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A REVIEW OF TIME-DEPENDENT CRACK ARREST MECHANISMS IN STEEL–BASALT HYBRID FIBER REINFORCED HIGH-STRENGTH CEMENTITIOUS COMPOSITES UNDER PROGRESSIVE FLEXURAL LOADING

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Abstract - *High-strength cementitious composites (HSCCs) are increasingly employed in advanced structural systems due to their superior compressive capacity and durability; however, their intrinsic brittleness makes them vulnerable to crack initiation and unstable propagation under flexural loading. Hybrid fiber reinforcement has emerged as an effective strategy to enhance fracture resistance and post-cracking ductility. In particular, the combination of steel and basalt fibers offers complementary mechanical characteristics—high tensile strength and stiffness from steel fibers, and chemical stability and fine crack control from basalt fibers. This review critically examines the time-dependent crack arrest mechanisms in steel–basalt hybrid fiber reinforced high-strength cementitious composites subjected to progressive flexural loading. The paper synthesizes current literature on crack initiation, fiber–matrix interfacial behavior, bridging action, pull-out resistance, stress redistribution, and crack tip shielding effects. Special emphasis is placed on the interaction between creep, microstructural evolution, and delayed crack propagation under sustained and incremental flexural loads. The synergistic role of hybrid fibers in modifying fracture energy, enhancing residual flexural strength, and controlling crack width over time is systematically analyzed. Existing analytical and numerical modeling approaches for simulating time-dependent fracture behavior are also reviewed, highlighting their limitations in capturing multi-scale hybrid fiber interactions. The study identifies critical research gaps, including the need for standardized testing protocols and unified constitutive models for long-term flexural performance prediction. The findings provide a comprehensive framework for understanding crack arrest mechanisms in hybrid fiber systems and offer guidance for material optimization and structural design applications.*

Key Words: Steel fibers; Basalt fibers; Hybrid fiber reinforced concrete; Time-dependent behavior; Crack arrest mechanisms; Progressive flexural loading

1. INTRODUCTION

The development of high-performance construction materials has become central to modern civil engineering practice, particularly in infrastructure subjected to complex and sustained loading conditions. High-strength cementitious composites (HSCCs) exhibit superior compressive strength and durability; however, their inherently brittle fracture behavior poses significant challenges under flexural loading. Crack initiation and unstable propagation often govern structural failure rather than compressive crushing. To mitigate such brittleness, fiber reinforcement strategies have been widely investigated. Among these, hybrid fiber systems combining metallic and mineral fibers have demonstrated promising synergistic effects in enhancing toughness, energy absorption, and crack resistance (Bentur and Mindess, 2007; Banthia and Gupta, 2004). This review focuses on time-dependent crack arrest mechanisms in steel–basalt hybrid fiber reinforced HSCCs subjected to progressive flexural loading.

1.1 Background

1.1.1 Importance of Advanced Cementitious Composites in Modern Civil Engineering

Rapid urbanization and the demand for resilient infrastructure have accelerated the adoption of advanced cementitious materials with enhanced mechanical and durability performance. High-strength and ultra-high-performance composites are now extensively used in bridges, high-rise buildings, marine structures, and precast elements due to their improved load-bearing capacity and reduced cross-sectional requirements (Neville, 2011). However, increasing matrix strength typically results in reduced strain capacity and fracture energy, thereby increasing susceptibility to brittle cracking. Consequently, research has shifted toward modifying fracture behavior rather than solely improving compressive strength.

1.1.2 Role of Hybrid Fibers in Enhancing Structural Performance

Fiber reinforcement enhances post-cracking behavior through crack bridging, pull-out resistance, and stress redistribution mechanisms. While steel fibers contribute significantly to flexural strength and toughness due to their high modulus and tensile capacity, micro-scale fibers are effective in controlling crack initiation and microcrack coalescence. Hybridization—using fibers of different geometries and mechanical properties—promotes multi-scale crack control and improved energy dissipation (Banthia and Gupta, 2004). This synergistic interaction delays crack localization and enhances residual strength under flexural loading.

1.1.3 Relevance of Steel–Basalt Hybrid Fiber Systems

Basalt fibers have gained attention because of their high tensile strength, corrosion resistance, and thermal stability compared to conventional synthetic fibers (Sim et al., 2005). When combined with steel fibers, basalt fibers primarily control microcrack formation, while steel fibers provide macrocrack bridging and ductility. Emerging studies suggest that this hybrid configuration improves fracture toughness and long-term durability, particularly under sustained or progressive loading regimes where time-dependent effects become significant.

