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Discontinuous micro-fibers as intrinsic reinforcement for ductile Engineered Cementitious Composites (ECC)

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ABSTRACT

Engineered Cementitious Composites (ECC) have demonstrated superior mechanical and durability performance than conventional concrete. In the micromechanical reinforcing system of ECC, fibers play a pivotal role in establishing the ultrahigh tensile ductility and autogenous crack width control. This article reviews the state-of-the-art of discontinuous micro-fibers as intrinsic reinforcement of ECC regarding technical performance as well as environmental and economic impacts. Mechanical properties of ECC made with different micro-fibers, man-made or natural, and their embodied energy, emissions and material cost, are comprehensively surveyed. Further, studies on fiber hybridization are discussed regarding the combination of different types of fibers to form synergetic reinforcements that mitigate total material cost, and potentially enhance the composite performance. Recommendations on fiber selections are highlighted and directions for future research are suggested.

1. Introduction

Cementitious materials are known to be brittle. To overcome the brittleness, Fiber Reinforced Cementitious Composites (FRCC) have been introduced and their use has been growing over the past 50 years [1]. As an ultra-ductile class of FRCC, Engineered Cementitious Composites (ECC) are essentially made with mortars and discontinuous micro-fiber reinforcement, and show tensile strain-hardening behavior and multiple fine cracking with the ultimate tensile strain of 3–8% [2] (Fig. 1), several hundred times that of ordinary concrete (about 0.01%). The crack widths in ECC can be autogenously controlled to less than 100 μm during the strain-hardening stage, irrespective of the imposed strains [3] (Fig. 1). The development of ECC is still evolving, even though a number of full-scale structural applications have already appeared in Asia, Europe, and the United States [4–7].

The adoption of new materials in the highly cost-sensitive construction industry generally requires justification of cost advantage. Compared to conventional concrete, typical ECC are often costly, largely due to the inclusion of polyvinyl alcohol (PVA) fibers needed for equipping the material with capabilities of crack width control and tensile ductility. For instance, in typical M45 ECC [3] (Fig. 1), the PVA fiber at only 2 vol% contributes approximately 60-80% of the total material cost. Although the low life-cycle impacts may drive this novel material to the construction market, mitigating cost and environmental footprints remains critical to scaling up large-volume applications of ECC. Therefore, seeking cost-effective fiber options for ECC is pivotal.

Facing the clear need for selecting high-performance, low-cost and environmental-friendly micro-fibers for ECC production, this article comprehensively reviews micro-fibers previously adopted in ECC and general FRCC regarding their technical, economic and environmental potentials. It is the particular focus of this review to guide future selections on alternative micro-fibers outperforming PVA fiber (i.e., the most commonly used type of fiber for ECC) for scaled implementations of ECC. Regarding material source and manufacturing process, fibers commonly used in FRCC can be classified as man-made and natural fibers as shown in Fig. 2. Fibers that are currently used in ECC, e.g., PVA, PP and PE, fall in the category of man-made polymeric fibers, known as synthetic fibers due to the chemical synthesis for their manufacture.

Abbreviations: HDPE, high-density polyethylene; HMPE, high-modulus polyethylene; PBO, poly(*p*-phenylene-2,6-benzobisoxazole); PE, polyethylene; PET, polyethylene terephthalate; PP, polypropylene; PVA, polyvinyl alcohol.

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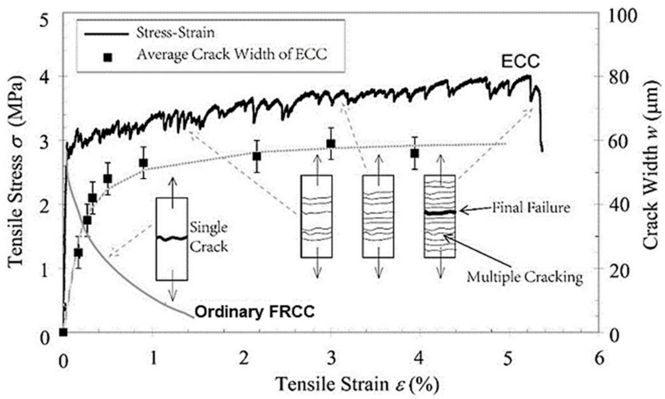

Fig. 1. Typical tensile stress-strain relation and crack width development of ECC (after [3]). The crack widths in ECC can be self-controlled to less than 100 μm during the strain-hardening stage.

