International Journal of GEOMATE, June 2023, Vol. 24, Issue 106, pp.101-110
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2023.106.s8681
Geotechnique, Construction Materials and Environment

# ENGINEERED CEMENTITIOUS COMPOSITES AS A HIGH-PERFORMANCE FIBER REINFORCED MATERIAL: A REVIEW

*Karl Michael H. Banaay[1,2], Orlean G. Dela Cruz[1] and Manuel M. Muhi[1]

[1]Graduate School, Polytechnic University of the Philippines, Philippines;
[2]WSP Philippines Inc., Philippines

*Corresponding Author, Received: 28 June 2022, Revised: 19 Feb. 2023, Accepted: 19 March 2023

**ABSTRACT:** Cementitious composites are one of the world's most consumed infrastructure construction materials because of their abundant resources, mature production process, and strong adaptability. Most of these materials, however, remain brittle. It highlights the need to develop low-cost, high-ductility cementitious materials for structural applications. These issues are the fundamental driving force behind Engineered cementitious composites (ECC) development due to the micromechanical interactions between its constituents and processing techniques. ECC is a high-performance, ultra-ductile fiber-reinforced cementitious composite material designed for high material volume and cost-sensitive applications in the construction sector. However, this material still lacks standardization regarding mix proportion and fiber used as a proper processing technique to balance economy and requirements for strength and durability. This paper aims to review some of the past researchers' design proportions and fiber types used as a reference and guide for future researchers utilizing ECC in their studies. This paper also covers ECC's results and target application in structural engineering.

*Keywords: Engineered Cementitious Composites (ECC), Fiber reinforced, High-performance fiber, Composite materials*

## 1. INTRODUCTION

Engineered cementitious composites (ECCs) or strain-hardening cementitious composites (SHCCs) are a type of high-performance fiber-reinforced cementitious composite (HPFRCC) with the tensile strain-hardening activity of several percent with relatively little fiber dosage, typically 2% by volume [1]. The majority of ECC standard combinations mentioned in this literature contain short, randomly dispersed polyvinyl alcohol (PVA) fibers and polyethylene (PE) fibers, which provide excellent tensile strain hardening behavior under increasing tensile stress via the creation of numerous fractures [2]. The interfacial interactions between the cementitious matrix and these fibers are essential in this tensile strain hardening behavior. The fracture width is typically less than 100 μm, and the strain capacity can reach up to 8% at peak strength. ECC may overcome several durability issues in constructions subjected to harsh climatic conditions due to its improved ductility, limited fracture widths, and superior tensile characteristics. [3].

The tuning of the synergistic interaction between fiber, matrix, and fiber/matrix interface results in ECC tensile strain-hardening behavior. Creating ECC micromechanics to connect material microstructures to composite tensile behavior [4]. Tensile characteristics of ECC, such as tensile strength, tensile strain capacity, fracture spacing, and crack breadth, may be measured and modeled with a given set of micromechanical parameters once defined. Utilizing ECC micromechanics to guide ingredient selection and component tailoring to obtain the requisite composite tensile performance [5]. ECC micromechanics, for example, has been used to choose optimal fiber type and diameter, to customize matrix fault size and distribution, and to change the fiber/matrix interface to reach the required tensile strain capacity. ECC micro-mechanics has also led to the development of function and performance requirements, such as low density, high early strength, ultra-high strength, self-healing, self-cleaning, and self-sensing materials [6-9].

ECC micromechanics has been developed and improved for decades in several areas, including the fiber-bridging constitutive law, the pseudo-strain-hardening criterion, and the ECC composite tensile behavior model. Li et al. pioneered ECC micromechanics in the early 1990s, demonstrating that multiple steady-state cracking depends on numerous micromechanical factors [6]. They develop closed-form analytical solutions of the fiber-bridging constitutive law for ECC reinforced with short and randomly oriented hydrophobic fibers with a friction-only fiber/matrix contact [10-11].

Although many researchers and engineers have used ECC in recent years, there is still a lack of standardization in its use to ensure that it will achieve micromechanical interactions between its constituents and processing techniques to create a balance between economy and requirements for strength and durability. As a result, the authors gathered multiple samples of mix proportions used by different studies, the kind of fiber utilized, and its properties to serve as a reference for future studies using ECC as its principal concrete element. ECC's mechanical behavior and target applications are also presented in this paper to help future researchers to uncover critical areas in the development of ECC.

## 2. RESEARCH SIGNIFICANCE

Developing low-cost, high-ductility cementitious materials for structural applications is essential considering the global environment. Furthermore, the greater demand for concrete and its raw materials justifies the need to develop a sustainable strengthening material, such as ECC, which will be more effective and structurally durable than any other type of FRP. Various types of fibers in ECC, processing techniques, and mix proportions exist. Thus, the need to significantly improve and standardize the use of ECC to balance the economy and requirements for strength and durability is vital.

## 3. OVERVIEW OF ECC

ECC is a type of High-Performance Fiber Reinforced Cementitious Composites (HPFRCC) developed in the early 1990s at the University of Michigan [6]. Unlike traditional Fiber Reinforced Composites (FRP), ECC displays tensile strain hardening with repeated microcracking during inelastic deformation. ECC is a family of micro-mechanically designed materials. As long as a cementitious material develops under micromechanics and fracture mechanics theory to exhibit high tensile ductility, it is ECC material. Therefore, ECC is not a set material design but a broad spectrum of subjects undergoing further study, development, and implementation. ECC resembles conventional Portland cement-based concrete, except it may flex (or bend) under Strain.

