

# Hybrid Fiber Engineered Cementitious Composites with CO<sub>2</sub> Curing: A Review on Mechanical Performance, Durability, and Sustainability

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## ABSTRACT

*Engineered Cementitious Composites (ECC) are high-performance materials known for their superior ductility, crack control, and durability; however, their high cement content raises environmental concerns. This review paper examines recent advancements in Hybrid Fiber Reinforced Engineered Cementitious Composites incorporating carbon dioxide (CO<sub>2</sub>) curing as a sustainable and green engineering solution for modern construction. The paper highlights CO<sub>2</sub> curing as an alternative to conventional water curing, emphasizing its ability to accelerate early-age strength development, improve microstructural density, and enable carbon sequestration within cementitious systems. Overall, the review concludes that hybrid fiber ECC with CO<sub>2</sub> curing offers enhanced mechanical properties, improved durability, and reduced environmental impact compared to conventional concrete. The integration of hybrid fiber technology with CO<sub>2</sub> curing aligns with sustainable construction practices and presents a promising, eco-friendly alternative for infrastructure development, particularly under the climatic and economic conditions of developing countries.*

**Keywords:-** Hybrid Fiber ECC, CO<sub>2</sub> Curing, PVA Fiber, PP, Mechanical Properties, Durability, Carbon Sequestration, Eco-Friendly Materials.

## 1. INTRODUCTION

Concrete remains the most widely used construction material due to its high compressive strength, durability, and adaptability to diverse structural applications. Nevertheless, conventional concrete exhibits inherently brittle behavior and low tensile strength, resulting in crack formation, durability degradation, and reduced service life of structures. These limitations have driven the development of advanced cementitious materials with enhanced tensile performance and damage tolerance.

Engineered Cementitious Composites (ECC) represent a class of high-performance fiber-reinforced concretes specifically designed to overcome the brittleness of conventional concrete. ECC exhibits strain-hardening behavior accompanied by the formation of multiple, tightly controlled microcracks instead of localized macrocracking. Tensile strain capacities of 2–5% and crack widths limited to less than 100 μm significantly improve durability by restricting the ingress of water, chlorides, and other aggressive agents, while enabling partial self-healing through continued hydration and carbonation processes. Owing to these characteristics, ECC has been successfully applied in bridge decks, pavements, repair overlays, and seismic-resistant structures requiring long-term performance and resilience.

The mechanical response of ECC is strongly influenced by fiber characteristics and fiber matrix interactions. Hybrid fiber systems, combining Polyvinyl Alcohol (PVA) and Polypropylene (PP) fibers, have gained increasing attention due to their synergistic effects on strength and durability. PVA fibers provide strong interfacial bonding with the cement matrix, promoting strain hardening and effective crack width control, while PP fibers enhance toughness, impact resistance, and resistance to plastic and drying shrinkage cracking. Compared to single-fiber ECC, hybrid systems offer improved stress redistribution and damage tolerance with reduced material cost.

In parallel, the environmental impact of cement production has intensified the search for sustainable curing and carbon-reduction strategies. CO<sub>2</sub> curing has emerged as a promising alternative to conventional water curing, where carbon dioxide reacts with calcium hydroxide to form calcium carbonate, resulting in pore refinement, matrix densification, and enhanced early-age strength. Moreover, CO<sub>2</sub> curing enables permanent sequestration of carbon dioxide, contributing to reduced embodied carbon in cement-based materials. Despite these

advantages, the combined influence of hybrid fiber reinforcement and CO<sub>2</sub> curing on ECC performance particularly using locally available Indian materials has not been comprehensively synthesized.

Accordingly, this review critically evaluates existing literature on hybrid fiber ECC and CO<sub>2</sub> curing, with emphasis on mechanical performance, crack control, durability, and sustainability. The review aims to identify performance trends, knowledge gaps, and future research directions for the development of optimized, eco-efficient ECC suitable for large-scale structural applications.

## 2. LITERATURE REVIEW

Engineered Cementitious Composites (ECC) have emerged as a transformative class of high-performance cementitious materials due to their exceptional ductility, crack control, and durability. Since the pioneering work of Victor C. Li (2003) [13], ECC has been recognized for its ability to undergo tensile strains of 2–5%, far exceeding the brittle behavior of conventional concrete. Subsequent large-scale validations by Li and his research team (2005) [12] demonstrated ECC's superior crack resistance, reduced life-cycle costs, and long-term structural reliability, establishing its feasibility for infrastructure applications.

