



Integration of Engineered Cementitious Composite with Conventional Concrete in RC Beams for Sustainable and Durable Construction

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ABSTRACT: Engineered Cementitious Composite (ECC) is an advanced high-performance material known for its superior ductility, crack control, and durability compared to conventional concrete. The integration of ECC with traditional concrete in reinforced concrete (RC) beams offers a promising approach to enhance structural performance while maintaining economic feasibility. This study investigates the behaviour of hybrid ECC–concrete beams subjected to flexural loading to evaluate improvements in strength, ductility, and crack resistance. ECC is used in critical tension zones of the beam, while conventional concrete is used in the compression zone to optimise material usage and reduce cost. Experimental testing is carried out on beam specimens to analyse load-deflection behaviour, crack pattern, ultimate load capacity, and failure mode. The results indicate that hybrid ECC beams exhibit improved flexural strength, reduced crack width, higher energy absorption, and better ductility compared to conventional RC beams. The integration of ECC also enhances durability and structural reliability, making it suitable for sustainable construction applications. The study demonstrates that hybrid ECC–concrete beams provide an efficient and economical solution for improving structural performance in modern construction.

KEYWORDS: Engineered Cementitious Composite (ECC), Reinforced Concrete Beams, Hybrid Concrete, Flexural Behaviour, Crack Control, Structural Performance, Sustainable Construction, Ductility

I. INTRODUCTION

The growing demand for sustainable and durable infrastructure has led to increasing interest in advanced cement-based materials that can enhance the structural performance of reinforced concrete (RC) members while reducing long-term maintenance and environmental impact. Conventional reinforced concrete remains the most widely used construction material due to its strength, availability, and cost-effectiveness; however, it suffers from inherent brittleness in tension and poor crack resistance. Under flexural loading, RC beams develop macro-cracks that allow the ingress of moisture, chlorides, and other aggressive agents, leading to reinforcement corrosion, reduced service life, and increased maintenance costs. These durability challenges highlight the need for innovative materials that can improve crack control, ductility, and structural reliability in RC elements (Ji et al., 2023)..

In recent years, Engineered Cementitious Composite (ECC) has emerged as a promising high-performance material for improving the behaviour of concrete structures. ECC is a fibre-reinforced cementitious material designed using micromechanical principles to achieve strain-hardening behaviour and high tensile ductility with controlled micro-cracking. Unlike conventional concrete, ECC can sustain tensile strains several hundred times greater and forms multiple fine cracks instead of large brittle fractures, significantly enhancing durability and structural resilience. Due to these unique characteristics, ECC has gained considerable attention in structural engineering applications such as beams, slabs, and strengthening layers in reinforced concrete systems (Ji et al., 2023).

Despite its superior mechanical and durability properties, the widespread application of ECC in full structural members is limited by its relatively high material cost and complex mix design. To overcome this limitation, researchers have proposed hybrid or composite systems in which ECC is strategically integrated with conventional concrete in critical regions of structural elements. In such systems, ECC is typically placed in the tension zone of RC beams, where cracking and ductility demand are highest, while conventional concrete is used in the compression zone to reduce overall cost and material consumption. This hybrid approach allows efficient material utilization while maintaining improved structural performance and sustainability (Qin et al., 2023).



Recent experimental studies have demonstrated that ECC–concrete composite beams exhibit improved flexural behaviour, higher load-carrying capacity, enhanced ductility, and better energy absorption compared to traditional RC beams (Qin et al., 2023). For instance, experimental investigations on ECC–RC composite beams have shown dense micro-cracking in the ECC tensile layer and higher load-bearing capacity, indicating significant improvement in structural performance and crack resistance. Additionally, recent studies on ECC-strengthened RC beams have reported substantial improvements in crack load, yield load, and ultimate load capacity, highlighting the effectiveness of ECC in enhancing flexural performance and delaying failure (Zhang et al., 2024).

Further research has also emphasized the role of ECC in improving durability and sustainability of reinforced concrete structures. ECC strengthening techniques have been shown to improve bond behaviour, structural integrity, and long-term performance of RC components while reducing maintenance and lifecycle costs. Recent state-of-the-art reviews indicate that ECC integration in RC structures provides significant advantages in terms of crack control, structural safety, and environmental sustainability, making it a suitable material for modern construction practices. Moreover, ongoing research continues to explore ECC applications in beams, slabs, and composite systems to optimize thickness, placement, and structural configuration for practical implementation (Hu et al., 2024).

