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REVIEW

Hybrid Fiber Engineered Cementitious Composites (HFECC): A Review

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ABSTRACT: Engineered Cementitious Composites (ECC) represent an advanced class of fiber-reinforced cement-based materials developed over the past three decades, characterized by remarkable tensile strain-hardening and multiple-cracking behavior. By incorporating hybrid fibers, Hybrid Fiber engineered cementitious composites (HFECC) can be tailored to meet specific engineering demands in terms of strength, deformation, dynamic mechanical performance, and cost-effectiveness. This paper provides a comprehensive review of the critical fiber volume theory, experimental investigations into quasi-static and dynamic mechanical properties, and the structural performance of HFECC. Furthermore, current research gaps and future directions for the development and application of HFECC are discussed, aiming to facilitate its broader engineering adoption. In addition, this review emphasizes the micromechanical design principles governing fiber–matrix interactions, highlighting how hybridization strategies optimize the synergy between different fiber types to balance ductility and strength. The practical implications of HFECC in seismic-resistant, impact-resistant, and repair applications are also analyzed. Through an integrated discussion of theoretical and experimental findings, this study seeks to provide a systematic understanding of HFECC behavior and promote its advancement toward sustainable and high-performance infrastructure applications.

KEYWORDS: Hybrid fiber; strain hardening cementitious composites; critical fiber volume; quasi-static properties; dynamic mechanical properties; durability

1 Introduction

Engineering cementitious composite (ECC) is a new type of fiber-reinforced cementitious composite that has developed in the past 30 years [1–4]. With a relatively low fiber dosage (generally no more than 2%), it significantly enhances the ductility and toughness of cementitious composites (with ultimate tensile strain reaching up to 4%) [5–8], and endows them with strain hardening and multi-crack opening properties similar to those of metallic materials [9], thereby greatly reducing crack width and significantly improving the durability of cementitious composites [10–13].

Studies have shown that when two or more types of fibers are mixed in cement-based composites, the phenomenon where hybrid fibers provide a superior enhancing effect on the composite compared to any single type of fiber is referred to as the fiber hybrid effect [14–17]. Similarly, in ECC—for instance, in steel-polyethylene (PE) shybrid fiber ECC—a higher content of steel fibers contributes to greater strength, while a higher dosage of PE fibers results in improved deformation capacity, i.e., enhanced strain hardening behavior. By adjusting the ratio between steel and PE fibers, it is feasible to efficiently tailor ECC to meet specific engineering requirements for both strength and deformation performance [18]. Consistent with the findings in reference [19], numerous recent studies have sought to use hybrid fibers to improve the static [20–23], dynamic mechanical properties, durability [24,25] and structural performances [26,27] as well as reduce production costs [28,29] of single-fiber ECC.

Despite the promising potential of HFECC, the existing research is relatively fragmented, and a systematic summary of its theoretical foundations, performance, and applications is still lacking. Therefore, the primary purpose of this review is to provide a comprehensive and systematic review of the current research progress on HFECC. The scope of this study encompasses the critical fiber volume theory, the quasi-static and dynamic mechanical properties, durability performance, and structural applications of various hybrid fiber systems. Ultimately, this review aims to identify current research gaps and outline future directions, thereby facilitating the targeted development and broader engineering adoption of HFECC.

2 Basic Properties of Fibers Used in HFECC

Reinforcement materials for ECC primarily include polymer fibers such as polyethylene (PE) fiber, polyvinyl alcohol (PVA) fiber, and polypropylene (PP) fiber. Other fibers, such as steel fiber, are often incorporated into the preparation of HFECC alongside PE and PVA fibers (fiber properties are summarized in Table 1). As shown, steel fibers generally exhibit higher elastic modulus and strength compared to most synthetic fibers [30,31]. Therefore, they are effective in enhancing the strength and elastic modulus of HFECC and are the most commonly used hybrid fiber in such composites.

Table 1: The physical and mechanical properties of common fibers

Fiber type	Density (g/cm^3)	Tensile strength (MPa)	Elastic modulus (GPa)	Diameter (mm)	Ultimate elongation (%)
SMA [26]	6.45	869	41	0.635	38
Basalt [30]	2.5–2.9	1300–4800	70–110	0.017–0.044	1.8–3.1
PVA [32]	1.3	1640	41.1	0.04	7
PE [33]	0.96	2900	116	0.025	3.5
PP	0.90–0.92	400	3.5	43	15–35
PET [33]	0.91	700–1000	8–10	0.14	–
Steel	7.43	2900	200	0.1–0.2	3.0–4.0
Glass [34]	2.68–2.7	1000–2800	42–90	8	2–3.5
Carbon	1.76–7.8	2800–4900	230	0.007–0.2	1.4

Note: Fiber abbreviation: PE-Polyethylene fiber, PP-Polypropylene fiber, PVA-Polyvinyl alcohol fiber, PET-Polyethylene Terephthalate fiber, SMA-shape memory alloy.

3 Theoretical Research on Critical Fiber Volume Fraction

The critical fiber volume fraction in ECC refers to the minimum fiber content required for the composite to achieve direct tensile strain-hardening and multiple cracking behavior [35]. Theoretically determining this critical value allows the fiber dosage to be controlled at a relatively low level, thereby improving the workability of fresh ECC and reducing production costs. The concept and micromechanical design theory of ECC were initially proposed by Li [36], and most of the micromechanical design theories for HFECC have been developed based on this foundation. Li [36] established a cracking stress criterion for achieving multiple cracking in fiber-reinforced cementitious composites:

$$\sigma_{cu} > \sigma_{fc} \tag{1}$$

That is, the ultimate fiber-bridging capacity of the fiber-reinforced cementitious composite must exceed the first-cracking strength of the matrix. On this basis, Ahmed et al. proposed expressions for the ultimate bridging strength of hybrid fiber-reinforced cementitious composites and the first-cracking strength of the matrix:

$$\sigma_{cu} = g_1\sigma_{o1}\left[1 - \frac{2\delta_2^*}{L_{f1}}\right] + g_2\sigma_{o2} \tag{2}$$

$$\sigma_{fc} = \frac{K_{tip}}{2}\sqrt{\frac{\pi}{2}} - \frac{1}{2}\left\{g_1\sigma_{o1}\left[-\frac{8}{3}(c)^{1/4}\sqrt{\frac{\delta_a}{\delta_1^*}} + \frac{\delta_a}{\delta_1^*}\sqrt{c}\right] + g_2\sigma_{o2}\left[-\frac{8}{3}(c)^{1/4}\sqrt{\frac{\delta_a}{\delta_2^*}} + \frac{\delta_a}{\delta_2^*}\sqrt{c}\right]\right\}(for\, \delta m = \delta_1^*) \tag{3}$$