Several studies have focused on improving the flexural performance of ECC structural elements. Chong Qui et al. (2025) [1] investigated layered ECC–concrete composite beams and reported significant improvements in crack resistance, flexural strength, and ductility, with minimal delamination at the interface. Their analytical models successfully predicted beam behavior, confirming ECC's compatibility with conventional concrete. Similarly, Zhao et al. (2025) [2] examined ECC slabs of varying strength grades and found that unreinforced ECC slabs achieved nearly 80% of the flexural capacity of reinforced slabs, highlighting ECC's potential to partially replace conventional reinforcement due to its superior strain-hardening behavior.

Fiber reinforcement plays a critical role in ECC performance. Studies by Al-Blairat et al. (2024) [5], Ganesh et al. (2018) [8], and Nandhini et al. (2017) [9] consistently identified an optimal PVA fiber content of approximately 1.5%, providing the best balance between compressive strength, flexural strength, and ductility. While Polyvinyl Alcohol (PVA) fibers enhance bonding and strain capacity, polypropylene fibers (PPF), as discussed by Telrandhe (2025) [3], contribute to toughness, crack resistance, and fire spalling control, though they lack strain-hardening capability. These findings support the growing interest in hybrid fiber ECC systems combining PVA and PP fibers to optimize performance and cost efficiency.

Recent research has emphasized sustainability through alternative curing methods. Luca Herian et al. (2023) [4] and Gilroy et al. (2020) [6] demonstrated that CO<sub>2</sub> curing and accelerated carbonation curing significantly improve early-age strength, densify the microstructure, and enable carbon sequestration. Solidia Technologies (2019) [7] further showed that combining innovative cement chemistry with CO<sub>2</sub> curing can reduce total CO<sub>2</sub> emissions by up to 70%, underscoring the environmental potential of carbonation-based curing. Ekolu (2016) [10] provided valuable insights into carbonation mechanisms, highlighting the influence of curing duration and cement type on carbonation efficiency.

Earlier technical reviews and reports [11] emphasized ECC's role in shifting concrete design philosophy from damage prevention to damage management, with additional benefits such as self-healing and extended service life. Overall, the literature confirms that hybrid fiber ECC combined with CO<sub>2</sub> curing represents a promising green engineering solution, offering enhanced mechanical performance, durability, and substantial reductions in environmental impact, making it highly suitable for sustainable infrastructure development.

## 3. PROBLEM STATEMENT

Engineered Cementitious Composites (ECC) offer superior ductility and durability, yet their large-scale adoption is limited due to high fiber costs, reliance on imported materials, and incompatibility with local aggregates. Additionally, cement production's environmental impact necessitates sustainable alternatives. The potential of CO<sub>2</sub> curing to enhance early strength while reducing carbon emissions in hybrid fiber ECC remains underexplored. This study aims to develop an optimized, sustainable ECC mix using locally available Indian materials under IS 12269, IS 383, IS 516, and ASTM C109/C1609 standards.

## 4. METHODOLOGY

This review systematically evaluates hybrid fiber Engineered Cementitious Composites (ECC) with CO<sub>2</sub> curing for sustainable construction. Relevant literature was collected from Scopus, Web of Science, and Google Scholar, focusing on ECC using Indian or comparable materials and referencing IS 12269, IS 383, IS 516, ASTM C109, and ASTM C1609 standards. Studies on material characterization, mix design, and hybrid fiber optimization (PVA, PP) were analyzed to assess effects on ductility, crack control, and mechanical performance. CO<sub>2</sub> curing mechanisms, process parameters, early-age strength enhancement, and carbon sequestration were reviewed. Performance metrics, including compressive, tensile, and flexural strength, durability, and

environmental impact, were compared across studies. Findings were synthesized to identify research gaps, challenges, and strategies for developing optimized, eco-friendly ECC suitable for Indian conditions.

## 5. CONCLUSIONS FROM LITERATURE

From the detailed study and literature review, it was found that ECC provides superior ductility, crack resistance, and flexural performance compared to conventional concrete. The inclusion of hybrid fibers improves both crack control and toughness, while CO<sub>2</sub> curing enhances early-age strength and permanently stores CO<sub>2</sub> through mineralization.

Using fine aggregates of 4.75-5.6 mm in the mix helps achieve better homogeneity and fiber distribution, which is essential for maintaining the strain-hardening behavior of ECC. The optimized mix design not only improves structural performance but also supports sustainability goals by reducing the carbon footprint of construction materials.

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