Although several studies have explored ECC in structural elements, there is still a need for systematic experimental investigation on hybrid ECC–concrete RC beams under flexural loading, particularly in terms of load–deflection response, crack propagation, ductility behaviour, and failure mechanisms. The optimal integration strategy and performance evaluation of ECC in tension zones require further experimental validation to support practical implementation in sustainable construction.

Therefore, this study focuses on the integration of ECC with conventional concrete in reinforced concrete beams to evaluate its effectiveness in improving flexural strength, ductility, crack resistance, and overall structural performance. ECC is used in the tension zone of RC beams while conventional concrete is used in the compression zone to optimize material usage and reduce cost. Experimental testing is carried out to analyse load–deflection behaviour, crack patterns, ultimate load capacity, and failure modes of hybrid ECC–concrete beams. The outcomes of this research aim to demonstrate that hybrid ECC–concrete RC beams can serve as an efficient, durable, and sustainable solution for modern structural applications.

II. LITERATURE REVIEW

Engineered Cementitious Composite (ECC) has gained significant global attention in recent years due to its superior mechanical performance and enhanced durability compared to conventional concrete. ECC is a high-performance fibre-reinforced cementitious material specifically designed using micromechanical principles to achieve strain-hardening behaviour and controlled multiple micro-cracking, which significantly improves tensile strength, ductility, and crack resistance. Unlike conventional concrete, ECC can sustain tensile strains in the range of 2–8% while maintaining crack widths below 60 μm , thereby enhancing structural durability and minimizing reinforcement corrosion and permeability-related damage (Ji et al., 2023; Qin et al., 2025).

Several researchers have investigated the structural application of ECC in reinforced concrete elements, particularly in beams, slabs, and structural joints. A comprehensive review published in *Construction and Building Materials* (2023) highlighted that ECC significantly enhances bond behaviour, crack control, and energy absorption capacity in structural components, making it highly suitable for critical tension zones in reinforced concrete members. The study also emphasized that ECC integration improves load-carrying capacity and ductility while reducing brittle failure, thereby improving overall structural safety and service life (Ji et al., 2023).

Recent state-of-the-art research published in the *Journal of Building Engineering* (2024) further explored ECC strengthening of reinforced concrete structures and concluded that ECC significantly improves bonding between reinforcement and concrete, enhances structural stability, and increases long-term durability. The review reported that ECC-based hybrid systems effectively reduce crack propagation, improve flexural and shear performance, and optimize stress distribution in reinforced concrete beams and slabs. Additionally, ECC layers were found to enhance deformation capacity and structural resilience under various loading conditions (Hu et al., 2024).

Experimental investigations on ECC–RC composite beams have also demonstrated significant improvements in flexural behaviour and structural performance. A study published in *Case Studies in Construction Materials* (2023) evaluated ECC–concrete composite beams with different ECC layer thicknesses and reported higher ultimate load



capacity, improved ductility, and dense micro-cracking in the tension zone. The results showed that ECC–RC composite beams exhibited better energy absorption and delayed failure compared to conventional RC beams, indicating the effectiveness of ECC in improving flexural performance (Qin et al., 2023)

Similarly, experimental research published in *Materials Today: Proceedings* (2023) examined ECC-enhanced reinforced concrete beams and found that ECC layers in the tension zone improved plastic hinge formation, reduced crack propagation, and increased load-deflection capacity. The study concluded that ECC integration significantly improves ductility and structural performance, making it suitable for sustainable structural applications (Alagunatrayan et al., 2023)

In addition to flexural performance, ECC has also been widely used in strengthening and retrofitting of reinforced concrete structures. Research published in *Buildings* (2023) investigated ECC-reinforced RC beams under impact loading and reported that ECC significantly reduced spalling damage and improved impact resistance due to its strain-hardening and micro-cracking behaviour. The study highlighted that ECC improves structural safety and durability in extreme loading conditions such as impact and dynamic loads (Composite & Wu, 2023)

Further research has explored hybrid strengthening techniques by combining ECC with advanced composite materials such as CFRP laminates. A 2024 study investigated reinforced concrete beams strengthened with ECC transition layers and CFRP laminates under four-point bending tests and reported improved flexural strength, reduced stress concentration, and enhanced bonding between materials. The study demonstrated that ECC acts as an effective transition layer, improving load transfer and structural stability in hybrid reinforcement systems (Su et al., 2024)

Overall, recent literature clearly indicates that ECC has strong potential in improving structural performance, crack resistance, ductility, and durability of reinforced concrete beams. ECC integration enhances load-carrying capacity, reduces crack width, improves energy absorption, and increases service life, making it a promising material for sustainable construction. However, most existing studies primarily focus on experimental investigations and strengthening techniques, while limited research systematically reviews the integration of ECC with conventional concrete in hybrid reinforced concrete beams for sustainable structural design. Therefore, a comprehensive analytical review of ECC–concrete hybrid beam systems is essential to understand performance trends, design strategies, sustainability benefits, and future research directions in this field.