Other man-made fibers, e.g., steel and carbon, are found more commonly in conventional FRCC. Basalt fiber is gaining increased attention due to the abundance of basalt mineral deposits in the Earth's crust and its relatively low cost and environmental impacts at manufacturing. Review on man-made fibers is taken up in Section 3. Amongst natural fibers, plant fibers show good promise for reducing shrinkage and improving flexural performance due to the presence of cellulosic components. However, plant fibers are generally weak in durability and require additional treatments to improve aging resistance. Studies on plant fibers as well as other natural fibers used in cementitious composites are reviewed in Section 4. Apart from mono-type fiber reinforcement, synergistic systems with hybrid fiber types demonstrate potentials of improving overall composite performance. Research status of fiber hybridization are given in Section 5.

As the purpose of this review is to gain insights into alternative micro-fibers for ECC production, the direct tensile performance (i.e., tensile strength and strain capacity) of ECC is particularly focused. Other pertaining aspects, including workability, compressive strength, flexural performance and durability, are briefly discussed. In the prior arts, ECC tensile properties are mostly obtained from specimens with thin cross sections. In this kind of geometry, fibers tend to become 2-D oriented when compared with thick sections where fibers could be more 3-D oriented. As a result, the measured properties may be affected. The essential features of ECC, however, are retained in larger structural members as documented by Lepech and Li [8].

2. Micromechanics-based guideline for fiber selection in ECC

Design of ECC has been established upon a suite of multi-scale experimentation guided by micromechanical methodologies [9–11]. The micromechanics of ECC serves as an effective tool for guiding fiber selections and matrix tailoring to achieve high tensile ductility and tight micro-crack widths at low fiber content (typically ~2 vol%). In the micromechanical framework of ECC, two complimentary criteria must be satisfied - the Strength criterion and the Energy criterion.

2.1. Strength criterion and energy criterion

The strength criterion requires that the tensile stress σ_{cr} to initiate a crack must not exceed the bridging capacity σ_0 (see Fig. 3) of the fibers crossing that crack, i.e.,

$$\sigma_0 \geq \sigma_{cr} \tag{1}$$

Satisfaction of this criterion ensures that the initiated crack does not cause catastrophic loss of load carrying capacity on this crack plane. On each crack plane, the load shed by the matrix is taken over by the bridging fibers, as a function of the crack opening characterized by the fiber-bridging σ-δ constitutive relation in Fig. 3. Detailed expressions for σ-δ relations have been previously derived for fibers and fiber/matrix interfaces with various characteristics [12,13]. The peak value of fiber bridging capacity σ_0 varies from one crack plane to another due to the inevitable spatial non-uniformity in fiber dispersion. The micro-crack tends to localize into a fracture and terminate the multiple cracking process if Eq. (1) is violated on the crack plane. If this occurs at the very first crack, only one crack will be formed followed by a tension-softening process, as is the typical case for ordinary FRCC shown in Fig. 1.

After the first crack initiates from a pre-existing flaw, the manner of crack propagation dictates whether the bridging fibers are pulled out or ruptured. To attain the desirable flat crack propagation mode, the energy criterion requires the crack tip toughness J_{tip} not to exceed the complementary energy $J_b^{'}$ (Fig. 3), i.e.,