1.2 Scope and Objectives of the Review

1.2.1 Focus on Crack Arrest Mechanisms

This review concentrates on fundamental crack arrest mechanisms operating in steel–basalt hybrid fiber reinforced HSCCs. Emphasis is placed on microstructural crack initiation, fiber–matrix interfacial bonding, bridging stress development, pull-out behavior, crack tip shielding, and energy dissipation processes. The objective is to synthesize existing theoretical and experimental findings to clarify how hybrid fibers modify fracture mechanics parameters such as fracture energy, critical stress intensity factor, and residual flexural strength (Naaman, 2003).

1.2.2 Time-Dependency under Progressive Flexural Loading

Unlike monotonic short-term loading, progressive or sustained flexural loading introduces creep, relaxation, and microstructural evolution effects that influence crack growth kinetics. Time-dependent deformation alters fiber bridging stresses and interfacial bond characteristics, thereby affecting crack arrest efficiency. This review evaluates how long-term loading conditions modify crack propagation pathways and residual load-carrying capacity, integrating fracture mechanics and rheological perspectives (Bazant and Planas, 1998).

1.2.3 Review Scope versus Experimental Research

It is important to clarify that this manuscript is a structured literature review rather than an experimental investigation. The paper critically evaluates and synthesizes published experimental, analytical, and numerical studies to identify trends, inconsistencies, and research gaps. No new experimental data are presented. The goal is to establish a coherent framework for understanding time-dependent crack arrest behavior in hybrid fiber systems and to outline future research priorities for material optimization and structural design.

2. FUNDAMENTALS OF HYBRID FIBER REINFORCED CEMENTITIOUS COMPOSITES

Hybrid fiber reinforced cementitious composites (HFRCs) represent an advanced class of quasi-brittle materials engineered to improve fracture resistance, ductility, and long-term durability. By incorporating fibers with distinct mechanical and physical properties into a high-strength cementitious matrix, these composites exhibit enhanced crack control at multiple scales. Understanding their fundamental material characteristics is essential for analyzing time-dependent crack arrest behavior under progressive flexural loading.

2.1 Cementitious Composites: Definitions and Classifications

Cementitious composites are heterogeneous materials composed of cement, aggregates, water, and supplementary cementitious materials, optionally reinforced with fibers to improve mechanical performance. Their classification is generally based on compressive strength, microstructural density, and reinforcement strategy.

2.1.1 High-Strength versus Normal Concrete

Normal strength concrete (NSC) typically exhibits compressive strength below 40–50 MPa and demonstrates relatively higher strain capacity before fracture. In contrast, high-strength concrete (HSC), often exceeding 60 MPa, is characterized by a dense microstructure and reduced porosity, achieved through low water–cement ratios and mineral admixtures such as silica fume (Neville, 2011). Although HSC provides superior compressive capacity and durability, it tends to exhibit brittle post-peak behavior due to limited microcrack redistribution capability. The fracture energy does not increase proportionally with compressive strength, making crack propagation more unstable in high-strength matrices (Bazant and Planas, 1998). Consequently, fiber incorporation becomes essential for mitigating brittle failure.

2.1.2 Fiber Reinforced Cementitious Composites

Fiber reinforced cementitious composites (FRCCs) are developed by dispersing discrete fibers randomly within the matrix to enhance tensile and flexural performance. Fibers act as crack-bridging elements that transfer stress across crack faces, thereby improving energy absorption and post-cracking ductility. Depending on fiber type, volume fraction, and aspect ratio, FRCCs can exhibit strain-hardening or strain-softening responses (Naaman, 2003). The primary mechanisms include fiber pull-out, debonding, and crack deflection, which collectively improve toughness and residual strength.

2.2 Steel Fibers

Steel fibers are among the most widely used reinforcements in structural concrete due to their high tensile strength and elastic modulus.

2.2.1 Geometry and Mechanical Properties

Steel fibers are manufactured in various geometries, including hooked-end, crimped, straight, and twisted forms. Their aspect ratio (length-to-diameter ratio) typically ranges from 40 to 100, significantly influencing pull-out resistance and bond performance. Steel fibers exhibit tensile strengths between 1000–2500 MPa and a modulus of elasticity comparable to reinforcing steel (~200 GPa), enabling efficient stress transfer across macrocracks (Bentur and Mindess, 2007). Surface deformation enhances mechanical anchorage, thereby increasing interfacial bond strength and pull-out energy.

2.2.2 Contribution to Toughness and Ductility

The primary contribution of steel fibers lies in improving flexural toughness and post-peak load-carrying capacity. Under flexural loading, steel fibers bridge macrocracks and delay crack widening through progressive pull-out rather than sudden rupture. This mechanism increases fracture energy and enhances residual strength, particularly in high-strength matrices prone to brittle failure. The ability of steel fibers to redistribute stresses reduces crack localization and improves structural ductility under service and ultimate loading conditions (ACI Committee 544, 2002).