By equating the ultimate fiber-bridging strength with the matrix's first-cracking strength and fixing the content of one type of fiber, the critical fiber volume fraction of the other fiber can be determined—that is, the minimum fiber dosage required to achieve multiple cracking and strain hardening in hybrid fiber-reinforced cementitious composites. This theoretical analysis was validated using steel-PE HFECC as an example: as reported in reference, when the volume fraction of steel fiber was fixed at 1%, the critical volume fraction of PE fiber was approximately 0.8%. When the PE fiber content was less than 0.8%, multiple cracking and strain hardening effects were not significant; conversely, pronounced multiple cracking and strain hardening behavior were observed. This method primarily addresses binary hybrid fiber systems composed of fibers with differing deformation capacities—specifically, the combination of a high-modulus fiber (e.g., steel fiber) and a low-modulus fiber (e.g., PE fiber).

$$\sigma_{fc} = \frac{K_{tip}}{2}\sqrt{\frac{\pi}{2}} - \frac{1}{2}\left(\begin{array}{l} g_1\sigma_{o1}\left\{2\left(\sqrt{1-\frac{c_1^2}{c^2}}-1\right) + 4\frac{\delta_a}{L_{f1}}\sqrt{c}\frac{c_1^2}{c^2} + \frac{8}{3}\frac{\delta_a^2}{L_{f1}^2}\right. \\ \left. + c\left[\left(1-\frac{c_1^2}{c^2}\right)^{3/2} - 1\right]\right\} + g_1\sigma_{o1}\left[-\frac{8}{3}(c)^{1/4}\sqrt{\frac{\delta_a}{\delta_1^*}}\left(1-\frac{c_1^2}{c^2}\right)^{3/4} + \frac{\delta_a}{\delta_1^*}\left(1-\frac{c_1^2}{c^2}\right)\sqrt{c}\right] \\ + g_2\sigma_{o2}\left[-\frac{8}{3}(c)^{1/4}\sqrt{\frac{\delta_a}{\delta_2^*}} + \frac{\delta_a}{\delta_2^*}\sqrt{c}\right] \end{array}\right)(for\, \delta_1^* \le \delta_m \le \delta_2^*) \tag{4}$$

$$V_{f,cr} = \frac{A_f 2(k_C)^2}{E_c p_f k_B}\left(1 + \sqrt{1 + \frac{(E_c)^2 p_f k_B}{A_f E_x (E_c)^2}}\right) \tag{5}$$

Eq. (5) expresses the critical fiber volume fraction [35]. This theory was initially developed to address multiple cracking in single-fiber reinforced ECC [9]. Later, when Fantilli et al. studied the hybridization of fibers with different sizes, they fixed the content of the smaller-sized fibers and treated them as part of the matrix. This approach allowed the theory to be applied to determine the critical fiber volume fraction of the larger-sized fibers.

In addition to the cracking stress criterion [36], Li et al. [37] also employed a reliability criterion to verify the steady-state multiple cracking behavior of nano-silica modified steel-PVA HFECC. The so-called reliability criterion ensures that after cracking under load, the crack surfaces in HFECC do not lead to overall failure due to fiber slip. To maintain stress equilibrium at the crack surface, the reliability index R for the fiber strength at the critical crack surface must be greater than or equal to the failure probability P. If the average crack spacing is x, the failure probability P of a single fiber at the critical crack surface and the reliability index R are given by:

$$P = \frac{L_f}{x^2}\delta_{\max} \tag{6}$$

$$R = 1 - \frac{\sigma_{fc}}{\sigma_{\max}} \tag{7}$$

Experimental results have also confirmed that steady-state multiple cracking and strain hardening in HFECC can only be achieved when both the cracking stress criterion and the reliability criterion are satisfied simultaneously. This approach can also be applied to calculate the critical fiber volume fraction.

4 Quasi-Static Mechanical Properties of HFECC with Various Fiber Combination Method

The quasi-static mechanical properties are the fundamental properties of concrete and also the most extensively studied property in HFECC research [23,38–40]. The framework of the research content of this chapter is shown in Fig. 1.

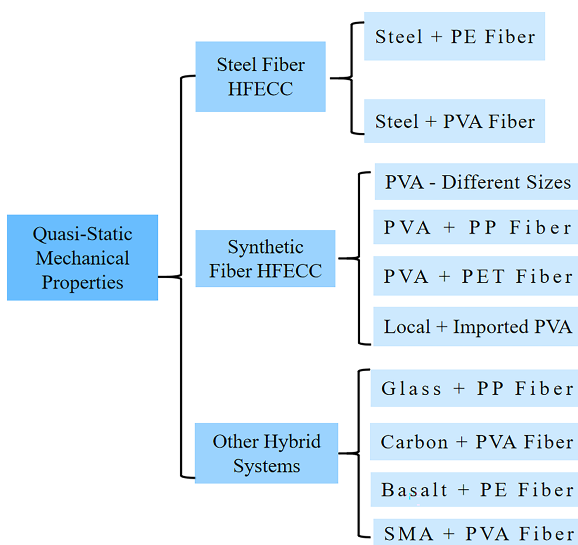

Figure 1: Framework of Section 4: Quasi-static mechanical properties of HFECC with various fiber combination method

4.1 HFECC with Steel Fiber

The relevant studies and main findings of HFECC with steel fiber are summarized in Table 2.