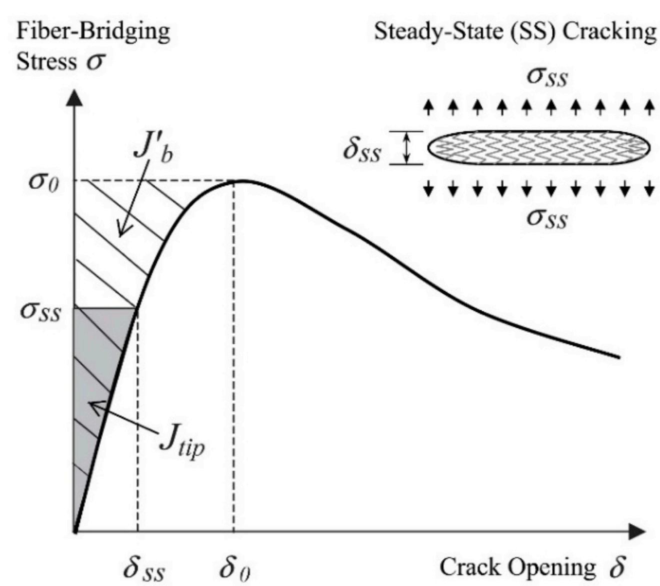

Fig. 3. Typical σ-δ constitutive relation of ECC (after [2]).

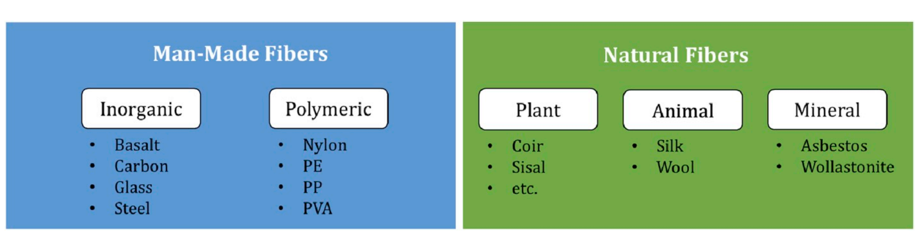

Fig. 2. Classification of fibers commonly used in cementitious materials.

$$J_b^{'} \equiv \sigma_0\delta_0 - \int_0^{\delta_0} \sigma(\delta)d\delta \geq \sigma_{ss}\delta_{ss} - \int_0^{\delta_{ss}} \sigma(\delta)d\delta = J_{tip} = K_{tip}^2(1-\nu^2)\Big/E_c \cong K_m^2\Big/E_m \tag{2}$$

where σ_0 is the maximum bridging stress corresponding to the crack opening δ_0, σ_{ss} is the steady-state bridging stress corresponding to the crack opening δ_{ss}, K_{tip} is the crack tip fracture toughness, and E_c is the Young's modulus of the composite. For ECC with small fiber volume fraction (~2%), K_{tip} and E_c can be simply taken as the matrix fracture toughness K_m and matrix modulus E_m, respectively [9].

To ensure validity of Eqs. (1)-(2) in the context of material variation, large margins between σ_0 and σ_{cr} as well as between $J_b^{'}$ and J_{tip} are needed [14]. In the aspect of matrix, low σ_{cr} in Eq. (1) can be attained by enlarging flaw size c and/or lowering matrix fracture toughness K_m, while low J_{tip} in Eq. (2) can also be attained by lowering K_m. Excessively large flaw size c or low K_m, however, may lead to inadequate compressive strength unsuitable for structural applications. In this regard, a more desirable approach is to increase σ_0 and $J_b^{'}$, through tailoring the fiber and fiber/matrix interface.

Table 1 describes how σ_0 and $J_b^{'}$ are conceptually improved by tailoring fiber properties in ECC. In general, σ_0 can be improved by increasing fiber volume and fiber/matrix bond and by employing high-strength fibers. However, high fiber volume may lead to low workability and inhomogeneous fiber dispersion, and inevitably increase material cost. From the energy perspective, $J_b^{'}$ can be enhanced by adopting fibers with low modulus and high aspect ratio. Excessively low modulus, however, tends to form poor crack control ability with large crack openings. Ensuring high $J_b^{'}$ also needs fiber/matrix interface to be tailored for attaining low chemical bond but adequately high frictional bond to absorb sufficient energy during fiber slippage. This needs an appropriate amount of wettability of the fiber surface in combination with appropriate densification of the interfacial transition zone (ITZ). The wettability of fiber surface is generally determined by the hydrophilicity of the fiber texture, and can be modified through fiber coating [15] and plasma treatment [16]. The delicate balance in PVA-ECC may be disturbed by the introduction of alternative fibers, which need to be tailored with matrix materials to simultaneously achieve sufficient margins in Eqs. (1)-(2).

