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REVIEW-CIVIL ENGINEERING

Macro- and Micro-Properties of Engineered Cementitious Composites (ECCs) Incorporating Industrial Waste Materials: A Review

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Abstract
Engineered cementitious composites (ECCs) possessing strain-hardening behavior have been developed utilizing supplementary cementitious materials and fibers. The developed ECCs exhibit excellent performance in terms of mechanical and thermal properties and are highly durable. However, the latest trend is to use industrial waste materials (IWMs), as alkali-activated materials, in the development of ECCs. In this paper, a state-of-the-art review on the development of sustainable-ECCs utilizing IWMs is presented. The formulations of binders and fibers, used in the production of ECCs, are described. The effect of mixture composition on the mechanical properties, such as compressive and tensile strength, and durability of ECCs is discussed. In addition, the importance of micromechanics modeling for producing a strain-hardened ECC is presented. Further, the engineering applications of ECCs in structural and repair fields are discussed along with suggestions for future research.

Keywords Engineered cementitious composite (ECC) · Alkali-activated binders · Strain-hardened materials · Industrial waste materials · Mechanical properties · Durability characteristics

1 Introduction

The environmental drawbacks of CO_2 emission during the manufacture of cement are of great concern due to the limitations imposed on greenhouse gas emission [1]. In 2016, the European Cement Association (CEMBUREAU) [2] estimated that the world cement production was about 4.65 billion tons, whereas it was only 10 million tons in 1900. Generally, the cement production contributes to about 5% of the total worldwide CO_2 emission [3]. As a result, many attempts were made to shift to next generation of green and environment-friendly binders. The cement-less composites are the promising green and ecofriendly materials that result in energy conservation and reduction in the CO_2 emission, compared to the conventional Portland cement.

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Over the last two decades, alkali-activated binders (AABs) are being developed to be used as a binder in place of ordinary Portland cement (OPC). In principle, alumino-silicate materials, such as fly ash (FA), ground-granulated blast furnace slag (GGBFS), metakaolin (MK), rice husk ash (RHA) and silica fume (SF), can be synthesized by mixing them with an alkaline solution [4]. Industrial waste materials (IWMs) containing alumino-silicate materials may also be used for this purpose. AABs exhibit superior mechanical and thermal properties compared to the Portland cement [5]. However, they have lower tensile and bending strength that may lead to a catastrophic failure of the structure. Therefore, the brittle and ceramic-like nature of AABs is the main drawback that limits their usage in structural applications [6].

The ductility of AAB can, however, be improved by the inclusion of fibers. Strain-hardening cementitious composite (SHCC), also known as engineered cementitious composite (ECC), is a fiber-reinforced composite which exhibits a metal-like strain-hardening behavior [7, 8]. With the inclusion of 2% or less fiber by volume, ECC displays a tensile strain ductility in the order of 3–5% [9]. One example of ECC is slag-based composite with polyethylene fiber (PVA), which is reported to have a very high tensile ductility and tensile strength of up to 7.5% and 13.06 MPa, respectively [9]. It was reported that PVA fibers performed satisfactorily in alkali-activated ECC with a tensile ductility similar to that of a cement-based composite [10]. Based on published work [4, 11–14], the low calcium fly ash-based alkali-activated composite was reported to exhibit excellent mechanical properties, namely compressive strength, tensile strength and tensile strain in a magnitude of 60 MPa, 4.7 MPa and 4.3%, respectively. In addition, it is highly advantageous in terms of cost and environmental protection.

In this paper, a state-of-the-art review on the properties of ECCs prepared utilizing alkali-activated binders with various types of fibers is presented. The mechanical properties, mainly compressive and tensile strength, along with the strain-hardening behavior are discussed. In addition, the micromechanics modeling of ECC, which is an important stage in the design of structures is discussed. Finally, the durability of ECC and its engineering applications in structural concrete and as a repair material are summarized.

2 Engineered Cementitious Composites (ECCs)

2.1 Overview

Since the early 1990s, when ECC was invented by Li [15], many attempts have been made to obtain a strain-hardening composite that conforms to the ductility characteristics and sustainability considerations of a ductile material. These two factors, namely ductility and sustainability, are the key for developing ECCs. Generally, a new methodology is applied to the design of ECC that adopts the relationship between the microstructure processing, properties and performance of the constituent materials [16, 17]. The application of science and technology for the optimization of properties is the reason behind the term "engineered" that is given to ECC. Therefore, ECC offers multifunctional properties [18, 19], such as self-healing [20–23], self-sensing [24, 25], self-cleaning [26, 27] and cracking behavior [28].

In general, ECC could be classified as an ultra-ductile fiber-reinforced cementitious composite in which the tensile ductility of about 5% can be achieved which is 500 times more than that of conventional fiber-reinforced concrete [29]. However, the main difference between ECC and the classical fiber-reinforced composite (FRC) is the application of micromechanical design [30]. Therefore, the interaction between the matrix, fiber and interface plays a vital role in the ductile behavior of ECC.

Two key techniques are used in the design formulation of ECC: the utilization of IWMs for sustainability considerations and the randomly oriented short fibers for ductility requirements. The proper formulations of these techniques along with micromechanics design result in an effective composite with desired mechanical, ductility and durability properties. The development of such a binder should lead to an improvement in the infrastructure durability and material greenness. The subsequent sections discuss the formulations of ECC and relevant production methodologies.

2.2 Fibers for Strain Hardening of ECC

Several types of fibers, such as polypropylene (PP), polyvinyl alcohol (PVA), polyethylene (PE) and steel (see Fig. 1), were used to develop a strain-hardening ECC [31, 32]. Among these types, PVA is widely used as fiber reinforcement in ECC in order to improve its strength and ductility and control cracking. PVA fibers possess high strength and elastic modulus that makes them suitable to be used in high-performance fiber-reinforced cementitious composites [33]. Currently, several types of PVA fibers are available, as shown in Fig. 2. Despite the positive effects of fibers, some drawbacks, such as increase in porosity and shrinkage and reduced compressive strength, are reported if they are used in excess quantity [34]. Table 1 and Fig. 3 present the physical and mechanical properties of the fibers commonly used in ECC.

To overcome the drawbacks associated with mono-type fibers, some attempts were made in hybridizing them [47], such as PVA/steel [48, 49], PVA/PET [41] and PVA/basalt [50]. Wang et al. [50] studied the effect of utilizing different fibers, such as steel and basalt, in conjunction with PVA fibers. A large volume of fly ash was used along with calcium sulfate as an admixture to accelerate the hydration of the matrix. It was reported that incorporation of fibers and fly ash improved the mechanical properties of the ECC. The blend of steel and PVA fibers improved the ultimate tensile strength and a marginal increase in the flexural strength. However, the tensile strain and deflection capacities were decreased. A combination of PVA and basalt fibers improved the tensile strength; however, the premature strength capacity of PVA resulted in a reduction in tensile and flexural strength. A noticeable improvement in the properties of ECC was observed due to the use of PVA fibers with calcium sulfate. Moreover, the mechanical properties of ECC are influenced by the orientation and distribution of fibers. Lu and Leung [51] investigated this factor and correlated it with the thickness of the structural member.

Ali et al. studied the feasibility of developing ECC with hybrid fibers, including PVA and shape memory alloy (SMA) fibers [46]. It was reported that the inclusion of SMA fibers increased the impact resistance and tensile strength of ECC. Consequently, the developed ECC possessed a potential for application in structures exposed to impact or explosive loadings.

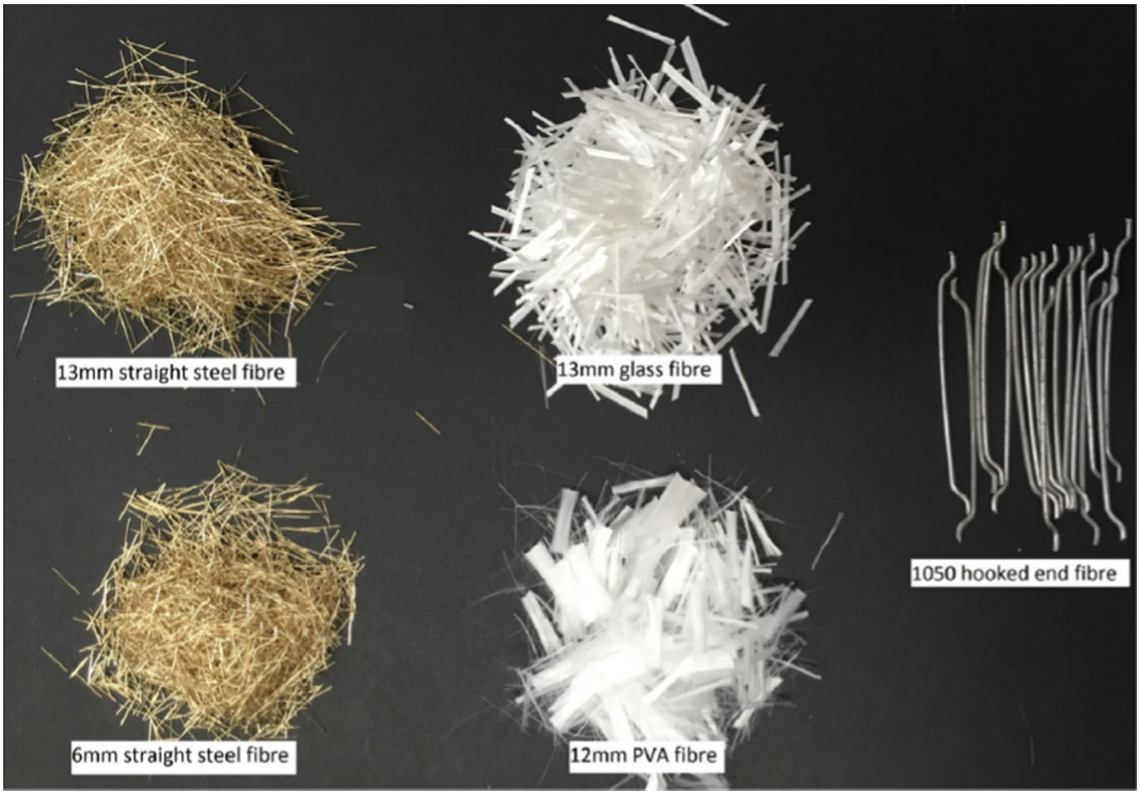

Fig. 1 Geometry and size of some fibers (steel, PVA and glass) [4]

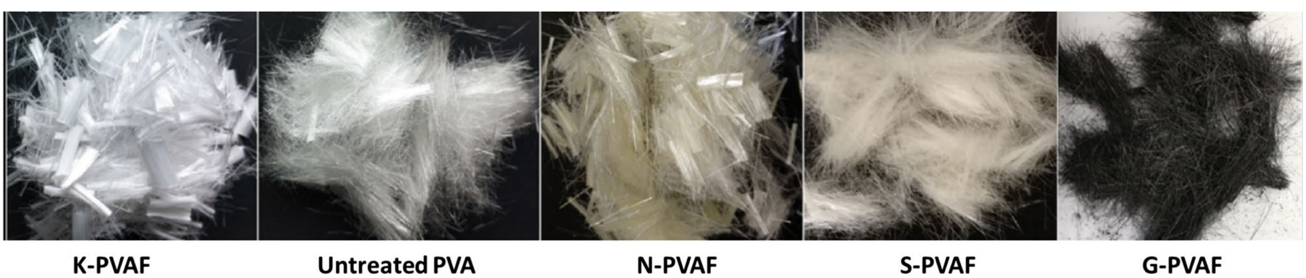

Fig. 2 Types of PVA fibers (K-PVAF and N-PVAF are PVA fibers coated with 1.2% oil, S-PVAF and G-PVAF are untreated-PVA fibers modified with hydrophobic silica and nanoscale graphite, respectively.) [35]

The advantages and drawbacks of ECC produced with commonly used fibers are listed in Table 2.