Several research organizations, including those at the University of Michigan, the University of California, Irvine, Delft University of Technology, the University of Tokyo, the Czech Technical University, the University of British Columbia, and Stanford University, are pursuing ECC science. The lack of durability and failure under Strain in traditional concrete, which results from brittle behavior, has been a driving force in ECC development [9-11].

Generally, ECC's three types of tensile failure are a brittle, quasi-brittle, and ductile loss. Each failure occurs in hardened cement paste material, most fiber-reinforced cement and concretes, and continuously aligned fiber-reinforced cement materials [2]. Typical Fiber Reinforced Concrete (FRC) displays pseudo strain hardening behavior with a high fiber volume content. In contrast to conventional FRC, ECC shows pseudo-strain hardening under tensile stress despite its modest fiber volume. Shown in Table 1 are the differences between ECC, FRC, and other common HPFRCC. Despite achieving superiority in terms of tensile strength, ECC has a lower Youngs's modulus (18-34 GPa) than traditional concrete (40-60 GPa) [3] with the same compressive strength, which indicates a lack of coarse aggregate [4].

Table 1 Comparative summary between FRC, ECC, and other HPFRCC

| Properties | FRC | ECC | HPFRCC | Ref. |
|---|---|---|---|---|
| Fiber Volume | 3-12% | <2% | 7-20% | [5]–[7] |
| Matrix | Coarse aggre-gate | Flyash, silica fume, and slag | Micro-silica, quartz sand | [4]–[10] |
| Fibers | Any type | PVA | Steel fibers | [7], [10], [11] |
| Properties | Strain softe-ning | Strain harde-ning | Both | [1], [12] |
| Tensile strain | 0.1-2.0% | 5.0% | <1.5% | [6], [8], [13] |
| Crack width | Unlimi-ted | <100μm | Several hundreds of microns | [8] |

## 4. MIX PROPORTION

ECC has various mixed proportions depending on the specific target of applications and other additives. Mainly, the balance consists of cement, fine silica sand, fly ash, polymeric fibers, water, and High Range Water Reducer Admixtures (HRWRA). The lack of coarse aggregates may influence the ductility of cementitious composites. The mixed design proportion for ECC is shown in Table 2, as different researchers propose.

Table 2 Mix design proportion

| Cement | Sand | Water | HRWRA | Fiber (%) | Ref. |
|---|---|---|---|---|---|
| 1.000 | 0.750 | 0.300 | 0.020 | 2.00 | [14] |
| 1.100 | 0.660 | 0.315 | 0.025 | 1.00 | [15] |
| 0.375 | 0.435 | 0.318 | 0.030 | 2.00 | [16] |
| 1.000 | 1.000 | 0.380 | 0.380 | 2.00 | [17] |
| 0.583 | 0.467 | 0.298 | 0.019 | 2.00 | [18] |

## 5. TYPES OF FIBERS IN ECC

Fibers are disintegrated reinforcing materials with distinctive qualities. It varies in form (circular, triangular, tri-global, and rectangular), kind (natural and synthetic), and aspect ratio. In addition, the fiber aspect ratio is a fraction of the fiber length to a diameter ranging from '30 to 50'. Table 3 shows that most studies utilized Polyvinyl Alcohol (PVA) fiber to strengthen ECC, whereas a few other researchers used natural fibers in ECC. According to the literature, short lengths (6–12 mm) of randomly distributed PVA or polymeric fibers were used in the study to enhance ECC. In general, the fiber volume of ECC is 2%. Low-modulus fibers, such as polyvinyl alcohol (PVA), polypropylene (PP), and polyethylene (PE), reduce cracking and significantly improve the ductility of concrete mixtures. The compressive, flexural, tensile, and Young's modulus values decreased as fiber concentration increased. The mechanical properties of the cementitious composite incorporating bagasse fiber are comparable to conventional concrete, enhancing the material's environmental friendliness. Increases in the bagasse fiber content of cementitious composites increased the air content of the matrix, resulting in a less compact matrix.

Table 3 Different types of fibers used in ECC by different researchers

| Fiber used | Count | References |
|---|---|---|
| Polyvinyl Alcohol (PVA) Fiber | 9 | [4], [19]–[26] |
| Polyethylene (PE) Fiber | 3 | [27]–[29] |
| Steel (SE) Fiber | 2 | [12], [19] |
| Polypropylene (PP) Fiber | 2 | [30], [31] |
| Basalt Fiber | 1 | [20] |

### 5.1 Fiber Dimension Effect on ECC

Fiber-reinforced ECC is a composite made up of various lengths of fibrous material. Also, it contains different dimensions of fibers with varying orientations (i.e., parallel and dispersed). Table 4 shows other pieces of literature's additional lengths and diameters of ECC. Most of the lengths and diameters used by different researchers range from 6mm – 500mm and 6μm - 40μm, respectively, depending on the type of fiber used. For PVA fibers, the average modulus of elasticity is 42.3 GPa. PE and Basalt each have 88 GPa and 42.8 GPa, respectively, while steel fiber has the highest modulus at 210 GPa. According to the literature in Table 4, the fiber diameters positively impact the flexural strength of concrete. In addition, the fibers inhibit the growth and coalescence of microcracks into macrocracks, indicating a shift in damage mechanism from crack development to crack opening and determining the composite's strength.

### 5.2 Composite Fiber Effect on ECC

Composite or hybrid fibers are by-products of combining different types of fibers. The use of fibers in hybridization highly affects different properties of ECC. Polypropylene (PP) fiber with irregular cross-sectional forms enhances the hybrid ECC's deformability when bent. The hybrid ECC composite's strength highly depends on the matrix's high modulus PVA fibers. However, substituting 25% volume of PP fibers for PVA fibers has significantly reduced the flexural strengths of ECC composites with equivalent PVA fibers [30]. Microfibers enhanced the probability of macro fibers breaking in the dense concrete matrix. This macro fiber failure occurred more often in the hybrid than in the concrete containing just the macro fiber. It is obvious evidence of interaction between the fiber types, and this interaction may offer an opportunity to improve the efficacy of hybrid blends by modifying microfibers and microfibers [19].