2.2. Favorable fiber characteristics

Based on existing literature and the discussion above, fiber characteristics that are potentially favorable for producing ECC include: target fiber content at or below 2 vol%; diameter of 20–50 μm; length between 6 and 12 mm; tensile strength ≥800 MPa; elastic tensile modulus ≥10 GPa; tensile strain capacity ≥3%; little or no interfacial chemical bond; interfacial frictional bond at 1–6 MPa depending on fiber strength; sufficient corrosion resistance and chemical stability in cementitious environment; and stable properties over time.

Table 1
Desirable fiber properties for enhancing σ_0 and $J_b^{'}$.

Parameters	Fiber properties	Disadvantage
σ_0	high volume	reduces workability and fiber dispersion, increases cost
	high fiber/matrix frictional bond	increases fiber rupture, may need additional fiber treatments
	high strength	increases cost
$J_b^{'}$	low modulus	increases crack width
	high aspect ratio	reduces workability and fiber dispersion, increases fiber rupture
	high fiber/matrix frictional bond	increases fiber rupture, may need additional fiber treatments
	low fiber/matrix chemical bond	may need additional fiber treatments

(a) Geometry: The ideally small fiber diameter for achieving high aspect ratio puts most metallic fibers at a disadvantage [17]. The recommended diameter range is, however, easily achievable by polymeric fibers due to its melt-spinning and fiber drawing manufacturing technique that results in high fiber strength with smaller diameter. A lower limit on fiber diameter may also be imposed to prevent overly large aspect ratio (~300) that would reduce workability and fiber dispersion. The desirable fiber diameter is governed by the specific fiber type and is affected by rheological design of the composite mixtures.

(b) Strength and modulus: Fiber tensile strength governs fiber rupture and therefore the maximum bridging stress σ_0 [12,13]. In general, fiber tensile strength is positively correlated to fiber tensile modulus. Fiber tensile modulus plays a minor role in the composite mechanical properties before cracking, but needs to be adequate to maintain tight crack width in cracked materials [12,13]. The recommended fiber strength and tensile modulus can be met by most metallic and some carbon fibers, as well as by the group of high-performance polymeric fibers.

(c) Strain capacity (elongation at break): The fiber tensile strain capacity is important in preventing fiber failure, especially during the mixing process [17]. Fiber breakage during mixing reduces fiber length and aspect ratio, and therefore weakens the composite reinforcing efficiency. Additionally, fiber breakage in hardened mixture poses a major challenge to low tensile strain capacity fibers when the randomly oriented fibers need to bend as they bridge across micro-cracks at an angle [18]. Most carbon fibers with low tensile strain capacity are vulnerable to this deterioration. In contrast, metallic fibers, and particularly polymeric fibers, do very well in this category [19,20].

(d) Interfacial bond: Establishing a desirable fiber/matrix interfacial bond is critical to ensure the mechanical performance of ECC. With a low interfacial bond, the crack bridging capability appears weak, promoting fibers to slip out easily and leading to low tensile ductility and large crack widths in ECC. If the bond is too high, however, fiber tends to break instead of frictionally sliding out, leading to the loss of energy absorption and reduction in composite strain capacity [21]. Polymeric fibers generally have low bond strengths (<1 MPa), except for the hydrophilic PVA fiber, which forms a frictional bond of 2–5 MPa. This high interfacial bond requires oil coating on PVA fibers to prevent excessive fiber rupture and loss of tensile ductility [15]. Desirable range of interfacial bond also needs to be scaled with fiber length, diameter and strength [17]. Interfacial bond has been reported to increase over time for some man-made fibers, such as glass, polymeric and carbon [20], whereas metallic fibers appear to possess the most stable bond at the fiber/matrix interface [17].

(e) Durability: Chemical stability of fibers is important for ensuring composite performance in the long term. Regarding corrosion resistance, carbon and polymeric fibers do well in comparison with metallic fibers. However, metallic fibers can be made corrosion resistant (e.g., stainless or brass-coated steel fiber) [22]. In terms of chemical stability, carbon fibers are mostly inert, whereas some polymeric and glass fibers, and most plant fibers are vulnerable to degradation or aging in the alkaline cementitious matrix [23].

