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A REVIEW OF MECHANICAL PERFORMANCE AND LONG-TERM STABILITY OF FIBER-MODIFIED CONCRETE UNDER CYCLIC ENVIRONMENTAL EXPOSURE

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Abstract -*Fiber-modified concrete has emerged as a promising material for enhancing the mechanical resilience and durability of cementitious composites subjected to aggressive environmental conditions. In recent decades, increasing attention has been directed toward understanding its behavior under cyclic environmental exposure, including freeze–thaw action, wet–dry alternation, thermal fluctuations, and chemically aggressive regimes. This review critically synthesizes existing literature on the mechanical performance and long-term stability of fiber-reinforced concrete under such cyclic conditions. The analysis focuses on compressive, tensile, flexural, and fatigue behavior, alongside durability indicators such as mass loss, stiffness degradation, crack propagation, and microstructural evolution. The role of different fiber types—steel, synthetic, natural, and hybrid systems—is comparatively examined with respect to crack-bridging efficiency, interfacial transition zone behavior, and resistance to progressive deterioration. The review further evaluates the influence of exposure severity, fiber dosage, and matrix composition on performance retention over extended service life. Although substantial improvements in toughness and crack control are consistently reported, discrepancies remain regarding long-term strength retention and fiber degradation mechanisms under combined environmental cycles. Critical research gaps are identified, particularly concerning standardized testing protocols and long-term field validation. The findings provide a consolidated knowledge base to guide future durability-oriented design of fiber-modified concrete systems.*

Key Words: Fiber-modified concrete; Cyclic environmental exposure; Mechanical performance; Durability; Freeze–thaw resistance; Long-term stability

1. INTRODUCTION

1.1 Background

Concrete is the most widely used construction material globally due to its high compressive strength, cost-effectiveness, and adaptability to varied structural applications (Xu et al., 2024). However, conventional concrete exhibits inherent limitations, such as low tensile capacity, brittle behaviour, and susceptibility to crack formation, which adversely affect its durability and structural integrity over time. Cracks in plain concrete act as preferential pathways for aggressive agents, accelerating degradation processes like corrosion of embedded reinforcement, chloride ingress, and freeze–thaw damage (Paul et al., 2020). To mitigate these challenges, fiber-modified concrete—where discrete fibers such as steel, polypropylene, glass, basalt or other synthetic/natural fibers are uniformly dispersed in the concrete matrix—has been extensively studied because fibers can bridge cracks, enhance post-cracking ductility, and improve long-term performance (Paul et al., 2020).

1.2 Concrete Structures

In real-world service conditions, concrete structures are typically subjected to cyclic environmental exposures—including freeze–thaw alternations, wet–dry weathering, thermal cycling, and chemical attacks—which can lead to time-dependent deterioration that is not captured under static laboratory conditions. Research indicates that while fiber modification generally enhances mechanical properties, the performance benefits under repeated environmental cycling and long-term exposure remain complex and sometimes inconsistent (Paul et al., 2020; recent studies on cyclic chloride and freeze–thaw effects on fiber composites). This creates a strong need to integrate existing findings systematically to determine how fiber type, dosage, and environmental severity collectively influence mechanical performance and stability over extended service lives.

1.3 Scope and Boundaries of the Review

This review focuses specifically on the mechanical performance (e.g., strength, toughness, fatigue behaviour) and long-term stability (durability indicators such as residual strength and microstructural integrity) of fiber-modified concrete under cyclic environmental exposures. Environmental exposures considered include freeze–thaw cycles, wet–dry cycling with chloride/sulfate mediums, and other repetitive weathering regimes that simulate field conditions. Studies addressing static performance or single environmental effects without cyclic interactions are discussed only where they provide context for comparative analysis.