Table 4 Fiber length and diameter used in ECC by different researchers

| Fiber used | Fiber length (mm) | Fiber diameter (μm) | Modulus of elasticity (GPa) | Ref. |
|---|---|---|---|---|
| PVA | 12.00 | 14.00 | 36.00 | [19] |
| Steel | 22.00 – 500.00 | 6.00 – 30.00 | 210.00 | [19] |
| PVA | 8.00 – 12.00 | 40.00 | - | [25] |
| PVA | 8.00 – 12.00 | 38.00 | 42.00 | [26] |
| PVA | 6.00 – 12.00 | 14.00 – 39.00 | 42.80 – 60.00 | [32] |
| PVA | 6.00 | 40.00 | 37.00 | [33] |
| PE | 18.00 | 12.00 | 88.00 | [27] |
| Basalt | 12.00 | 39.00 | 42.80 | [20] |
| PVA | 12.00 | 17.00 | 78.00 | [20] |

## 6. BEHAVIOR OF ECC IN EXTREME CONDITIONS

### 6.1 Resistance to Permeability

A significant factor influencing permeability in uncracked concrete is particle density, which is usually a function of the water-to-cement ratio in the mixture. Fluids can flow through the matrix more freely as the particle density rises, but fewer holes are available. Crack development often improves the transport characteristics of concrete, enabling oxygen, water, and chloride ions to rapidly enter and reach the reinforcing steel and expedite the start of steel corrosion in concrete [34]. When the fracture width is less than 100 μm, the crack has minimal impact on the permeability of the concrete. In reinforced concrete, the maximum fracture width was directly proportional to the square of the concrete cover thickness [35]. Table 5 shows reasonable crack control of ECC with an average crack width of less than 100 μm. With a fracture diameter of less than 60 µm, ECC permeability may stabilize in 3-4 days. The fracture width of over 100 µm required 7-10 days or longer to stabilize ECC permeability. ECC with a closed fracture may rapidly complete self-healing, successfully avoiding water and corrosive ion impacts [36].

Table 5 Crack width and tensile strain in ECC specimens

| Crack width (µm) | Tensile strain (%) | Ref. |
|---|---|---|
| 25.333 | 2.900 | [27] |
| 44.167 | 3.700 | [50] |
| 60.333 | 2.900 | [51] |
| 33.000 | 3.500 | [52] |
| 101.225 | 5.900 | [30] |
| 49.640 | 3.500 | [53] |

### 6.2 Resistance to High Temperature

Ordinary concrete's mechanical characteristics deteriorate at high temperatures, resulting in spalling damage. When the temperature reaches 200 - 300°C, the pieces begin to peel away from the concrete, and dramatic spalling may develop as the temperature increases—the attribution of spalling failure of concrete under elevated temperatures to the accumulated internal tensile stress [38]. Due to the ductility preserved by internally randomly dispersed fibers, ECC offers superior performance at high temperatures. Reduced ECC spalling leads to increased endurance in a high-temperature environment. When exposed to high temperatures, ECC's strain-hardening ability diminishes or vanishes, leading to decreased ductility, early failure, or excessive deformation [22].

The amount of microcracks changes due to a change in the strain-hardening ability of ECC following exposure to high temperatures. Polyvinyl Alcohol Fiber Reinforced Engineered Cementitious Composite (PVA-ECC) strain capacity increased with strain rate at 100 °C, while ECC lost ductility and exhibited strain rate impact at 150 °C [21]. Steel fiber enhances the integrity of ECC at high temperatures; for example, at 600 °C, the amount of debris produced by PVA-ECC is four times that of steel fiber ECC [39]. Table 6 shows the effect of elevated temperature on the tensile properties of concrete. Fibers have a significant effect on the tensile strain capacity of ECC at high temperatures. The combined impact of increased hydration of cementitious materials to raise the interfacial tension between fiber and matrix and the inherent tensile capabilities of fibers at high temperatures may ascribe to the improvement in tensile qualities. On the other hand, a higher temperature of 100 °C causes damage to ECC fibers and reduces tensile ability. At 200°C, the fiber melts, and the bridging action of the fibers is lost.

Table 6 Impact of elevated temperature on ECC

| Temperature (°C) | Tensile strain capacity (%) | Ultimate tensile strain (MPa) | Ref. |
|---|---|---|---|
| 20.00 | 2.68 | 3.83 | [37] |
| 100.00 | 4.68 | 4.91 | |
| 200.00 | 3.10 | 3.97 | |
| 20.00 | 9.30 | 9.30 | [40] |
| 100.00 | 13.90 | 13.90 | |
| 200.00 | 7.40 | 0.02 | |
| 20.00 | 1.81 | 3.21 | [20] |
| 100.00 | 0.43 | 3.03 | |
| 200.00 | 0.44 | 2.50 | |

### 6.3 Resistance to shrinkage

Constant concrete shrinkage significantly contributes to the brittleness that leads to cracking in the material. ECC has a more significant shrinkage than ordinary concrete because it has more cementitious elements in the mix [41]. ECC's excessive shrinking creates long-term durability issues. Water-binder ratio, sand-binder ratio, cement quantity, fiber volume, and additive are all variables that influence ECC drying shrinkage [42]. ECC shrinkage increased as the water-binder ratio increased and reduced as the sand-binder and fly ratio, while fiber volume content did not impact ECC shrinkage strain [43].

