

# Hybrid Engineered Cementitious Composites (ECC) for Building Structures: A Literature Review on Material Characteristics and Applications

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Indonesia lies within the Pacific Ring of Fire and faces high seismic risk, especially in soft-soil areas. Low stiffness and low density in soft soils can amplify seismic waves and increase surface acceleration, demanding earthquake-resistant infrastructure that is also sustainable. Engineered Cementitious Composites (ECC) are advanced cement-based materials reported to provide superior crack control and ductility compared with conventional concrete. This paper presents a qualitative-descriptive literature review on ECC behavior and its potential for seismic-resistant construction on soft ground, emphasizing hybrid fiber and hybrid cementitious approaches. ECC is characterized by strain-hardening, high tensile ductility, controlled micro-cracking, and high energy-absorption capacity, which are beneficial under earthquake loading. The reviewed studies indicate that combining fibers (e.g., PVA-PP hybrids) with supplementary cementitious materials such as fly ash and silica fume can enhance mechanical performance while supporting green building objectives through the use of industrial by-products and locally available ingredients. Overall, hybrid ECC is consistently reported to address key challenges in soft soils, including differential deformation and moisture-related durability concerns, and is therefore a promising adaptive and sustainable option for earthquake-resistant infrastructure in Indonesia.

**Keywords:** Engineered Cementitious Composites, Hybrid Fiber, Hybrid Cementitious, Sustainable Green Building, Soft Soil

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## Introduction

Indonesia lies within the Pacific Ring of Fire, one of the most seismically active regions in the world. This setting increases the potential for major earthquakes and tsunamis that can severely damage structures, particularly those built on soft-soil areas (Arianto, 2020; Librian et al., 2024). Therefore, improving the ductility and crack resistance of construction materials is essential for enhancing structural performance under seismic loading. One material that has shown strong capability in controlling cracks and increasing structural ductility is Engineered Cementitious Composites (ECC) (Han et al., 2025).

ECC is a mortar-based composite technology developed in the early 1990s by Victor C. Li (Li, 2003). Compared to normal concrete, ECC exhibits strain-hardening behavior under tensile loading, enabling it to sustain increasing strain after the first crack forms (Malik et al., 2024). In addition, ECC demonstrates

multiple micro-cracking behavior rather than localized cracking, which helps delay damage concentration and reduces the risk of brittle failure (Ji et al., 2023).

To further enhance performance and practicality, ECC can be developed through a hybrid cementitious–fiber approach. For example, a hybrid mixture of polyvinyl alcohol (PVA) and polypropylene (PP) fibers can maintain ECC flexibility and deformation capacity (Piscosa et al., 2024). Moreover, incorporating supplementary cementitious materials such as fly ash (FA) and silica fume (SF) can improve ECC mechanical properties at 28 days (Zhu et al., 2023).

Given the need for environmentally friendly materials that are also resistant to seismic loads, developing ECC with FA and SF, combined with hybrid fiber reinforcement, offers a promising direction to improve the performance of building structures in Indonesia. Therefore, this study presents a literature review focusing on ECC variables, hybrid fibers, hybrid cementitious materials, sustainable green building

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considerations, and the relevance of ECC for construction on soft soil.

## Method

This study uses a literature review method with a qualitative-descriptive approach. The purpose of an in-depth literature study is to identify, analyze, and summarize the results of previous research related to characteristics of materials and the applications of Hybrid ECC in building structures without conducting direct experiments.

To ensure a transparent and reproducible selection process, the literature search and screening followed a PRISMA-like flow (Identification–Screening–Eligibility–Included), as illustrated in Figure 1. In the identification stage, articles were collected using keyword-based searches from ScienceDirect and Google Scholar, resulting in 105,724 records (ScienceDirect: 10,624; Google Scholar: 95,100). During screening, records were filtered using a year criterion (2022–2026), and irrelevant records outside the year range were excluded. Next, title screening was conducted based on the inclusion criteria, followed by abstract screening to retain only articles that were relevant to Hybrid ECC behavior and application. Finally, full-paper review was performed to confirm suitability and completeness of information, resulting in a final set of 26 articles for synthesis (Figure 1).

