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

Surydeep Maurya[1], Mr. Ushendra Kumar[2]

[1]Master of Technology, Civil Engineering, Lucknow Institute of Technology, Lucknow, India
[2]Head of Department, Department of Civil Engineering, Lucknow Institute of Technology, Lucknow, India

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Abstract *High-strength cementitious composites (HSCC) are widely used in modern infrastructure due to their superior compressive strength; however, their inherent brittleness and susceptibility to cracking under flexural loading remain critical challenges. This study investigates the time-dependent crack arrest mechanisms in steel–basalt hybrid fiber reinforced HSCC subjected to progressive flexural loading. An experimental program was conducted using beam specimens with varying proportions of steel and basalt fibers to evaluate their individual and synergistic effects on crack behavior. Progressive displacement-controlled loading was applied to simulate realistic structural conditions and to capture crack initiation, propagation, and arrest over time. Crack development was monitored using visual mapping and crack width measurements, while load–deflection responses were recorded to assess flexural performance and toughness. The results indicate that hybrid fiber systems significantly delay crack initiation and reduce crack propagation rates compared to mono-fiber and control mixes. Steel fibers primarily contribute to macro-crack bridging and post-cracking strength, whereas basalt fibers effectively control micro-crack initiation and distribution. The combined action results in enhanced crack arrest capability, improved energy absorption, and increased ductility. The study demonstrates that optimized hybrid fiber combinations can substantially improve the durability and structural performance of HSCC under progressive flexural loading conditions.*

***Key Words*: Hybrid fibers; Steel fiber; Basalt fiber; Crack arrest; Time-dependent behavior; Flexural loading**

1. INTRODUCTION

1.1 Background

1.1.1 High-Strength Cementitious Composites (HSCC) and Brittleness Issues

High-strength cementitious composites (HSCC) have gained widespread acceptance in modern civil engineering applications due to their superior compressive strength, dense microstructure, and enhanced durability characteristics. These materials are typically designed with low water–cement ratios and supplementary cementitious materials such as silica fume, which contribute to improved mechanical performance and reduced permeability. However, despite these advantages, HSCC inherently exhibits brittle behavior, characterized by low tensile strength and limited deformation capacity. Under flexural loading conditions, tensile stresses develop in the tension zone, leading to the initiation and rapid propagation of cracks. Unlike conventional concrete, the high stiffness and reduced internal microcracking capacity of HSCC often result in sudden failure without significant warning, posing challenges in structural safety and serviceability (Neville, 2011; Mehta and Monteiro, 2014).

1.1.2 Importance of Crack Control in Structural Durability

Crack control is a critical aspect in ensuring the long-term durability and performance of concrete structures. Cracks serve as primary pathways for the ingress of aggressive agents such as water, chlorides, and sulfates, which can lead to reinforcement corrosion, chemical degradation, and reduction in structural integrity. In high-strength composites, where permeability is otherwise low, the presence of cracks significantly compromises durability. Effective crack control not only enhances service life but also reduces maintenance costs and improves structural reliability. Therefore, mitigating crack initiation and controlling crack propagation under loading conditions are essential for achieving sustainable and durable infrastructure systems (Bentur and Mindess, 2007).

1.2 Fiber Reinforcement in Concrete

1.2.1 Steel Fibers → Macro-Crack Control

Steel fibers are widely used in cementitious composites due to their high tensile strength, modulus of elasticity, and ability to improve post-cracking behavior. When incorporated into concrete, steel fibers act as crack-bridging elements that transfer tensile stresses across crack surfaces. This mechanism significantly enhances resistance against macro-crack propagation, which typically occurs after initial cracking. The pull-out resistance and mechanical anchorage of steel fibers contribute to increased energy absorption and improved ductility. As a result, steel fiber reinforced concrete exhibits enhanced load-carrying capacity even after crack formation, thereby transforming the brittle nature of concrete into a more ductile response (Naaman, 2003).