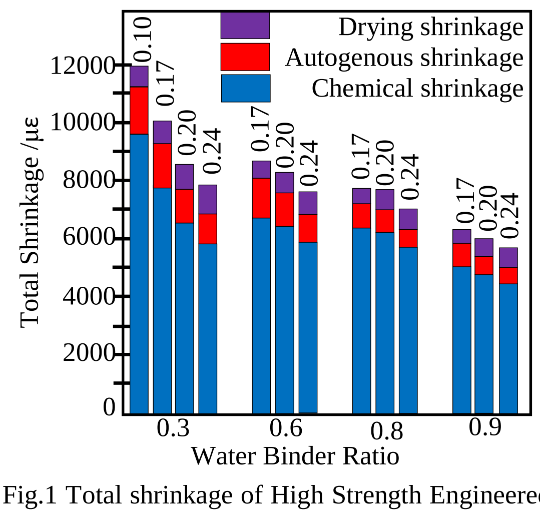


Fig.1 Total shrinkage of High Strength Engineered Cementitious Composites (HSECC) [42]

Fig.1 shows the high-strength ECC's overall shrinkage, including drying, autogenous and chemical shrinkage [44]. Chemical shrinkage accounts for the majority of ECC's overall shrinkage.

The increase in sand-binder and water-binder ratios lowers the overall shrinkage rate of ECC, and the autogenous and drying shrinkage is likely to be equivalent. For example, within 90 days, the addition of 20% saturated lightweight aggregate decreased the autogenous shrinkage of ECC by 67% and drying shrinkage by 37% [43]. On the other hand, incorporating lightweight aggregate had a substantial detrimental impact on the durability and strength of ECC.

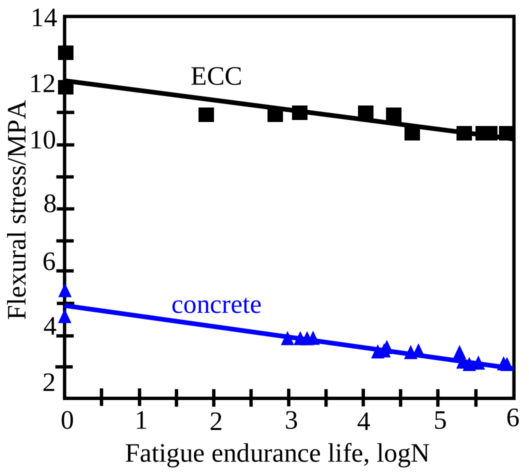


Fig. 2 Relationship between flexural stress and fatigue life of the concrete and ECC [45]

### 6.4 Resistance to Fatigue

Fatigue-induced crack propagation substantially decreases the service life of concrete material. Under flexural stress, Fig.2 compares the fatigue behavior of ECC and ordinary concrete [45]. Under the same flexural load, ECC has a more excellent fatigue life of many orders of magnitude than standard concrete. It is because the random orientation of fibers increases the buffering effect of ECC, and the fiber bridging effect suppresses damage under fatigue loading. The stress intensity factor $\Delta K_{tip}$ influences the development rate of a flexural fracture during flexural fatigue, calculated at the fracture tip based on external loads and fiber bridging stress [46]. In estimating the fracture propagation of ECC during flexural fatigue, the connection between fatigue crack propagation rate and $\Delta K_{tip}$ states as follows:

$$\frac{da}{dN} = C \cdot \Delta\left(K_{tip}\right)^m \tag{1}$$

where $a$ is the crack length, $N$ is the number of fatigue cycles, $C$ and $m$ are the Paris constants depending on the matrix properties. Hence the fatigue life $N_f$ is equal to:

$$\boldsymbol{N_f = \int_{a_o}^{a_f=H} \left[\frac{1}{C\cdot\Delta(K_{tip})^m}\right] da} \tag{2}$$

where $a_o$ and $a_f$ represent the initial and ultimate crack lengths, respectively [46]. ECC is repaired quickly at a low pre-damaged level, significantly increasing its eventual fatigue life [47]. The fracture bridging stress of ECC reduced significantly under tensile fatigue loading during the first 600-1000 load cycles [45]. The extended finite element technique investigates the deterioration of ECC's fiber bridging stress during fatigue loading. Fatigue and fiber bridging stress correlates with the maximum crack opening displacement, and there was no evidence of deterioration in fiber bridging stress when the crack opening was small [48].

## 7. TARGET APPLICATIONS OF ECC

### 7.1 Structures Subjected to Severe Mechanical Loading

Seismic-resistant structural elements subjected to completely reversed cyclic stress are the most extensively studied subset of structure. Table 7 summarizes ECC reinforced beams' superiority over normal concretes' average ultimate loads and deflection from different researchers. Table 8 shows the improved compressive strength of concrete with ECC applied to columns compared with ordinary concrete (17 – 28 MPa). Other notable applications of ECC include hybrid steel beam-concrete column connections [49], precast segmental bridge decks [50], and damping elements [51].

These studies show that ECC provides a more seismically resistant reaction and requires less post-earthquake maintenance than conventional RC. Although it is reasonable to infer that the ductility of ECC materials is related to the high energy absorbed by ECC components when subjected to cyclic loading, the connection is more nuanced.

### 7.2 Durable Infrastructure Exposed to Extreme Environmental Loads

The applications in this area are for infrastructure restoration utilizing ECC. These include dam repairs in Japan, bridge underdeck repairs in Japan, a sewage connection in Korea, and tunnel linings in Switzerland [52]. ECC has various properties that make it appealing as a repair material. In an ECC/concrete repaired system, ECC may prevent early delamination or surface spalling [53]. ECC offers better fatigue resistance than traditional repair materials such as polymer cement [54]. Finally, the low rate of aggressive agent movement via ECC may postpone steel corrosion, resulting in longer service life in buildings in coastal areas. More investigation is required to verify this speculation.

