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Research Progress on the Tensile Properties of Engineered Cementitious Composites

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Abstract

Engineered cementitious composites (ECC) exhibit tensile strain hardening and multiple cracking, providing a means of overcoming the limited tensile deformation capacity of conventional concrete. This review summarizes recent studies on the tensile behavior of ECC, with particular attention to stress–strain responses and crack control mechanisms. It examines the effects of fiber type, content and orientation, matrix composition, fiber–matrix interfaces, and temperature. Applications in bridge deck link slabs, structural repair and strengthening, additive construction, and marine infrastructure are also discussed. The reviewed studies indicate that tensile performance depends on the coordinated design of fibers, matrix, and interfaces. Further research should address material cost, fiber dispersion, construction methods, and the optimization of mixtures incorporating industrial and agricultural by-products.

Keywords

Engineered Cementitious Composites; Tensile Properties; Fiber Types; Fiber–Matrix Interface

1. Introduction

Concrete is widely used in civil engineering because its raw materials are inexpensive and it can be mixed and cast using relatively simple processes. However, its low tensile strength and susceptibility to cracking can compromise structural durability. Cracks provide pathways for water, chloride ions, and other aggressive substances, accelerating reinforcement corrosion and potentially impairing structural safety. Consequently, some structures lose their intended functionality before the end of their de-sign service life. These limitations have motivated the development of cementitious materials with improved tensile performance.

Early studies introduced fibers into cement concrete to exploit their comparatively high tensile strength. Although fiber reinforcement can improve tensile resistance, the resulting strength and ductility do not necessarily meet design expectations.

Achieving substantial tensile deformation requires appropriate coordination between fiber properties and the surrounding matrix.

Since the 1990s, Li and co-workers have developed engineered cementitious compo-sites through micromechanics-based matrix and interface design [1]. ECC mixtures commonly incorporate cement, water, a water-reducing admixture, fine quartz sand, supplementary cementitious materials, and polymer fibers such as polyvinyl alcohol (PVA). Their crack control, tensile ductility, and durability have attracted considerable research interest [2,4]. Unlike conventional concrete, ECC can exhibit pronounced tensile strain hardening accompanied by multiple cracking. Reported ultimate tensile strains typically range from 3% to 7%. The source literature describes strain capacities above 3% as approximately 150–300 times those of conventional concrete and 30–300 times those of conventional fiber-reinforced concrete [2]. These comparisons depend on the particular reference materials and test conditions.

The tensile performance of ECC relies strongly on fiber reinforcement, with PVA and polyethylene (PE) among the most widely used fibers. Interactions between fibers and the cementitious matrix govern crack bridging. By tailoring fiber type, matrix composition, and interfacial properties, researchers seek to distribute cracking throughout the material, delay crack localization, and increase overall ductility. New fibers and multiscale mechanical models have provided further opportunities to improve tensile behavior.

Nevertheless, widespread implementation remains constrained by material cost and fiber dispersion. Fiber clusters can generate stress concentrations and reduce ductility, whereas regions containing too few fibers may become weak zones and fail prematurely. This review examines tensile behavior, its governing factors, and engineering applications, and identifies priorities for further research.

2. Tensile Behavior of ECC

Tensile strain hardening and multiple cracking are defining characteristics of ECC. Its response is discussed below in terms of the tensile stress–strain curve and the mechanisms responsible for controlling crack development.

2.1. Tensile Stress–Strain Response

The tensile stress–strain response of ECC can be divided into three stages, as illustrated in Figure 1.

The elastic stage extends from the beginning of loading to the formation of the first matrix crack. Tensile stress is approximately proportional to tensile strain, and the slope of the curve, corresponding to the elastic modulus, is governed primarily by the cementitious matrix [3].

The stable cracking stage extends from first cracking to the ultimate tensile strain. As loading continues, additional fine cracks develop while both stress and strain

increase. Local stress drops associated with successive cracking events produce a serrated response. This stage distinguishes strain-hardening ECC from conventional concrete and accounts for much of its tensile deformation capacity.

The failure stage begins after the ultimate tensile strain is reached. Cracking localizes, fiber bridging progressively deteriorates through fiber rupture and/or pullout, and the tensile stress decreases until failure.