2.3 Basalt Fibers

Basalt fibers are mineral-based fibers produced by melting naturally occurring basalt rock and extruding it into fine filaments.

2.3.1 Chemical Composition and Properties

Basalt fibers primarily consist of silica (SiO_2), alumina (Al_2O_3), iron oxides, and calcium–magnesium oxides. They exhibit tensile strengths in the range of 3000–4800 MPa and a modulus of elasticity between 80–95 GPa, positioning them between glass and carbon fibers in mechanical performance (Sim et al., 2005). Basalt fibers demonstrate excellent chemical stability, alkali resistance, and thermal durability, which are advantageous in cementitious environments.

2.3.2 Advantages over Traditional Synthetic Fibers

Compared to polypropylene or glass fibers, basalt fibers offer superior tensile strength, improved thermal resistance, and better compatibility with cement matrices. They are non-corrosive and exhibit higher resistance to chemical degradation in alkaline pore solutions. Additionally, their relatively small diameter enables effective control of microcracks during early-age shrinkage and initial loading stages. This micro-scale crack control enhances durability by reducing permeability and limiting crack coalescence (Fiore et al., 2015).

2.4 Hybridization of Steel and Basalt Fibers

Hybrid fiber systems combine fibers of different mechanical characteristics to optimize multi-scale crack resistance.

2.4.1 Synergistic Effects

Hybridization leverages the high stiffness and macrocrack bridging capacity of steel fibers with the microcrack control and durability benefits of basalt fibers. Basalt fibers primarily delay crack initiation and restrict microcrack growth, while steel fibers arrest macrocrack propagation and enhance post-cracking strength. This complementary interaction improves fracture toughness and energy dissipation capacity more effectively than mono-fiber systems (Banthia and Gupta, 2004). The result is enhanced crack distribution, reduced crack width, and improved residual flexural performance.

3. MECHANISMS OF CRACK FORMATION AND PROPAGATION IN CEMENTITIOUS MATERIALS

Cementitious materials are inherently heterogeneous and quasi-brittle, and their fracture behavior is governed by microstructural defects, stress concentrations, and energy dissipation mechanisms. Crack formation and propagation in these materials involve complex interactions between aggregates, cement paste, interfacial transition zones (ITZ), and any embedded fibers. Understanding these mechanisms is fundamental for evaluating crack arrest performance in hybrid fiber reinforced high-strength composites.

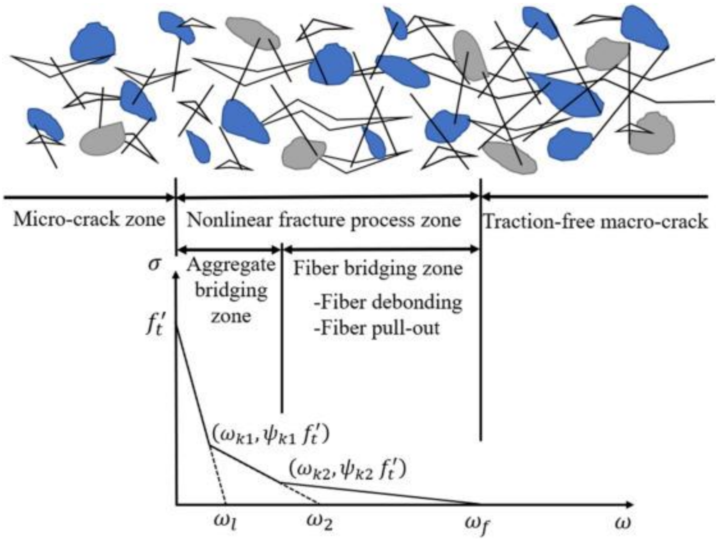

Figure-1: Fiber Bridging Mechanism

3.1 Microstructural Defects and Initiation of Cracks

Crack initiation in cementitious materials typically originates at microscopic flaws where local tensile stresses exceed the tensile strength of the matrix. These flaws may exist prior to loading or develop during hydration and curing.

3.1.1 Matrix Heterogeneity

Concrete is a multiphase composite consisting of aggregates embedded in a hydrated cement matrix, with the interfacial transition zone forming a mechanically weaker region around aggregates. Variations in stiffness and strength between these phases create localized stress concentrations under applied loads. The ITZ, characterized by higher porosity and micro cracking, often acts as the preferential site for crack nucleation (Scrivener et al., 2004). Microcracks initiate within this zone and gradually coalesce under increasing tensile stresses, leading to visible macrocrack formation. The stochastic distribution of flaws and aggregate geometry significantly influences crack trajectory and fracture energy (Bazant and Planas, 1998).