The literature review process covers five main aspects of material properties, namely: Behavior, Composition, Constituent Characteristics, Successful Case Studies, Application Development, and Material Development.

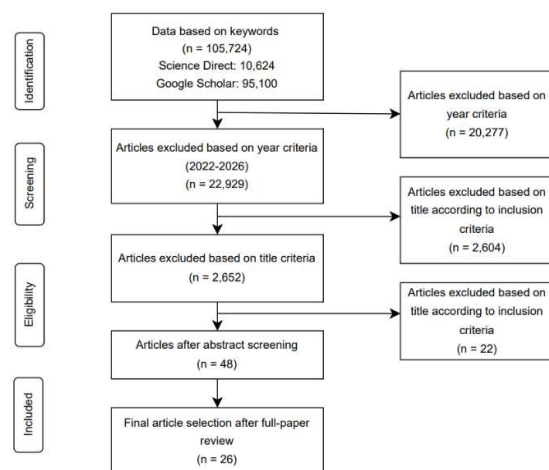


Figure 1 Prism of Literature Analysis

## Review Findings and Synthesis

This section presents synthesized findings from the selected literature. The “findings” refer to key patterns and consistent observations reported across studies on ECC behavior and performance, while the synthesis highlights

their implications for crack control and seismic-resistant applications.

### ECC Behavior

ECC exhibits strain-hardening behavior up to failure, whereas normal concrete and conventional fiber-reinforced concrete typically show a post-cracking reduction in stress capacity after reaching the crack resistance limit. Figure 2 illustrates the tensile stress–strain response of cement-based composites reported in the reviewed literature.

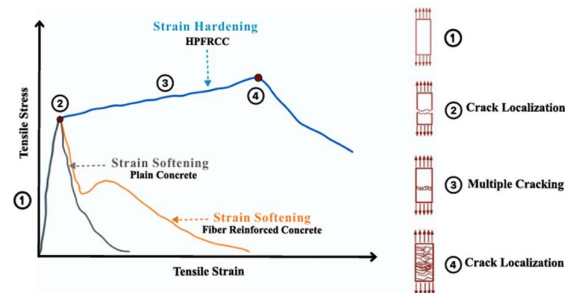


Figure 2 Tensile Stress-Strain Curve of Cement-Based Composites (Malik et al., 2024)

As indicated in Figure 2, ECC demonstrates higher energy dissipation and toughness compared with other cement-based composites. These characteristics support the suitability of ECC for structural components that are frequently subjected to seismic loading (Malik et al., 2024).

In terms of cracking behavior, ECC is consistently reported to exhibit multiple micro-cracking and to prevent localized (centralized) crack development. This differs from conventional concrete, which tends to develop one or a few dominant cracks that propagate until failure (Ji et al., 2023), as shown in Figure 3. This observation is further supported by surface displacement/strain measurements using Digital Image Correlation (DIC) reported in previous studies (Jaya et al., 2024).

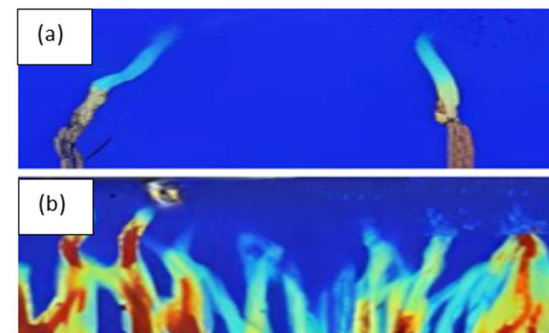


Figure 3 Behavior Cracking: (a) Normal Concrete and (b) ECC (Ji et al., 2023)

Based on DIC observations shown in Figure 4, cracks in normal concrete appear wider and more localized up

to failure than those in ECC. Consequently, ECC is associated with better energy absorption capacity and improved damage tolerance under earthquake-type loading, primarily due to its controlled micro-cracking mechanism (Ji et al., 2023; Li, 2003).