### 7.3 Productivity of Infrastructure Building

ECC has the potential to increase construction productivity in a variety of ways. The most direct means is eliminating the labor-intensive installation of shear reinforcing bars in seismic structures. ECC's various processing pathways lend themselves to effective ECC application techniques on building sites or precast factories. Spray processing, for example, may speed up the building process in various repair applications or tunnel-lining construction. Similarly, ECC extrusion may continuously produce high-quality ECC products with little waste [58]. Self-compacting ECC lends itself to difficult building circumstances, such as horizontal formwork or "concrete" filled tubes, substantially decreasing labor needs.

Table 7 Ultimate load and deflection of ECC and standard concrete (NC) applied to beams

| ECC | | NC | | |
|---|---|---|---|---|
| Ultimate load (kN) | Deflection (mm) | Ultimate load (kN) | Deflection (mm) | Ref. |
| 59.50 | 42.50 | 51.95 | 67.00 | [14] |
| 238.42 | 21.25 | 211.10 | 18.30 | [53] |
| 127.74 | 26.08 | 97.20 | 34.10 | [15] |
| 238.71 | 24.88 | 219.58 | 20.54 | [16] |
| 47.63 | 20.31 | 22.10 | 24.40 | [17] |

Table 8 Compressive behavior of ECC applied to columns

| Compressive strength (MPa) | Compressive strain (%) | Ref. |
|---|---|---|
| 59.86 | 0.49 | [4] |
| 57.20 | 0.97 | [54] |
| 78.56 | 0.35 | [55] |
| 75.01 | 0.45 | [56] |
| 61.84 | 0.30 | [57] |

## 8. CHALLENGES AND LIMITATION

Many new applications for ECC have emerged over the past decade, completely changing the face of technology. Notable development includes the use of ECC as fireproofing material for steel. ECC outperforms Cementitious Fire-Resistive Material (CFRM) in cohesive performance with steel substrate following reverse loading without delamination. ECC is a resilient fireproofing coating that can replace CFRM for steel buildings [59]. The development of ECC to masonry wall retrofitting has also taken notice recently. An ECC coating applied to one or both sides of a Confined Masonry (CM) wall is an effective retrofitting method for enhancing its in-plane performance. An ECC coating toweled on both sides of the wall may boost lateral strengths by 94–116% and 77–247%, respectively. In addition, the failure displacement of retrofitted walls is considerably less than that of un-retrofitted walls.

On the other hand, the residual lateral strengths of retrofitted walls upon failure are much greater than the maximum lateral strengths of un-retrofitted walls [60], [61]. In precast, the enhancing mechanical characteristics by incorporating ECC into the tension zone of Precast Concrete (PC) beams [62]. However, many studies have yet to be related to applying ECC to slab panels. Maximizing the full potential of ECC's high performance in terms of high ductility benefits the construction industry in the long run. In conclusion, further, development is needed in these areas before realizing ECC's full potential.

While significant advancements in ECC technical development have occurred over the past decade, it is reasonable to anticipate that the next decade will be even more enjoyable. As research progresses, the additional discovery of valuable features of ECC is to offer new infrastructure applications. It is possible to envisage the technologies and the development of ECC material that combines the benefits of steel and concrete.

Table 9 Research and development areas of ECC

| Limitations | References |
|---|---|
| Standard mix design | [14]–[18] |
| Material specifications | [14]–[18] |
| Standard test methods<br>Numerical tools | [51], [66]<br>[50], [67] |
| Consolidation of existing research | [61]–[68] |
| Sustainable development | [3], [66] |
| Structural innovations | [50], [66], [67] |
| Integrated structures and material design | [50], [67] |

These new design materials are to fulfill specific structural performance criteria while being socially, economically, and environmentally sustainable. In addition, these new materials come with a new infrastructure system with one or more features. The expected advancements of ECC include being safe with minimal repair needs even after exposure to extreme loading conditions; smart with self-adapting capacity; mega-scale but without the size-effect setback; zero maintenance even after being subjected to severe environmental conditions and being constructible at a fast pace with minimal waste [63]. Meanwhile, Table 9 shows the attention needed for the improvement of ECC.

## 9. CONCLUSION

Standardization of ECC's mix proportion, fibers used, and processing techniques significantly improves to balance economy and requirements for strength and durability. It will make its future application more efficient, economical, and durable.

This paper intends to systematically collate and review past papers to summarize most processing techniques. The author can present information, application, and challenges for future studies through this method. This paper found that the average mix proportion of cement, sand, water, HRWRA, and fiber is 1:1.5:2.5:8.5:0.5. In addition to this, most researchers used PVA as their primary fiber due to its low-modulus characteristics. Compared to other types of fibers, PVA has a shorter fiber length and smaller strand diameter, which ensure superior tensile strain hardening behavior under increasing tensile loading through the formation of multiple cracks.

Moreover, past researchers proved that ECC has a superior advantage over standard concrete under extreme conditions using the processing technique and proportions they have used in their studies, tabulated in this paper. Although collating these techniques and standard fiber properties and proportioning is beneficial to future ECC users, several gaps and challenges exist, such as a lack of standard mix design, material specifications, standard test methods, and numerical tools. To conclude this paper, the standardization of ECC's proper mix and processing technique is significant in construction to save cost while maintaining strength and durability in structures.