3.1.2 Shrinkage and Curing Effects

Early-age cracking may occur due to autogenous and drying shrinkage, especially in low water–cement ratio high-strength concretes. Chemical shrinkage during hydration and moisture gradients during curing generate internal tensile stresses, which may exceed the early tensile capacity of the matrix (Neville, 2011). Improper curing exacerbates these stresses, promoting microcrack development even before external loading is applied. These pre-existing microcracks reduce effective stiffness and serve as initiation sites for subsequent crack propagation under flexural or tensile loading.

3.2 Modes of Crack Propagation

Crack propagation in cementitious materials depends on the type of loading and the stress state within the structural element. Fracture mechanics principles classify crack growth according to dominant stress modes.

3.2.1 Flexural Cracking

Under flexural loading, tensile stresses develop at the extreme tension fiber of a beam or slab. Once the tensile strength of the matrix is exceeded, cracks initiate perpendicular to the principal tensile stress direction. Flexural cracks typically propagate vertically from the tension zone toward the neutral axis. As loading increases, crack widening and localization occur, eventually leading to unstable fracture if not restrained by reinforcement or fibers. The load–deflection response is governed by fracture energy and post-peak softening behavior (Hillerborg et al., 1976).

3.2.2 Direct Tensile Cracking

In uniaxial tension, cracks form when the applied stress surpasses the tensile capacity of the matrix. Crack propagation is generally rapid due to limited stress redistribution capability in plain concrete. The stress–strain curve exhibits a sharp post-peak drop, reflecting brittle fracture. In fiber-reinforced systems, bridging stresses develop across crack faces, modifying propagation kinetics and enhancing ductility (Naaman, 2003).

3.2.3 Shear Cracking

Shear cracks develop under combined shear and bending stresses and are typically inclined relative to the longitudinal axis of the member. These cracks result from principal tensile stresses exceeding the tensile strength of the material. Shear cracking is often more complex due to aggregate interlock, dowel action, and frictional resistance mechanisms. In high-strength matrices, reduced aggregate interlock may accelerate shear crack propagation (Mindess et al., 2003).

3.3 Influence of High-Strength Matrix on Cracking Behavior

The mechanical characteristics of high-strength cementitious matrices significantly influence crack initiation and propagation mechanisms.

3.3.1 Brittleness and Reduced Fracture Energy

Although high-strength concrete exhibits improved compressive performance and reduced porosity, it often demonstrates increased brittleness due to its dense microstructure and reduced microcrack redistribution capacity. The fracture process zone becomes narrower, limiting energy dissipation prior to failure. As compressive strength increases, tensile strain capacity and fracture energy do not increase proportionally, leading to sudden crack localization (Shah et al., 1995). Furthermore, the stronger bond between aggregates and matrix in high-strength systems may shift crack propagation from the ITZ into the aggregate itself, resulting in more abrupt fracture behavior. Consequently, high-strength matrices require external toughening mechanisms—such as fiber reinforcement—to enhance crack arrest capability and ensure stable crack growth under progressive flexural loading.

4. TIME-DEPENDENT BEHAVIOR OF CEMENTITIOUS COMPOSITES

Time-dependent phenomena significantly influence the long-term mechanical performance of cementitious composites subjected to sustained or progressive loading. Unlike purely elastic materials, cement-based systems exhibit rheological behavior due to the viscoelastic nature of hydrated cement paste and ongoing microstructural evolution. Under flexural loading, time-dependent effects alter stress redistribution, crack growth kinetics, and fiber–matrix interaction mechanisms. Therefore, understanding creep, environmental exposure, and long-term degradation is essential for evaluating crack arrest performance in hybrid fiber reinforced high-strength composites.

4.1 Creep and Relaxation Phenomena

Creep and stress relaxation are fundamental rheological characteristics of cementitious materials that influence deformation and stress transfer over time.

4.1.1 Definitions and Mechanical Implications

Creep refers to the gradual increase in strain under sustained stress, whereas relaxation denotes the gradual reduction in stress under constant strain conditions. In cementitious composites, creep arises primarily from viscous flow within the calcium silicate hydrate (C–S–H) gel and microstructural rearrangements at the nano- and micro-scales (Bazant and Baweja, 2000). Under sustained flexural loading, tensile creep in the tension zone can accelerate crack opening and reduce stiffness. This time-dependent deformation modifies the stress distribution between matrix and fibers, potentially reducing fiber bridging stress if interfacial slip occurs. High-strength matrices typically exhibit lower creep strain than normal-strength concrete; however, the reduced fracture process zone may intensify crack localization under long-term loading (Aïtcin, 2000). Consequently, creep directly affects crack arrest mechanisms by altering crack tip stress intensity and fiber pull-out resistance over time.