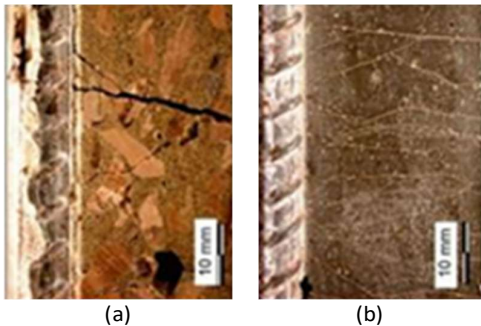


Figure 4 DIC results on (a) Normal Concrete; (b) ECC (Li, 2003)

Composition

Based on the reviewed literature, ECC is generally composed of silica sand, cement, fibers, water, superplasticizer, and supplementary cementitious materials such as fly ash (FA) and silica fume (SF). The proportion and selection of these constituents are commonly adjusted to achieve strain-hardening behavior, controlled micro-cracking, and adequate workability for practical application.

Characteristics of Fiber ECC

Fibers play a critical role in enabling strain-hardening and multiple micro-cracking behavior in ECC. Figure 5 presents tensile stress–strain curves and related DIC observations reported in previous studies, indicating that ECC can achieve tensile strain capacity exceeding 9% depending on mixture design and fiber parameters (Zhang et al., 2023).

| Table 1 ECC Fiber Characteristic Requirements (Zhang et al., 2020) |              |
|--------------------------------------------------------------------|--------------|
| Characteristics                                                    | Requirements |
| Percentage                                                         | ≤ 2% Volume  |
| Diameter                                                           | 20-50        |
| Length                                                             | 6-12 mm      |
| Tensile Strength                                                   | ≥ 800 MPa    |
| Modulus of Elasticity                                              | ≥ 10 MPa     |
| Tensile Tensile Capacity                                           | ≥ 3%         |

To maintain stable strain-hardening behavior, the fiber properties and dosage should meet key requirements. As summarized in Table 1, the reviewed literature commonly emphasizes low fiber volume (≤2%) combined with adequate tensile strength and stiffness to support crack bridging and controlled crack width (Zhang et al., 2020).