## 10. REFERENCES

[1] Li J., Qiu J., Weng J., and Yang E.H., Micromechanics of Engineered Cementitious Composites (ECC): A Critical Review and New Insights, Construction and Building Materials, Unpublished work but accepted, Vol. 362, 2022.

[2] Singh M., Saini B., and Chalak H. D., Performance and Composition Analysis of Engineered Cementitious Composites (ECC) – A Review, Journal of Building Engineering, Unpublished work but accepted, Vol. 26, 2019.

[3] Kang J. and Bolander J., Event-based Lattice Modeling of Strain-Hardening Cementitious Composites, International Journal of Fracture, Vol. 206, 2017, pp. 245-261.

[4] Meng D., Huang T., Zhang Y. X., and Lee C. K., Mechanical Behaviour of a Polyvinyl Alcohol Fibre Reinforced Engineered Cementitious Composite (PVA-ECC) using Local Ingredients, Construction and Building Materials, Vol. 141, 2017, pp. 259-270.

[5] Zhao A., Yang J., and Yang E. H., Self-cleaning Engineered Cementitious Composites, Cement and Concrete Composites, Vol. 64, 2015, pp. 74-83.

[6] Li V. C., On Engineered Cementitious Composites (ECC). A Review of the Material and its Applications, Journal of Advanced Concrete Technology, Vol. 1, No. 3, 2003, pp. 215–230.

[7] Naaman A .E., and Reinhardt H. W., Interface Tailoring for Strain-hardening Polyvinyl Alcohol-Engineered Cementitious Composite (PVA-ECC), Aci Materials Journal, Vol. 99, No. 5, 2002, pp. 463-472.

[8] Singh S. B. and Munjal P., Engineered Cementitious Composite and its Applications, Materials Today: Proceedings, Vol. 32, 2020.

[9] Zhu Y., Zhang Z., Yang Y. and Yao, Y., Measurement and Correlation of Ductility and Compressive Strength for Engineered Cementitious Composites (ECC) Produced by Binary and Ternary Systems of Binder Materials: Fly Ash, Slag, Silica Fume and Cement, Construction, and Building Materials, Vol. 68, 2014, pp. 192-198.

[10] Farhat F.A., Nicolaides D., Kanellopoulos A. and Karihaloo B.L., High Performance Fibre-Reinforced Cementitious Composite (CARDIFRC) – Performance and Application to Retrofitting, Engineering Fracture Mechanics, Vol. 74, No. 1–2, 2007, pp. 151-167.

[11] Said S. H., Razak H. A., and Othman I., Flexural Behavior of Engineered Cementitious Composite (ECC) Slabs with Polyvinyl Alcohol Fibers, Construction and Building Materials, Vol. 75, No.1, 2015, pp. 176-188.

[12] Kang S.-T., Lee Y., Park Y.-D. and Kim J.-K., Tensile Fracture Properties of an Ultra High Performance Fiber Reinforced Concrete (UHPFRC) with Steel Fiber, Composite Structures, Vol. 92, No. 1, 2010, pp. 61-71.

[13] Pyo S., El-Tawil S., and Naaman A. E., Direct Tensile Behavior of Ultra High-Performance Fiber Reinforced Concrete (UHP-FRC) at High Strain Rates, Cement and Concrete Research, Vol. 88, 2016, pp. 144-156.

[14] Siva M., Sasikumar, T., Raj, P. S. A. and Divahar, R., Ductility Enhancement of Reinforced Concrete Beam using Engineered Cementitious Composites in the Tension Zone, Materials Today: Proceedings, Vol. 33, 2020, pp. 189-195.

[15] Afefy H. M., Kassem N., and Hussein M., Enhancement of Flexural Behaviour of CFRP-Strengthened Reinforced Concrete Beams using Engineered Cementitious Composites Transition Layer, Structure and Infrastructure Engineering, Vol. 11, No. 8, 2015, pp. 1042-1053.

[16] Keskin S. B. et al., Self-Healing Capability of Large-Scale Engineered Cementitious Composites Beams, Composites Part B, Vol. 101, 2016, pp. 1-13.

[17] Dai J. G., Wang B., and Xu, S. L., Textile Reinforced Engineered Cementitious

Composites (TR-ECC) Overlays for the Strengthening of RC Beams, Journal of Materials in Civil Engineering, 2009, pp. 75-80.

[18] Shuxin Wang and Li V., Polyvinyl Alcohol Fiber Reinforced Engineered Cementitious Composites: Material Design and Performances, International RILEM workshop on HPFRCC in Structural Applications, 2006, pp. 65-73.

[19] Lawler J. S., Zampini D. and Shah S. P., Microfiber and Macrofiber Hybrid Fiber-Reinforced Concrete, Journal of Materials in Civil Engineering, Vol. 17, No. 5, 2005, pp. 595-604.

[20] Wang Z., Han S., Sun P., Liu W., and Wang Q., Mechanical Properties of Polyvinyl Alcohol-Basalt Hybrid Fiber Engineered Cementitious Composites with Impact of Elevated Temperatures, J. Cent. South Univ., Vol. 28, No. 5, 2021, pp. 1459-1475.

[21] Mechtcherine V., de Andrade Silva F., Müller S., Jun P. and Filho R. D. T., Coupled Strain Rate and Temperature Effects on the Tensile Behavior of Strain-Hardening Cement-Based Composites (SHCC) with PVA Fibers, Cement and Concrete Research, Vol. 42, No. 11, 2012, pp. 1417-1427.

[22] Şahmaran M., Özbay E., Yücel H. E., Lachemi M., and Li V. C., Effect of Fly Ash and PVA Fiber on Microstructural Damage and Residual Properties of Engineered Cementitious Composites Exposed to High Temperatures, Journal of Materials in Civil Engineering, Vol. 23, No. 12, 2011, pp. 1735-1745.