2.3 Alkali-Activated Binders (AABs)

ECC can be produced using alkali-activated binders (AABs), such a binder is also denoted as engineered geopolymer composite (EGC) [11, 65–67]. The AABs cover a variety of materials whose differences depend on the origin and composition of the precursor material [68] and alkaline materials used. The synthesis of these binders involves a chemical reaction between alumino-silicate materials, natural or artificial and alkaline materials. Generally, such a reaction yields an activated compound with binding property similar to that of calcium silicate hydrate gel [69]. Industrial byproducts, such as fly ash, GGBFS, silica fume, etc., have been used to produce AABs. Table 3 shows the chemical composition of precursor materials commonly used in the synthesis of AABs. The process of developing AAB is sometimes called geopolymerization as alumina and silica in the precursor material react with the alkaline materials to form an alumino-silicate gel [70]. Thus, the silica and alumina content in the precursor material and the concentration of the alkaline activators

Table 1 Physical properties of fibers commonly used in ECC

Fiber type	Diameter (μm)	Length (mm)	Tensile strength (MPa)	Young's modulus (GPa)	Elongation (%)	References
PVA (REC15)	39	12	1620	42.8	6.0	Lee et al. [36]
PVA (REC15)	40	8	1600	41	6	Nematollahi et al. [37]
PVA (Unoiled)	26	12	1560	36.3	7	Pan et al. [38]
PE (SK71)	12	12	3500	123	3–5	Nematollahi et al. [39]
PE (UHMWPE)	20	18	3000	100	2–3	Yu et al. [40]
PET	33	10	950	11	–	Yu et al. [41]
PP	36	12	482	5	–	Yu et al. [41]
HTPP	11	8	750	11.6	–	Yu et al. [41]
TPET	38	12	1095	11.5	–	Yu et al. [41]
UPET	38	12	1160	11.5		Yu et al. [41]
Steel	120	10	2500	200	–	Shaikh [42]
Basalt fiber (BF)	14-20	24	4840	89	3.15	Girgin [43]
Polyester fibers	0.025–0.035	12	480	–	30	Singh and Munjal [44]
Carbon fibers	6.8–20	3–18	525–4660	33–268	0.8–2.4	Zhang et al. [45]
Glass fibers	6–20	3-6	2000–4000	70–80	2.0–3.5	Zhang et al. [45]
Shape memory alloy (SMA) fibers	0.635	16	869	41	38	Ali et al. [46]

PVA polyvinyl alcohol; *PE* polyethylene; *PP* polypropylene; *PET* polyethylene terephthalate; *UPET* virgin polyethylene terephthalate; *TPET* treated polyethylene terephthalate; *HTPP* high tenacity polypropylene

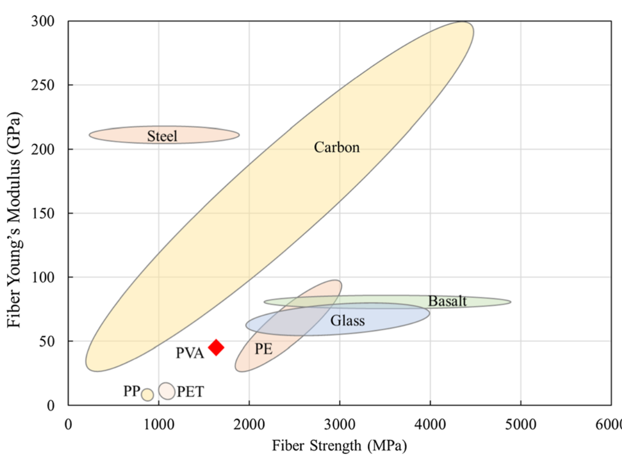

Fig. 3 Properties of fibers commonly used in ECC (adopted from Zhang et al. [45])

influence the physical and chemical properties of the resulting AAB [71].

The widely used precursor material is fly ash, which is composed of fine particles that are collected from coal-fired power plants [76]. The improved mechanical behavior and environmental effects of fly ash makes it desirable for developing AAB. Type-F fly ash is more preferred than Type-C since the former has more alumina and silica than the latter. Among many factors affecting the properties of AAB, the chemical composition of the precursor material, type and concentration of alkaline activators, as well as curing temperature and duration are considered the most influencing ones. Another commonly used precursor material is GGBFS which is a byproduct of the steel making process from the iron ore [77].

Nematollahi et al. [37] formulated a geopolymer composite with fly ash using four different activator combinations, including Na-based and K-based solutions and powder form of Ca-based activator. PVA fibers with a volume fraction of 2% were added to the geopolymer matrix. In addition to fly ash, nanosilica was also used in developing the ECC. It was reported that all the mixtures showed deflection hardening behavior, regardless of the type of activator used. In another study by Xu et al. [13], PVA fibers and SiO_2 nanoparticles and fly ash were used to develop sustainable EGC. Ling et al. [67] developed an EGC by partially substituting fly ash with GGBFS. Although the strength-related properties were enhanced, the ductility was decreased [66].

In most of ECC formulations, a superplasticizer is used to achieve the desired fresh properties and to ensure uniformity of fiber dispersion. In a study conducted by Choi et al. [63], an alkali-activated slag-based composite was developed. They used GGBFS with alkali activator and PE fibers, a superplasticizer and a viscosity-modifying agent. In another study, Choi et al. [61] investigated the rheological and mechanical properties of the composite that was

Table 2 Advantages and drawbacks of ECC prepared with a combination of fibers and binders

Fiber type	Binders	Advantages	Drawbacks	References
PVA	GGBFS and FA	Good improvement in the mechanical properties and failure mode Strong bond to resist various types of loading and exposure conditions	Fiber pullout and rupture	Nedeljkovic [34]
PE	GGBFS	High tensile strain Small crack width	Failed to improve the compressive and tensile strength	Choi et al. [10]
PVA	FA	High compressive strength (63 MPa) and tensile strength (4.7 MPa)	–	Nematollahi et al. [11]
PP	GBFS and Metakaolin	Good corrosion resistance and excellent adhesion to the substrate	Slow development of compressive strength under seawater curing	Zhang et al. [52–54]
PVA	GGBFS	Improved tensile strain up to 4.7%	–	Lee et al. [36]
PVA and PVC	Metakaolin and slag	Enhanced post-cracking response and overall ductility	–	Natali et al. [6]
Steel	GGBFS	Improved impermeability Enhanced splitting strength and flexural capacity	Decrease in compressive strength	Bernal et al. [55]
Basalt	Slag and FA	Increased energy absorption capacity	No remarkable improvement in the dynamic strength	Li and Xu [56]
Glass	GGBFS	Considerable reduction in the drying shrinkage (20%) with reasonable strength	–	Puertas et al. [57]
PVA	FA	Ultimate flexural strain exceeds 4% Ultimate flexural strength of about 4.5 MPa	–	Nematollahi et al. [58]
PE/PVA	FA and slag	Ductility of PE-based composite was more than that of PVA-based composite Tensile strength of PVA-based composite was more than that of PE-based composite	–	Nematollahi and Sanjayan [59]
Carbon	GGBFS	Drying shrinkage decreased by 50%	No improvement in strength Higher corrosion levels when exposed to accelerated carbonation	Alcaide et al. [60]
PVA	GGBFS	Low viscosity and high ductility	–	Choi et al. [61]
Non-oil-coated PVA	FA	Ductility of low-cost PVA fibers in the magnitude of 5.2%	Low compressive and tensile strength	Zhang and Zhang [62]
PE	GGBFS	Ductility of 7.50% and tensile strength of 13.06 MPa	–	Choi et al. [63]
PVA	FA	Anti-cracking performance improved as the volume fraction of PVA fiber increased	Increase in drying shrinkage strain as fiber content increased from 0.5 to 2%	(Gao et al. [64]
PVA/PE	FA + Slag	Higher tensile strain capacity compared to the PVA-composite	PE-composite displayed lower compressive and tensile strengths	Nematollahi et al. [39]
Oiled/unoiled PVA	FA	Unoiled PVA fibers are cost-effective Oiled PVA fibers possess high tensile ductility Moderate cost and high tensile strain of hybrid PVA fibers	The tensile ductility of unoiled PVA fibers was low compared to the costly oiled PVA fibers	Pan et al. [38]

Table 2 (continued)

Fiber type	Binders	Advantages	Drawbacks	References
PVA/PET	FA	Good mechanical performance with hybrid fibers (50% PVA + 50% PET) Decrease in the material cost and environmental impact	–	Yu et al. [41]

Table 3 Chemical composition of precursor materials commonly used in the production of AAB

Precursor	Chemical composition (by weight, %)									Loss on ignition (%)
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	TiO_2	K_2O	Others	
FA [70]	70.3	23.1	1.4	0.2	0.6	0.2	2.6	0.9	0.6	2.0
GGBFS [63]	31.5	13	0.5	44.6	4.9	3.4	0.8	0.5	0.9	0.3
Silica fume [72]	93.67	0.83	1.30	0.31	0.84	0.16	–	1.10	1.24	2.1
Kaolin [72]	45.3	38.38	0.3	0.05	0.25	–	–	0.44	0.27	14.0
Slag [73]	32.76	12.37	0.54	44.64	5.15	4.26	0.51	0.33	0.6	0.1
POFA* [74]	66.91	6.44	5.72	5.56	3.13	0.33	–	5.20	0.19	2.3
Kaolinite [75]	48.92	25.16	7.52	0.68	0.21	2.94	0.9	1.4	0.37	11.9

**POFA* Palm oil fuel ash

produced using GGBFS with PVA fibers. Due to the higher drying shrinkage of the conventional ECC and also shrinkage differences between concrete and fibers, other admixtures, such as shrinkage-reducing admixture and expansive agent, were used. Gao et al. [64] designed ECC with water-binder ratio, sand-binder ratio and fly ash content of about 0.25–0.33, 0.33–0.45 and 65%, respectively, along with a chemical admixture.

Generally, geopolymer binders that are used in the production of ECC require large quantities of chemical liquid activators and heat curing [78], which are the two main drawbacks for its applications in engineering applications. However, a study was carried out by Nematollahi et al. [39] who tried to develop a geopolymer composite that used a solid activator instead of alkaline solutions with heat curing. In another work, Nematollahi and Sanjayan [73] developed air-cured EGC that utilizes solid activators without heat curing. The developed geopolymer matrix composed of a ternary system of slag and fly ash with a powder solid activator. In addition, 2% volume fraction of PVA fibers was added. The ultra-high-ductile behavior of a slag-based composite was studied by Choi et al. [63]. GGBS and powder alkali activator along with 1.75% PE fibers by volume were used.

Further progress has been made in the development of greener ECC utilizing cement-less binders. Al-Majidi et al. [4] developed a ternary blend of geopolymer binder composed of FA, GGBFS and silica fume. They used different fibers, namely steel, PVA and glass, to reinforce the alkali-activated matrix. A binary system of silica fume and kaolin was used by Okoye [72] to produce geopolymer concrete with sodium silicate and sodium hydroxide. Palm oil fuel ash (POFA) [79], an agricultural waste material, was utilized by Salami et al. [74, 80] for producing engineered geopolymer composite (POFA-EGC). POFA, fine aggregate, alkaline activators, superplasticizer and PVA fibers were used in developing the POFA-EGC. Recently, Tuyan et al. [81] developed a geopolymer utilizing waste clay brick powder (WCBP).

The ECC formulations were used as alternative to OPC and they were developed using proper alkali activators to obtain the desired mechanical and durability properties. In addition, they are reported to be highly beneficial in terms of lower cost with positive environmental effect. Fibers, mainly PVA, were used to produce a strain-hardening composite. Also, chemical admixtures were sometimes added to obtain the desired fresh properties.

