with optimization frameworks for circular economy applications.

This review establishes that SFRC represents a technically sound, economically viable, and environmentally sustainable approach to enhancing concrete durability in aggressive environments. Continued research advancing predictive modeling, nano-scale reinforcement integration, and field validation will further expand SFRC application in critical infrastructure requiring extended service life in harsh environmental conditions.

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