[23] Tambusay A., Suprobo P., Faimun F. and Amiruddin A., Finite Element Analysis on the Behavior of Slab-Column Connections using PVA-ECC Material, Jurnal Teknologi, Vol. 79, No. 5, 2017, pp. 23-32. (In Indonesian)

[24] Zhang Z. and Zhang Q., Matrix Tailoring of Engineered Cementitious Composites (ECC) with Non-Oil-Coated, Low Tensile Strength PVA Fiber, Construction and Building Materials, Vol. 161, 2018, pp. 420-431.

[25] Sasmal S. and Avinash G. Investigations on Mechanical Performance of Cementitious Composites Micro-Engineered with Poly Vinyl Alcohol Fibers, Construction and Building Materials, Vol. 128, 2016, pp. 136-147.

[26] Said S. H., Razak H. A. and Othman I., Flexural Behavior of Engineered Cementitious Composite (ECC) Slabs with Polyvinyl Alcohol Fibers, Construction and Building Materials, Vol. 75, 2015, pp. 176-188.

[27] Choi J.-I., Lee B. Y., Ranade R., Li V. C., and Lee Y., Ultra-High-Ductile Behavior of a Polyethylene Fiber-Reinforced Alkali-Activated Slag-Based Composite, Cement and Concrete Composites, Vol. 70, 2016, pp. 153-158.

[28] Kawamata A., Mihashi H., and Fukuyama H., Properties of Hybrid Fiber Reinforced Cement-Based Composites, Journal of Advanced Concrete Technology, Vol. 1, No. 3, 2003, pp. 283-290.

[29] Deng H., Utilization of Local Ingredients for the Production of High-Early-Strength Engineered Cementitious Composites, Advances in Materials Science and Engineering, Vol. 2018, 2018, pp. 1-15.

[30] Felekoglu B., Tosun-Felekoglu K., Ranade R., Zhang Q., and Li V. C., Influence of Matrix Flowability, Fiber Mixing Procedure, and Curing Conditions on the Mechanical Performance of HTPP-ECC, Composites: Part B, Vol. 60, 2014, pp. 359-370.

[31] Pakravan H., Jamshidi M., and Latifi M., The Effect of Hybridization and Geometry of Polypropylene Fibers on Engineered Cementitious Composites Reinforced by Polyvinyl Alcohol Fibers, Journal of Composite Materials, Vol. 50, No. 8, 2016, pp. 1-14.

[32] Li V., Wang S. X., and Wu C., Tensile Strain-hardening Behavior of Polyvinyl Alcohol Engineered Cementitious Composites (PVA-ECC), ACI Materials Journal, 2001, pp. 483–492.

[33] Said M., El-Azim A.A. Abd, Ali M. M., El-Ghazaly, H. and Shaaban I., Effect of Elevated Temperature on Axially and Eccentrically Loaded Columns Containing Polyvinyl Alcohol (PVA) Fibers, Engineering Structures, Vol. 204, 2020 pp. 1-15.

[34] Şahmaran M. and Li V. C., Engineered Cementitious Composites: An Innovative Concrete for Durable Structure, Structures Congress, 2009, pp. 2219-2231.

[35] Shiradhonkar S.R. and Sinha R., Maximum and Residual Flexural Crack Width Estimation in Reinforced Concrete Frame Members under Seismic Excitation, Journal of Structural Engineering, Vol. 144, No. 8, 2018, pp. 1-10.

[36] Ma H., Qian S., and Zhang Z., Effect of Self-Healing on Water Permeability and Mechanical Property of Medium-Early-Strength Engineered Cementitious Composites, Construction and Building Materials, Vol. 68, 2014, pp. 92-101.

[37] Yu J., Lin J., Zhang Z. and Li V. C., Mechanical Performance of ECC with High-volume Fly Ash after Sub-elevated Temperatures, Construction and Building Materials, Vol. 99, 2015, pp. 82-89.

[38] Krishna D. A., Priyadarsini R. S., and Narayanan S., Effect of Elevated Temperatures on the Mechanical Properties of Concrete,