2.4 Other ECC Formulations Using Industrial Waste Materials

In addition to fly ash and slag, other waste materials including recycled fine-powder (RFP) [82], recycled concrete fines [83], crumb rubber [7, 84], recycled glass [85] and iron ore tailings (IOTs) [12] were used as precursor materials in the development of ECC. Table 4 presents a summary of sources and properties of the IWMs that were utilized in producing sustainable ECC having low environmental impact and high strength as well as high ductility. A study was conducted by Huang et al. [12] to formulate ECC using OPC, fly ash (Class F), iron ore tailings (as

Table 4 Sources and properties of IWMs utilized in producing sustainable ECC

Material	Source and properties
Industrial by-products	
Fly ash (FA)	FA is a solid residue composed of fine particles that are collected from coal-fired power plants [76] Type-F fly ash is more preferred than Type-C since the former has more aluminum and silica than the latter. FA has high reactivity due to finer particle size than slag [42]. FA has specific gravity of 2.12–2.43 [70, 86]
GGBFS	GGBFS is a byproduct of the steel-making process from the iron ore [77] It has specific gravity of 2.85–2.97 [70, 87] and specific surface area of 430 m^2/kg [88]
Silica fume (SF)	SF is a byproduct of the smelting process in the production of silicon metal and ferrosilicon alloys [89] It has specific surface area of 23,000 m^2/kg [90]. SF has specific gravity of 2.21 [91]
Rice husk ash (RHA)	RHA is an agro-waste obtained as a residue of the parboiling process of rice grains [92] It has specific gravity of 2.06 and pozzolanic activity index of 162.48% [92]
Palm oil fuel ash (POFA)	POFA is a byproduct of palm oil industry. It is collected from the combustion of palm oil plant resides, fibers and empty fruit bunches to heat the boiler for electrical generation in the palm oil mill [74, 93] It has a specific gravity of 2.53 and specific surface area of 1521 m^2/kg [80]
Cement kiln dust (CKD)	CKD is collected from cement kiln exhaust gases during Portland cement production [94] It has a specific gravity of 2.79 [95]
Filler materials (substituting sand)	
Limestone powder (LSP)	LSP is obtained from aggregate production plant It has a specific gravity of 2.65 and an average grain size of 425 μm [86]
Bottom ash	Bottom ash is generated from combustion of coal in power plant, and it is collected in the bottom of the burning furnace [96, 97] It has grain size distribution of 150 μm and water absorption of 2.88% [97]
Fly ash cenosphere (FAC)	FAC is lightweight filler spheres found within fly ash waste from coal-fired power plant [12] It has an average size of 200 μm and bulk density of 800 kg/m^3 [12]
Iron ore tailings (IOTs)	IOTs are waste ground rocks generated during the beneficiation process of iron ore concentration [98] They have an average size of 135 μm and nominal maximum size of 300 μm [12]
Recycled materials	
Hollow glass microsphere (HGM)	HGM is a hollow space glass material which comprises 45% of waste glass and it is used to produce lightweight concrete [85, 99] It has a density of 120–490 kg/m^3 [99]
Recycled concrete fine (RCF)	RCF (or recycled fine-powder [82]) is obtained from demolition waste of old concrete [83, 88] It has a density of 1900–2070 kg/m^3 [83]
Crumb rubber	Crumb rubber is produced by grinding scrap tyres It has a density of 1200 kg/m^3 [7]

aggregate) and PVA fibers. Industrial wastes constituted about 89% of total volume of solids and the unit weight of the developed material was less than 1850 kg/m^3, which is a limit for lightweight concrete.

Ismail et al. [100, 101] partially replaced fly ash with slag, metakaolin (MK) and silica fume (SF) in the development of ECC. In addition, crushed granite sand (CS) was replaced with microsilica sand. It was reported that the developed ECC has good abrasion and impact resistance; therefore, incorporation of MK, SF and CS resulted in a cost-effective ECC. Recently, Yu et al. [82] used recycled fine-powder (RFP) to produce sustainable ECC. RFP was collected from the waste concrete and clay bricks and it was substituted with cement in different proportions. Additionally, silica fume, GGBFS and PE fibers were used. A series of experiments, including isothermal calorimetry and thermo-gravimetric analysis were carried out and it was reported that RFP had an accelerating effect on hydration and pozzolanic reactions. It was also reported that the incorporation of RFP decreased the autogenous shrinkage of the developed ECC.

Nanosilica was used to produce self-compacting ECC [102, 103]. It was reported that ECC with 2% PVA and 1.89% nanosilica resulted in a self-compacting concrete with desired properties. Mohammed et al. [104] concluded that the desired tensile properties of self-consolidated ECC could be achieved with 2% PVA and 1.3% nanosilica. Xu et al. [105] explored the effect of titanium dioxide (TiO_2) nanoparticles on the fiber/matrix interface and tensile strength of ECC. It was reported that as the weight of TiO_2 was increased, the site-effect and dilution became more pronounced. Therefore, the authors suggested that the optimum binder replacement of TiO_2 is 5% in order to avoid the degradation of the mechanical properties of ECC. Xu et al. [48] demonstrated the feasibility of developing ECC incorporating multi-walled carbon nanotubes with hybridization of PVA and steel fibers. The authors reported that incorporation of carbon nanotubes enhanced the initial cracking fracture toughness and other essential mechanical properties.

The effect of seawater (with a soluble chloride content of 0.288%), used as a mixing water, on the properties of ECC was investigated by Jiangtao [106]. It was reported that seawater had a negligible effect on the strength, toughness and ductility of ECC. In addition, the developed ECC was used to cast beams without steel reinforcement and tested under flexural load. It was reported that the flexural capacity of ECC beams was similar to that of normal RCC beams with 0.57% reinforcing steel.

Zhang et al. [7] developed a lightweight ECC using air entraining agent (AEA) and lightweight filler (LWF), such as crumb rubber. It was reported that incorporation of AEA improved the pore structure, thus enhancing the compressive and tensile strength of ECC. In contrast, addition of LWF decreased the compressive and tensile strength; however, the compressive strength was still more than 60 MPa. Moreover, the micromechanics investigation exhibited a multiple-cracking behavior of the developed ECC which resulted in increased ductility. Crumb rubber was used as 20% replacement of sand in a study carried out by Noorvand [84]. The same observations were reported regarding its adverse influence on the compressive strength and positive effect on the ductility. Aslani et al. [85, 91] utilized hollow glass microspheres (HGMs) along with carbon nanofibers (CNFs) to produce lightweight ECC (LW-ECC). It was reported that HGM marginally decreased the mechanical properties of the ECC while CNF increased the fire resistance of the composite. Zhou et al. [107] utilized fly ash cenospheres (FAC) as a filler in ECC. The density of produced ECC was 38.7% less than that of normal weight ECC. It was concluded that an increase in the quantity of FAC had an undesirable influence on the strength-related properties; however, the ductility was slightly affected.

Zhang et al. [108] studied the effect of adding bacteria cells on the properties of ECC [108]. The bacterial clusters were mixed with water and added to PVA-ECC. There was an improvement in the properties of bacterial-ECC; however, the tensile strain capacity decreased slightly. The fracture toughness of the bacterial-ECC was more than that of the control ECC. Richard and Krithika [109] also concluded that the intrusion of bacteria resulted in an improvement in the mechanical and durability properties of bacterial-ECC.

3 Properties of ECC

3.1 Mechanical Properties

This section presents a review on the mechanical properties of ECC. The effects of the IWMs and fibers on the compressive strength, tensile strength and ductility are discussed. Generally, ECC exhibited a larger tensile strain capacity with multiple-cracking behavior compared with conventional concrete and ultra-high-performance concrete (UHPC), as illustrated in Fig. 4 [110]. Yu et al. [32] reported that the basic properties of ECC including compressive strength, tensile strength and tensile strain capacity were in the range of 20–150 MPa, 4–20 MPa and 3–12%, respectively.

3.1.1 Effect of Industrial Waste Materials

Several studies on ECCs incorporating IWMs have been reported in the literature, toward the development of sustainable composites. Table 5 presents the mechanical properties of some environment-friendly ECCs, incorporating IWMs. The range of compressive strength and tensile strain capacity of ECCs, including the ones utilizing IWMs, is depicted in Fig. 5 [17].

The effect of agro-wastes, such as RHA and POFA, on the properties of ECC has been investigated by few researchers. Righi et al. [111] investigated the utilization of RHA, as a cement replacement at different levels (10%, 20% and 30%), in ECC. It was reported that ECC with 30% RHA exhibited tensile strength and strain capacity of 2.26 MPa and 1.3%, respectively. In addition, Costa et al. [92] reported that ECC with 30% RHA exhibited a compressive strength of 48 MPa. Altwair et al. [112] studied the mechanical properties of ECC incorporating high volume of POFA (40% as a replacement of cement). The compressive strength and flexural strength of the developed ECC was 30 MPa and 9.57 MPa, respectively.

Siad et al. [113] investigated the properties of ECC admixed with LSP. Cement and FA were partially replaced with LSP at different levels (5%, 10% and 20%). It was reported that ECC with 20% LSP exhibited a compressive strength of 28.3 MPa. Turk and Demirhan [115] investigated the use of LSP as a replacement of silica sand. They concluded that the ECC with higher quantity of LSP exhibited

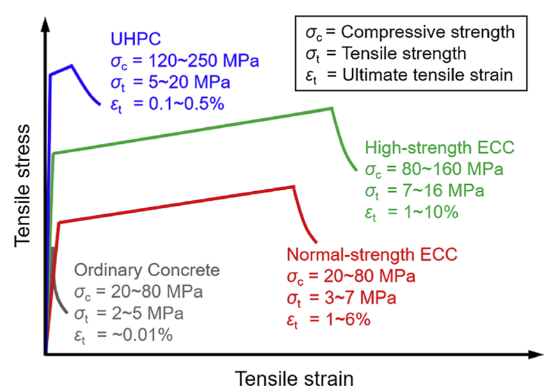

Fig. 4 Mechanical behavior of ECC compared to conventional concrete and ultra-high-performance concrete (UHPC) [110]