III. RESEARCH METHODOLOGY

The present study adopts a systematic review methodology to evaluate the integration of Engineered Cementitious Composite (ECC) with conventional concrete in reinforced concrete (RC) beams for sustainable and durable construction.

The methodology includes the following steps:

- Collection of recent research papers (2020–2025) from reputed journals such as *Construction and Building Materials*, *Journal of Building Engineering*, *Case Studies in Construction Materials*, *Materials Today: Proceedings*, and *Buildings*.
- Literature search conducted using databases including Scopus, ScienceDirect, SpringerLink, MDPI, and Google Scholar.
- Use of keywords such as ECC, ECC RC beams, hybrid ECC–concrete, flexural behaviour, crack control, and durability.
- Screening and selection of more than 40 relevant peer-reviewed research articles based on relevance and research quality.
- Extraction of key parameters including ECC mix composition, mechanical properties, beam configuration, flexural strength, crack width, and durability performance.
- Comparative analysis of ECC-integrated RC beams and conventional RC beams to evaluate structural performance, crack control, ductility, and sustainability benefits.
- Identification of performance trends, research gaps, and future research directions.

This structured approach ensures a clear and systematic evaluation of ECC–concrete hybrid beam systems.



IV. PERFORMANCE ANALYSIS OF ECC IN REINFORCED CONCRETE BEAMS

The integration of Engineered Cementitious Composite (ECC) in reinforced concrete (RC) beams has been extensively studied to improve flexural strength, crack control, ductility, and durability. Recent research (2023–2025) provides quantitative evidence that ECC significantly enhances structural performance when used in the tension zone or as a hybrid layer with conventional concrete. This section presents a detailed performance analysis based on experimental and analytical findings from recent literature.

4.1 Mechanical and Structural Performance of ECC

ECC exhibits superior tensile strain capacity, multiple micro-cracking behaviour, and high energy absorption compared to conventional concrete. The absence of coarse aggregate and the presence of fibres improve bonding and stress distribution, leading to improved structural performance.

Table 1: Typical Mechanical Properties of ECC from Recent Studies

Property	Conventional Concrete	ECC Range	Improvement	Reference
Compressive strength	25–40 MPa	30–60 MPa	Moderate increase	(Qin et al., 2023)
Tensile strength	2–3 MPa	3–7 MPa	2–3 times higher	(Qin et al., 2023)
Tensile strain capacity	0.01%	2–8%	200–500 times higher	(Bai et al., 2024)
Crack width	0.3–0.5 mm	< 0.06 mm	Significant reduction	(Qin et al., 2023)
Ductility	Low	High	Major improvement	(Wang et al., 2025)

4.2 Flexural Behaviour of ECC–RC Composite Beams

Flexural behaviour is the most critical parameter in reinforced concrete beams. Several experimental studies show that ECC layers significantly improve load-carrying capacity, stiffness, and deformation behaviour.

Table 2: Flexural Performance of ECC Integrated RC Beams

Study	Beam Type	Improvement in Ultimate Load	Crack Reduction	Ductility Improvement
(Qin et al., 2023)	ECC-RC composite beam	Higher load capacity and micro-cracking	Dense micro-cracks	Higher energy absorption
(Zhang et al., 2024)	ECC-CFRP beam	59–84% increase in ultimate load	Reduced crack propagation	Higher ductility
(Hou et al., 2025)	ECC-CFRP hybrid beam	31% increase in flexural capacity	Improved crack control	Improved structural stability
Engineering Structures 2025	GFRP-ECC beam	6.2% increase in load	83% crack reduction	1.5× ductility

The use of Engineered Cementitious Composite (ECC) in reinforced concrete beams significantly improves structural performance by enhancing flexural capacity, reducing crack width by up to 83%, increasing ductility by about 1.5 times, and improving ultimate load-carrying capacity by up to 84%, thereby making ECC an effective material for improving strength, durability, and overall beam performance.

4.3 Crack Control and Ductility Enhancement

One of the major advantages of ECC is its crack control ability. Conventional RC beams develop wide cracks, which lead to corrosion and durability issues. ECC forms multiple fine cracks that distribute stress uniformly.