Procedia Structural Integrity, Vol. 14, 2019, pp. 384-394.
[39] Pourfalah S., Behaviour of Engineered Cementitious Composites and Hybrid Engineered Cementitious Composites at High Temperatures, Construction and Building Materials, Vol. 158, 2018, pp. 921-937.
[40] Luo J., Cai Z., Yu K., Zhu W., and Lu Z., Temperature Impact on the Micro-structures and Mechanical Properties of High-strength Engineered Cementitious Composites, Construction and Building Materials, Vol. 226, 2019, pp. 686-698.
[41] Zhang J., Gao Y., and Wang Z., Evaluation of Shrinkage Induced Cracking Performance of Low Shrinkage Engineered Cementitious Composite by Ring Tests, Composites: Part B, Vol. 52, 2013, pp 21-29.
[42] Ye B., Zhang Y., Han J., and Pan P., Effect of Water to Binder Ratio and Sand to Binder Ratio on Shrinkage and Mechanical Properties of High-strength Engineered Cementitious Composite, Construction and Building Materials, Vol. 226, 2019, pp. 899-909.
[43] Gao S., Wang Z., Wang W., and Qiu H., Effect of Shrinkage-reducing Admixture and Expansive Agent on Mechanical Properties and Drying Shrinkage of Engineered Cementitious Composite (ECC), Construction and Building Materials, Vol. 179, 2018, pp. 172-185.
[44] Şahmaran M., Lachemi M., Hossain K. M. A., and Li V. C., Internal Curing of Engineered Cementitious Composites for Prevention of Early Age Autogenous Shrinkage Cracking, Cement and Concrete Research, Vol. 39, No. 10, 2009, pp. 893-901.
[45] Zheng X., Gao S., Liu K., Wang F., and Wu Z., Influence of Zeolite Internal Curing on Shrinkage-Creep-Cracking Behavior of ECC and Tensile Property of Rebar Reinforced ECC, Journal of Building Engineering, Vol. 54, 2022, pp. 1-9.
[46] Huang T., Zhang Y. X., Lo S. R., and Lee C. K., Experimental Study on Crack Bridging in Engineered Cementitious Composites under Fatigue Tensile Loading, Construction and Building Materials, Vol. 154, 2017, pp. 167-175.
[47] Qiu J., and Yang E.-H., Micromechanics-based Investigation of Fatigue Deterioration of Engineered Cementitious Composite (ECC), Cement and Concrete Research, Vol. 95, 2017, pp. 65-74.
[48] Qiu J., Aw-Yong W. L., and Yang E.-H., Effect of Self-healing on Fatigue of Engineered Cementitious Composites (ECCs), Cement and Concrete Composites, Vol. 94, 2018, pp. 145-152.
[49] Huang T. and Zhang Y.X., Numerical Modelling on Degradation of Mechanical Behaviour for Engineered Cementitious Composites under Fatigue Tensile Loading, Engineering Fracture Mechanics, Vol. 188, 2018, pp. 1-11.
[50] Li V., Reflection on the Research and Development of Engineered Cementitious Composites (ECC), Materials Today: Proceedings, 2002, pp. 1-21.
[51] Li M., Engineered Cementitious Composites for Bridge Decks, Advanced Composites in Bridge Construction and Repair, 2014, pp. 177-209.
[52] Fukuyama H., and Suwada H., Experimental Response of HPFRCC Dampers for Structural Control, Journal of Advanced Concrete Technology, Vol. 1, No. 3, 2003, pp. 317-326.
[53] Qin F., Zhang Z., Yin Z., Di J., Xu L., and Xu X., Use of High Strength, High Ductility Engineered Cementitious Composites (ECC) to Enhance the Flexural Performance of Reinforced Concrete Beams, Journal of Building Engineering, Vol. 32, 2020, pp. 124-134.
[54] Hou W., Lin G., Li X., Zheng P., and Guo Z., Compressive Behavior of Steel Spiral Confined Engineered Cementitious Composites in Circular Columns, Advances in Structural Engineering, Vol. 23, No. 14, pp. 1-14.
[55] Ding Y., Yu K., and Mao W., Compressive Performance of All-grade Engineered Cementitious Composites: Experiment and Theoretical Model, Construction and Building Materials, Vol. 244, 2020, pp. 1251-1263.
[56] Lee C. K., Khan M. K. I., Zhang Y. X. and Rana, M. M., Engineered Cementitious Composites (ECC) Encased Concrete-steel Composite Stub Columns under Concentric Compression, Structures, Vol. 24, 2020, pp. 386-399.
[57] Yu K., Ding Y. and Zhang Y. X., Size Effects on Tensile Properties and Compressive Strength of Engineered Cementitious Composites, Cement and Concrete Composites, Vol. 113, 2020, pp. 124-135.
[58] Li V. C., On Engineered Cementitious Composites (ECC), Journal of Advanced Concrete Technology, Vol. 1, No. 3, 2003, pp. 215-230.
[59] Lim Y. M., and Li V. C., Durable Repair of Aged Infrastructures using Trapping Mechanism of Engineered Cementitious Composites, Cement and Concrete Composites, Vol. 19, No. 4, 1997, pp. 373-385.
[60] Suthiwarapirak P. Matsumoto T. and Kanda T. Flexural Fatigue Failure Characteristics of an Engineered Cementitious Composite and

Polymer Cement Mortars, Doboku Gakkai Ronbunshu, Vol. 2002, No. 718, 2002, pp. 121-134.

[61] Stang H. and Li V. C., Extrusion of ECC-Material, Materials Today: Proceedings, 1999, pp. 101-112.

[62] Cai Z., Liu F., Yu J., Yu, K., and Tian L. Development of Ultra-high Ductility Engineered Cementitious Composites as a Novel and Resilient Fireproof Coating, Construction and Building Materials, Vol. 288, 2021, pp. 151-163.

[63] Deng M., and Yang S., Experimental and Numerical Evaluation of Confined Masonry Walls Retrofitted with Engineered Cementitious Composites, Engineering Structures, Vol. 207, 2020, pp. 1-23.

[64] Kazem Sharbatdar M., and Tajari, A., Experimental In-plane Seismic Strengthening of Masonry Infilled Reinforced Concrete Frames by Engineered Cementitious Composites (ECC), Construction and Building Materials, Vol. 293, 2021, pp. 1-15.

[65] Cui T., Haoxiang HE, Zhao X., and Zhou D. "Bending Performance Analysis of Precast Composite Beams with Precast ECC Plate, Structures, Vol. 33, 2021, pp. 986-998.

[66] Li V. C., Tailoring ECC for Special Attributes: A Review, International Journal of Concrete Structures and Materials, Vol. 6, No. 3, 2012, pp. 135-144.

[67] Li V. C. Integrated Structures and Materials Design, Materials and Structures, Vol. 40, No. 4, 2007, pp. 387-396.

[68] Fazli H., Yassin A., Shafiq N., and Wee T., The Behavior of Carbon Fiber Reinforced Polymer (CFRP) strengthened beams under a Marine Environment, International Journal of GEOMATE, Vol. 13, No. 39, 2017, pp. 179-184.