1.2.2 Basalt Fibers → Micro-Crack Control

Basalt fibers, derived from natural volcanic rock, have emerged as an effective reinforcement material due to their high tensile strength, chemical stability, and resistance to corrosion. Owing to their fine diameter and uniform dispersion within the cement matrix, basalt fibers are particularly effective in controlling micro-crack initiation at early stages of loading. These fibers reduce stress concentration within the matrix and delay the formation of visible cracks. Additionally, basalt fibers promote the development of multiple fine cracks rather than a single dominant crack, thereby improving crack distribution and enhancing durability. Their role is especially significant in improving the initial cracking resistance and overall integrity of the composite (Sim et al., 2005).

1.3 Hybrid Fiber Concept

1.3.1 Synergistic Multi-Scale Crack Resistance

The concept of hybrid fiber reinforcement involves the use of two or more types of fibers with different mechanical and geometrical properties to achieve enhanced composite performance. In steel–basalt hybrid systems, the complementary behavior of fibers enables crack control at multiple scales. Basalt fibers operate at the micro-level by delaying crack initiation and controlling early-stage crack growth, while steel fibers become effective at later stages by bridging and arresting macro-cracks. This multi-scale reinforcement mechanism ensures continuous resistance to crack propagation throughout the loading process, resulting in improved toughness, ductility, and fracture resistance (Banthia and Gupta, 2004).

1.3.2 Need for Combined Performance

Single-fiber systems often fail to provide comprehensive crack control due to their limitation in addressing different stages of crack development. While steel fibers are effective in controlling large cracks, they are less efficient in preventing micro-crack formation. Conversely, basalt fibers excel in early-stage crack control but lack the stiffness required to arrest wider cracks. Therefore, combining these fibers in a hybrid system is necessary to achieve balanced performance across all stages of cracking. This combined approach enhances both structural performance and durability, making hybrid fiber reinforced composites a promising solution for advanced construction applications (Yoo and Banthia, 2016).

1.4 Research Gap

1.4.1 Limited Studies on Time-Dependent Crack Propagation

Although extensive research has been conducted on fiber reinforced concrete, most studies focus on instantaneous mechanical properties rather than the time-dependent evolution of cracks. The progressive nature of crack development under sustained or incremental loading conditions is not fully understood, particularly in hybrid fiber systems. There is a lack of experimental data capturing crack growth rates, delay in crack initiation, and crack arrest duration over time, which are critical for evaluating long-term performance (Mindess et al., 2003).

1.4.2 Progressive Flexural Loading

The majority of existing studies employ monotonic loading conditions, which do not accurately represent real structural behavior where loads are applied gradually or cyclically. Progressive flexural loading provides a more realistic simulation of in-service conditions, allowing detailed observation of crack initiation and propagation stages. However, limited research has been conducted using such loading techniques, especially for high-strength hybrid fiber composites.

1.4.3 Steel–Basalt Hybrid Interaction Mechanisms

While hybrid fiber systems have shown promising results, the specific interaction mechanisms between steel and basalt fibers in controlling crack evolution are not well established. The synergistic behavior, optimal fiber proportions, and their influence on crack arrest efficiency require systematic investigation. Understanding these mechanisms is essential for optimizing mix design and improving structural performance, which remains an important research gap addressed in this study (Yoo et al., 2017).

2. LITERATURE REVIEW

2.1 Behavior of Plain Concrete under Flexure

2.1.1 Crack Initiation and Brittle Failure

Plain concrete exhibits inherently weak tensile properties, which significantly influence its behavior under flexural loading. When subjected to bending, tensile stresses develop at the bottom fibers of a beam, leading to the initiation of micro-cracks at locations of stress concentration, particularly within the interfacial transition zone (ITZ) between aggregates and cement paste. These micro-cracks, often present even before loading due to shrinkage and thermal effects, gradually propagate and coalesce into macro-cracks as the load increases. Due to the absence of internal reinforcement mechanisms, crack growth in plain concrete is rapid and unstable, resulting in sudden brittle failure with minimal warning. This lack of post-cracking load-carrying capacity and energy absorption makes plain concrete unsuitable for applications requiring ductility and crack resistance (Neville, 2011; Mehta and Monteiro, 2014).