Table 2: Quasi-static mechanical properties of HFECC with steel fiber

Authors	Fiber combination (vol.%)	Mechanical properties	Main findings
Ahmed and Maalej [19,41]	0.5 steel + 2.0 PE 1.0 steel + 1.5PE 1.5 steel + 1.0PE	Uniaxial tensile Bending	Steel fibers enhance the tensile and flexural strength, while PE fibers contribute to higher ultimate tensile strain and deflection.
Xie et al. [33]	1.0 PE + 0.5 steel 1.0 PE + 1.0 steel 0.5 PE + 1.0 steel 0.5 PE + 1.5 steel 1.0 PE + 1.0 PET	Compressive strength Uniaxial tensile Thin plate four-point bending Bending toughness	Steel fibers greatly improve resistance to crack growth but reduce axial tensile strain.
Zhao et al. [42]	1.85 PE + 0.15 steel 1.7 PE + 0.3 steel 1.55 PE + 0.45 steel 1.4 PE + 0.6 steel	3D print Uniaxial tensile Interfacial splitting tensile	A small amount of steel fiber in 3D-printed ECC improves structural integrity
Soe et al. [43]	1.75 PVA + 0.58 steel 1.5 PVA + 0.5 steel	Uniaxial tensile Compressive strength	Higher PVA fiber content doesn't markedly improve ultimate tensile strain.
Zhang et al. [44]	2.0 PVA + 0.3 steel 2.0 PVA + 0.6 steel 2.0 PVA + 1.0 steel 2.0 PVA + 2.0 steel	Compressive strength Uniaxial tensile Bending strength	Increasing steel fiber content in high-strength matrices improves both strength and strain capacity.
Li et al. [37]	2/2.5 PVA + 1.0 steel 2/2.5 PVA + 1.2 steel 2/2.5 PVA + 1.4 steel	Bending	Hybrid steel-PVA fibers effectively controlled crack width

Steel fiber is the most widely used reinforcing material in cementitious composites, effectively enhancing the strength and shrinkage crack resistance of ECC [42]. Synthetic fibers, on the other hand, offer significant advantages such as low cost and reduced density. Consequently, considerable research has focused on steel-synthetic hybrid fiber ECC for producing high-strength, low-shrinkage materials.

Since relatively low volumes of PE fiber can achieve high ultimate tensile strain, early studies often utilized PE-based systems, leading to investigations into steel-PE HFECC. Ahmed and Maalej [19,41] examined the uniaxial tensile and flexural behaviors of steel-PE HFECC. Their results indicated that steel fibers enhance the tensile and flexural strength, while PE fibers contribute to higher ultimate tensile strain and deflection. Similarly, Xie et al. [33] found that steel fibers greatly improve resistance to crack growth but reduce the material's ability to dissipate energy and its axial tensile strain. When added in appropriate amounts, however, they provide superior crack control by limiting microcrack width, which enhances durability. Increasing the length of PE fibers (e.g., from 12 to 18 mm) and incorporating fly ash (at 50% cement replacement) were found to improve strain hardening and multi-cracking capacity. However, higher fine aggregate content was shown to degrade strain hardening performance.

Zhao et al. [42] developed 3D-printed steel-PE hybrid fiber ECC, which exhibited compressive strength exceeding 90 MPa and interfacial split tensile strength more than 50% higher than that of mono-PE fiber

ECC. This improvement is largely attributed to the high stiffness of steel fibers, which tend to align during printing, enhancing crack-bridging efficiency. Thus, even a small amount of steel fiber in 3D-printed ECC significantly improves structural integrity—a crucial factor for printed concrete applications. It should be noted, however, that the uniaxial tensile strain capacity decreased by approximately 19% with the hybrid system. Therefore, the mix proportion of hybrid fibers must be carefully optimized according to specific engineering requirements.

Given that PVA fiber is more cost-effective than PE fiber (approximately one-eighth the price) and provides toughening effects adequate for most engineering applications, increasing attention has been directed toward steel-PVA HFECC. Ahmed et al. [41,45] investigated the flexural performance of steel-PVA HFECC. Under a constant total fiber volume of 2.5%, a mix with 1.5% PVA and 1% steel fibers exhibited the highest flexural strength and deformation capacity. While steel-PVA HFECC showed superior flexural strength compared to steel-PE systems, the latter demonstrated better post-peak load retention and deformation capability [41]. Soe et al. [43] studied the elastic modulus, flexural, and uniaxial tensile properties of steel-PVA HFECC using fiber volumes of 1.75% PVA with 0.58% steel and 1.5% PVA with 0.5% steel. Their findings indicated that increasing steel fiber content significantly enhances composite strength, whereas higher PVA fiber content does not markedly improve ultimate tensile strain. Some studies, however, reported limited strength improvement with steel fiber addition [30], highlighting the importance of compatibility between the matrix and fiber type.

In recent years, research has expanded to examine the behavior of steel-PVA HFECC with different matrix designs to achieve multifunctional composites and broaden application potential. Zhang et al. [44] studied the tensile and flexural properties of steel-PVA HFECC with a high-strength matrix. By incorporating mineral admixtures, a matrix strength of up to 108 MPa was achieved, resulting in a composite with a tensile strength of 8.1 MPa and an ultimate tensile strain of 0.5%. Their results confirmed that increasing steel fiber content in high-strength matrices improves both strength and strain capacity; however, to avoid significant degradation in tensile strain, the steel fiber content should be limited to around 1%. Additionally, steel fiber incorporation contributed to reduced crack width. Li et al. [37] investigated the mechanical properties of nano-silica modified steel-PVA HFECC. By adjusting superplasticizer dosage, the incorporation of nano-silica and hybrid fibers did not markedly reduce the workability of fresh mortar. Microstructural analysis revealed that although nano-silica increased overall porosity, it reduced pore size. Three-point bending tests showed that nano-silica enhanced strength without significantly compromising deformability, though it led to wider cracks. The hybrid steel-PVA fibers effectively controlled crack width, with the mix containing 2.5% PVA and 1.4% steel fibers exhibiting optimal flexural performance.

4.2 HFECC with Synthetic Fibers of Different Sizes and Properties

The relevant studies and main findings of HFECC with Synthetic Fibers of Different Sizes and Properties are summarized in Table 3.

Table 3: Quasi-static mechanical properties of HFECC with synthetic fibers of different sizes and properties

Authors	Fiber combination (vol.%)	Mechanical properties	Main findings
Ahmed and Mihashi [46]	2 12 mm thick + 1 6 mm thin PVA 2 24 mm thick + 1 6 mm thin PVA	3-point bending fracture	Optimal of various hybrid PVA fiber achieve the highest flexural tensile strength and CMOD at peak load.