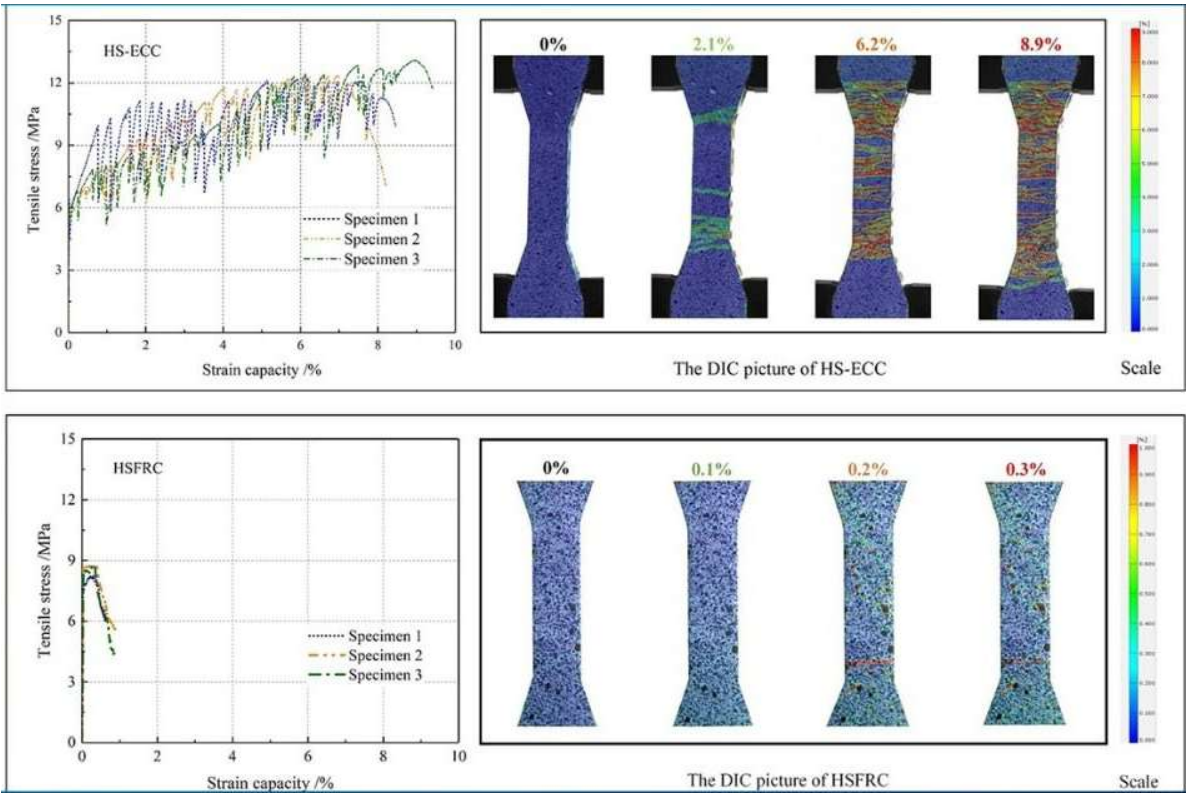


Figure 5 Tensile Tension-Strain Curves and DIC HS-ECC and HSFRCC Drawings (Zhang et al., 2023).

### ECC Application Method

The reviewed literature generally describes ECC application as beginning with micromechanics-based material design, which aims to control fiber–matrix interactions and interface properties to produce strain-hardening and multiple micro-cracking behavior at low fiber volume (<2%) (Li et al., 2004). A commonly reported mixture proportion uses a water-to-binder ratio (w/b) of approximately 0.26 and a sand-to-binder ratio (s/b) of about 0.36 to support volume stability and self-consolidating properties (Li et al., 2004).

In practice, mixing is performed by sequentially adding ECC constituents until a homogeneous mixture is achieved. Fresh properties are typically checked using slump flow and Marsh cone tests to ensure adequate viscosity and deformability before casting (Li et al., 2004). Reported placement methods include in-situ casting, pre-casting, and spraying (shotcrete) for repair and protective overlays. Curing is commonly conducted under moist conditions for at least two days to reduce early-age cracking risk, followed by strength testing and micro-crack width observation up to 28 days (Li et al., 2004).

### Successful Application of ECC

Several studies report successful field applications of ECC in construction, particularly for bridge decks and joint regions, as illustrated in Figures 6–9. For example, ECC overlays applied to the Michigan bridge deck reportedly performed well through multiple winter cycles, indicating favorable durability under harsh environmental exposure (Yildirim, 2018). In addition, ECC-based link slab applications, such as those reported for the Grove Street Bridge, have been described as durable for extended service periods (Yildirim, 2018).

Other reported applications include ECC used in expansion joint regions (e.g., Second Ring Viaduct Expressway Project), where reduced shear cracking was observed after several years of service (Yin et al., 2019). ECC has also been reported as beneficial for tunnel secondary lining retrofitting, with multiple cases indicating improved ductility and crack control performance (Boughanem et al., 2013).



**Figure 6** Successful Study of ECC Application to Michigan Bridge Deck (Boughanem et al., 2013; Yildirim, 2018; Yin et al., 2019).