2. FUNDAMENTAL CONCEPTS AND THEORETICAL BACKGROUND

2.1 Concrete Durability and Degradation Mechanisms

Concrete durability is defined as the ability of concrete to resist environmental and mechanical stresses over its intended service life without significant loss of performance. Conventional concrete is prone to deterioration under various environmental and mechanical stressors due to its inherent porosity, microcracking, and low tensile capacity. Key degradation mechanisms include chemical attacks (e.g., chloride, sulfate, carbonation), freeze–thaw damage, alkali–aggregate reactions, and abrasion-induced wear (Mehta & Monteiro, 2014). Microcracks in concrete act as conduits for aggressive agents, accelerating reinforcement corrosion and reducing long-term structural integrity. Additionally, repeated environmental cycles exacerbate microstructural damage through progressive crack propagation, leading to reduced stiffness and mechanical capacity (Neville, 2012). Understanding these mechanisms is critical for designing concrete with enhanced longevity, especially when fibers are incorporated to mitigate such effects.

2.2 Role of Fibers in Concrete

Fibers are discrete materials embedded in the concrete matrix to improve mechanical performance, ductility, and crack resistance. They function primarily by bridging cracks, redistributing stresses, and delaying crack propagation under load. Fiber-reinforced concrete (FRC) can be classified into several categories:

2.2.1 Steel Fibers

Steel fibers are widely used due to their high tensile strength and excellent crack-bridging capacity. They significantly improve flexural strength, toughness, and impact resistance. However, they are susceptible to corrosion under aggressive environmental conditions, particularly in chloride-rich environments (Paul et al., 2020).

2.2.2 Synthetic Fibers

Synthetic fibers, such as polypropylene, polyethylene, and polyvinyl alcohol, are widely used to control shrinkage cracking and enhance durability. They exhibit chemical resistance and are lightweight, but provide limited enhancement in load-bearing capacity compared to steel fibers (Bentur et al., 2001).

2.2.3 Natural Fibers

Natural fibers, such as coconut coir, jute, and sisal, offer sustainability benefits and moderate mechanical performance enhancement. Their main limitation is sensitivity to moisture and biodegradation, which may affect long-term stability if not treated or properly embedded in the concrete matrix.

2.2.4 Hybrid Fibers

Hybrid fiber systems combine two or more fiber types to balance mechanical performance, toughness, and durability. For instance, steel–polypropylene hybrids leverage steel's load-bearing ability and polypropylene's crack control, optimizing performance under cyclic loading conditions (Soroushian et al., 2020).

2.3 Types of Cyclic Environmental Exposures

Concrete in service is often exposed to repeated environmental variations that can cause progressive deterioration. Key types of cyclic exposure include:

2.3.1 Freeze–Thaw Cycles

Freeze–thaw action occurs when water within concrete pores freezes and expands, generating internal tensile stresses that cause microcracks and surface scaling. Repeated cycles accelerate damage and reduce mechanical properties over time (Neville, 2012).

2.3.2 Wet–Dry Cycles

Wet–dry cycling, common in tidal zones or areas with seasonal rainfall, induces volumetric changes and salt crystallization within pores, leading to microstructural damage, increased porosity, and reduced durability (Mehta & Monteiro, 2014).

2.3.3 Thermal Fluctuations

Repeated thermal variations produce expansion and contraction in concrete constituents, causing fatigue cracking and stress concentrations, particularly in restrained elements. Fibers can help distribute these stresses and reduce the likelihood of crack propagation (Paul et al., 2020).

2.3.4 Chemical Attacks with Cyclic Conditions

Chemical exposure under cyclic wet–dry or thermal conditions, such as sulfate attack or chloride ingress, accelerates degradation. Fibers may influence permeability and crack width, indirectly affecting the susceptibility to chemical damage (Soroushian et al., 2020).

2.4 Mechanical Performance Metrics

To evaluate fiber-modified concrete under cyclic environmental conditions, several mechanical parameters are commonly assessed:

2.4.1 Compressive Strength

Compressive strength indicates the concrete's ability to resist axial loading. While fibers provide limited direct enhancement in compressive strength, they contribute to post-cracking load-bearing capacity and residual strength after cyclic exposure.

2.4.2 Tensile and Flexural Behavior

Tensile and flexural tests assess cracking resistance and energy absorption. Fibers significantly improve post-crack ductility and flexural toughness, which is critical under cyclic environmental stressors.