(Continued)

Table 3 (continued)

Authors	Fiber combination (vol.%)	Mechanical properties	Main findings
Tosun-Felekoglu and Felekoglu [47]	2 PP + 1PVA 1.5 PP + 1.5PVA 1 PP + 2PVA	Compressive strength, Thin plate four-point bending	While a higher PP/PVA fiber ratio resulted in improved ductility of the composites, a concurrent decrease in flexural strength was observed.
Pakravan et al. [48]	0.9 PVA + 0.3 PP 0.6 PVA + 0.6 PP 1.5 PVA + 0.5 PP 1.0 PVA + 1.0 PP	Thin plate 3-point bending	Hybridization of PVA and PP fibers caused no significant improvement of bending strength, but the strain capacity was increased.
Yu et al. [29]	1.5 PVA + 0.5PET 1.0 PVA + 1.0PET 0.5 PVA + 1.5PET	Compressive strength Uniaxial tensile	Replacing 50% of PVA fibers with recycled polyester fibers still yielded satisfactory mechanical performance
Pan et al. [28]	0.6 unoiled + 1.0 oiled PVA	Compressive strength Uniaxial tensile Thin plate four-point bending	Proposing 3 ECC mix proportions offering different mechanical performances and cost levels

Ahmed and Mihashi [46] investigated the influence of hybrid PVA fibers with varying lengths and thicknesses on the flexural fracture behavior of ECC with normal fine aggregate and lightweight aggregate matrices. Their results demonstrated that mixes containing 2% 12 mm long/thick PVA fiber plus 1% 6 mm long/thin PVA fiber, and 2% 24 mm long/thick PVA fiber plus 1% 6 mm long/thin PVA fiber exhibited optimal mechanical performance, achieving the highest flexural tensile strength, the maximum crack mouth opening displacement (CMOD) at peak load, and superior multiple cracking capacity. The flexural strength of ECC with normal aggregate was higher than that of lightweight aggregate ECC, while fine lightweight aggregate further outperformed coarse lightweight aggregate. Tosun-Felekoglu and Felekoglu [47] and Pakravan et al. [48] separately studied the flexural behavior of PVA-polypropylene (PP) hybrid fiber ECC. Both studies concluded that the hybrid fiber system did not significantly enhance the flexural strength compared to mono-PVA fiber ECC but improved the composite's ductility, particularly in post-peak deformation capacity. Additionally, Tosun-Felekoglu and Felekoglu [47] emphasized that the matrix plays a decisive role in the mechanical performance of ECC, indicating that compatibility between the hybrid fiber system and matrix properties is critical.

Although PVA fiber is the most widely used fiber in ECC, high-quality PVA fibers are produced by only a few manufacturers in Japan, resulting in high costs that hinder large-scale engineering application [28]. To address this, several researchers have explored combining high-grade PVA fibers with lower-cost alternatives to reduce production expenses. Yu et al. [29] examined the feasibility of using recycled polyester fibers to partially replace PVA fibers in waterproof ECC. Flexural and uniaxial tensile tests indicated that replacing 50% of PVA fibers with recycled polyester fibers still yielded satisfactory mechanical performance, confirming the viability of this approach.

Domestically produced PVA fibers in China typically have less effective oil-coating treatment, leading to excessively strong fiber-matrix bonding and relatively poor strain-hardening behavior. However, their production cost is lower—approximately one-fifth that of Japanese fibers. Pan et al. [28] studied the mechanical properties of ECC incorporating hybrid fibers made from low-cost Chinese PVA fibers and Japanese PVA fibers. Through experimental investigation, they proposed three ECC mix proportions offering different mechanical performances and cost levels, providing practical options for engineering applications based on specific requirements.

4.3 Other Hybrid Fiber System HFECC

The relevant studies and main findings of HFECC with Other Hybrid Fiber System are summarized in Table 4.

Table 4: Quasi-static mechanical properties of HFECC with other hybrid fiber system

Authors	Fiber combination (vol.%)	Mechanical properties	Main findings
Shabakhty et al. [34]	2.25 PP + 0.75 glass 1.5 PP + 1.5 glass 0.75 PP + 2.25 glass	Uniaxial tensile	12 mm glass fibers reached 2.5% strain, while those with 100 mm PP fibers achieved up to 24% strain.
Luo [49]	0.26 carbon + 0.74PVA 0.27 carbon + 1.03 PVA 0.5 carbon +2.0 PVA	Compressive strength, Thin plate four-point bending, Bending strength	Incorporating high-modulus and high-strength carbon fibers hybridized with PVA fibers lead to a reduction in both flexural toughness and ductility.
Wang et al. [30]	1.5 PVA + 0.5 steel 1.5 PVA + 0.5 basalt	Compressive strength, Uniaxial tensile, Thin plate four-point bending	Adding basalt or steel fibers to ECC did notably improve uniaxial tensile strength but only moderately enhanced load-bearing capacity in the small-deformation stage.
Tian et al. [50]	0.25 basalt + 1.0 PE 0.5 basalt + 1.0 PE 0.75 basalt + 1.0 PE 1.0 basalt + 1.0 PE	Compressive strength, Uniaxial tensile, Four-point bending	Adding basalt fibers to PE-based ECC increased crack strength by up to 40% at 1% fiber volume and tensile strength by up to 15% at 0.5% volume.
Ali et al. [26]	2 PVA + 0.5 SMA 2 PVA + 1.0 SMA 2 PVA + 1.5 SMA	Uniaxial tensile	Significant improvement in the direct tensile capacity of the composite due to the addition of SMA fibers.

The addition of fibers is an effective method for reducing the brittleness of concrete. For decades, elastic fibers such as glass fibers have been incorporated to enhance strength; in recent years, the use of hyperelastic fibers like PP fiber has enabled significant strain-hardening behavior, leading to the development of ECC. While improving a single property such as strength is relatively straightforward, designing a multipurpose cementitious composite that balances both strength and deformation requires careful micromechanical design.

Shabakhty et al. [34] investigated cementitious composites reinforced with hybrid elastic/hyperelastic fibers (glass/PP) at volume ratios of 100/0, 75/25, 50/50, 25/75, and 0/100, and fiber lengths of 12, 25, 50, and 100 mm, under uniaxial tension. The results showed that PP fibers outperformed glass fibers in tensile strength, particularly as fiber length increased. Glass fiber composites exhibited an increase in tensile strength from 4.7 to 6.5 MPa when fiber length was increased from 12 to 100 mm, whereas PP fiber composites showed a more significant improvement from 3.7 to 11.3 MPa. In terms of strain capacity, mixes with 12 mm glass fibers reached 2.5% strain, while those with 100 mm PP fibers achieved up to 24% strain along with pronounced strain hardening.