**Figure 7** Successful study of the application of ECC on Linkslab using ECC on the Grove Street Bridge (Boughanem et al., 2013; Yildirim, 2018; Yin et al., 2019).

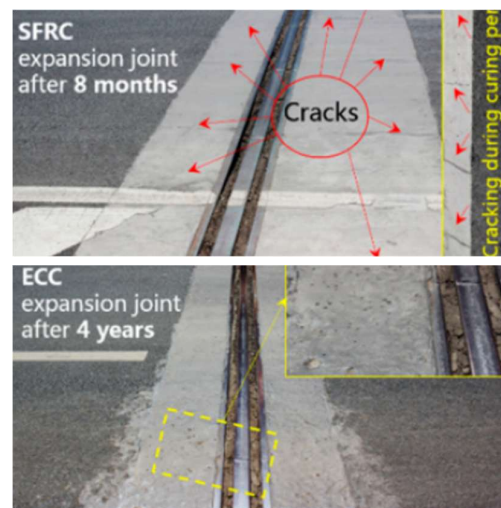


**Figure 8** The successful study of the application of ECC on the Expansion joint ECC was successfully applied to the Second Ring Viaduct Expressway (Boughanem et al., 2013; Yildirim, 2018; Yin et al., 2019).

### Weaknesses and Methods of Overcoming ECC

The main disadvantage of ECC lies in the quality control and homogeneity aspects of the mixture when applied on an industrial scale. Although ECC formulations can be well controlled in the laboratory, they are difficult to replicate in the field because they are influenced by the mixing sequence, process, Pumping and Finishing, and control of Superplasticizer, which affect the rheological properties of the mixture.

In addition, fiber dispersion during mixing often leads to fiber phenomena, such as Exfoliation and uneven fiber orientation, thereby reducing the efficiency of interfacial voltage delivery and lowering tensile strength and ductility. The high viscosity of the matrix also worsens the distribution of the fibers and results in inhomogeneity of mechanical results. Therefore, the application of ECC in mass production requires stricter quality control standards and mixing process control so that the performance of materials in

the field can be on par with the results in the laboratory (Liew et al., 2020; Lv et al., 2020; Soleimani et al., 2023).

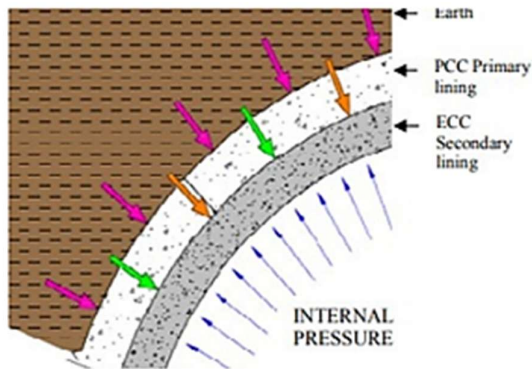


**Figure 9** Study of the success of ECC Application on Tunnel Layers using ECC Secondary Lining (Boughanem et al., 2013; Yildirim, 2018; Yin et al., 2019).

These problems can be overcome by controlling the rheological parameters of the matrix through regulating the ratio of water to binding materials and dosage Superplasticizer. For the viscosity of the mixture to remain optimal to allow for the movement and spread of the fibers evenly during the mixing process, it is necessary to adjust gradually after the paste reaches a sufficiently homogeneous consistency, to avoid the occurrence of fibers Exile during the ECC stirring process (Liew et al., 2020; Lv et al., 2020; Soleimani et al., 2023).

#### Application Development Potential

The development of ECC continues to be driven by numerous experiments. ECC is considered to be able to be developed both in application in structural reinforcement and in terms of material development in the form of fiber and cement replacement, and the use of artificial aggregate.

A Bridge That Can Withstand Seismic Loads can be seen on Figure 11. ECC reinforcement on the bridge pillars is under review at 2 points under seismic load. (Figure 10) shows that ECC material has an advantage in holding Displacement excess in longer earthquake periods.