4.2 Environmental Influences

Environmental exposure plays a critical role in the time-dependent performance of cementitious composites by influencing moisture transport, thermal expansion, and chemical stability.

4.2.1 Temperature Effects

Elevated temperatures accelerate hydration reactions and moisture evaporation, potentially increasing shrinkage-induced stresses and micro crack formation. Thermal gradients generate differential expansion between aggregates and matrix, producing internal stresses that may initiate or propagate cracks (Mehta and Monteiro, 2014). Long-term exposure to fluctuating temperatures can also affect the mechanical properties of fibers and interfacial bond strength, thereby modifying crack bridging efficiency.

4.2.2 Humidity and Moisture Diffusion

Relative humidity strongly influences creep and shrinkage behavior. Drying conditions promote moisture diffusion from capillary pores, resulting in drying shrinkage and microcracking. Conversely, saturated conditions may reduce shrinkage but increase susceptibility to chemical degradation mechanisms. Moisture movement within the pore network contributes to time-dependent deformation through capillary tension and disjoining pressure effects (Neville, 2011). In fiber reinforced systems, repeated wet–dry cycles can alter fiber–matrix adhesion, affecting long-term crack control capacity.

4.3 Time-Dependent Degradation Mechanisms

Beyond rheological deformation, cementitious composites experience progressive microstructural degradation that influences crack growth and arrest behavior.

4.3.1 Micro-Crack Coalescence

Under sustained or cyclic flexural loading, distributed microcracks gradually coalesce into dominant macrocracks. This process is governed by subcritical crack growth mechanisms, where crack propagation occurs even when stress intensity remains below the instantaneous fracture toughness threshold (Shah et al., 1995). Time-dependent crack extension reduces effective stiffness and accelerates damage accumulation. In high-strength matrices with limited energy dissipation capacity, microcrack coalescence may occur more abruptly once critical conditions are reached.

4.3.2 Aging Effects in the Fiber–Matrix Interface

The fiber–matrix interfacial transition zone evolves over time due to continued hydration, shrinkage, and environmental exposure. Chemical interactions in alkaline pore solutions may influence bond characteristics, particularly for mineral fibers. Long-term exposure can modify interfacial frictional resistance, affecting fiber pull-out behavior and bridging stress development (Bentur and Mindess, 2007). In hybrid systems, differential aging between steel and basalt fibers may alter the balance between micro- and macrocrack control mechanisms. Such changes directly impact the efficiency of crack arrest under progressive flexural loading conditions.

5. CRACK ARREST MECHANISMS IN FIBER REINFORCED COMPOSITES

Crack arrest in fiber reinforced cementitious composites is governed by a combination of micro-mechanical and fracture mechanics-based mechanisms that operate across multiple length scales. In high-strength matrices, where intrinsic brittleness reduces the size of the fracture process zone, fiber reinforcement plays a decisive role in stabilizing crack growth. Hybrid fiber systems, particularly steel–basalt combinations, enhance resistance to crack initiation, propagation, and localization through complementary mechanical interactions. This section synthesizes the principal mechanisms responsible for crack arrest under progressive flexural loading.

5.1 Fiber Bridging Effect

5.1.1 Mechanism and Significance

Fiber bridging is the primary mechanism through which discrete fibers resist crack opening. When a crack forms, fibers intersecting the crack plane transfer tensile stresses across crack faces, thereby reducing the effective stress intensity at the crack tip. This bridging stress counteracts crack opening displacement and increases the composite's fracture energy. The development of a bridging stress–crack opening relationship (σ–w curve) governs post-cracking behavior and determines whether crack propagation remains stable or unstable (Hillerborg et al., 1976). In high-strength cementitious composites, fiber bridging transforms brittle fracture into a more ductile response by enabling gradual stress redistribution rather than sudden failure.

5.1.2 Role of Fiber Volume Fraction

The efficiency of crack bridging depends strongly on fiber volume fraction, orientation, and aspect ratio. Increased fiber content enhances the probability of fibers intersecting potential crack planes, thereby increasing bridging stress and residual strength. However, excessive fiber dosage may impair workability and induce fiber clustering, reducing mechanical efficiency. Optimal fiber volume fractions create a balance between mechanical performance and dispersion quality, enabling distributed cracking and improved energy absorption (Naaman, 2003).