In an attempt to develop ECC with high toughness and ductility at a low water-to-binder ratio of 0.25, Luo [49] incorporated high-modulus and high-strength carbon fibers hybridized with PVA fibers. However, test results indicated a reduction in both flexural toughness and ductility, with no significant change in strength. Similarly, Wang et al. [30] observed that adding basalt fibers or steel fibers to PVA-based ECC did notably improve uniaxial tensile strength but only moderately enhanced load-bearing capacity in the small-deformation stage. These additions considerably reduced the uniaxial tensile deformation capacity. It should be noted that the flexural deformation capacity was not significantly compromised with steel fiber incorporation. Conversely, the use of calcium sulfate allowed a reduction in PVA fiber content, lowering cost while maintaining deformation capacity and effectively increasing composite strength. Differing findings were reported by Tian et al. [50], who noted that adding basalt fibers to PE-based ECC increased crack strength by up to 40% at 1% fiber volume and tensile strength by up to 15% at 0.5% volume. However, when the basalt fiber content exceeded 0.5%, the ductility and multi-cracking capability of the hybrid system decreased, which is attributed to the differing reinforcement mechanisms of PE and basalt fibers under tension.

Ali et al. [26] incorporated shape memory alloy (SMA) fibers into a PVA fiber-reinforced ECC system and observed a significant improvement in the direct tensile capacity of the composite due to the addition of SMA fibers. Specimens containing 2% PVA and 1% SMA fibers exhibited the highest tensile capacity among all mixtures at the same testing age.

5 Dynamic Mechanical Properties of HFECC at Various Strain Rates

As an ultra-high toughness concrete material, the large deformation capacity of ECC enables it to better resist dynamic mechanical actions, particularly impact loading. Therefore, investigating the dynamic mechanical properties of HFECC is of great significance for its engineering applications in fields such as military protection [51]. The relevant studies and main findings of Dynamic Mechanical Properties of HFECC at various strain rates are summarized in Table 5. The framework of the research content of this chapter is shown in Fig. 2.

Table 5: Dynamic mechanical properties of HFECC at various strain rates

Authors	Fiber combination (vol.%)	Test methods	Main findings
Maalej et al. [52]	1.5 PE + 0.5 steel	Uniaxial tensile at strain rates of 2×10^{-6} $-2 \times 10^{-1} s^{-1}$, Gas-Gun Test	HFECC still be able to maintain pronounced tensile strain-hardening behavior, providing improved functionality as a protective material.
Soe et al. [43]	1.75 PVA + 0.58 steel 1.5 PVA + 0.5 steel	Uniaxial tensile test with strain rate of 1×10^{-5}–$1 \times 10^{-1} s^{-1}$	Tensile strength increases with the increase of the strain rate, whereas the strain capacity decreases.
Zhang et al. [53]	1.5 PE + 0.5 steel	Drop weight impact test	HFECC panels exhibit superior impact resistance, characterized by minimal surface damage, a largely intact structure after perforation.
Ali et al. [26]	2 PVA + 0.5 SMA 2 PVA+ 1.0 SMA 2 PVA + 1.5 SMA	Drop weight impact test	HFECC specimens subjected to impact loading was improved due to SMA fiber addition.
Soe et al. [54]	1.75 PVA + 0.58 steel	Gas-Gun Test	HFECC material has an excellent impact resistance to projectile penetration.
Li et al. [55]	2.0 PVA + 0.5 steel 2.0 PVA + 1.0 steel 2.0 PVA + 1.5 steel	SHPB test	Higher steel fiber volume fractions exhibit lower rate sensitivity in dynamic strength.
Wan [56]	1.5 PVA + 0.5 steel 1.0 PVA + 1.0 steel 0.5 PVA + 1.5 steel	Drop weight impact test, SHPB test	Hybrid mix of 1.5% PVA and 1% steel fibers yielded superior performance compared to the individual fiber mixes

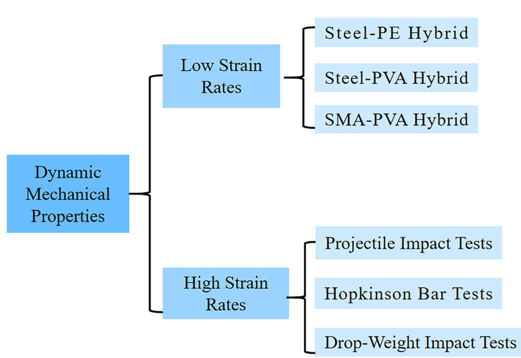

Figure 2: Framework of Section 5: Dynamic mechanical properties of HFECC at various strain rates

5.1 Dynamic Mechanical Properties at Low Strain Rates

ECC with different hybrid fiber systems exhibits notable differences under varying strain rate loadings. Specifically, Maalej et al. [52] and Soe et al. [43] studied the dynamic tensile behavior of steel-PE and steel-PVA hybrid fiber ECC, respectively, under different strain rates. The results indicated that steel-PE HFECC maintained good strain hardening and multiple cracking properties within the strain rate range of 2×10^{-6} to $0.2\ s^{-1}$, showing no significant degradation compared to quasi-static loading. In contrast, steel-PVA HFECC demonstrated pronounced strain rate dependence: the first-crack strength and tensile strength increased with higher strain rates, while the deformation capacity decreased, accompanied by a reduction in strain hardening and multiple cracking capabilities. This distinct behavior may be attributed to differences in the bond properties between PVA or PE fibers and the matrix, warranting further investigation.

Zhang et al. [53] examined the effects of drop-weight impact on reinforced concrete, steel fiber-reinforced concrete, and steel-PE HFECC plates. The study confirmed that HFECC plates exhibited reduced damage extent, along with significantly improved ductility and energy dissipation capacity after repeated impacts. Ali et al. [26] reported in their drop-weight tests that the incorporation of SMA fibers enhanced the impact resistance of ECC. The mixture with 2% PVA and 1% SMA fibers showed the highest impact resistance among all specimens. However, exceeding this fiber volume led to issues such as fiber clustering, disrupted matrix continuity, increased porosity, and consequently reduced impact performance. Heat treatment activated the SMA fibers, introducing a local prestressing effect that further improved impact resistance, despite some damage caused to the PVA fibers during heating.