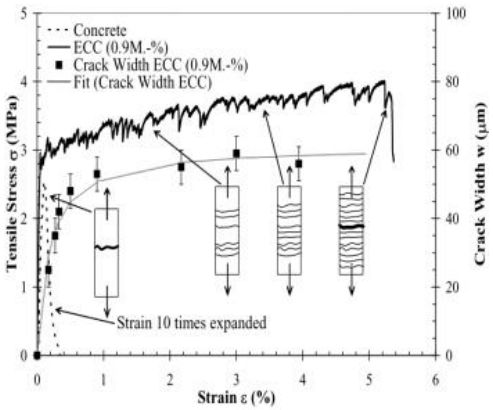

Figure 1. Tensile response and crack width of conventional concrete and ECC [5].

Conventional concrete generally enters a softening regime shortly after its initial elastic response and has an ultimate tensile strain of approximately 0.01%. In contrast, ECC can attain tensile strains of 3%–7% and sustain strain hardening during the multiple cracking stage [6]. This deformation capacity can improve the ability of structural components to accommodate imposed movements.

2.2. Crack Control Mechanisms

Multiple cracking is central to the high ductility of ECC. When the matrix cracks, fibers bridge the crack and transfer tensile stress between its opposing faces [6]. This bridging action restricts crack opening, with crack widths commonly below 100 μm in appropriately designed mixtures [7]. Stress transfer also redistributes stresses around existing cracks, allowing additional matrix cracks to develop instead of concentrating all deformation at a single location [8].

Crack width and cracking distribution depend on fiber characteristics, matrix properties, and the fiber–matrix interfacial transition zone. These factors must be considered together when designing ECC for both deformation capacity and crack control.

3. Factors Affecting Tensile Properties

3.1. Fiber Characteristics

Fibers should provide sufficient tensile strength, elastic modulus, and deformation capacity to sustain crack bridging. Carbon fibers can increase strength, but their

brittleness and possible breakage during processing may restrict composite ductility. A reported mixture containing 4% carbon fibers by volume achieved a tensile strain of only 0.9% [9]. Zhang et al. [10] discussed the influence of replacing some polymer fibers with steel fibers; changes in matrix strength and debonding resistance can alter the tensile response. These observations highlight the need to evaluate carbon and steel fibers within a complete composite design. PE and PVA fibers remain common choices for ECC. PE fibers are hydrophobic and combine high strength with a high elastic modulus, making them suitable for mixtures requiring substantial tensile performance.

Fiber volume fraction determines the density of potential crack bridges. Within a suitable range, increasing fiber content enhances reinforcement and energy absorption. Zhou and Peng [11] investigated PVA volume fractions from 0% to 2% and found that tensile strain increased with fiber content, reaching a maximum of 4.73%. At a fiber volume fraction of 2.0%, numerous fine cracks developed and clear strain hardening was observed. Excessive fiber addition, however, can impair workability and promote clustering. Accordingly, the appropriate upper limit depends on fiber geometry, matrix rheology, and the mixing process rather than a universal volume fraction.

Fiber distribution includes both spatial dispersion and orientation. Soltan and Li [12] reported advantages in first-cracking strength, ultimate tensile strength, and tensile strain for a cementitious composite produced by three-dimensional printing compared with conventional casting. Preferential fiber alignment along the loading direction contributed to this behavior. Ding et al. [13] examined the relationship between fiber orientation and mechanical performance using specimens cut at 0°, 45°, and 90° to the casting direction. Their results demonstrated the importance of orientation to bridging and flexural behavior. Collectively, these studies indicate that alignment with the principal tensile direction can improve performance, although the resulting directional dependence should be considered in structural design.

3.2. Matrix Properties

The cementitious matrix occupies most of the composite volume, and its pore structure and fracture resistance influence tensile behavior. Incorporating a superabsorbent polymer can reduce matrix fracture toughness and facilitate the development of multiple fine cracks, thereby improving strain-hardening behavior [14]. The source manuscript also attributes improved tensile performance to replacing ordinary Portland cement with fly ash, which can reduce fiber–matrix bonding and shift failure from fiber rupture toward pullout [15]. Yu et al. [16] investigated recycled powder derived from construction waste as a replacement for fly ash and reported stable strain hardening and multiple cracking under uniaxial tension.