(f) Density: Fiber density is not critical given the comparatively low fiber volume fraction in ECC [17]. However, they are important in determining the economic feasibility of the fibers used in ECC, since fibers are generally priced on a unit mass basis, whereas their reinforcing effectiveness responds to the fiber content in volume [3]. Hence, for the same fiber volume fraction, a high-density fiber tends to weigh and cost more than a corresponding fiber with low density.

From the above discussion, it is clear that proper fiber selection and tailoring are critical in achieving tensile strain-hardening and multiple cracking in ECC. Guided by the Strength and Energy criteria, decisions on which fiber to be used depend on the fiber properties including mechanical characteristics, diameter ranges and surface characteristics; on the workability, mechanical, durability and sustainability performance of the resulting ECC; on economics; and a delicate balance among these factors [3].

3. Man-made fibers

Geometries and mechanical properties of single fiber filaments are the common criteria for the evaluation of fiber performance. Tables 2-3 list the range of technical specifications for man-made fibers, taken from scientific publications and spec sheets provided by manufacturers. Their technical properties are graphically compared in Figs. 4–5. Taking PVA fiber as a baseline, PET, PP and nylon fibers are of low modulus, low tensile strength and high elongation at break; whereas, carbon, steel, PBO, glass and basalt fibers have high modulus and tensile strength but are weak in elongation. Cementitious materials reinforced with the latter tend to be more brittle compared to PVA-ECC. In addition, PE fiber exhibits simultaneously higher modulus, tensile strength and elongation than PVA fiber. These features promote PE fiber to be successfully adopted for high-strength ECC [80,81].

Following a descending order of fiber's Young's modulus, this section discusses previous research on applications of man-made fibers in cementitious materials in reference to PVA fiber typically used in ECC, with particular focus on technical, economic and environmental impacts.

3.1. PBO fiber

Poly(*p*-phenylene-2, 6-benzobisoxazole) (PBO) fiber is new to cementitious materials. Typical PBO fiber has high tensile strength and Young's modulus, hence it has been used to develop high-strength ECC [27]. Table 4 lists technical specifications of two types of PBO fibers, i.e., as-spun (AS) and high-modulus (HM), and mechanical performance of ECC made with the two fibers. Both fibers display superior tensile strength and Young's modulus than PVA fiber, with HM-PBO showing even higher modulus than steel. Curosu et al. [27] compared tensile performance of PBO-ECC and HDPE-ECC using a high-strength binary blend of Portland cement (PC) and silica fume, and suggested that using AS-PBO promoted ultimate tensile strength of ECC (9.8 MPa versus 7.6 MPa for HDPE-ECC) but decreased strain capacity to 1.4% (3.9% for HDPE-ECC). The PBO-ECC displayed multiple cracking character, with visible reductions in both crack width and crack spacing than HDPE-ECC. This was partially attributed to the less hydrophobic nature of PBO fibers than the HDPE fibers as shown in Table 3 [27,30].

Table 3
Water contact angle of man-made fibers used in cementitious materials. A higher contact angle tends to make the fiber more hydrophobic with lower fiber/matrix bonds.

Fiber type	Contact angle θ °	Data source
PP	102.1	Diversified Enterprises [26]
HDPE/PE	78–96	Curosu et al., Diversified Enterprises [26,27]
Steel	81.4–87.2	Lu et al. [28]
Carbon	29.0–84.7	Diversified Enterprises [26]
Glass	78.9	Trejbal et al. [29]
PET	72.5	Diversified Enterprises [26]
PBO-HM	58–70	Curosu et al. [27]
Nylon 6	62.6	Diversified Enterprises [26]
Aramid	32–61	Curosu et al. [27]
PVA (non-coated)	60.6	Diversified Enterprises [26]
PBO-AS	42–58	Curosu et al. [27]

Note: A descending order of water contact angle is followed.