5.2 Dynamic Mechanical Properties at High Strain Rates

Similar conclusions were drawn by Maalej et al. [52] and Soe et al. [54] based on high-velocity projectile impact tests. HFECC significantly enhanced energy absorption and impact resistance through distributed multi-cracking mechanisms. Li et al. [55] investigated the influence of steel fibers on the impact compression performance of steel-PVA HFECC under different strain rates.

Wan [56] conducted low- and high-speed impact tests on steel-PVA hybrid fiber ECC and steel fiber ECC. Drop-weight impact tests demonstrated that steel-PVA HFECC beams exhibited significantly better flexural impact resistance than those with only PVA or steel fibers. However, high-speed impact tests using a Hopkinson bar indicated that steel fiber-reinforced cementitious composites outperformed those with only PVA or hybrid fibers in terms of impact resistance. Clearly, steel-PVA HFECC displays markedly different behaviors under low- and high-speed impacts. Overall, the incorporation of steel fibers enhances the impact resistance of ECC to varying degrees.

In summary, the impact resistance of hybrid fiber ECC is generally improved compared to single-fiber ECC. Hybrid systems such as steel-PVA/PE and SMA-PVA fibers exhibit significant positive synergistic effects. However, their performance varies noticeably under different strain rate conditions.

6 Durability of HFECC at Different Service Environments

The framework of the research content of this chapter is shown in Fig. 3.

6.1 Freeze-Thaw and Salt Resistance

For engineering structures in cold regions, the freeze-thaw resistance of concrete materials is critically important. Yun [57] investigated the mechanical properties of PVA-PE HFECC after 300 freeze-thaw cycles and found that the multiple-cracking characteristics tended to degrade after cyclic freezing and thawing. This phenomenon deserves attention from both researchers and engineers, particularly in cold climates. In contrast to conventional ECC, which often show reduced tensile ductility at subzero temperatures, steel-PE HFECC exhibited improved ductility under the same conditions [58]. This enhancement can be attributed to two main factors: the increased slip capacity of steel fibers, which dominate the hybrid system, and the reduced fracture toughness of the matrix. Together, these effects contribute to the improved tensile ductility of HFECC at low temperatures. Wen and Cao [31] developed seawater sea-sand HFECC using hybrid calcium carbonate whiskers, stainless steel fibers, and PVA fibers. Similar to conventional HFECC, the addition of stainless steel fibers increased the strength but reduced the deformation capacity. In contrast, calcium carbonate whiskers were found to improve both strength and deformability.

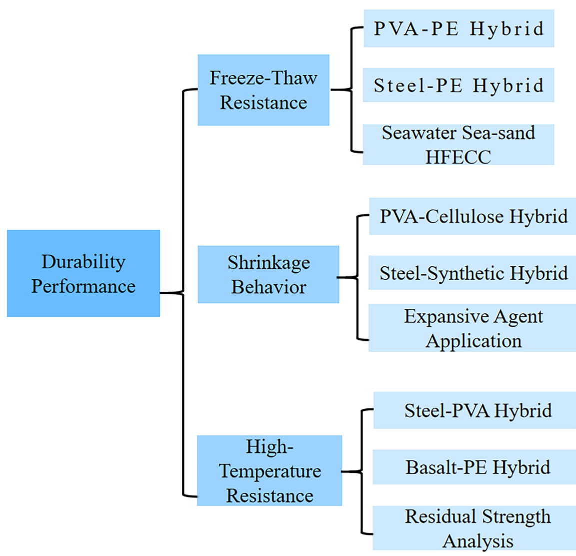

Figure 3: Framework of Section 6: Durability of HFECC at different service environments

6.2 Shrinkage Behavior

Adjusting the fiber ratio can also improve the volume shrinkage of ECC, reduce cracking, and enhance long-term durability. Deng and Xue [59] investigated the shrinkage resistance of HFECC incorporating Chinese PVA fiber PVA fibers blended with cellulose fibers. Test results indicated that, at a water-cement ratio of 0.40, the hybrid fiber system more effectively controlled shrinkage deformation compared to systems using only Chinese or Japanese PVA fibers alone. According to Huang et al. [60], PVA fiber addition postpones crack initiation in ECC. Specifically, the cracking age of ECC containing 2% PVA fibers reaches 28.2 days, which is later than that of ECC mixes with PP or PE fibers. While Cao et al. [61] demonstrated that steel fibers effectively restrict drying shrinkage, whereas PVA fibers and $CaCO_3$ whiskers are more efficient against plastic shrinkage, respectively. Hence, a hybrid approach combining steel and synthetic fibers is recommended for comprehensive shrinkage control in ECC. Expansive agent can be used to further reduce the drying shrinkage of steel-PE HFECC [33].

6.3 High-Temperature Resistance

Due to their low melting points, synthetic fibers are susceptible to degradation at high temperatures, whereas steel and basalt fibers exhibit superior high-temperature resistance. Therefore, hybrid systems combining steel/basalt with synthetic fibers can provide HFECC with higher residual strength after fire exposure compared to composites reinforced solely with synthetic fibers. For example, Li et al. [62] studied the high-temperature performance of PVA-steel HFECC and observed that the compressive strength remained largely unchanged up to 400°C, while the flexural strength, toughness, and stiffness gradually degraded with increasing temperature. This is primarily due to the melting of PVA fibers, which diminishes their bridging capacity, whereas the high thermal resistance and stiffness of steel fibers help maintain higher compressive strength within a certain temperature range. Similarly, Xiong et al. [63] reported that basalt fibers effectively inhibited crack development in PE-basalt HFECC even after exposure to high temperatures. The incorporation of basalt fibers increased the residual compressive strength by 5.3% after exposure to 200°C, and improved the tensile strength by 16.6%, 17.1%, and 56.3% at 200°C, 400°C, and 600°C, respectively. Consistently, Rawat et al. [64] also confirmed that the addition of basalt fibers enhances the residual strength of HFECC after high-temperature exposure.

7 Structural Performance of HFECC

The framework of the research content of this chapter is shown in Fig. 4.