2.2 Steel Fiber Reinforced Concrete (SFRC)

2.2.1 Crack Bridging and Pull-Out Mechanisms

Steel Fiber Reinforced Concrete (SFRC) incorporates discrete steel fibers within the cementitious matrix to improve its tensile and flexural performance. The primary mechanism by which steel fibers enhance concrete behavior is through crack bridging. When a crack forms, fibers intersecting the crack plane carry tensile stresses across the crack faces, thereby delaying crack opening and propagation. As loading progresses, fibers undergo pull-out or rupture, during which significant energy is dissipated. The pull-out mechanism, governed by fiber–matrix bond strength and mechanical anchorage (such as hooked ends), contributes to improved toughness and ductility. This process transforms the brittle nature of concrete into a more ductile response, allowing the material to sustain loads even after cracking (Naaman, 2003).

2.2.2 Limitations in Micro-Crack Control

Despite their effectiveness in controlling macro-cracks, steel fibers have limited efficiency in preventing the initiation of micro-cracks. This limitation is primarily due to their relatively larger diameter and lower dispersion density within the matrix. As a result, micro-cracks may form and propagate before the fibers become fully effective in bridging larger cracks. This early-stage cracking can still compromise durability and structural integrity, indicating that steel fibers alone may not provide comprehensive crack control across all stages of loading (Mindess et al., 2003).

2.3 Basalt Fiber Reinforced Concrete (BFRC)

2.3.1 Micro-Crack Control and Durability Benefits

Basalt Fiber Reinforced Concrete (BFRC) has emerged as a promising alternative due to the favorable mechanical and chemical properties of basalt fibers. These fibers are characterized by fine diameter, high tensile strength, and excellent resistance to chemical attack and temperature variations. Their small size allows for uniform dispersion within the cement matrix, making them highly effective in controlling micro-crack initiation at early stages of loading. By reducing stress concentrations and interrupting crack formation, basalt fibers delay the onset of visible cracking and promote a more distributed crack pattern. Additionally, their resistance to corrosion enhances the durability of concrete structures, especially in aggressive environmental conditions (Sim et al., 2005).

2.3.2 Limitations in Macro-Crack Resistance

Although basalt fibers are effective in controlling micro-cracks, they exhibit limitations in resisting macro-crack propagation. Due to their relatively lower stiffness and pull-out resistance compared to steel fibers, basalt fibers are less capable of bridging wider cracks that develop at later stages of loading. Consequently, once macro-cracks form, the ability of basalt fibers to prevent rapid crack widening is limited. This shortcoming highlights the need for combining basalt fibers with stronger reinforcement elements to achieve comprehensive crack control (Yoo and Banthia, 2016).

2.4 Hybrid Fiber Reinforced Systems

2.4.1 Synergistic Effects

Hybrid fiber reinforced systems involve the use of multiple fiber types with different properties to achieve enhanced composite performance. The combination of steel and basalt fibers provides a synergistic effect, where each fiber type contributes at different stages of crack development. Basalt fibers act at the micro-level by controlling early-stage crack initiation, while steel fibers operate at the macro-level by bridging and arresting larger cracks. This complementary action results in improved crack resistance across multiple scales, enhancing overall structural performance. The synergy between fibers leads to more efficient stress redistribution and improved fracture resistance compared to mono-fiber systems (Banthia and Gupta, 2004).

2.4.2 Improvement in Toughness and Ductility

The incorporation of hybrid fibers significantly improves the toughness and ductility of cementitious composites. Toughness, defined as the energy absorption capacity of a material, is enhanced due to the combined effects of fiber bridging, pull-out, and crack deflection mechanisms. Hybrid systems exhibit a larger area under the load–deflection curve, indicating higher energy dissipation before failure. Additionally, the presence of multiple fiber types results in a more gradual and controlled failure process, improving deformation capacity and reducing the risk of sudden collapse. This enhanced ductility is particularly beneficial in structural applications subjected to dynamic or progressive loading conditions (Yoo et al., 2017).

2.5 Time-Dependent Crack Behavior

2.5.1 Crack Initiation → Propagation → Failure Stages

Crack development in cementitious composites under loading is a time-dependent process that evolves through distinct stages. Initially, micro-cracks form due to stress concentrations and inherent material defects. As loading continues, these micro-cracks propagate and coalesce into larger cracks in a stable manner, leading to gradual stiffness degradation. In the final stage, macro-cracks dominate and propagate rapidly, resulting in failure. This progression from initiation to failure is influenced by material properties, loading conditions, and internal microstructure. Understanding these stages is essential for evaluating structural performance and predicting failure behavior (Mehta and Monteiro, 2014).