ECC in reinforcement Jacketing at the joints of column beams can distribute the load on the building structure very well and prevent macro cracking (Figure 12) (Hung et al., 2023; Zhang et al., 2021). This helps prevent structural failure under earthquake loads, particularly in soft-ground construction.

In addition, research by Xu (2022) shows that ECC can be developed by the use of artificial aggregates, where the behavior of stress – strain looks like Figure 13. Behavior Strain Hardening on ECC with Artificial Aggregate, as seen in the Figure 13 Depending on the type of artificial aggregate used, cement-bonded aggregate exhibits the highest level of stress resistance,

whereas geopolymer and desert sand aggregates exhibit strain hardening, which is preferable.

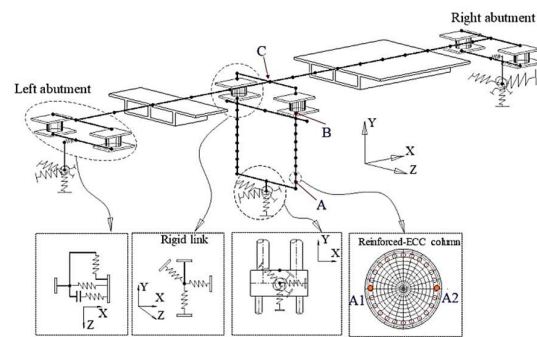


**Figure 10** Model Finite Element Bridges with ECC reinforcement (Zhang et al., 2021)

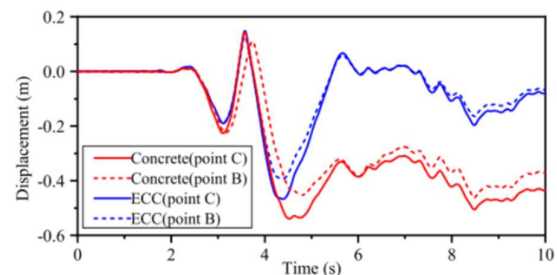


**Figure 11** Potential Application of ECC on Pillars (Zhang et al., 2021)

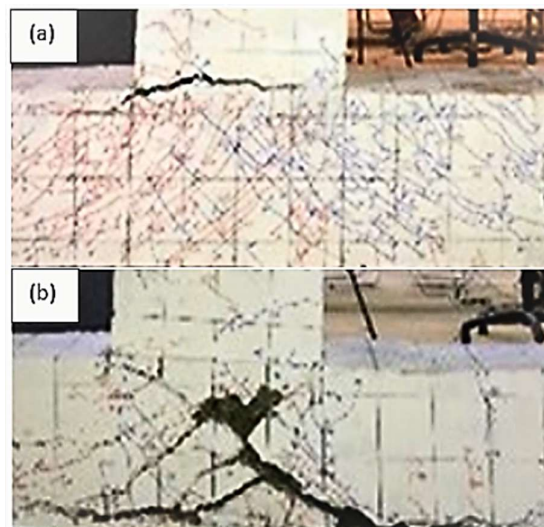


**Figure 12** Jacketing ECC on Column-Beam Joints: (a) ECC and (b) Normal Concrete (Hung et al., 2023)

In addition, ECC can be developed into Engineered Geopolymer Composites (EGC), with 80% lower CO<sub>2</sub> emissions due to the use of FA and SF instead of cement. (Zahid & Shafid, 2020). EGC has the same tensile and flexural properties as ECC at static loads, but is mechanically superior at dynamic loads (Cai et al., 2022). EGC has better mechanical performance with

even and small cracks compared to ECC (Wang et al., 2024). A comparison of the mechanical performance of EGC and ECC can be seen in Figure 14.