Table 5 Mechanical properties of ECC incorporating IWMs

References	Industrial waste material		Sand substitution	Fiber volume	Mechanical properties		
		Proportion*			Compressive strength (MPa)	Tensile strength (MPa)	Tensile strain (%)
Ling et al. [67]	FA + slag	0.7:0.3	–	PVA (2%)	83	5.2	0.74
Zhang et al. [7]	FA + SF	0.4:0.1	–	PE (2%)	85	9.73	4.16
Costa et al. [92]	RHA	0.3	–	PP (2%)	48	–	–
Righi et al. [111]	RHA	0.3	–	PP (2%)	–	2.26	1.3
Altwair et al. [112]	POFA	0.4	–	PVA (2%)	30.02	4.5	4.0
Siad et al. [113]	FA + LSP	0.5:0.2	–	PVA (2%)	28.3	–	–
Yu et al. [114]	limestone-calcined clay	0.7		PVA (2%)	64.52	5.19	0.63
Yu et al. [114]	limestone-calcined clay	0.8		PVA (2%)	43.58	4.65	0.57
Aslani and Wang [85]	FA + SF + HGM	0.5:0.03:0.2	–	PVA (1.75%)	56.7	–	–
Al-Gemeel et al. [99]	FA + HGM	0.5:0.04	–	PVA (2%)	55.5	–	–
Al-Gemeel et al. [99]	FA + HGM	0.5:0.05	–	PVA + steel fiber (1.25%:)	54.3	–	–
Yu et al. [82]	GGBFS + SF + RCA	0.6:0.1:0.2	–	PE (2%)	85	13.86	5.0
Turk and Nehdi [86]	FA	0.8	LSP (100%)	PVA (2%)	40	–	–
Turk and Demirhan [115]	FA	0.6	LSP (100%)	PVA (2%)	67.27	–	–
Siad et al. [116]	FA	0.5	Recycled glass sand (100%)	PVA (2%)	60	–	–
Adesina and Das [117]	FA	0.7	Recycled glass sand (100%)	PVA (2%)	55	4.4	3.31
Zhang et al. [7]	FA + SF	0.4:0.1	Crumb rubber (30%)	PE (2%)	83	8.37	6.66
Noorvand et al. [84]	FA	0.7	Crumb rubber (20%)	PVA (1.75%)	15.1	3.5	3.83
Zhang et al. [7]	FA + SF	0.4:0.1	Fly ash cenosphere (100%)	PE (2%)	65	8.80	12.50
Bang et al. [97]	FA + slag	0.12:0.12	Bottom ash aggregate (30%)	PVA (2%)	35.79	4.7	1.4
Bang et al. [97]	FA + slag	0.12:0.12	Bottom ash aggregate (10%)	PVA (2%)	33.12	4.0	3.3
Huang et al. [12]	FA	0.7	IOTs (100%)	PVA (2%)	47	5.8	2.8
Huang et al. [12]	FA	0.8	IOTs (100%)	PVA (2%)	20.8	4.8	4.1
Huang et al. [98]	FA	0.7	IOTs (100%)	PVA (2%)	50	5.8	2.9
Huang et al. [12]	FA	0.7	Fly ash cenosphere (100%)	PVA (2%)	43	5.5	3.5
Huang et al. [12]	FA	0.8	Fly ash cenosphere (100%)	PVA (2%)	20.5	4.9	4.3
Li and Yang [83]	Slag	0.8	Recycled concrete fine (100%)	PVA (2%)	52.96	–	1.64
Lee et al. [88]	GGBFS	0.8	Recycled concrete fine (100%)	PP (2%)	43.35	7.16	–

*Numbers are mass ratios of total binder, by weight

enhanced flexural strength and tensile ductility. In addition, Turk and Nehdi [86] reported that high dosages of LSP (used as a replacement of silica sand) increased the fracture toughness of ECC. Al-Gemeel et al. [99] developed ECC with hollow glass microspheres (HGMs) and hybrid fibers (1.25% PVA and 0.75% steel fiber). It was reported that incorporation of HGMs decreased the compressive and flexural strength of ECC. Same observations were also reported

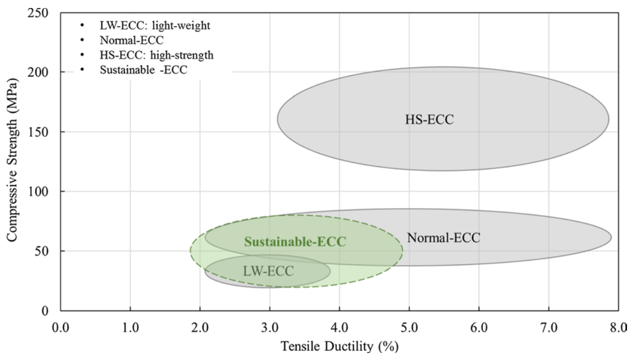

Fig. 5 Range of properties of ECCs (adopted from Li [17] with some modifications)

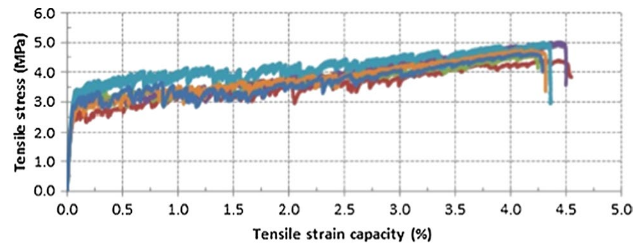

Fig. 6 Tensile stress–strain response of Na-based EGC [58]

by Aslani et al. [85, 91]. The properties of ECC mixtures admixed with recycled fine-powder (RFP), as a supplementary cementitious material, were investigated by Yu et al. [82]. They reported that the compressive strength and tensile strength were 85 MPa and 13.86 MPa, respectively, at an RFP content of 25%.

Salami et al. [80] demonstrated the potential of developing POFA-based ECC. POFA, fine aggregate, alkaline activators, superplasticizer and PVA fibers were utilized in developing ECC. The developed ECC exhibited a low strength at an early age and this was associated with high SiO2/Al2O3 ratio in the POFA matrix and high volume of POFA that contains unreacted particles. However, after 14 days, as the geopolymer reaction progressed, a more hardening gel of AAB was formed resulting in a gradual decrease in the strength. The authors also investigated the influence of added water and superplasticizer (SP) on the compressive strength of POFA-based ECC. Although the fresh properties were significantly enhanced with the addition of SP, adding 10% water without SP resulted in the best compressive strength compared to adding SP alone or a combination of SP and water. The reduction in the strength was attributed to the excess amount of SP, which in turn adversely affected the compressive strength, and it could also be due to the active solid ingredient of SP which decreased the geopolymerization reaction.

The effect of compositions of fly ash on the properties of ECC was extensively reported in the literature. Huang et al. [12] investigated the mechanical properties of lightweight ECC. It was reported that the use of fly ash cenospheres (FAC) slightly decreased the compressive strength. However, there was an improvement in the tensile ductility. Depending on the quantity of fly ash and FAC, the developed composite exhibited a 28-day compressive strength of 25.0–47.6 MPa and tensile first cracking strength of 2.5–3.6 MPa while the ultimate tensile strength was 4.8–5.9 MPa. In another study by Ohno and Li [118], fly ash from different sources having different chemical compositions, mainly in the composition of CaO, was studied. The authors used a combination of two types of fly ash that was classified as Type-F fly ash. It was reported that the compressive and tensile strength were in the range of 17.4–27.6 MPa and 2.9–3.4 MPa, respectively. Kan et al. [119] investigated the calcium content and fineness of fly ash on the mechanical properties of ECC. They reported that the fineness of FA affects its chemical activity while the concentration of calcium increased the compressive strength.

The influence of different activator combinations on the mechanical properties of EGC was discussed by Nematollahi et al. [58]. It was reported that Na-based activator combination was highly beneficial in terms of lower cost, higher compressive strength (63.7 MPa and 30.8 MPa for two Na-based solutions), and superior uniaxial tensile behavior (4.7 MPa and 3.9 MPa for two Na-based solutions), as shown in Fig. 6. The authors also reported, in a separate study [37], that the Na-based activator combination exhibited a good matrix fracture properties compared to other activator combinations. The elastic modulus, fracture toughness and crack tip toughness were 8.5 GPa, 0.436 MPa $m^{1/2}$ and 0.0224 kJ/m^2, respectively. In addition, the developed composite exhibited a superior flexural ductility, as shown in Fig. 7. With regard to the fresh properties, K-based activator exhibited higher slump and lower viscosity than Na-based activator [11].

The effect of water-curing period on the mechanical properties of ECC was experimentally examined by Zhu et al. [120]. ECCs were produced with 50%, 70% and 80% fly ash replacing cement. Five different curing conditions, namely room storage and laboratory storage after water-curing for different days, were evaluated. It was reported that the compressive strength and flexural strength increased as the water-curing period increased and total curing age was extended, as shown in Fig. 8. The higher quantity of fly ash is advantageous in lowering the negative influence of water-curing time on the strength of ECC. It was reported that ECC with 70% fly ash and seven-day water curing exhibited good mechanical properties and ductility. In another study, Nematollahi et al. [39] used polyethylene (PE) fiber-based ECC with two different curing regimes: ambient temperature (23 ± 3 °C

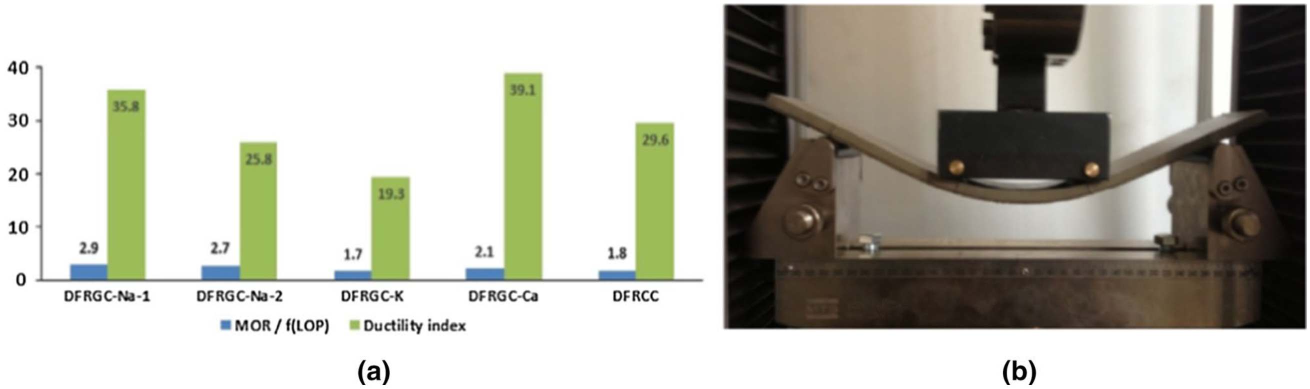

Fig. 7 **a** Ductility index of ECC **b** extremely high ductile behavior of typical Na-based composite specimen in bending [37]

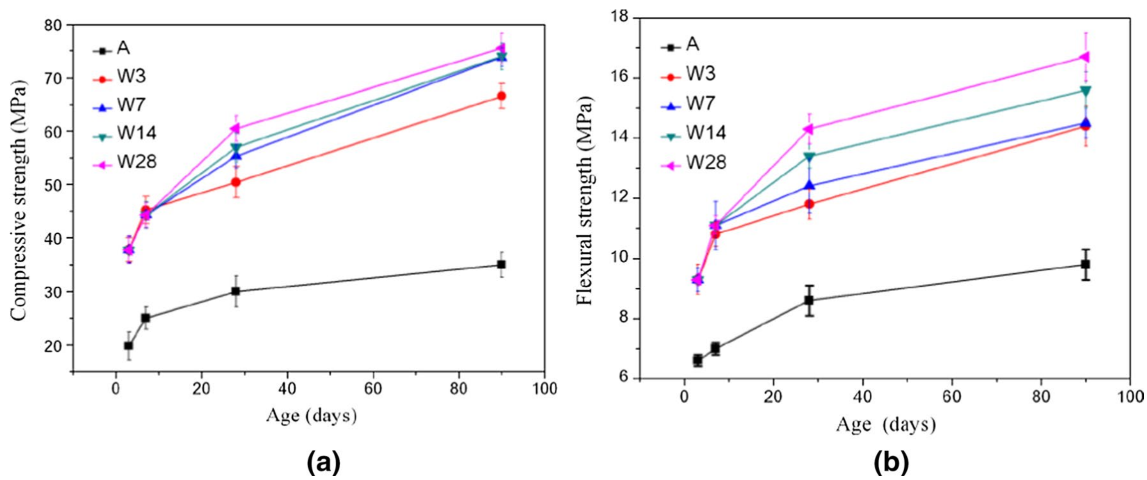

Fig. 8 Effect of water-curing period on strength of ECC: **a** compressive strength; **b** flexural strength, (A: Air curing; W3: Water curing for 3 days; W7: Water curing for 7 days; etc.) [120]

for 24 h) and heat (60 °C for 24 h). It was reported that the compressive strength of air (ambient) cured specimens was more than that of heat-cured specimens. A similar trend of results was obtained in the tensile performance where the heat-cured composites exhibited lower tensile strength (3.3 MPa) compared to that of ambient curing (4.2 MPa), and this was attributed to the fiber-matrix interface properties.