The water-to-binder ratio is another influential parameter. Zhang et al. [17] reported that increasing this ratio from 0.25 to 0.30 and 0.35 increased the mean ultimate tensile strain by 47.06% and 65.10%, respectively. Increasing the ratio can reduce matrix toughness and interfacial chemical and frictional bonding. Lower matrix fracture resistance may favor multiple cracking, but a concurrent reduction in maximum bridging stress can undermine strain hardening if bridging becomes insufficient. Excessively high water contents can also increase local bleeding and reduce matrix strength. The ratio must therefore balance matrix cracking resistance against available fiber bridging capacity.

3.3. Fiber–Matrix Interfaces

Interfacial chemical bonding and frictional resistance govern stress transfer between fibers and the matrix. Excessively strong bonding can inhibit sliding and cause premature fiber rupture. Conversely, very weak bonding allows fibers to pull out without developing adequate bridging resistance. Effective interface design seeks a balance that sustains stress transfer while permitting controlled debonding and sliding.

Hydrophobic PE fibers interact with the matrix predominantly through friction, and pullout is an important component of their tensile response. Hydrophilic PVA fibers can develop strong chemical bonds with cementitious matrices, potentially restricting sliding. Surface oiling has therefore been used to reduce PVA interfacial bonding and improve pseudo-strain-hardening behavior [18]. Chu [19] investigated surface modification in a PVA–polyethylene terephthalate (PET) fiber system. Dopamine-assisted deposition of graphene oxide increased PET surface roughness and raised interfacial frictional bond strength by 76%. The reported composite tensile strength increased from 3.10 to 4.08 MPa, while tensile strain increased from 2.20% to 3.97%.

3.4. Temperature

Temperature affects both the matrix and the reinforcing fibers; the resulting tensile response depends on mixture composition and exposure conditions. Some systems can show an initial improvement followed by deterioration, whereas others lose strain capacity at relatively low elevated temperatures. Once polymer fibers soften or melt, their bridging capacity can fall substantially. Zhang et al. [20] reported appreciable reductions in strain capacity after exposure to 100 °C and 200 °C. Yu et al. [21] found decreases in both tensile strength and tensile strain of PVA-ECC after exposure to 200 °C. Luo et al. [22] associated brittle behavior at 200 °C with fiber melting. Figure 2 summarizes reported temperature effects on residual tensile properties [23].

3.5. Some Common Mistakes

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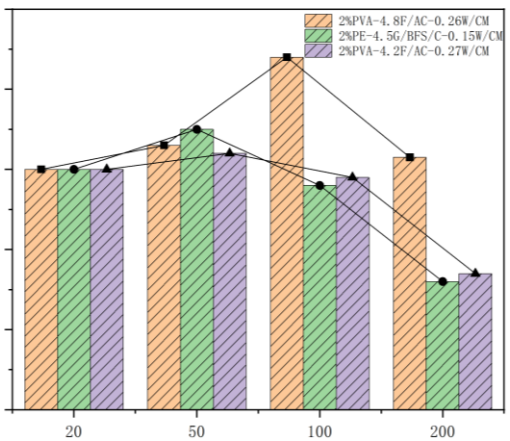
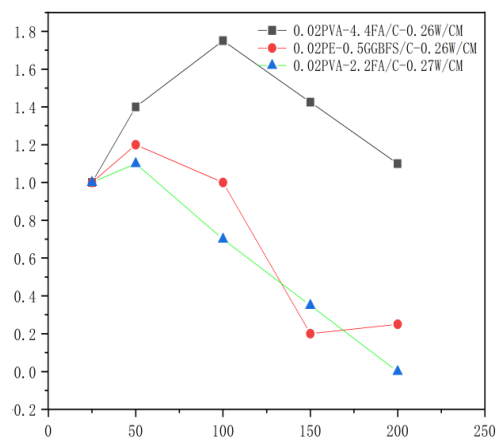


(a) Relative residual tensile strength; temperature (°C)



(b) Relative residual tensile strain; temperature (°C)

Figure 2. Influence of temperature on the tensile properties of ECC [23].

4. Engineering Applications

4.1. Bridge Deck Link Slabs

Bridge decks experience complex loading and restraint conditions. Transverse cracks can develop in deck surfacing after construction and subsequently grow into

more severe damage, including fragmentation and potholes. The tensile ductility of ECC allows deformation to be distributed among numerous fine cracks and enables energy dissipation during loading. Figure 3 illustrates the use of ECC in bridge decks without conventional expansion joints.