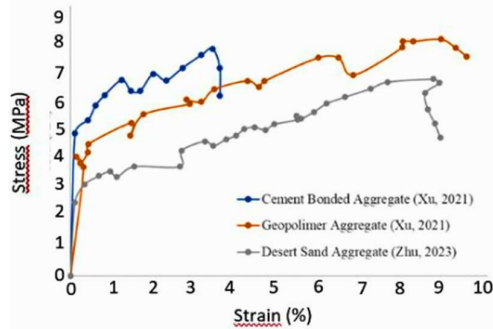


**Figure 13** ECC Strain-hardening Curve with Artificial Aggregate (Xu et al., 2022)

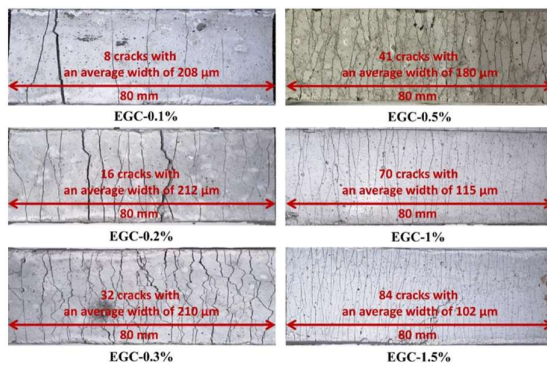


**Figure 14** Comparison of properties: Multiple Cracking, EGC, and ECC (Wang et al., 2024)

### Hybrid Fiber ECC

Properties Fiber Fiber used to play a very important role in behavior Multiple Cracking ECC. Like an experiment by Yu (2017) and Picesca et al. (2024), indicates PVA Fiber. It is more rigid, so it can withstand higher voltages. In addition, the research of Picesca et al. (2024) prove that hybrid PVA and PP fiber mixtures are proven to be able to maintain ECC flexibility and deformation with better cost efficiency (Figure 15). This makes PP fiber a viable alternative material for ECC with Properties Close to PVA fiber (Table 2). The research synthesis table on ECC can be seen at Table 3.

### Hybrid Cementitious ECC

Zhu (2023) indicates that the addition of the material Cementitious can be combined with FA and SF. The addition of FA and SF to the ECC increased the first crack load, peak load, and bending strength, as well as reduced deflection at peak load, fracture energy, and toughness index at 28 days and beyond, as seen in Figure 16.

This shows that the addition of cementitious material offers advantages over ECC. SF is used to improve the mechanical properties of ECC, particularly

at concrete ages above 28 Days. FA can help keep the ECC from cracking during the treatment period.

**Table 2** Properties ECC Fiber Optics (Saljoughian et al., 2024)

| Properties                  | Polypropylene (PP) | Polyvinyl Alcohol (PVA) |
|-----------------------------|--------------------|-------------------------|
| Length (mm)                 | 12                 | 6                       |
| Diameter (mm)               | 0,019              | 0,015                   |
| Unit Weight (kg/m3)         | 910                | 1,300                   |
| Tensile Strength (MPa)      | 400                | 1,588                   |
| Modulus of Elasticity (MPa) | 4100               | 35000                   |