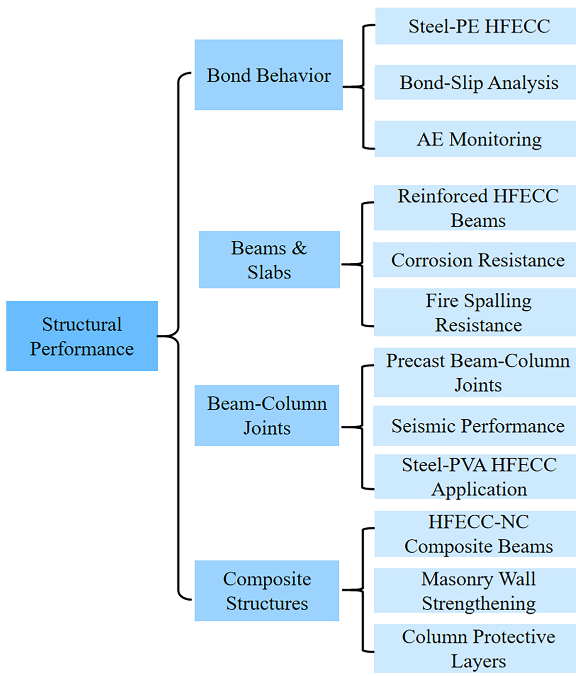

Figure 4: Framework of Section 7: Structural Performance of HFECC

7.1 Bond Behavior between Steel Reinforcement and HFECC

A strong bond between steel reinforcement and the concrete matrix is essential for composite action and full utilization of the reinforcement's mechanical properties. Shan et al. [2] investigated the bond behavior between steel-PE HFECC and steel bars, revealing significantly superior interfacial bond performance compared to that of ordinary concrete. During pull-out tests, the acoustic emission historical index displayed more intense peak signals, indicating enhanced bond integrity. However, the difference in bond behavior between HFECC and single-fiber ECC remains unclear.

7.2 Performance of Reinforced HFECC Beams and Slabs

In reinforced concrete members, reinforcement corrosion is a primary cause of durability degradation and reduced service life. A key factor in determining the widespread use of HFECC in reinforced structures is its ability to mitigate corrosion. Mihashi et al. [65] studied the chloride corrosion resistance of steel-PE

HFECC reinforced beams. Their findings demonstrated that the hybrid steel-PE fibers significantly reduced chloride-induced corrosion of the reinforcement. After a long-term exposure of 52 weeks, the corrosion resistance of the HFECC beams was markedly better than that of mortar and mono-PE fiber ECC beams.

For high-strength, high-density concrete, spalling during fire exposure can compromise structural integrity, leading to reduced load-bearing capacity or even complete failure. Thus, researchers have examined the anti-spalling performance of reinforced HFECC slabs. Rawat et al. [64] investigated the spalling resistance of both single and hybrid PE fiber-reinforced ECC under fire conditions. Replacing 12 mm, 0.75% PE fibers using basalt fiber did not improve the spalling resistance of HFECC panels. Enhanced performance was achieved with longer PE fibers (18 mm) or through the incorporation of PP fibers. A hybrid mixture containing 12 mm 0.3% PP, 1.25% PE, and 0.75% basalt fibers demonstrated the best spalling resistance. Further analysis suggested that fiber melting may not be the main mechanism for improving spalling resistance. Instead, fiber distribution and bonding within the matrix play a critical role in forming an effective network for dissipating vapor pressure.

7.3 Mechanical Performance of Beam-Column Joints

Given that the material cost of ECC is significantly higher than that of conventional concrete, its use is more advantageous in critical structural regions where enhanced toughness is required. For instance, in seismic design, the principle of "strong joints, weak members" is widely adopted, making ECC a potentially viable material for beam-column connections [56]. Precast concrete (PC) beam-column joints are critical components influencing the seismic performance of precast structures. Poor joint performance has led to the collapse of numerous PC buildings during past earthquakes. To address this, Ghayeb et al. [66] conducted a study on novel hybrid PC beam-column joints fabricated with HFECC containing 1.75% hybrid fibers (1% PVA and 0.75% hooked-end steel fibers). Quasi-static cyclic tests on three specimens—including one monolithic joint—revealed that the use of HFECC in the joint and adjacent beam regions prevented brittle failure due to the superior mechanical properties of ECC. The hybrid joints exhibited better seismic performance than the monolithic joint in terms of load-displacement capacity, ductility, strength, energy dissipation, and failure mode. The application of HFECC promoted ductile failure in the beam, thereby avoiding shear failure. Han et al. [67] further confirmed that ECC effectively suppresses the formation and propagation of shear cracks in beam-column joints, significantly improving load-carrying capacity, ductility, and energy dissipation. HFECC beam-column joints demonstrated better seismic performance both before and after peak loading compared to those with mono-PVA fiber ECC. Therefore, the use of steel-PVA HFECC in beam-column joints in high seismic risk regions represents a feasible design strategy.

7.4 Performance of Composite Structures

Wu et al. [68] investigated the mechanical behavior of HFECC-normal concrete (NC) composite beams. A comprehensive analysis was carried out to evaluate the effects of fiber type, reinforcement ratio, and steel fiber content on the flexural performance of the composite beams. The results indicated that the stiffness of composite beams with 1.7% PVA fibers increased by 14.7% compared to NC beams, while those with 1.7% PE fibers showed a 26.1% increase. The addition of steel fibers at volume fractions of 0.6% and 1.0% enhanced the flexural capacity of PVA-based composite beams by at least 8.1%.

In addition to enhancing the toughness of new structures, existing engineering structures often require strengthening and rehabilitation to improve mechanical performance and durability, thereby extending their service life. For example, Maalej et al. [69] presented experimental results from quasi-static and low-velocity impact tests on unreinforced masonry (URM) walls strengthened with ECC. Under quasi-static loading, the ECC retrofit system significantly enhanced the out-of-plane resistance of masonry walls. The strengthened specimens exhibited increases in ultimate load capacity and deflection capacity by factors of 6.5–22 and 4.2–15.9 in Test Series I and II, respectively. Incorporating a steel mesh within the ECC layer further increased the ultimate load-bearing capacity by 40%–68%, although it reduced deflection capacity by 17%–74% compared to ECC-only specimens. The tests also confirmed that ECC exhibits strain-hardening behavior and multiple micro-cracking in masonry strengthening applications. Unlike URM walls, which failed catastrophically upon initial impact, ECC-strengthened walls sustained repeated low-velocity impacts without sudden collapse. The use of ECC layers considerably reduced fragmentation under impact, thereby lowering the risk of injury from flying debris in blast or explosion scenarios. In summary, Maalej's study demonstrates that ECC-based strengthening systems significantly improve the impact resistance of URM walls and prevent abrupt failure. These results suggest that ECC-retrofitted masonry can help mitigate damage in events such as blasts or explosions. Li et al. [61] showed that reinforced concrete columns with an HFECC protective layer could prevent spalling and mitigate cracking under high temperatures, effectively enhancing the residual load-bearing capacity of the columns after fire exposure.