Silica sand is generally used in the development of ECC; however, the amount, size and roughness of the sand influences the properties of ECC. A study by Wu et al. [121] investigated the effect of morphological parameters of sand on the properties of ECC. It was reported that a decrease in the roughness and sphericity of natural sand improved the strength-related properties as well as the strain capacity of ECC. Therefore, the authors concluded that the utilization of natural sand in ECC will lead to environmental and economic benefits.

A study was conducted by Guan et al. [122] to produce an economical ECC. High volume of ordinary river sand, with a maximum particle size 20 times that of silica sand, was used. It was reported that at a sand/binder ratio varying from 0.36 to 0.75, the compressive strength and tensile strength of ECC were not significantly affected. In addition, ECC prepared with river sand exhibited a tensile strain capacity of 9% and pseudo strain hardening (PSH) of more than 30. Therefore, the authors reported that the developed ECC meets the requirements of ultra-high ductile composite with an advantage of 10% reduction in the cost. Siad et al. [123] also tried to replace silica sand with crumb rubber. The experimental results indicated that the mechanical properties decreased while the ductility increased. In addition, the incorporation of crumb rubber along with metakaolin and FA exhibited better transport properties. Noorvand [84] reported that the inclusion of 20% crumb rubber in ECC mixtures resulted in a low strength (15.1 MPa). The authors attributed the adverse effect of crumb rubber on the strength of ECC to its defect-like behavior through the poor bonding with the cementitious matrix.

Li and Yang [83] explored the feasibility of utilizing RCF as an alternative to silica sand in ECC. They reported that RCF could be used to produce an ECC with compressive strength and ductility of 52.96 MPa and 1.64%, respectively. In addition, Lee et al. [88] utilized 100% RCF as a replacement of sand in ECC mixtures. The produced ECC exhibited compressive and tensile strength of 43.35 MPa and 7.16 MPa, respectively. Bang et al. [97] utilized bottom ash aggregate as a partial replacement of sand (substitution rate of 10%, 20 and 30%). It was reported that 10% of bottom ash can be effectively used in producing ECC where the compressive strength, tensile strength and tensile capacity are 33.12 MPa, 4.0 MPa and 3.3%, respectively. In addition, ECC with IOTs, as fine aggregates, was studied by Huang et al. [12, 98]. It was reported that the IOTs with appropriate size range enhanced the mechanical properties of ECC compared with the commonly used silica sand. The developed ECC showed a compressive strength, tensile strength and tensile capacity of 47 MPa, 5.8 MPa and 2.8%, respectively.

The influence of water-binder and sand-binder ratio on the mechanical properties of ECC was investigated by Gao et al. [64]. Different mixtures were produced using OPC, quartz sand, fly ash, low-alkali cement, superplasticizer and PVA fiber. As expected, the compressive strength of ECC decreased with an increase in the water-binder ratio (the compressive strength was 23.70 MPa, 16.40 MPa and 11.30 MPa corresponding to water-binder ratio of 0.25, 0.33 and 0.41, respectively). Similarly, the tensile strength decreased with an increase in the water-binder ratio. On the other hand, the compressive strength increased with an increase in the sand-binder ratio. However, the tensile strength decreased with an increase in the sand-binder ratio as the fine aggregate increased the porosity of matrix leading to internal defects and internal microcracks. Consequently, the ultimate tensile strain decreased due to a reduction in the tensile strength. Choi et al. [63] confirmed that an increase in the water-to-binder ratio adversely affected the compressive strength and tensile strength. However, a decrease in the water-to-binder ratio necessitated addition of a high-range water-reducing admixture (HRWRA) in order to achieve the desired rheological properties. Choi et al. [61] investigated this issue by studying the rheological and mechanical properties of alkali-activated composite that was produced using GGBS along with PVA fibers. They also used a viscosity-modifying agent (VMA) in the mixtures to ensure adequate interfacial properties since the water-to-binder ratio was 0.25. It was reported that low viscosity and high ductility can be obtained by using a water-to-binder ratio of 0.4 and 1.3% PVA fibers by volume.

Generally, ECC exhibits a large shrinkage deformation. Gao et al. [64] conducted research to decrease the shrinkage deformation associated with ECC by adding expansive agent and shrinkage-reducing agent. The compressive strength of ECC increased with an increase in the quantity of expansive agent but it was adversely affected by the proportion of shrinkage-reducing agent. The reasons for this phenomenon were attributed to two mechanisms of these admixtures, where the first lead to the formation of more ettringite (i.e., when the concrete is restrained, the ettringite is forced to fill the pores yielding more compactness) and the second is related to the formation of more pores in the matrix. However, both expansive agent and shrinkage-reducing agent decreased the tensile strength of ECC.

3.1.2 Effect of Fibers on Properties of ECC

Fibers are the most important constituent of ECC. They play a vital role in the tensile ductility and crack width control of ECC [45]. Nematollahi et al. [39] examined the effect of PVA and PE fiber on the strength-related properties of ECC. It was reported that the compressive strength of PVA-ECC (48.7 MPa) was slightly more than that of PE-ECC (44.3 MPa). The authors reported that this may be attributed to the less damaging effect of the PVA fibers due to their low aspect ratio compared to PE fibers. In addition, the PE-ECC exhibited an ultimate tensile strength of 4.2 MPa, which is marginally less than that of PVA-ECC (4.6 MPa). Two studies carried out by Choi et al. [61, 63] investigated the effect of fiber type (PVA and PE) on the mechanical properties of GGBFS-based ECC. It was reported that PE-ECC exhibited a significant improvement in the compressive strength of around 2.9 times that of PVA-ECC. In addition, it was concluded that the ratio of tensile strength to compressive strength of the PE-ECC was 19.8%, which is almost double that of normal concrete. Moreover, the PE-composite had a tensile strain capacity and tensile strength of 7.5% and 13.06 MPa, respectively.

Al-Majidi et al. [4] explored the effect of different types of fibers, namely steel, PVA and glass fibers on the properties of ECC. The improvement in the compressive strength was attained by using composite steel fibers. The improvement was in the range of 15–25 MPa, depending on the aspect ratio, shape and volume fraction of fibers, compared to mixtures without fibers. On the other hand, utilizing glass or PVA fibers resulted in an insignificant enhancement in the compressive strength (42 MPa and 34 MPa for PVA and glass fiber composites, respectively). The early-age tensile strength (at 7 days) of the PVA-ECC (2.13 MPa) was more than that of steel fiber-ECC (0.85 MPa and 1.3 MPa for 6 mm and 13 mm fiber length, respectively) and glass fiber (1.7 MPa). The improvement in the strength was mainly attributed to the development of early interfacial bond between the PVA fibers and the binder. At 28 days, the tensile strength of ECC with steel fiber, and PVA and glass fiber composites improved by 95%, 65% and 77%, respectively, compared to the 7-day strength.

Xu et al. [13] studied the influence of fiber content and its influence on the mechanical properties of ECC. Different quantity (3%, 5% and 7%, by weight) of PVA fiber was used to prepare ECC. The composites were prepared using nano-silica and fly ash as binder materials. It was reported that the compressive strength improved due to the addition of fibers. The compressive strength was 41.3, 42.4 and 43.6 MPa with fiber content of 3%, 5% and 7%, respectively. However, the workability of ECC with 7% fibers decreased significantly; therefore, improved fresh and hardened properties were obtained with 5% fibers. Gao et al. [64] studied the effect of PVA fiber content on the mechanical properties of ECC. It was reported that the compressive strength decreased as more fiber volume was added. In fact, the increase in the quantity of fibers resulted in entanglement with each other making them easy to bend under compression. However, with increasing volume of fiber, the tensile strength and ultimate tensile strain capacity (1.547 MPa and 1.265%, respectively) was noted at 2% PVA. This was attributed to the role of fibers in restraining the propagation of cracks and redistribution of the load transfer between the matrix and fibers.

Table 6 presents a summary of type of binder, activator, fiber and curing regime on the properties of ECC. Generally, the compressive strength, tensile strength and tensile strain capacity of ECC is in the range of 17–47 MPa, 3–6 MPa and 3.3–4.3%, respectively, [12, 67, 118].

3.2 Micromechanics-Based Investigations

The ductility and fracture behavior is of primary importance to ECC since the fiber-binder interaction plays a vital role in its strain-hardening behavior. Consequently, micromechanics studies are used to understand the macro-scale observations of the tensile ductility of ECC composites [9]. Theoretically, two criteria are to be fulfilled in order to attain the strain-hardening response, first is strength-based condition

Table 6 Mechanical properties of alkali-activated composites

References	Binder		Activator	Fiber volume	Curing condition	Mechanical properties		
	Type	Proportion ratio*				Compressive strength (MPa)	Tensile strength (MPa)	Tensile strain (%)
Nematollahi et al. [58]	OPC (Control)	1.0	–	PVA (2%)	23 °C for 24 h	59.8	3.3	0.34
	Fly ash (Class F)	1.0	Na-based	PVA (2%)	60 °C for 24 h	63.7	4.7	4.3
	Fly ash (Class F)	1.0	K-based	PVA (2%)	60 °C for 24 h	37.3	1.8	2.0
	Fly ash (Class F)	1.0	Lime-based (powder)	PVA (2%)	60 °C for 24 h	13.6	1.7	1.1
Choi et al. [63]	GGBFS	1.0	Na_2SiO_3 + NaOH	PE (1.75%)	23 °C for 2 days	36.3	5.06	4.58
Nematollahi et al. [124]	Fly ash (Class F)	1.0	Na_2SiO_3 + NaOH	PVA (1.2%)	60 °C for 24 h	–	4.7	4.3
Salami et al. [80]	POFA	1.0	Na_2SiO_3 + NaOH	PVA (2%)	60 °C for 24 h	28	–	–
Xu et al. [13]	Fly ash (Class F)	1.0	Na_2SiO_3 + NaOH	PVA (3%)	Normal curing	42	1.51	–
				PVA (5%)		43	2.36	–
				PVA (7%)		44	2.21	–
Ohno and Li [66]	Fly ash (Class F)	1.0	Na_2SiO_3 + NaOH	PVA (1.0%)	60 °C for 24 h	38.5	3.5	3.0
				PVA (1.5%)		43.1	5.3	4.7
				PVA (2.0%)		43.3	5.4	4.4
Nematollahi et al. [73]	Fly ash (Class F) + Slag	1:1	sodium metasilicate powder	PVA (2.0%)	Air temperature	48.7	4.6	4.2
Nematollahi et al. [59]	Fly ash (Class F) + Slag	1:1	Sodium metasilicate powder	PE (2.0%)	60 °C for 24 h	33.9	3.3	5.5
				PVA (2.0%)		47.6	4.4	3.6
Nematollahi et al. [125]	Fly ash (Class F) (with sand)	1.0	Na_2SiO_3 + NaOH	PVA (2.0%)	60 °C for 24 h	60.7	5.2	1.3
	Fly ash (Class F) (without sand)	1.0				52.6	4.3	3.0
Choi et al. [61]	GGBFS	1.0	Na_2SiO_4	PVA (1.0%)	Room temperature	18.5	1.66	1.2
				PVA (1.3%)		18.3	2.26	2.38

*Numbers are mass ratios of total binder, by weight (or stress performance index), and second is energy-based condition (or energy performance index) [9, 126]. The micromechanical properties of ECC were evaluated using techniques, such as SEM and AFM [35], X-ray micro-computed tomography (μCT) [127] and single-fiber pullout test [35, 124].