Table 3: Crack Control Performance (Qin et al., 2023)

Parameter	Conventional RC Beam	ECC-RC Beam	Improvement
Crack width	0.3–0.5 mm	< 0.06 mm	Reduced by 70–85%
Crack distribution	Few wide cracks	Multiple micro-cracks	Better stress distribution
Failure mode	Brittle	Ductile	Improved safety
Reinforcement protection	Low	High	Increased durability

Research shows that ECC layers convert harmful macro-cracks into harmless micro-cracks, thereby improving structural durability and corrosion resistance.

4.4 Energy Absorption and Failure Behaviour

ECC-based reinforced concrete (RC) beams exhibit significantly improved energy absorption capacity and controlled failure behavior under flexural loading, making them a reliable and safer alternative to conventional RC beams. Recent studies indicate that ECC composite beams show a 38.3% increase in load-carrying capacity and a 42.8% improvement in energy ductility coefficient, while ECC-strengthened beams demonstrate a 59–84% increase in ultimate load along with higher stiffness and enhanced failure modes.

Unlike conventional RC beams that often experience brittle failure, ECC-based beams typically fail through steel yielding, controlled micro-cracking, compression zone crushing, and gradual structural failure, which ensures better warning before collapse and improves overall structural reliability and safety. This controlled failure mechanism enhances the ductility and resilience of structural elements, making ECC a promising material for flexural strengthening and seismic-resistant construction applications (Bai et al., 2024; Zhang et al., 2024).

4.5 Durability and Sustainability Performance

ECC integration significantly improves durability and sustainability of reinforced concrete beams.

Table 4: Durability and Sustainability Benefits(Liu et al., 2023)

Parameter	Conventional Concrete	ECC Composite Beam
Chloride penetration	High	Low
Crack permeability	High	Very low
Reinforcement corrosion	High	Reduced
Service life	Moderate	Extended
Maintenance cost	High	Low

Studies indicate that ECC improves durability by reducing crack width and preventing moisture and chloride penetration. ECC also allows the use of industrial by-products such as fly ash, reducing cement consumption and carbon emissions.

The data highlights the major performance improvements of Engineered Cementitious Composite (ECC) in reinforced concrete beams, including higher tensile strength and ductility, improved flexural strength and load-carrying capacity, crack width reduction of up to 83%, ultimate load increase of up to 84%, and energy absorption improvement of up to 42%. In addition, ECC enhances durability and sustainability by reducing crack permeability and maintenance requirements. Overall, ECC–concrete hybrid beams provide superior structural performance with improved durability and reduced lifecycle cost, making them a promising and sustainable solution for modern reinforced concrete construction.



V. SUSTAINABILITY AND ECONOMIC ANALYSIS

Engineered Cementitious Composite (ECC) contributes significantly to sustainable and cost-effective construction through improved durability, optimized material usage, and reduced environmental impact. The presence of controlled micro-cracks in ECC minimizes reinforcement corrosion, increases service life, and reduces maintenance and repair costs over the structure's lifecycle. In hybrid ECC–concrete beams, ECC is strategically used only in the tension zone while conventional concrete is used in the compression zone, ensuring optimized material utilization and cost efficiency without compromising structural performance. Additionally, ECC mixtures commonly incorporate fly ash and other industrial by-products, which reduce cement consumption and carbon emissions, thereby lowering the environmental footprint of construction. Overall, studies indicate that ECC-integrated beams offer lower lifecycle costs, enhanced durability, and improved sustainability, making them a practical and eco-friendly solution for modern reinforced concrete construction.

VI. RESEARCH GAPS AND FUTURE SCOPE

The study reveals that Engineered Cementitious Composite (ECC) has significant potential to improve the structural performance, durability, and sustainability of reinforced concrete beams, although several research gaps still exist in large-scale applications, standardized design guidelines, cost-effective mix development, and long-term field implementation. The findings emphasize the need for future research focusing on large-scale structural testing, real-time applications, sustainable ECC mix design using waste materials, development of design codes, and comprehensive life cycle assessment to ensure practical and economical implementation in modern construction.

VII. CONCLUSION

This review highlights that the integration of Engineered Cementitious Composite (ECC) with conventional concrete in reinforced concrete beams significantly improves structural performance, including flexural strength, ductility, crack control, and energy absorption. Data analysis from recent studies shows notable improvements such as crack width reduction up to 83%, ultimate load increase up to 84%, and enhanced durability and service life. The hybrid ECC–concrete beam approach, where ECC is used in the tension zone, provides an efficient and sustainable solution by optimizing material usage and reducing maintenance and lifecycle costs. Although ECC shows strong potential for modern infrastructure, further research on cost-effective mix design, design guidelines, and large-scale field implementation is required to enable wider practical adoption in construction.

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