5.2 Pull-Out Resistance and Energy Dissipation

5.2.1 Influence of Fiber Type and Surface Treatment

Pull-out resistance governs the energy dissipation capacity of fiber reinforced composites. When crack opening occurs, fibers either rupture or undergo progressive debonding and pull-out. Controlled pull-out is generally preferred, as it dissipates significant energy through frictional sliding and mechanical anchorage. Steel fibers with hooked or deformed ends exhibit enhanced mechanical interlock, increasing pull-out load and toughness (ACI Committee 544, 2002). Basalt fibers, owing to their smaller diameter and relatively smooth surface, primarily contribute through frictional resistance and chemical bonding. Surface treatments or coatings can further modify interfacial bond strength, influencing crack arrest efficiency. The balance between bond strength and slip capacity determines whether the composite exhibits strain-hardening or softening behavior.

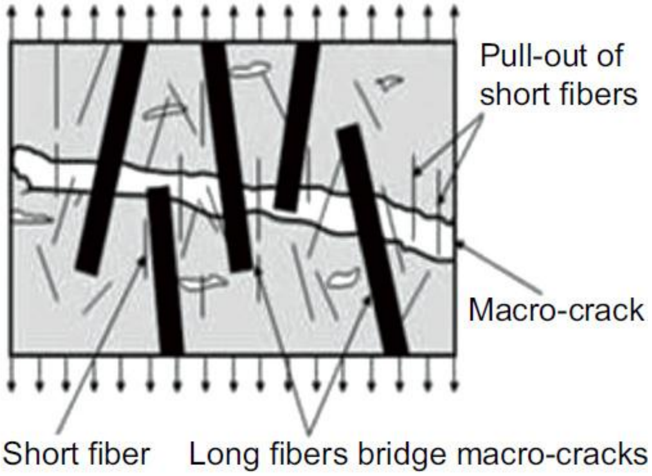

Figure-2: Pull-Out and Macro-Crack Interaction

5.3 Stress Redistribution and Crack Tip Shielding

5.3.1 Contribution of Hybrid Fibers

Stress redistribution refers to the ability of fibers to transfer tensile stresses away from highly stressed regions, thereby reducing crack tip stress intensity. This phenomenon, often termed crack tip shielding, lowers the effective driving force for crack propagation. In hybrid systems, basalt fibers control early-stage microcracks, while steel fibers engage at larger crack widths to provide macro-level bridging. The multi-scale reinforcement enhances the size and effectiveness of the fracture process zone, resulting in improved crack stability (Bentur and Mindess, 2007). Such synergistic action reduces crack localization under flexural loading and increases residual load-bearing capacity.

5.4 Microcrack Deflection and Crack Path Tortuosity

5.4.1 Interaction between Matrix, Steel, and Basalt Fibers

Crack deflection occurs when propagating cracks encounter inclusions such as aggregates or fibers, causing deviation from a straight path. Increased crack path tortuosity raises the fracture surface area and energy required for propagation. In hybrid composites, basalt fibers dispersed at the micro-scale disrupt crack continuity at early stages, while steel fibers impose mechanical constraints at larger scales. This interaction produces distributed microcracking rather than a single dominant crack. The heterogeneous microstructure enhances aggregate interlock and frictional resistance, increasing overall fracture energy (Mindess et al., 2003). Consequently, crack propagation becomes more gradual and controlled.

5.5 Time-Dependent Aspects of Crack Arrest

5.5.1 Delayed Crack Propagation

Under sustained or progressive flexural loading, crack growth may occur through subcritical propagation mechanisms even when instantaneous stress levels remain below peak capacity. Fiber bridging delays crack extension by reducing crack opening rates and distributing stresses over time. The gradual mobilization of fiber pull-out resistance provides resistance against delayed crack instability. Time-dependent fracture models indicate that fiber reinforcement increases the critical energy release rate required for sustained crack growth (Bazant and Planas, 1998).

5.5.2 Creep Retardation by Fiber Reinforcement

Fiber reinforcement also influences tensile creep behavior within the cracked zone. Fibers restrain crack widening under sustained loading, thereby limiting creep-induced strain accumulation. Steel fibers, due to their high stiffness, are particularly effective in reducing long-term deflection in flexural members, while basalt fibers enhance microcrack stability during early stages of sustained loading.

6. PROGRESSIVE FLEXURAL LOADING: BEHAVIOR AND RESPONSE

Progressive flexural loading is a critical assessment method for evaluating fracture performance and crack arrest mechanisms in cementitious composites. Unlike monotonic short-term tests, progressive loading—whether incremental static or cyclic—allows detailed observation of crack initiation, propagation stability, stiffness degradation, and residual load-carrying capacity. In high-strength cementitious composites reinforced with hybrid fibers, flexural response provides insight into multi-scale crack control and time-dependent performance.