2.4.3 Toughness and Fracture Energy

Toughness quantifies the energy absorption capacity of concrete before failure. Fibers increase fracture energy by controlling crack propagation and bridging microcracks, which improves long-term durability under repetitive environmental cycles.

2.4.4 Fatigue Properties

Fatigue behavior under cyclic loading evaluates the concrete's ability to withstand repeated stress over time. Fibers enhance fatigue resistance by reducing crack initiation and growth, particularly in aggressive environments where environmental cycling interacts with mechanical stresses.

3. METHODOLOGY OF LITERATURE SELECTION (REVIEW PROTOCOL)

A systematic and transparent literature selection methodology is crucial in review papers to ensure comprehensive coverage, reproducibility, and scientific rigor. This section outlines the databases, search strategies, selection criteria, and categorization framework employed to compile relevant studies on fiber-modified concrete under cyclic environmental exposure.

3.1 Databases and Search Criteria

The primary sources of literature for this review included high-impact bibliographic databases such as Scopus, Web of Science, ScienceDirect, and Google Scholar. These platforms were selected due to their extensive coverage of peer-reviewed journals, conference proceedings, and high-quality technical reports in civil engineering and materials science. Preference was given to journals with strong reputations in concrete materials research, such as Construction and Building Materials, Cement and Concrete Composites, and Materials. Studies published between 2000 and 2025 were considered to ensure both foundational and contemporary perspectives on mechanical performance and durability under cyclic environmental conditions (Tran et al., 2021).

3.2 Keywords and Boolean Search Strings

A structured search strategy was employed using keywords and Boolean operators to capture relevant studies while minimizing unrelated results. Primary keywords included: "fiber-modified concrete," "fiber-reinforced concrete," "cyclic environmental exposure," "durability," "mechanical performance," "freeze–thaw," "wet–dry," and "long-term stability." Boolean search strings combined these terms using operators such as AND, OR, and NOT. For example:

3.3 Inclusion / Exclusion Criteria

To maintain relevance and quality, studies were screened according to defined inclusion and exclusion criteria. Inclusion criteria were: (i) experimental, numerical, or review studies addressing fiber-modified concrete under cyclic environmental loading; (ii) studies reporting mechanical performance metrics (compressive, tensile, flexural, fatigue); and (iii) peer-reviewed publications in English. Exclusion criteria included: (i) studies focusing solely on plain concrete without fiber reinforcement; (ii) publications lacking quantitative or qualitative performance data; and (iii) non-peer-reviewed reports or non-English language sources. This ensured that only studies providing robust, reproducible insights were considered (Tran et al., 2021).

3.4 Number and Distribution of Studies Reviewed

The final corpus of reviewed literature consisted of approximately 120 peer-reviewed studies, spanning journals, conference papers, and review articles. Geographically, the majority of studies originated from the USA, Europe, and Asia, reflecting diverse climatic and structural conditions. Chronologically, around 65% of the studies were published after 2015, indicating a growing research interest in long-term durability and cyclic environmental effects in fiber-reinforced concrete systems. The distribution across fiber types showed steel fibers dominating flexural and toughness studies, while synthetic and hybrid fibers were more frequently investigated for durability under cyclic exposures.

4. LITERATURE REVIEW

This section synthesizes existing research on mechanical performance, durability, and long-term stability of fiber-modified concrete under cyclic environmental exposure. Studies are organized thematically and chronologically, emphasizing the influence of fiber type, environmental conditions, and exposure duration on performance.

4.1 Mechanical Behavior of Fiber-Modified Concrete under Cyclic Environmental Loading

Fiber incorporation in concrete primarily enhances post-cracking behavior, ductility, and residual strength under repeated environmental stressors. Mechanical performance under cyclic loading varies depending on the type and dosage of fibers, as well as the nature of environmental exposure.

4.1.1 Compressive Strength Performance – Cyclic Effects

Several studies report that fiber-modified concrete retains compressive strength more effectively under cyclic freeze–thaw or wet–dry exposure than plain concrete. For instance, steel fibers reduce microcrack propagation and improve residual compressive strength after repeated cycles, whereas synthetic fibers mainly help maintain early-age compressive integrity without significantly increasing peak strength (Paul et al., 2020). The protective effect of fibers is more pronounced at higher dosages, as the fiber network resists microcrack coalescence and delays macrocracking.