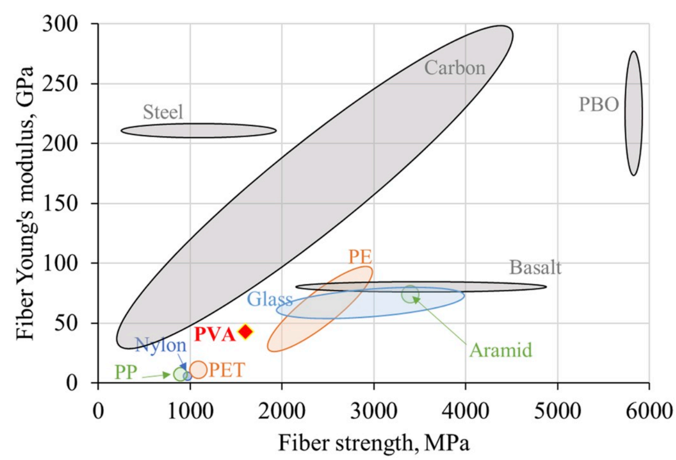

Fig. 4. Fiber strength and Young's modulus.

3.1.1. Summary for PBO fiber

Due to high strength and modulus, PBO fiber enhances tensile strength and reduces crack width when applied to ECC. However, ECC made with PBO fiber tends to be more brittle than HDPE-ECC. PBO fiber can be potentially used for developing high-strength ECC if low composite ductility is needed.

Table 2
Technical specifications of man-made micro-fibers used in cementitious materials.

Fiber type	Diameter, μm	Length, mm	Density, g/cc	Tensile strength, MPa	Young's modulus, GPa	Elongation, %	Melting/decomposition temp, °C
PVA[a]	39	8–12	1.3	1600	42.8	6	230
PBO	13	6	1.54–1.56	5800	180–270	2.5–3.5	650
Carbon	6.8–20	3–18	1.57–1.80	525–4660	33–268	0.8–2.4	1150–1200
Steel	150–1000	13–25	7.8	350–2000	210	2–4	>1425
PE	24–38	12	0.97	1950–3000	39–100	3.1–8.0	150
Basalt	15–16	12	2.6–2.8	2230–4840	85.8–89.0	2.85–3.15	>1400
Glass	6–20	3–6	2.6	2000–4000	70–80	2.0–3.5	>1400
Aramid	12	6	1.39	3400	74	4.5	500
PET	38	12	1.37	1095	10.7	22	255
PP	12–41	6–12	0.91–0.97	850–928	2.7–9.0	7.3–30	160
Nylon	8	19	1.14	966	6	18	220

Note: A descending order of Young's modulus is followed except for PVA fiber.
[a] Kuraray™ K-II REC15 PVA fiber with 1.2% oil coating.

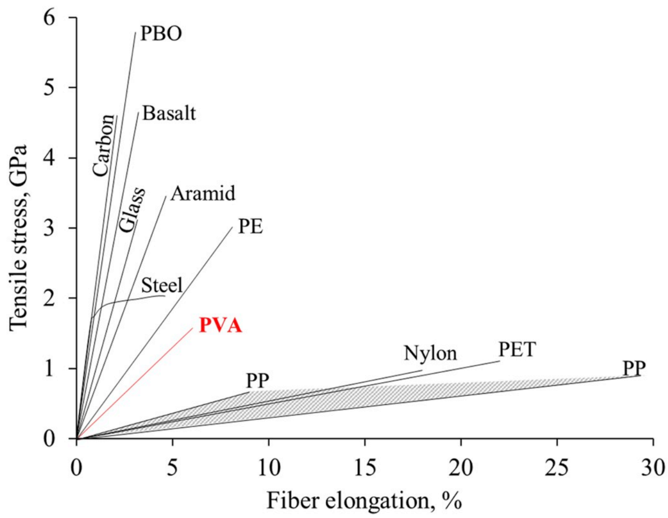

Fig. 5. Fiber tensile stress versus elongation.

Table 4
Physical and mechanical properties of PBO fibers and PBO-ECC (after [27]).