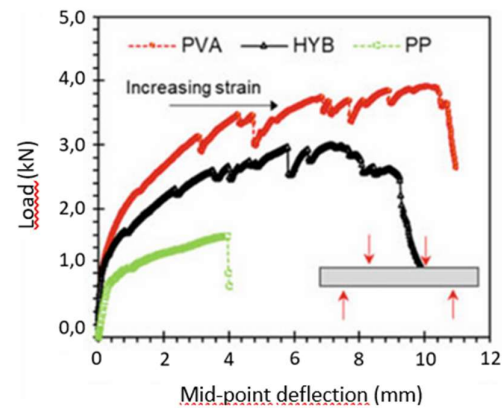


**Figure 15** ECC Deflection Comparison (Picesca et al., 2024)

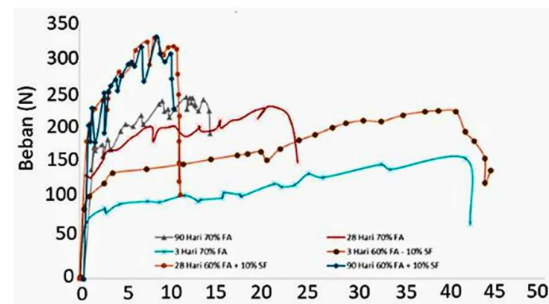


**Figure 16** Deflection Comparison Hybrid Cementitious ECC (Zhu et al., 2023)

## Conclusion

The reviewed literature indicates that Hybrid ECC exhibits high ductility, strain-hardening behavior, and controlled micro-cracking. Hybrid fiber systems and hybrid cementitious materials (e.g., FA and SF) are widely reported to enhance mechanical performance while improving sustainability, which supports the potential of ECC for seismic-resistant construction in soft-soil regions. However, successful field implementation remains dependent on consistent quality control and mixing procedures to ensure homogeneous fiber dispersion and stable fresh properties.

Table 3 ECC Research Synthesis

| Author/Year                           | Hybrid ECC Composition                    | Fiber Type   | Main Mechanical Parameters                                 | Structural Application                  | Core Findings                                                                     |
|---------------------------------------|-------------------------------------------|--------------|------------------------------------------------------------|-----------------------------------------|-----------------------------------------------------------------------------------|
| Li (2003); Malik et al. (2024)        | Cement + Silica Sand + FA/SF + SP         | PVA          | Tensile strain > 3–9%, strain-hardening, multiple cracking | Earthquake resistant structure          | ECC shows much higher ductility and energy dissipation than normal concrete       |
| Yu et al. (2017)                      | Cement + FA + Fine Sand                   | PVA          | Tensile strain capacity up to ±8%                          | Bending structural elements             | PVA fiber contributes greatly to tensile strength and micro-crack control         |
| Zhu et al. (2023)                     | Hybrid cementitious: FA + SF              | PVA          | Increased first cracking load, peak load, bending strength | Long-lived structures                   | FA maintains workability and curing, SF increases strength at ages >28 years      |
| Piscese et al. (2024)                 | Cement + FA                               | Hybrid + PVA | High ductility, controlled deflection                      | Low-cost structure                      | Hybrid fiber enhances ECC flexibility with cost efficiency                        |
| Saliouhian et al. (2024)              | Cement + high slag                        | PP           | High tensile stretch, large tensile strain                 | Environmentally friendly infrastructure | PP fiber is an economical alternative to PVA with adequate mechanical performance |
| Zhang et al. (2021)                   | Conventional ECC + FA                     | PVA          | Seismic displacement reduction                             | Earthquake-resistant pillars & bridges  | ECC reinforcement effectively increases seismic resistance of bridges             |
| Hung et al. (2023)                    | ECC Jacketing                             | PVA          | Increased deformation capacity & crack control             | Beam-column connection                  | ECC is more effective than concrete and FRP in seismic retrofit                   |
| Yin et al. (2019)                     | PVA-based ECC                             | PVA          | Long-term shear & crack resistance                         | Bridge joint expansion                  | ECC maintained >4 years of performance without significant cracking               |
| Boughanem et al. (2013)               | Conventional ECC                          | PVA          | High ductility, micro-cracking                             | Tunnel lining                           | ECC improves safety and service life of underground structures                    |
| Wang et al. (2024); Cai et al. (2022) | Engineered geopolymer composite (FA + SF) | PVA          | Multiple cracking, superior dynamic performance            | Sustainable structure                   | EGC has much lower CO <sub>2</sub> emissions with ECC-equivalent performance      |
| Xu et al. (2022)                      | ECC + artificial aggregate                | PVA          | Strain-hardening remains achieved                          | Innovative structure                    | Artificial aggregate types affect peak strength and ductility                     |

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