Nematollahi et al. [9] evaluated the properties of matrix fracture and fiber/matrix interface of ECC. These properties were evaluated to examine the effects of three variables: type of alkaline activator (Na- and K-based), water-to-binder ratio (0.2 and 0.23) and fiber surface (virgin and oil-coated PVA fibers). It was reported that the Na-based activator increases the ductility of fly ash-based matrix, whereas the fracture properties decreased due to an increase in the water-to-binder ratio to 0.23. With regard to the fiber/matrix interface properties, the oil-coated fiber-based composites exhibited a significant lower chemical bond strength than the composites with the virgin fiber. Another detailed study was conducted by Kanda and Li [126] to experimentally evaluate and practically design the strain-hardening behavior of ECC. The authors suggested values of 1.3 and 2.7 for the stress and energy performance indices, respectively.

The surface condition of PVA fibers has a significant influence on the mechanical properties of ECC. Recently, Ding et al. [35] explored the effects of surface treatment on the behavior of ECC, based on the micromechanics theory. The PVA fibers were treated with three different agents, namely oil, hydrophilic silica and nanoscale graphite. Single-fiber pullout and tensile tests were carried out to assess the bridging capacity of the treated fibers. It was reported that the nanoscale graphite coating exhibited better hydrophobicity, larger surface roughness and higher tensile ductility. In addition, SEM and AFM images showed a rough surface after treatment with hydrophilic silica and nanoscale graphite, as shown in Fig. 9. However, with regard to the single-fiber pullout test (Fig. 10), oil-coated PVA fibers exhibited better chemical bond energy compared to PVA subjected to other treatments. Arain et al. [128] examined the modification of PVA fibers using different oiling agents. The results of single-fiber pullout test and SEM analysis showed an enhancement in the fiber/matrix interface with a reduction in the chemical debonding energy. Meanwhile, the flexural tests proved that there was an increase in the toughness and cracking strength of ECC incorporating 2% PVA. In another study, Fahad et al. [129] demonstrated that ECC with treated-PVA had a tensile ductility and tensile stress of 2% and 3.9 MPa, respectively, which is far more than that of ECC with untreated-PVA (< 1% and 2 MPa, respectively).

4 Durability of ECC

The ductility of a cementitious composite is mainly dependent on the interaction between the cementitious matrix and the fibers [77]. In these materials, crack initiation is a function of matrix toughness and the crack-bridging ability of the fiber. Therefore, ductility is the backbone of producing a highly durable composite. In principle, ECC maintains a

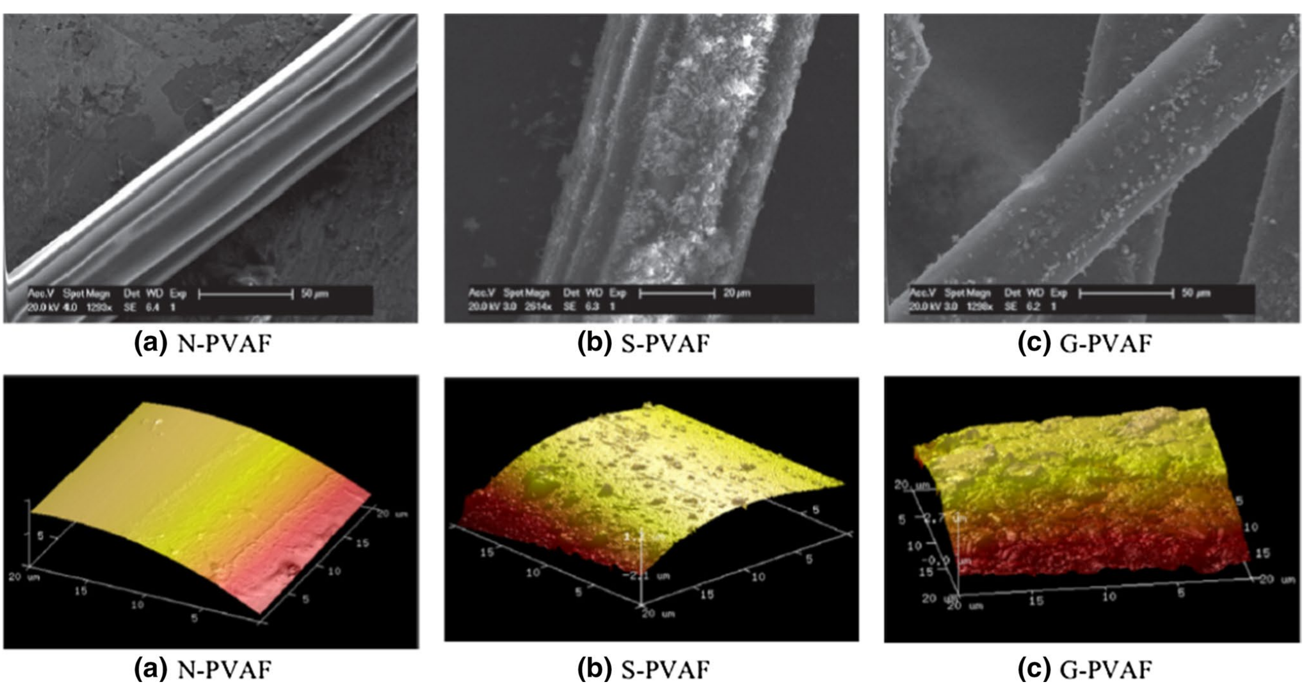

Fig. 9 SEM and AFM images of ECC with treated-PVA fiber **a** oil **b** hydrophilic silica and **c** nanoscale graphite [35]

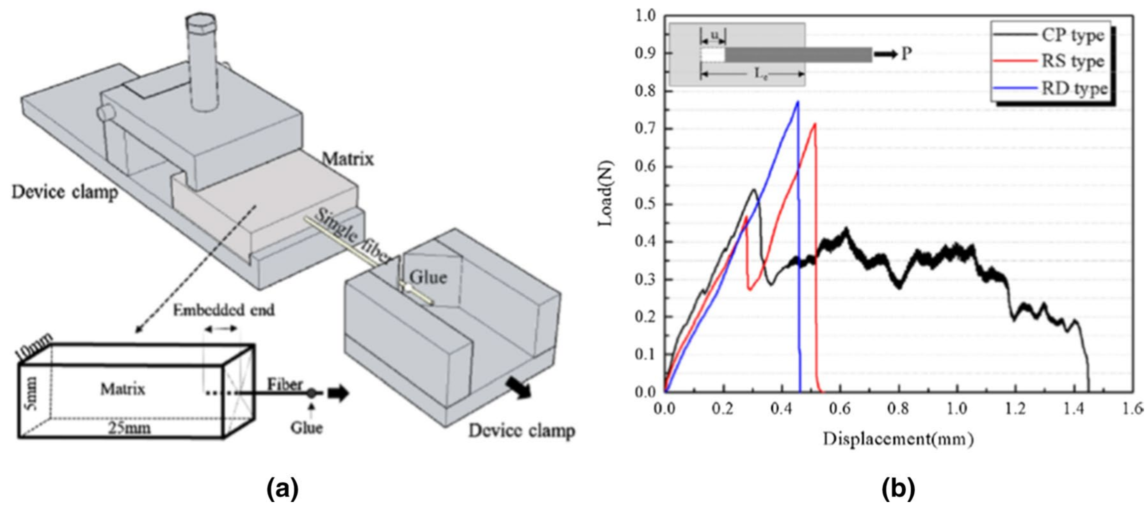

Fig. 10 Single-fiber pullout test: **a** specimen and test setup, **b** typical response curves of PVA fibers [35]

ductile behavior due to its strain-hardening response under loading. However, this is true if only the performance conditions in terms of strength and energy criteria are satisfied. Failure to satisfy these conditions may result in tension softening response under tensile loading.

Several studies have been conducted on the durability of ECC [18, 130]. Generally, alkali-activated ECCs exhibit superior properties in terms of high strength, low creep and shrinkage, and good chemical resistance [74]. Salami et al. [74, 80] studied the durability of POFA-EGC in sulfate environment. It was reported that specimens exposed to 5% $MgSO_4$ solution exhibited better durability than those exposed to 5% Na_2SO_4. Puertas et al. [131] reported on the durability of alkaline PE-composites. It was indicated that the shrinkage of slag-based ECC was more than that of fly ash-composites.

The transport properties (permeability, diffusion and absorption) of ECC were investigated by Sahmaran and Li [132], and Yildirim et al. [133]. Sahmaran and Li [132] reported that ECC possess good resistance to aggressive species, such as water, chloride, oxygen, etc., and this was attributed to the finely distributed microcracks (i.e., multiple cracks of self-limiting width). Yildirim et al. [133] concluded that the self-healing property of ECC effectively contributed to its low transport properties. Wagner et al. [134] evaluated the water permeability of ECC. This study focused on the permeation measurements of ECC that had already cracked under service-loading. It was reported that the rate of flow of water was directly related to the crack pattern. In addition, Wagner et al. [135] investigated and modeled the water absorption of cracked ECC. It was reported that the ECC possessed a higher sorption coefficient and this was attributed to the presence of fibers that introduced higher macro-pores. Lepech and Li [136] investigated the water permeability of ECC under uniaxial tension. It was reported that ECC with 1.5% tensile deformations displayed six times lower permeability than normal reinforced mortar. Liu and Tan [137] evaluated the permeability of PVA-ECC at elevated temperature. It was reported that due to interfacial transition zone between the fibers and matrix, the permeability of ECC was more than that of mortar without fibers. In addition, it was highlighted that PVA at elevated temperature, less than the melting point of PVA, significantly contributed to the impermeability of ECC.

The water absorption and sulfate resistance of ECC were evaluated by Xu et al. [13]. It was reported that incorporation of 5% PVA fiber (by weight) decreased the water absorption by 60% compared with the specimens without fibers. The expansion of ECC with 5% PVA immersed in 5% MgSO4 solution was 0.071% which is much less than the threshold value of 1.5%. Further, a significant pore refinement was noted in ECC due to the inclusion of nanosilica and PVA fibers. The porosity and average pore diameter in 5% PVA-ECC specimens were 43.1% and 0.717 µm, respectively.

Sahmaran et al. [138] studied the chloride transport properties of ECC under combined static and environmental loadings. The ECC beam specimens were subjected to bending deflection while they were immersed in NaCl solution. It was reported that microcracks were less than 50 µm and the depth of chloride penetration was less than that in the normal mortar specimens. Moreover, ECC exhibited a behavior of self-healing that resulted in decreasing the chloride diffusion, as shown in Fig. 11 [138].

The instantaneous corrosion rate in an alkali-activated slag binder prepared with carbon fibers (1 and 3%) was evaluated by Alcaide et al. [60]. Two types of exposures were used for corrosion measurements, accelerated carbonation and chloride immersion (akin to marine environment). It was

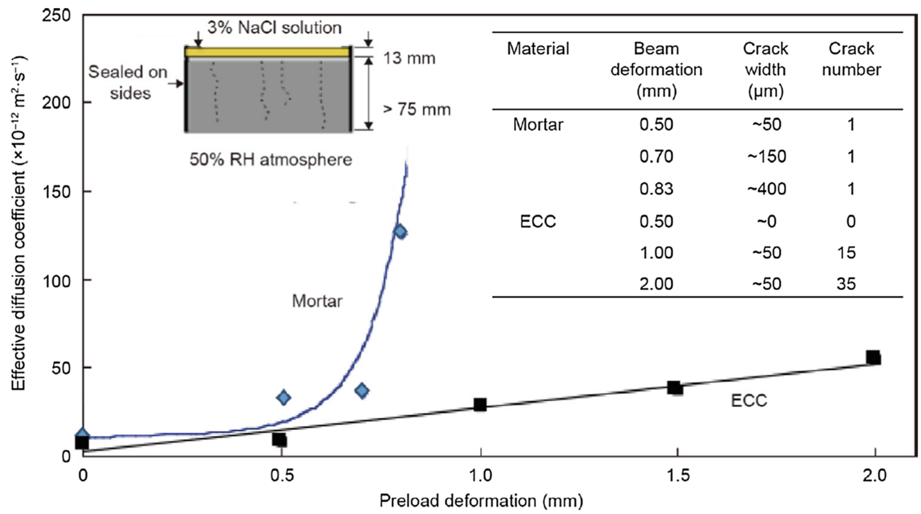

Fig. 11 Coefficient of chloride diffusion in ECC and normal mortar under deformation [18, 138]

reported that the incorporation of carbon fibers increased the corrosion levels in both carbonation and chloride media. The authors attributed the accelerated corrosion in ECC due to the fact that carbon fibers are noble than steel and thus they decrease the electrical resistivity of composite medium.