Fiber type		As-spun (AS)	High-modulus (HM)
Fiber properties	Diameter, μm	13	13
	Length, mm	6	6
	Density, g/cc	1.54	1.56
	Tensile strength, MPa	5800	5800
	Young's modulus, GPa	180	270
	Elongation, %	3.5	2.5
PBO-ECC properties	Tensile strength, MPa	9.8	8.4
	Strain capacity, %	1.4	1.6
	Residual average crack width, μm	14.8	20.3
	Average crack spacing, mm	1.7	2.4

3.2. Carbon fiber

Carbon fiber can be manufactured through two different precursors, i.e., Polyacrylonitrile (PAN) and pitch. Both fiber types have been used in cementitious materials [31]. Their dimensions and mechanical properties are compared in Table 5. Incorporating carbon fiber into cementitious materials substantially improves tensile and flexural strengths and ductility [32]. However, tensile strain capacity of carbon fiber-reinforced cementitious composites is generally below 1% [33] and carbon fiber appears to be used more commonly for improving strength than ductility in cementitious materials.

Extensive research has been conducted on optimizing tensile/flexural performance of carbon fiber-reinforced cementitious materials. Toutanji et al. [35,36] found that over a range of 1–3 vol%, increasing fiber volume could significantly improve tensile strength. The composite fracture toughness was found to be optimized at 2 vol% fiber inclusion in high performance concrete (HPC) and ultra-high performance concrete (UHPC) [37]. Kim and Park [38] investigated the composite mechanical performance with different fiber cross-section shapes shown in Fig. 6 and found that the C-shape fiber derived the highest composite tensile and flexural strengths. The composite tensile strength and strain capacity can also be improved through increasing fiber surface wettability using ozone treatment to gain higher fiber/matrix interfacial bond [39]. More recently, Hambach et al. [40] applied the nozzle injection method (nozzle diameter = 2 mm) to improve the alignment of short carbon fibers (length = 3 mm) in cement pastes. With 3 vol% fiber inclusion and aligned fiber orientation along the stress direction, the composite achieved flexural strength over 100 MPa and distinct deflection-hardening behavior at 28 days.

Table 5
Mechanical properties of PAN and Pitch-derived carbon fibers [1].

Fiber type	PAN		Pitch
	Type I	Type II	
Diameter, μm	7.0–9.7	7.6–8.6	18
Density, kg/m^3	1950	1750	1600
Modulus of elasticity, GPa	390	250	30–32
Tensile strength, MPa	2200	2700	600–750
Elongation, %	0.5	1	2.0–2.4
Coefficient of thermal expansion, $\times 10^{-6}$/°C	−0.5 to −1.2 (parallel), 7-12 (radial)	−0.1 to −0.5 (parallel), 7-12 (radial)	–

Carbon fiber is alkali resistant and therefore has been applied to alkali-activated composites. Alcaide et al. [41] developed an alkali-activated slag composite and decreased drying shrinkage by 50% through the inclusion of carbon fiber. Lin et al. [42] examined the effect of fiber length on mechanical properties and fracture character of metakaolin-based geopolymer composites, and concluded that the composite flexural strength and fracture energy were optimized at the fiber length of 7 mm. Additionally, the composite heat resistance could be enhanced due to the high melting point of carbon fiber [43,44].

Apart from mechanical properties, carbon fiber has been used to establish multifunctionality [45–48], particularly for developing composite electrical attributes, such as high conductivity, electrostatic discharging and thermal stability. This has stimulated the applications of carbon fiber-reinforced cementitious composites for electromagnetic interface (EMI) shielding in the electronics industry [49–53]. The strain sensitive electrical resistivity of carbon fiber equips cementitious composites with self-sensing ability, which could be further improved by increasing fiber surface wettability [39] and fiber aspect ratio [54]. Implementations of carbon fiber for developing self-sensing ECC can be found in Refs. [55,56]. Fiber surface treatments, such as graphene oxide deposition, were reported to enhance the electrical properties [57]. Carbon fiber can also be used as a thermistor for temperature sensing in cementitious composites [58].

3.2.1. Summary for carbon fiber

Carbon fiber generally induces low tensile ductility (strain capacity below 1%) of cementitious composites. Carbon fiber is alkali and heat resistant, and can be used for alkali-activated materials. Its electrical attributes are potentially helpful for developing multifunctional cementitious materials.