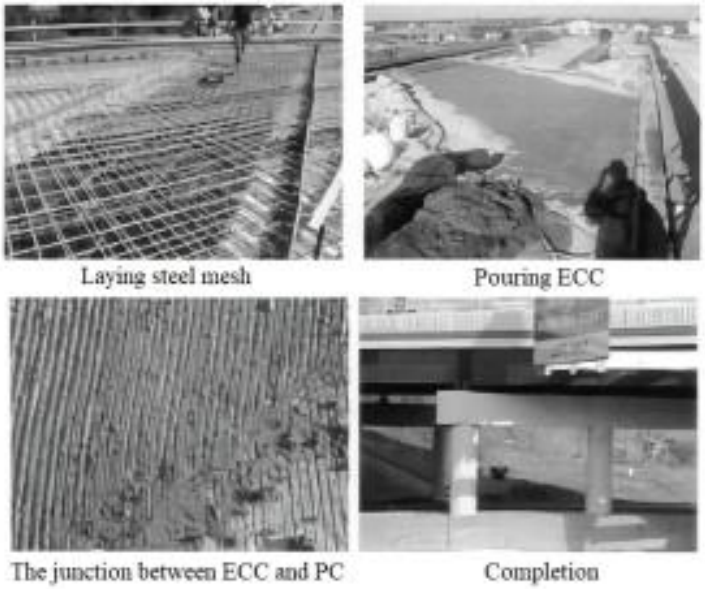


Figure 3. Application of ECC in bridge decks without expansion joints.

Li and co-workers developed ECC bridge deck link slabs to accommodate movements through distributed cracking and tensile deformation [24]. The source manuscript describes an application on an Interstate 94 bridge in Michigan. Replacing conventional expansion joints with an appropriately designed ECC link slab can improve movement accommodation and reduce maintenance demands. Transition-zone design further supports the performance of the connection between the link slab and adjoining concrete [25]. Qian [26] used finite element analysis to examine ECC link-slab behavior and proposed improvements to their structural design.

4.2. Repair and Strengthening

The ductility and crack control of ECC make it a candidate for repairing and strengthening existing structures. Fine distributed cracks, together with self-healing under suitable conditions, can help limit crack growth and reduce the ingress of water and aggressive substances. ECC overlays have therefore attracted interest for historical buildings and masonry structures. Applying an ECC layer approximately 10–20 mm thick to masonry walls can improve deformation capacity and structural integrity, with potential benefits for seismic performance. Figure 4 shows an example of strengthening an existing building using ECC.



Figure 4. Strengthening an existing building using ECC.

4.3. Other Applications

ECC also offers opportunities in three-dimensional printed construction, where materials are deposited layer by layer without conventional formwork. Tensile ductility may help manage cracking during construction and service. However, interlayer bond strength remains a separate requirement for structural integrity. Xiao et al. [27] investigated interlayer bonding and pore characteristics in printed ECC, highlighting the importance of material composition and printing conditions. Fiber content and process parameters should be optimized together to improve bonding and limit interfacial defects.

Marine structures are exposed to seawater, temperature changes, and mechanical loading. By distributing tensile deformation among multiple fine cracks, ECC can reduce crack localization and improve resistance to imposed movements. Controlling crack width can also limit the transport of aggressive ions and thereby support longer service life. These benefits depend on the mixture, exposure conditions, and crack state; fine cracks do not completely prevent ingress.

5. Conclusions and Future Research

Research has established tensile strain hardening and multiple cracking as the principal advantages of ECC. These characteristics arise from the combined effects of fiber reinforcement, matrix properties, and interfacial behavior, while temperature can substantially modify the response. Their interactions determine both material-scale performance and the effectiveness of engineering applications.

The tensile strength, energy absorption, and deformation capacity of ECC create opportunities in bridge decks, repair, strengthening, and emerging construction methods. High material costs and demanding construction procedures continue to constrain broader use. Further work should optimize mixture proportions, improve fiber dispersion, reduce production costs, and simplify placement while maintaining

reliable tensile behavior.

Environmental performance is another priority as ECC use expands. Fly ash, silica fume, rice husk ash, and recycled powders offer opportunities to reduce reliance on conventional raw materials. The tensile behavior of these mixtures requires further investigation, particularly the balance among matrix fracture resistance, interfacial bonding, and fiber bridging. Mixture optimization should consider tensile performance, constructability, cost, and environmental impact together.

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