The corrosion resistance of ECC was also evaluated by Sahmaran et al. [139]. In their study, corrosion was accelerated by impressing a constant anodic potential on steel in reinforced ECC specimens. It was reported that ECC extended the propagation of corrosion period, and this was attributed to its enhanced ductility and micro-cracking behavior. Miyazato and Hiraishi [140] concluded that micro-cell corrosion is formed in ECC and that the corrosion rate, chloride penetration and carbonation depth were generally lower than that in normal concrete.

Liu et al. [90] studied the feasibility of developing an ECC that possessed improved performance under freezing–thawing cycles. Instead of using high-volume fly ash (FA), ECC was developed using a binary system comprising FA and GGBFS. It was reported that ECC with 30% FA and 40% GGBFS offered improved frost resistance. The damage at the interface between ECC and concrete under freeze–thaw exposure was studied by Tian et al. [141]. The composite specimens were immersed in 3.5% NaCl solution for four days and then to 25 freeze–thaw cycles. The results indicated a significant degradation of the interfacial bonding strength between ECC and concrete. However, it was suggested that this negative effect could be minimized by controlling the strength of ECC and the degree of surface roughness of the substrate. This observation was also reported by Tian et al. in their later publication [142].

The durability of ECC prepared with non-processed rice husk ash (RHA) along with PP fibers was studied by Costa et al. [92] and Righi et al. [111]. Although the inclusion of RHA increased the total pores, it led to an increase in the tortuosity by limiting the flow of water through the matrix [92]. Further, it was reported that the presence of RHA restricted the shrinkage of ECC [90] causing a decrease in the cracks.

5 Structural Applications of ECC

5.1 Structural Behavior

Generally, ECC exhibited a good flexural and shear behavior compared to the normal concrete, and this is mainly attributed to its strain hardening. The flexural and shear behavior of ECC beams was experimentally investigated by Meng et al. [143]. They reported that the flexural behavior and ductility of ECC beams were improved and even beams without stirrups failed in flexure rather than in shear, as shown in Fig. 12.

Sui et al. [144] studied the fatigue performance of ECC under cyclic loading at four different levels of fatigue loading. It was reported that the ECC specimens exhibited a ductile failure after fatigue stress. In addition, PVA-ECC exhibited a higher fatigue life than PE-ECC, where the latter had a good fatigue performance under low stress levels. Meng et al. [145] also investigated the performance of steel-reinforced PVA-ECC beams under constant amplitude fatigue loading. It was reported that ECC beams exhibited shorter fatigue life compared to normal RC beams. The authors attributed this behavior to the higher stiffness degradation of the ECC beams.

5.2 Recent Applications

The structural applications of ECC is still limited. The main obstacles for the limited application of ECC is the absence of code of practices and data on its long-term performance [146]. However, some attempts have been made by the

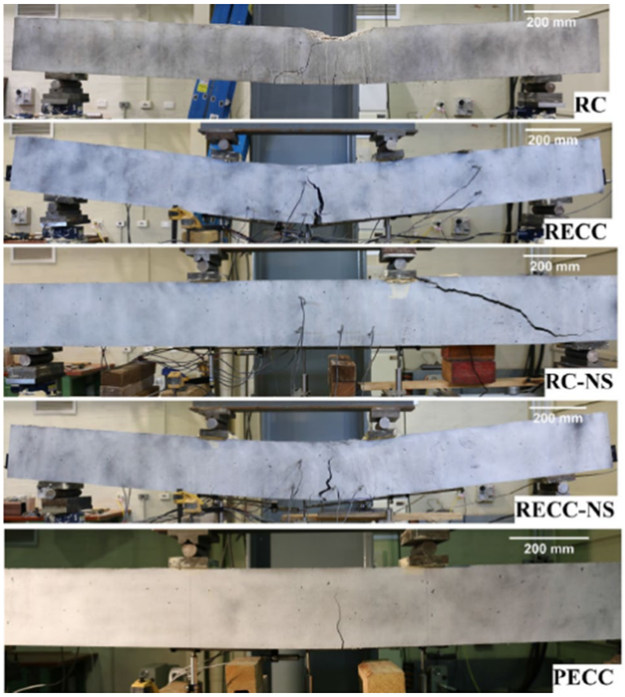

Fig. 12 Failure behavior of plain and ECC beams; RC: Reinforced concrete; RECC: Reinforced engineered cementitious composite; RC-NS: Reinforced concrete with nanosilica; RECC-NS: Reinforced engineered cementitious composite with nanosilica; PECC: Plain engineered cementitious composite [143]

engineering research community to develop sustainable ECC due to the pressing concerns toward a greener construction material with considerable ductility. Since ECC exhibits improved flexural and shear properties compared to the normal concrete, it can be used as a repair or retrofitting material and in new RC structures.

To negate the high cost of ECC, an attempt was made by Qiao et al. [147] to cast U-shaped ECC beams with core RC, as shown in Fig. 13. The failure was characterized by concrete crushing and debonding was not observed. Compared to normal RC beams, the U-shaped ECC-RC composite beams exhibited improved flexural behavior in terms of ductility and load-bearing capacity.

The repair and retrofitting of existing RC structures necessitates the development of a new system that satisfies both structural and serviceability requirements. ECC may offer such a requirement, and therefore, some research has been conducted in this regard [148]. The bond between the existing concrete and ECC at elevated temperatures was evaluated by Gao et al. [149] using slant shear and splitting tensile tests. The ECC was used to strengthen the existing normal concrete, and the repaired component was exposed to two different schemes, firstly by heating the substrate concrete and then reinforced by ECC, secondly by applying the strengthening system (concrete/ECC) and exposing to temperature. It was reported that the critical temperature was 200 °C and for a temperature of more than this, the slant shear and splitting tensile strength decreased. Therefore, ECC can be successfully used in repairing existing damaged concrete structures or those that are exposed to elevated temperature.

ECC was used as a protective layer in concrete wind turbine towers for crack control purposes by Jin and Li [150, 151]. Under flexure testing, the ECC coating-layer restricted the initiation of cracks and the beam failed in a ductile manner, as shown in Fig. 14. In addition, the results of fatigue loading showed that the fatigue life of ECC is 50 times that of conventional concrete at flexural fatigue stress of 4 MPa. Therefore, tight crack openings and longer fatigue life of ECC can effectively enhance the durability of wind turbine towers. Huang et al. [152] investigated the feasibility of utilizing ECC as a strengthening material for RC beams subjected to static and fatigue loading. Different thickness of ECC (40 mm and 50 mm) was applied at the tensile zone of

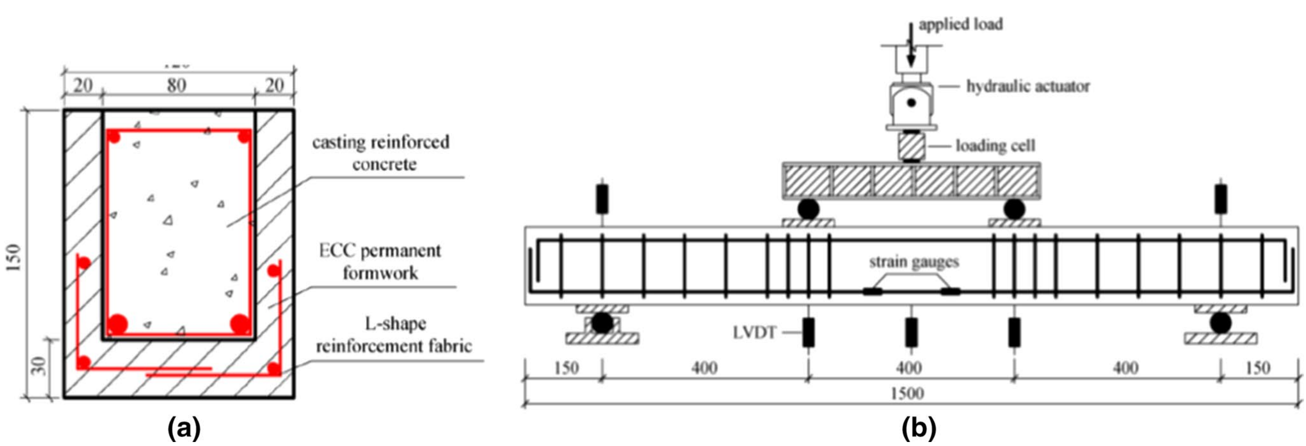

Fig. 13 Details of U-shaped ECC-RC composite beam: **a** cross section, **b** longitudinal view of the specimen and test setup [147]

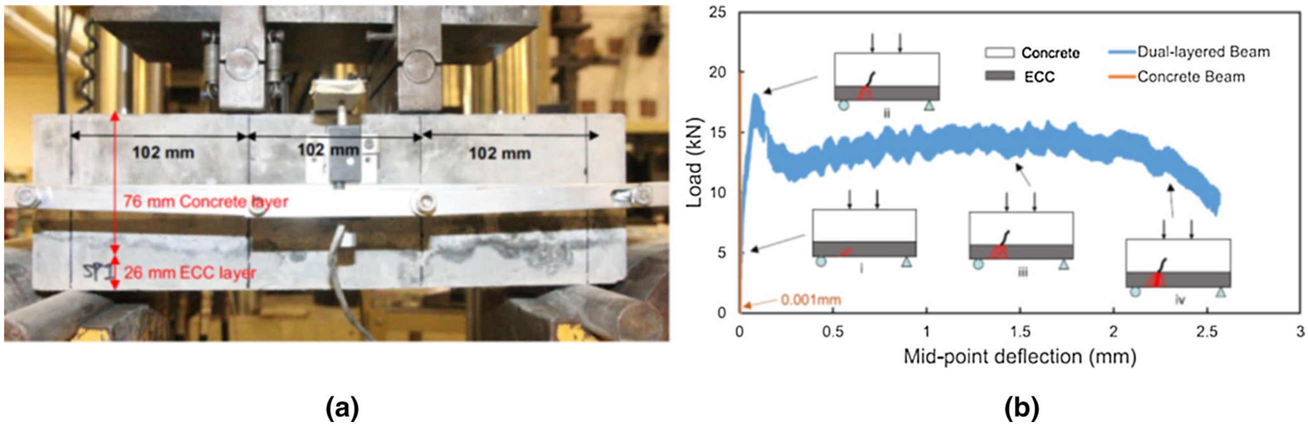

Fig. 14 Hybrid ECC/concrete beam: **a** flexural test setup, **b** load–deflection response [150]

RC beams. It was reported that the strengthening layers of ECC contributed well to the enhancement of the load-carrying capacity and fatigue life of the beams. In addition, the retrofitted beams showed less strain localization and stress concentration in the steel reinforcement.

ECC was used as an external strengthening solution of shear deficient RC beams [153]. It was applied at the longitudinal opposite sides of RC beams and two different layer thicknesses (20 mm and 40 mm) were studied. It was reported that the ECC layers enhanced the shear behavior of the retrofitted beams and the load-bearing capacity was increased by 89%.