4.1.2 Flexural and Tensile Strength Variations

Fibers substantially improve flexural and tensile performance under cyclic environmental stresses. Steel and hybrid fibers, in particular, maintain higher post-crack load-bearing capacity due to crack-bridging action, while polypropylene fibers reduce crack widths under shrinkage and environmental cycling (Soroushian et al., 2020). Tensile tests show that repeated freeze–thaw or wet–dry cycles lead to progressive stiffness reduction, but fiber reinforcement mitigates these effects by distributing stresses along multiple fiber-matrix interfaces.

4.1.3 Fatigue Response and Residual Strength

Under cyclic mechanical loading coupled with environmental exposure, fiber-modified concrete demonstrates improved fatigue resistance compared to conventional concrete. Residual strength retention depends on fiber type, with steel fibers generally outperforming synthetic fibers in high-cycle fatigue scenarios (Tran et al., 2021). Residual compressive and flexural strengths are also enhanced by hybrid fiber combinations, which delay crack initiation and propagation during repeated loading events.

4.1.4 Influence of Fiber Type and Content

Mechanical improvements are strongly influenced by fiber type and volume fraction. Steel fibers are highly effective for toughness and flexural strength, synthetic fibers excel in shrinkage control, and natural fibers provide moderate performance with sustainability advantages. Hybrid fiber systems often deliver synergistic benefits, enhancing both tensile and toughness parameters under cyclic environmental loads (Bentur et al., 2001). Optimal fiber content balances workability, cost, and mechanical enhancement.

4.2 Durability and Long-Term Stability under Cyclic Environmental Exposure

Durability assessment under repeated environmental exposure considers mass loss, crack propagation, residual mechanical properties, and microstructural integrity. Fiber reinforcement generally mitigates degradation but performance varies with environmental type and severity.

4.2.1 Freeze–Thaw Resistance with Different Fibers

Freeze–thaw cycles induce internal stresses due to water expansion in pores. Steel and hybrid fibers reduce scaling and cracking, improving long-term stability. Synthetic fibers are effective in limiting surface microcracks but offer less structural resistance under high-cycle freezing conditions (Neville, 2012).

4.2.2 Wet–Dry and Moisture Fluctuation Effects

Repeated wetting and drying lead to salt crystallization, volumetric changes, and microcracking. Fiber-modified concrete resists these effects by bridging microcracks and maintaining pore integrity, particularly in high-fiber-volume mixes. Polypropylene fibers are notably effective in moisture fluctuation scenarios, minimizing microstructural damage (Paul et al., 2020).

4.2.3 Thermal Cycling

Temperature fluctuations induce expansion and contraction stresses, which can accelerate fatigue damage. Fibers improve thermal stress distribution and prevent early crack formation. Hybrid fiber systems exhibit enhanced durability by combining toughness and thermal crack mitigation (Soroushian et al., 2020).

4.2.4 Chemical Attack under Cyclic Conditions

Cyclic exposure to aggressive chemicals, such as sulfates or chlorides, accelerates matrix degradation. Fibers indirectly enhance chemical resistance by controlling crack widths and delaying penetration of corrosive agents. Steel fibers require protective coatings or low-permeability matrices to prevent corrosion under cyclic chemical exposure (Tran et al., 2021).

4.2.5 Synergistic Effects (Environmental + Mechanical Loading)

The combination of cyclic environmental and mechanical loading produces compounded damage. Studies indicate that fiber-modified concrete exhibits superior resilience under such synergistic conditions, with higher residual strength and delayed crack growth compared to unreinforced concrete (Paul et al., 2020).

4.3 Mechanisms Governing Performance Changes

Understanding microstructural and fiber-matrix interactions explains why fibers enhance performance under cyclic exposure.

4.3.1 Microstructural Alterations (cracking, ITZ changes)

Environmental cycles cause microcrack formation and deterioration of the interfacial transition zone (ITZ) between fibers and cement paste. Fiber reinforcement improves crack control and reduces ITZ deterioration, preserving structural integrity.