6.1 Flexural Loading Protocols in Literature

Experimental methodologies adopted in the literature significantly influence the interpretation of fracture behavior. Flexural performance is typically assessed using three-point or four-point bending tests under displacement-controlled loading.

6.1.1 Static-Incremental Loading

In static-incremental loading, the load or displacement is gradually increased in steps, allowing measurement of crack mouth opening displacement (CMOD), mid-span deflection, and load redistribution after each increment. This approach facilitates observation of crack stabilization and fiber bridging development. The fictitious crack model proposed by Hillerborg and colleagues forms the theoretical basis for interpreting softening behavior in such tests (Hillerborg et al., 1976). Incremental protocols are particularly useful for identifying transition points from elastic response to cracking and from stable to unstable crack growth.

6.1.2 Cyclic Loading

Cyclic flexural loading introduces repeated load–unload sequences to simulate service conditions such as traffic or wind-induced vibrations. Under cyclic regimes, stiffness degradation and progressive crack widening can be monitored. Fatigue-induced microcrack accumulation often precedes macrocrack formation, especially in brittle high-strength matrices. Repeated loading also affects fiber–matrix bond integrity, influencing pull-out resistance and residual strength (Mindess et al., 2003). Cyclic protocols therefore provide insight into durability and crack arrest efficiency under realistic loading scenarios.

6.2 Flexural Toughness and Post-Peak Behavior

The flexural response of fiber reinforced composites is characterized not only by peak load but also by post-peak load retention and energy absorption capacity.

6.2.1 Evaluation Parameters

Crack Mouth Opening Displacement (CMOD) is widely used to quantify crack propagation under controlled fracture tests. The load–CMOD curve enables determination of fracture energy, defined as the area under the curve normalized by ligament area. Residual flexural strength, often measured at specified CMOD levels or deflection values, indicates the effectiveness of fiber bridging after matrix cracking. Standardized guidelines such as those from RILEM provide procedures for evaluating toughness indices and residual performance (RILEM TC 162-TDF, 2003). These parameters are particularly relevant for high-strength matrices where post-peak brittleness is otherwise pronounced.

6.2.2 Post-Peak Softening and Hardening Behavior

Plain high-strength concrete typically exhibits abrupt post-peak softening due to rapid crack localization. In contrast, fiber reinforcement modifies this response, potentially leading to strain-hardening or gradual softening depending on fiber dosage and bond characteristics. The shape of the descending branch in the load–deflection curve reflects crack stability and energy dissipation capacity. Enhanced post-peak ductility indicates improved crack arrest efficiency and greater resistance to catastrophic failure (Shah et al., 1995).

6.3 Influence of Hybrid Fibers on Flexural Performance

6.3.1 Comparison with Single Fiber Systems

Hybrid fiber systems demonstrate superior flexural performance compared to mono-fiber composites due to complementary crack control mechanisms. Steel fibers significantly enhance peak load and residual strength by bridging macrocracks, while basalt fibers improve microcrack distribution and delay crack initiation. Studies on hybrid reinforcement indicate improved fracture energy and reduced crack width compared to systems reinforced solely with steel or mineral fibers (Banthia and Gupta, 2004). The synergistic interaction increases the size of the fracture process zone and stabilizes crack growth under progressive loading. Moreover, hybrid systems often exhibit reduced deflection growth under sustained loads due to combined stiffness contribution and improved bond characteristics. Such performance enhancements are particularly beneficial for structural elements subjected to serviceability limit states governed by crack width control.

7. LITERATURE REVIEW: COMPARATIVE ANALYSIS

A rigorous review paper must not merely describe prior studies but critically synthesize their findings, identify methodological trends, and highlight unresolved research questions. This section comparatively evaluates published work on steel fiber, basalt fiber, and hybrid steel–basalt reinforced high-strength cementitious composites, with particular emphasis on flexural performance and time-dependent crack arrest mechanisms.

7.1 Summary of Key Studies on Steel Fiber Reinforced Composites

Steel fiber reinforced concrete (SFRC) has been extensively investigated over the past decades, particularly for enhancing post-cracking ductility and fracture toughness.

7.1.1 Authors, Materials and Principal Findings

Early fracture mechanics-based studies demonstrated that the addition of hooked-end steel fibers significantly increases fracture energy and residual flexural strength compared to plain high-strength concrete (Shah et al., 1995). Subsequent experimental programs reported that fiber aspect ratio and volume fraction strongly influence crack bridging stress and post-peak load retention (ACI Committee 544, 2002).

7.2 Summary of Key Studies on Basalt Fiber Reinforced Composites

Basalt fiber reinforced concrete (BFRC) has gained attention more recently due to its mineral origin, corrosion resistance, and environmental compatibility.