The protection of RC beams against reinforcement corrosion using a repaired layer of ECC (25 mm and 50 mm) was assessed by Al-Majidi et al. [146]. Both the structural performance, using the flexural testing, and corrosion resistance, using induced accelerated corrosion (Fig. 15), were evaluated. It was reported that the overlay enhanced the corrosion resistance in terms of mass loss of the reinforcing steel (5.5% in case of 50 mm overlay thickness) compared to unrepaired beams (8.5%). In addition, both repaired and control beams exhibited a similar behavior in flexure; however, the ultimate loading capacity of repaired beams was noticeably increased, irrespective of the layer thickness. Another study was carried out by Zhang et al. [52–54] utilizing geopolymeric composite composed of GGBFS and metakaolin with PP fibers as a protective coating in structures exposed to marine environment. The field results confirmed the experimental outcomes that the proposed composite configuration exhibited excellent anti-corrosion properties and chemical stability under marine conditions.

Chen et al. [154] studied the suitability of utilizing ECC as a repair material. It was developed using cement, silica fume and PE fibers and applied on RC members with

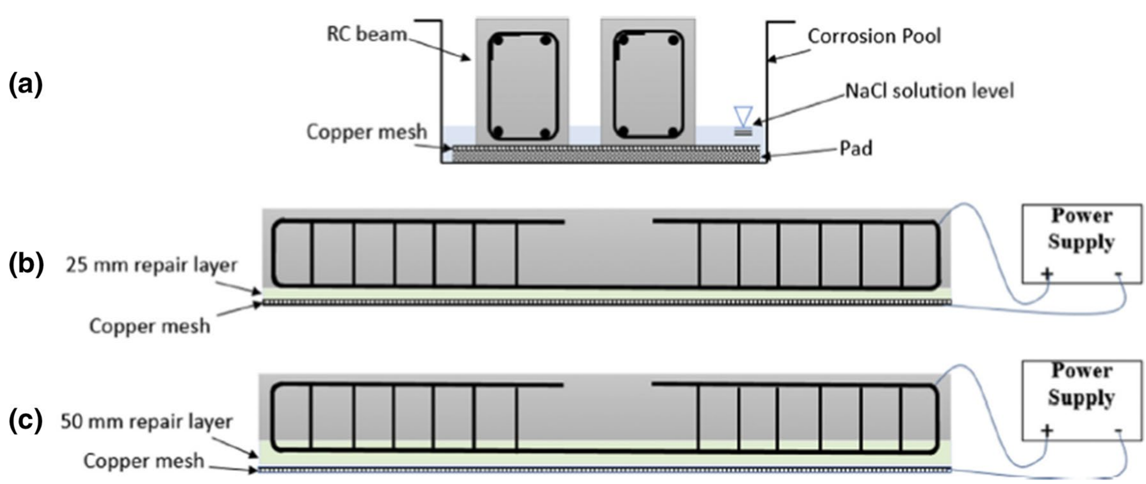

Fig. 15 Accelerated corrosion test: **a** test setup (5% sodium chloride solution); **b** specimen with 25 mm repair layer and **c** specimen with 50 mm repair layer [146]

corroded steel. The steel reinforcement was fabricated with reduced cross section in order to simulate severely corroded steel bars. It was reported that the developed ECC restored 90% load-carrying capacity of the repaired beams. In a study conducted by Fakhri et al. [155], ECC was used as a protection cover to mitigate corrosion of steel reinforcement. It was reported that the rate of rebar mass loss decreased due to the application of ECC.

Another application of ECC is the encasement of steel beams in which the compression flanges were not restrained against the lateral torsional buckling. In this regard, Kabir et al. [156] examined the flexural performance and bond-slip behavior of steel beams encased with ECC. The encasing approach had three configurations: either casting ECC on the whole section of bare steel, or hybrid encasing of ECC and lightweight concrete, or even encasing only the compression flange. A bending test was performed on the composite beams, and it was reported that the flexural strength as well as the stability of the encased beams were enhanced due to the application of ECC. Further, bond-slip was not observed in fully encased beams even at the failure stage. However, some bond-slip was detected in partially encased beams at the failure load. Bai et al. [157] investigated the bond behavior between the H-shaped steel beams encased with ECC under the push-out test. Different variables were studied including the quantity of PVA, thickness of ECC thickness and the length of H-shaped steel. It was reported that an increase in the quantity of PVA fraction and ECC cover thickness increased the bond stress.

Few researchers studied the seismic behavior of ECC members [158–160]. Wu et al. [161] investigated the seismic response of ECC columns under the combined axial and cyclic loading. ECC columns exhibited better seismic response, on the basis of ductility and energy dissipation, than the traditional RC columns. Another study conducted by Zhang [162] confirmed the possibility of utilizing ECC in short columns under seismic loading. The authors reported that the plastic deformability in terms of lateral displacement and energy dissipation improved by 41–72% and 134–241%, respectively, compared to RC short columns. An attempt was made by Zhang [163] to enhance the load-carrying capacity of bridge columns by using precast ECC elements. The ECC was used as a jacketing system in the regions of plastic hinges. It was reported that the precast ECC improved the structural performance compared to conventional cast in situ RC columns. Deng et al. [164] carried out an experimental study to evaluate the bond between ECC and steel bars. They reported that the strength and thickness of ECC had a direct influence on the bond between the steel bars and ECC.

ECC can be used in place of conventional concrete at beam-column joints (BCJs) to overcome the problems of placing the former concrete due to congestion of steel reinforcement at those locations. Gou et al. [165] experimentally investigated the seismic performance of precast BCJs made of U-shaped ECC. They reported that the proposed ECC technique met the seismic requirements even when sufficient transverse reinforcement was not provided. The seismic behavior of ECC flexural members was also investigated and modeled by Tariq et al. [166]. Abouhussien et al. [167] examined the effect of varying the type of fibers (PVA, PPT and steel) in ECC beam-column joints that were subjected to cyclic loading. The experimental observations and acoustic emission (AE) readings indicated that the use of fibers resulted in insignificant effects on the signal characteristics of AE. Table 7 summarizes the recent applications of ECC in repair and retrofitting of structures.

6 Concluding Remarks and Recommendations for Future Research

This paper presents a state-of-the-art review on engineered cementitious composites (ECCs). Based on the literature review, the following conclusions are drawn and areas of future research are suggested:

(1) Industrial waste materials were utilized in developing ECC with certain alkali activators to obtain the desired mechanical properties and durability characteristics. Binders, such as fly ash, GGBS and kaolin are highly beneficial in terms of lower cost and positive environmental effect.
(2) Generally, the geopolymer-based composite exhibited compressive strength, tensile strength and strain capacity in the range of 17–47 MPa, 3–6 MPa and 3.3–4.3%, respectively.
(3) The composition of ECC can be modified by incorporating some IWMs, such as recycled fine-powder, crumb rubber, recycled glass, iron ore tailings and the resulting composite satisfied the requirements of high strength and ductility. However, other IWMs, such as cement kiln dust, silico-manganese fume, red mud, etc., can be used to develop sustainable ECC.
(4) Although many fibers were used to reinforce ECC, PVA fibers significantly enhanced its ductility.
(5) The micromechanical methodology of designing ECC is the key factor in the transition of a cementitious composite from brittle to ductile composite. The micromechanical study is of primary importance for producing ECC of desired properties.
(6) Although considerable research has been conducted on the mechanical properties, the durability aspects of ECC need to be further investigated. Generally, ECC with minimum cracking will result in good durability in

Table 7 Potential applications of ECC

Application	Materials used	Remarks
Bridge decks [168–172]	Cement, fly ash, silica sand and PVA fibers	ECC is a good option for bridge decks due to its high deformation capacity under tension and flexure
Column confinement [173, 174]	Cement, fly ash, fine sand and PP or PVA fibers	ECC improved the ductility and confinement of columns under compression
Columns subjected to eccentric compression loading [175, 176]	Cement, fly ash, silica sand and PE fibers	The load-carrying capacity increased by 35% in steel-reinforced ECC columns compared to normal RC columns. In addition, the deformability and failure mode of ECC columns were also enhanced
3D printable ECC [177–179]	Cement, fly ash, sulfo-aluminate cement, silica sand and PE or PVA fibers	The developed printable ECC exhibited a tensile strength and strain of 5.7 MPa and 11.4%, respectively
ECC with FRP confinement [180, 181]	Cement, fly ash, quartz sand and PE fibers	The strength of ECC significantly affected the efficiency of FRP confinement
ECC reinforced with FRP bars [182–184]	Cement, fly ash, silica fume, quartz sand, PVA fibers	The load-carrying capacity, post-yielding stiffness and ductility of ECC reinforced with FRP bars were enhanced
ECC for pavements [185–187]	Cement, fly ash or GGBFS, quartz sand and PVA fibers	Improves the skid resistance and decreases the drainage
Fire resistance ECC [85, 188]	Cement, fly ash, silica fume, silica sand, glass microsphere and PVA fibers	The developed ECC is able to sustain 50% of its strength even at a temperature of 900 °C. Therefore, ECC is a good solution as a fire-proofing material
Textile-reinforced ECC [189–191]	Cement, fly ash, silica sand and PE or PVA fibers	ECC offered a promising alternative to normal textile-reinforced mortar (TRM)
Functionally graded reinforced concrete using ECC [192]	Cement, fly ash, microsilica, silica sand and PVA and steel fibers	The hybrid-fibered ECC exhibited an overall enhancement in the structural behavior
ECC under impact loading [46, 100, 193–195]	Cement, fly ash, silica sand and PVA and/or steel shape memory alloy (SMA) fibers	The impact resistance was greatly enhanced due to the incorporation of 1% SMA fibers. The supplementary cementitious materials (including MK and SF) could also be used as a partial replacement of fly ash in order to produce impact resistance ECC
ECC for tunnel linings [196]	Cement, fly ash, silica sand and PVA fibers	The ECC lining exhibited a better deformation and crack control behavior than the normal concrete
Strengthening of masonry members [197, 198]	Cement, fly ash, silica sand and PVA fibers	ECC, as a retrofitting material, improved the load-carrying capacity, deformability and ductility of masonry walls
ECC for dapped-end beams [199]	Cement, fly ash, silica fume, river sand and PVA fibers	The structural behavior of dapped-end beams with ECC showed a higher structural performance compared to normal RC. In addition, the strength of ECC influences the extent of failure load of the beams
ECC-filled and encased steel tubes [200, 201]	Cement, fly ash, silica fume, river sand and PVA fibers	The steel tube columns filled or encased with ECC exhibited higher failure load and improved ductility
Seismic-resistant ECC-framed structures [202]	Cement, fly ash or GGBFS, silica fume, silica sand and PE fibers	ECC frames behaved in a similar way to the conventional RC beams. However, the former exhibited better vibration resistance than the latte

Table 7 (continued)

Application	Materials used	Remarks
ECC for abrasion resistance [101]	Cement, fly ash, slag, metakaolin (MK), silica fume (SF), crushed granite sand (CS) and PVA fibers	Incorporation of slag, MK, SF, and CS in addition to fly ash increased the abrasion resistance of ECC with a cost-effective potential

terms of reduced chloride diffusion and improved corrosion resistance along with low cost of maintenance.

(7) In most cases, ECC is successfully applied in thin members or for repair and retrofitting of existing structures.

(8) ECC satisfying high strength, ductility and low maintenance requirements should be developed. A design methodology that can consider the micromechanical modeling and sustainability considerations should be adopted. In addition, experimental design needs to be effectively used to optimize the composition of ECC. Finally, for successful large-scale structural applications with engineering confidence, the long-term performance of ECC needs to be investigated.

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