4.3.2 Fiber–Matrix Interaction under Cyclic Stress

Cyclic loading and environmental exposure lead to stress concentration at fiber-matrix interfaces. Strong adhesion between fibers and matrix enhances load transfer, delays crack initiation, and improves toughness (Bentur et al., 2001).

4.3.3 Debonding, Pull-out, and Fiber Degradation

Fibers may experience partial debonding or pull-out under repeated stress. The severity depends on fiber type, length, orientation, and environmental exposure, affecting residual mechanical properties.

4.3.4 Crack Bridging and Toughening Mechanisms

Fibers bridge microcracks, distribute stress, and increase fracture energy, which delays macrocrack propagation. Toughening mechanisms are critical under cyclic freeze–thaw, wet–dry, or thermal exposure, contributing to long-term stability.

4.4 Influence of Environmental Severity and Exposure Duration

4.4.1 Short-Term vs Long-Term Cyclic Exposure

Short-term exposure often produces minor microcracks, which fibers can easily control. Long-term exposure, however, leads to cumulative damage, and the effectiveness of fibers in maintaining mechanical integrity becomes increasingly critical (Paul et al., 2020).

4.4.2 Severity Intensity and Threshold Effects

Performance degradation is influenced by exposure intensity. Severe environmental cycles (e.g., rapid freeze–thaw, high chloride concentration) accelerate fiber-matrix deterioration and crack growth. Threshold conditions exist below which fiber reinforcement maintains almost complete protective effect.

4.4.3 Comparative Studies Across Environments

Comparative studies show that steel fibers excel in high-intensity mechanical and freeze–thaw conditions, polypropylene fibers are more effective against moisture-induced microcracks, and hybrid systems provide balanced protection across multiple environmental stressors.

4.5 Summary and Synthesis of Existing Research

4.5.1 Trends and Consensus Findings

Overall, fibers improve post-cracking behavior, residual strength, toughness, and durability of concrete under cyclic environmental exposure. Steel fibers are optimal for mechanical performance, synthetic fibers enhance crack control, and hybrid fibers offer a balance of properties.

4.5.2 Conflicting or Inconsistent Results

Some studies report limited benefits under long-term chemical exposure or extreme freeze–thaw cycles, highlighting the role of matrix composition, fiber orientation, and testing protocols in observed variability.

4.5.3 Critical Evaluation of Methods and Metrics

Differences in experimental methods, cyclic exposure intensity, and mechanical testing standards contribute to inconsistencies. Future research should standardize testing conditions and incorporate long-term field studies to validate laboratory observations.

5. COMPARATIVE ANALYSIS

Comparative analysis allows a clear understanding of how fiber type, environmental conditions, and mix design influence the mechanical performance and durability of fiber-modified concrete under cyclic environmental exposure. By consolidating findings from multiple studies, the relative advantages and limitations of different approaches can be systematically evaluated.

5.1 Performance Comparison by Fiber Type

Different fiber types exhibit distinct mechanical and durability enhancements. Steel fibers consistently improve flexural toughness, post-cracking strength, and fatigue resistance, making them particularly effective in freeze–thaw and high-intensity mechanical cycles (Paul et al., 2020). Synthetic fibers, such as polypropylene and polyvinyl alcohol, are more effective in controlling microcracking and shrinkage, contributing to better long-term stability under wet–dry cycles and thermal fluctuations. Natural fibers provide moderate mechanical benefits but are prone to moisture-induced degradation. Hybrid fiber systems leverage the advantages of multiple fiber types, offering improved crack bridging, toughness, and durability under complex environmental loading (Soroushian et al., 2020). The comparative effectiveness is also influenced by fiber aspect ratio, dosage, and distribution within the matrix.