8 Conclusions and Perspectives

8.1 Conclusions

This review has systematically examined the recent advances in Hybrid Fiber Engineered Cementitious Composites (HFECC), with emphasis on micromechanical design theories, mechanical performance under quasi-static and dynamic loading, durability, and structural applications. The following key conclusions can be drawn:

(1) The incorporation of hybrid fibers, particularly combining high-modulus (e.g., steel) with low-modulus polymeric fibers (e.g., PVA, PE), enables a more tunable mechanical performance compared to single-fiber ECC. Through micromechanical design, HFECC can achieve improved multi-cracking and strain-hardening behavior, allowing designers to balance strength, ductility, and cost according to engineering requirements.

(2) The critical fiber volume theory provides a fundamental basis for optimizing hybrid fiber proportions. Both strength-based and energy-based criteria must be satisfied to ensure robust strain-hardening. Hybrid fiber systems often exhibit synergistic effects, enhancing crack control and composite toughness beyond what is achievable using individual fibers.

(3) Under quasi-static loading, steel-PVA and steel-PE hybrid systems significantly improve flexural and tensile strength while retaining high deformation capacity. The incorporation of high-volume fly ash and nanomaterials such as nano-silica can further refine microstructure and interface properties, contributing to higher performance and better crack width control.

(4) HFECC exhibits pronounced strain-rate sensitivity. Under low to high strain-rate loading, hybrid fibers effectively improve impact and blast resistance. Steel-PE systems demonstrate better retention of ductility under dynamic tension compared to PVA-based hybrids. The combination of shape memory alloy fibers with PVA also shows promising improvements in energy dissipation under impact.

(5) Durability performance—especially under freeze-thaw cycles, high temperatures, and chloride exposure—requires further investigation. Initial studies indicate that hybrid fibers can mitigate spalling under elevated temperatures and reduce shrinkage cracking. However, long-term durability under combined mechanical and environmental loads remains inadequately studied.

(6) Structural applications—including reinforced beams, beam-column joints, and composite members—demonstrate that HFECC can enhance load capacity, energy dissipation, and damage tolerance.

Its use in critical regions (e.g., joints in seismic designs) and in repair/strengthening applications shows significant potential for improving structural resilience.

(7) Despite these advantages, high material costs—mainly due to the dependence on high-performance imported PVA fibers—still hinder large-scale implementation. The development of low-cost domestic fibers and optimized hybrid combinations remains essential for broader adoption.

8.2 Perspectives

Despite promising progress, several challenges and research opportunities remain for HFECC:

(1) Cost Reduction and Localization: There is an urgent need to develop and promote cost-effective domestic fibers and hybrid combinations. Further research should explore the use of recycled and natural fibers in hybrid systems to reduce cost and environmental impact without compromising mechanical performance.

(2) Dynamic and High-Strain Rate Behavior: The underlying mechanisms governing rate-dependent behavior in different hybrid systems are not fully understood. Further experimental and numerical studies are needed to clarify fiber-matrix interactions under dynamic loads and to establish standardized impact-resistant design guidelines.

(3) Durability under Multi-Action Environments: Comprehensive studies are needed to evaluate HFECC performance under coupled conditions—such as mechanical loading plus freeze-thaw cycles, chloride attack, or carbonation—especially for structures in harsh environments.

(4) Full-Structural Application Validation: Most existing studies focus on material-level properties. More large-scale experiments and real-world demonstrations are necessary to validate the structural performance and economic feasibility of HFECC in beams, columns, joints, and composite systems.

(5) Multi-Scale Modeling and Design Integration: Advanced numerical models that link micromechanical behavior to structural response should be developed. Integration of machine learning for mix-proportion optimization and performance prediction could further accelerate the design of tailored HFECC.

(6) Standardization and Specification Development: The absence of standardized testing and design codes for HFECC limits its regulatory acceptance. Efforts should be made to establish unified material specifications and design guidelines to support practical engineering application.

In summary, HFECC offers significant potential for next-generation resilient infrastructure. With continued research focusing on performance optimization, sustainability, and real-world validation, HFECC is expected to play an increasing role in advanced construction and rehabilitation projects.

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Availability of Data and Materials: Data available on request from the authors. The data that support the findings of this study are available from the Corresponding Author, [Dan Wang], upon reasonable request.

Ethics Approval: This study did not involve human or animal subjects; therefore, ethical approval was not required.

Conflicts of Interest: The authors declare no conflicts of interest to report regarding the present study.

Notation List

σ_{cu}	Ultimate Crosslinking Strength of Fibers in Fiber-Reinforced Cementitious Composites
σ_{fc}	Initial Tensile Strength of Matrix
g_1	Impact Factor of Fiber 1
g_2	Impact Factor of Fiber 2
σ_{01}	Ultimate crosslinking stress of fiber 1
σ_{02}	Ultimate crosslinking stress of fiber 2
δ_{1^*}	Anchorage length of Fiber 1
δ_{2^*}	Anchorage length of Fiber 2
L_{f1}	Length of Fiber 1
K_{tip}	Crack Tip Fracture Toughness
C	Crack size (half the crack length)
c_1	Crack size corresponding to δ_{1^*}
δ_a	Theoretical crack opening displacement
$V_{f,\ cr}$	Critical fiber content
A_f	Fiber cross-sectional area
P_f	Fiber cross-sectional perimeter
k_B	Fiber Bonding Coefficient
k_C	Bonding coefficient of the matrix
E_c	Elastic modulus of the matrix
E_s	Elastic modulus of fibers
L_f	Fiber length
X	Average crack spacing
δ_{max}	Half the maximum crack width value
σ_{fc}	Initial Crack Strength of Matrix
σ_{max}	Ultimate crosslink strength of fibers

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