7.2.1 Comparative Mechanical Performance

Experimental investigations indicate that basalt fibers are particularly effective in controlling plastic shrinkage and early-age microcracking (Sim et al., 2005). Flexural strength improvements are typically moderate compared to steel fibers; however, crack distribution is more uniform and crack widths are reduced. Research on durability performance has shown improved resistance to alkali and thermal degradation compared to glass fibers (Fiore et al., 2015). Despite these advantages, basalt fibers alone may not provide sufficient post-peak load-carrying capacity in high-strength matrices due to their relatively lower modulus compared to steel. Consequently, while BFRC enhances serviceability performance, its contribution to macrocrack arrest under high flexural loads remains limited in comparison with metallic fiber systems.

7.3 Hybrid Fiber Systems: Steel–Basalt Composites

Hybrid fiber systems combine the advantages of macro-scale steel fibers and micro-scale basalt fibers to achieve multi-level crack control.

7.3.1 Observed Trends and Synergistic Effects

Hybridization studies report improved fracture energy and more stable crack propagation compared to mono-fiber systems (Banthia and Gupta, 2004). Steel fibers primarily enhance residual flexural strength, whereas basalt fibers delay crack initiation and reduce crack spacing. Experimental comparisons show that hybrid composites often exhibit improved load–deflection response and greater energy absorption capacity than single-fiber mixtures at equivalent total fiber volume fractions.

7.3.2 Gaps and Conflicting Findings

Despite promising results, inconsistencies exist in reported improvements. Some investigations indicate only marginal synergistic benefits when fiber proportions are not optimally balanced. Variations in fiber length, orientation distribution, and interfacial bonding conditions significantly influence results. Additionally, most studies focus on short-term mechanical performance, with limited attention to sustained loading or long-term crack growth behavior. The absence of standardized hybridization ratios further complicates cross-study comparisons.

7.4 Time Dependency in Flexural Behavior from Literature

Time-dependent flexural performance remains comparatively underexplored in hybrid fiber systems.

7.4.1 Approaches to Time-Dependent Assessment

Studies on tensile creep in fiber reinforced composites demonstrate that fibers restrain crack widening under sustained loading by providing continuous bridging stresses (Bazant and Baweja, 2000). Investigations into long-term deflection behavior of steel fiber reinforced beams report reduced creep-induced curvature compared to plain concrete members (Aïtcin, 2000). However, limited research specifically addresses hybrid steel–basalt systems under progressive flexural loading. Existing studies often rely on short-duration monotonic tests, neglecting subcritical crack growth and interfacial aging effects. This indicates a significant research gap concerning delayed crack propagation and long-term fracture stability.

8. CONCLUSION

This review critically examined the time-dependent crack arrest mechanisms in steel–basalt hybrid fiber reinforced high-strength cementitious composites subjected to progressive flexural loading. The synthesis of existing literature demonstrates that crack propagation in high-strength matrices is governed by brittle fracture behavior, reduced fracture process zone width, and limited intrinsic energy dissipation capacity. The incorporation of hybrid fibers effectively modifies this response through multi-scale crack control mechanisms. Basalt fibers primarily restrain microcrack initiation and delay crack coalescence, whereas steel fibers provide macrocrack bridging, enhanced pull-out resistance, and improved residual flexural strength. The interaction between these fibers promotes stress redistribution, crack tip shielding, and increased fracture energy, leading to more stable crack growth under monotonic and cyclic flexural loading.

Time-dependent effects, including creep, environmental exposure, and interfacial aging, significantly influence long-term crack stability. Fiber reinforcement mitigates creep-induced crack widening and sustains bridging stresses, thereby improving serviceability performance. However, current research largely emphasizes short-term mechanical response, with limited comprehensive evaluation of sustained or progressive loading conditions in hybrid systems. Overall, steel–basalt hybridization presents a promising strategy for enhancing fracture stability and durability in high-strength cementitious composites, particularly in structural members governed by flexural performance and crack width control.

9. LIMITATIONS OF THE REVIEW

This review is limited to published experimental and analytical studies available in indexed literature, which may not fully represent ongoing industrial or unpublished research developments. Variations in specimen size, testing configurations, fiber geometry, and evaluation parameters across studies restrict direct quantitative comparison. Additionally, limited long-term experimental data on sustained flexural loading in steel–basalt hybrid systems constrain the depth of time-dependent analysis. The review focuses primarily on mechanical and fracture behavior, while chemical degradation, durability under aggressive environments, and life-cycle assessment aspects are discussed only briefly. Finally, due to inconsistencies in reporting standards, some interpretations rely on qualitative synthesis rather than uniform statistical evaluation. Further standardized experimental frameworks are necessary for more conclusive comparative assessments.

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