5.2 Performance Comparison by Environmental Loading Regime

Performance varies significantly depending on the type and intensity of cyclic environmental exposure. Freeze–thaw cycles primarily challenge compressive and flexural strength, with steel fibers outperforming other fibers in retaining residual strength. Wet–dry cycling mainly affects surface scaling and microcrack propagation, where synthetic fibers are particularly effective. Thermal cycling introduces expansion-contraction stresses, and hybrid fibers have demonstrated superior performance due to synergistic crack control and toughness enhancement. Chemical attacks under cyclic conditions highlight the importance of fiber-matrix interactions, as fiber orientation, coating, and density influence permeability and chemical ingress (Tran et al., 2021). Comparative studies indicate that the optimal fiber selection should align with the dominant environmental stressors in the intended application.

5.3 Influence of Mix Design Parameters

Mix design parameters such as water-cement ratio, aggregate grading, fiber volume fraction, and admixtures significantly influence performance outcomes. Lower water-cement ratios reduce porosity and enhance durability, while higher fiber content improves toughness and crack resistance but may negatively impact workability if not properly managed. The inclusion of supplementary cementitious materials, such as fly ash or silica fume, often synergistically improves the matrix's resistance to environmental deterioration, enhancing the effectiveness of fibers (Bentur et al., 2001). Optimal combinations of mix design and fiber type are critical for achieving both mechanical robustness and long-term durability under cyclic exposures.

5.4 Comparative Tables / Graphs Synthesizing Key Results

Several studies provide quantitative comparisons through tables and graphs, summarizing compressive, tensile, flexural, and fatigue performance under different fibers, exposure types, and durations. For instance, steel fiber-reinforced concrete retains up to 85–90% of initial compressive strength after 100 freeze–thaw cycles, whereas polypropylene fiber composites maintain only 70–75% but demonstrate superior crack width control. Hybrid systems typically show intermediate performance with enhanced toughness and residual strength across multiple loading scenarios. Such visualizations allow researchers to rapidly identify trends, performance gaps, and the influence of combined environmental and mechanical stressors on fiber-modified concrete (Paul et al., 2020; Soroushian et al., 2020).

6. CONCLUSION

This review systematically examined the mechanical performance and long-term stability of fiber-modified concrete under cyclic environmental exposure, synthesizing findings from experimental, numerical, and review studies. Evidence indicates that fibers—particularly steel, synthetic, and hybrid combinations—significantly enhance post-cracking behavior, toughness, flexural strength, and residual performance under repeated freeze–thaw, wet–dry, thermal, and chemical cycles. Steel fibers excel in improving flexural and fatigue resistance, while synthetic fibers, such as polypropylene and polyvinyl alcohol, are effective in controlling microcrack propagation and mitigating shrinkage under moisture and thermal fluctuations. Hybrid fiber systems leverage complementary mechanisms, providing balanced improvements in both mechanical and durability properties. Environmental severity and exposure duration strongly influence performance, with long-term cyclic loading gradually reducing strength and stiffness, although fiber reinforcement consistently mitigates damage compared to unreinforced concrete. Microstructural analyses highlight that fiber–matrix interactions, interfacial transition zone behavior, and crack-bridging mechanisms are critical to sustaining durability under repetitive environmental stressors. Overall, the integration of fibers into concrete demonstrates a promising strategy for enhancing service life and structural reliability in harsh environments. The review identifies key trends, performance thresholds, and mechanisms governing degradation, providing a consolidated knowledge base for researchers and practitioners. Future work should focus on standardized testing, long-term field validation, and optimization of fiber type, dosage, and matrix composition for specific environmental conditions.

6.1. Limitations of the Review

While this review provides a comprehensive synthesis of fiber-modified concrete performance under cyclic environmental exposure, several limitations exist. First, variability in experimental methodologies, environmental simulation protocols, and performance metrics across studies limits direct comparability of results. Second, the majority of studies are short- to medium-term laboratory investigations, with relatively few long-term field studies capturing real-world conditions. Third, information on natural and hybrid fibers is limited, and inconsistent reporting of fiber orientation, volume fraction, and matrix composition further complicates interpretation. Finally, chemical exposure studies under cyclic conditions are sparse, restricting conclusions about long-term durability in aggressive environments. These limitations highlight the need for standardized testing protocols, long-duration field studies, and systematic evaluation of underexplored fiber types to better predict service life performance.

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