2.5.2 Role of Fibers in Delaying Crack Growth

Fibers play a crucial role in modifying time-dependent crack behavior by interacting with developing cracks and altering their growth patterns. They increase the fracture energy of the composite, making it more resistant to crack propagation. Fiber bridging delays crack opening, while pull-out mechanisms dissipate energy and reduce crack growth rates. Additionally, fibers can cause crack deflection and branching, increasing the effective crack path and further resisting propagation. In hybrid systems, this effect is amplified due to the combined action of different fiber types, resulting in delayed crack initiation, reduced propagation rate, and enhanced crack arrest capability. These mechanisms contribute to improved durability, ductility, and long-term structural performance (Bentur and Mindess, 2007).

3. MATERIALS AND METHODS

High-strength cementitious composites were prepared using OPC 53 cement, well-graded fine and coarse aggregates, silica fume, and a superplasticizer to achieve adequate workability at a low water–cement ratio. Hooked-end steel fibers and basalt fibers were incorporated to provide macro- and micro-crack control, respectively. The mix design targeted a compressive strength of 60–80 MPa, and five different mixes were developed: M0 (control), M1 (1.0% steel), M2 (0.3% basalt), M3 (0.7% steel + 0.3% basalt), and M4 (0.5% steel + 0.5% basalt) to evaluate individual and hybrid fiber effects. Beam specimens of size 100 × 100 × 500 mm were cast using proper mixing and vibration techniques to ensure uniform fiber distribution, followed by water curing for 28 days. The experimental program included compressive strength testing and flexural strength evaluation using standard third-point loading as per ASTM C1609. Progressive flexural loading was applied under displacement-controlled conditions with incremental loading and holding stages to capture time-dependent crack behavior. Crack development was monitored using visual crack mapping, crack width measurements, and, where applicable, digital image analysis techniques to assess crack initiation, propagation, and arrest characteristics.

4. Results

4.1 Compressive Strength

4.1.1 Comparison Across Mixes

The compressive strength results for all mixes were obtained after 28 days of curing. The control mix (M0) exhibited the baseline compressive strength within the targeted range of high-strength concrete. The inclusion of steel fibers in mix M1 resulted in a marginal increase in compressive strength compared to M0. Similarly, the basalt fiber mix (M2) showed a slight improvement over the control specimen. Hybrid mixes M3 and M4 demonstrated comparatively higher compressive strength values than mono-fiber mixes. Among all specimens, mix M3 (0.7% steel + 0.3% basalt) recorded the highest compressive strength, followed by mix M4. The variation in compressive strength across mixes remained within a limited range, indicating that fiber addition had a moderate influence on compressive behavior.

4.2 Flexural Strength

4.2.1 Strength Enhancement Due to Fibers

Flexural strength results indicated a significant improvement in fiber-reinforced mixes compared to the control mix. The control specimen (M0) showed the lowest flexural strength and failed abruptly after crack initiation. Mix M1 (steel fiber) exhibited a noticeable increase in flexural strength due to enhanced crack-bridging capacity. Mix M2 (basalt fiber) showed moderate improvement over the control mix. Hybrid mixes M3 and M4 demonstrated the highest flexural strength values among all specimens. Mix M3 recorded the maximum enhancement, followed by M4, indicating improved load-carrying capacity under bending conditions.

4.3 Load–Deflection Behavior

4.3.1 Ultimate Deflection

The load–deflection curves revealed variations in deformation capacity among different mixes. The control mix (M0) exhibited the lowest ultimate deflection, indicating brittle behavior. Fiber-reinforced mixes showed increased deflection capacity before failure. Steel fiber mix (M1) demonstrated higher deflection compared to M0, while basalt fiber mix (M2) showed moderate improvement. Hybrid mixes M3 and M4 exhibited the highest ultimate deflection values, indicating enhanced deformation capacity.

4.3.2 Post-Cracking Response

Post-cracking behavior differed significantly across mixes. The control mix displayed a sudden drop in load after initial cracking. In contrast, fiber-reinforced mixes exhibited gradual load reduction beyond the first crack. Steel fiber mix showed a stable post-cracking response with sustained load capacity. Basalt fiber mix exhibited limited post-cracking resistance. Hybrid mixes demonstrated improved post-cracking performance, with extended load-carrying capacity and smoother load–deflection curves.

4.4 Crack Pattern

4.4.1 Control vs Mono vs Hybrid

Crack patterns varied noticeably among the mixes. The control mix (M0) developed a single dominant crack leading to sudden failure. The steel fiber mix (M1) exhibited fewer but wider cracks, indicating effective macro-crack bridging. The basalt fiber mix (M2) showed multiple fine cracks distributed along the tension zone. Hybrid mixes M3 and M4 displayed a combination of both behaviors, with multiple fine cracks and controlled crack widths. Crack distribution in hybrid specimens was more uniform compared to control and mono-fiber mixes.

4.5 Time-Dependent Crack Behavior

4.5.1 Crack Initiation Time

The time required for initial crack formation varied across mixes. The control mix exhibited the earliest crack initiation under loading. Fiber-reinforced mixes showed delayed crack initiation. Basalt fiber mix (M2) demonstrated greater delay compared to steel fiber mix (M1). Hybrid mixes M3 and M4 showed the longest crack initiation time among all specimens.

4.5.2 Crack Propagation Rate

The rate of crack propagation differed significantly between mixes. The control mix showed rapid crack growth after initiation. Steel fiber mix reduced the propagation rate due to crack-bridging effects. Basalt fiber mix exhibited slower initial crack growth. Hybrid mixes demonstrated the lowest crack propagation rates, with gradual crack development observed during loading.

4.5.3 Crack Arrest Duration

The duration for which cracks remained stable before further propagation was recorded as crack arrest duration. The control mix showed negligible crack arrest behavior. Fiber-reinforced mixes exhibited increased crack arrest duration. Steel fiber mix provided moderate crack arrest, while basalt fiber mix showed limited resistance at later stages. Hybrid mixes M3 and M4 exhibited the highest crack arrest duration, indicating improved resistance to crack growth over time.

5. CONCLUSIONS

This study investigated the time-dependent crack arrest mechanisms in steel–basalt hybrid fiber reinforced high-strength cementitious composites subjected to progressive flexural loading. The experimental results demonstrate that the incorporation of fibers significantly enhances both mechanical performance and crack resistance compared to plain concrete. Compressive strength showed only marginal variation with fiber addition, indicating that fibers primarily influence tensile and flexural behavior. In contrast, flexural strength improved considerably, with hybrid fiber mixes exhibiting the highest load-carrying capacity.

The load–deflection response revealed that fiber-reinforced composites possess superior deformation capacity and improved post-cracking behavior. Steel fibers contributed effectively to macro-crack bridging and sustained load resistance, whereas basalt fibers controlled micro-crack initiation and distribution. The hybridization of these fibers resulted in a synergistic effect, leading to enhanced toughness and ductility.

Crack pattern analysis indicated that hybrid mixes developed multiple fine cracks with controlled widths, as opposed to the single dominant crack observed in control specimens. Time-dependent observations further confirmed that hybrid fiber systems delayed crack initiation, reduced crack propagation rates, and increased crack arrest duration. Among all mixes, the combination of 0.7% steel and 0.3% basalt fibers demonstrated the most effective performance.

Overall, the study establishes that steel–basalt hybrid fiber reinforcement significantly improves crack arrest capability and structural performance of high-strength cementitious composites under progressive flexural loading conditions.

6. FUTURE SCOPE

Future research can extend this study by investigating the long-term durability performance of hybrid fiber reinforced composites under environmental exposure conditions such as freeze–thaw cycles, chloride ingress, and chemical attack. The influence of creep and shrinkage on time-dependent crack behavior also requires detailed examination. Advanced monitoring techniques, including digital image correlation (DIC) and acoustic emission analysis, can be employed for more precise crack tracking. Numerical modeling and finite element analysis may be developed to simulate crack propagation mechanisms and optimize fiber combinations. Additionally, exploring different fiber geometries, lengths, and hybrid ratios can help identify more efficient reinforcement strategies. Field-scale validation and application in real structural elements would further support the practical implementation of these composites.

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