3.3. Steel fiber

Discontinous steel fiber has been widely applied to both conventional and novel cementitious materials. The main purpose of adding steel fibers to concrete is to improve toughness and ductility. Steel fiber has high water contact angles as listed in Table 3 and generally forms a weak interfacial bond with cementitious matrix. To counter the inadequate fiber/matrix bond, various fiber geometries have been introduced [59] as graphically summarized in Fig. 7 [60]. Deformed steel fibers generally outperform straight and smooth ones, and significantly improve composite flexural strength and toughness [61–63]. Higher fiber volumes and aspect ratios emphasize these improvements, whereas compressive strength is found to marginally increase with steel fiber inclusions [64].

Fiber geometries adopted in previous studies are summarized in Table 6. Note that achieving the optimal fiber diameter is one of the most challenging aspects of steel fiber. Manufacture of the ideally small diameter (20–50 μm, see Section 2.2) steel fiber is expensive and can cause injury to workers handling needle-like fibers in the field. Rusting and tire puncturing on roadways are additional concerns related to small diameter steel fibers.

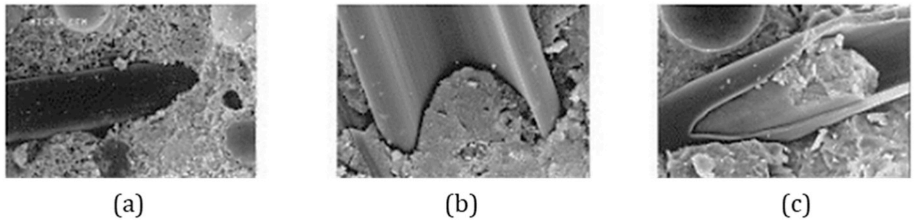

Fig. 6. Geometries of carbon fibers under microscopy, (a) round shape, (b) C-shape, and (c) hollow shape (after [38]).

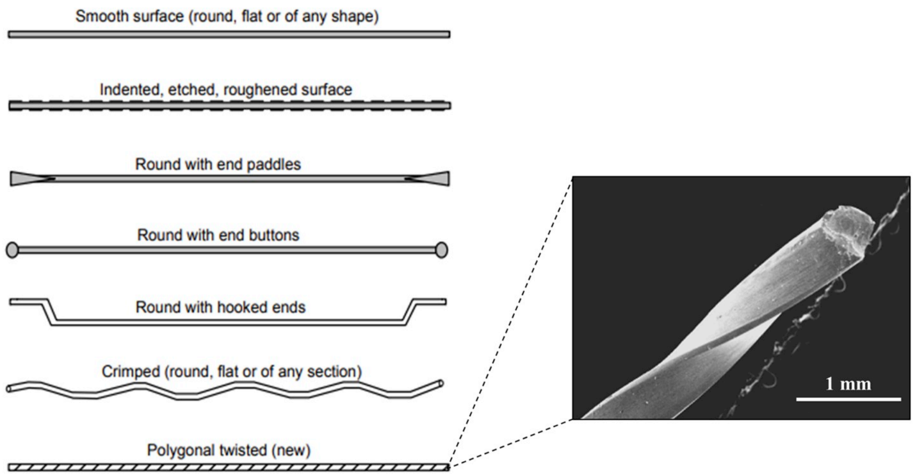

Fig. 7. Geometries of steel fibers commonly used in cementitious composites (left) and example of a polygonal twisted fiber, Torex (right), with higher mechanical bond to cementitious matrix than others (after [60]).

Table 6
Steel fiber parameters and tensile performance of steel fiber-reinforced cementitious composites.

Ref	Fiber parameters			Fiber volume, %	Tensile performance	
	Length, mm	Diameter, μm	Fiber shape		Strength, MPa	Strain capacity, %
[65]	6–20	150	straight	2.3	8	0.49
[66]	13–30	200, 300, 380	twisted, hooked	2.5	12.4	0.49
[60]	30	300	twisted	2	13.6	1.25
[67]	6	150	straight	1	4	quasi-brittle
[68]	30	300, 380	twisted, hooked	2	8.7	0.52
[69]	30	300, 375	twisted, hooked	1	6	0.5
[70]	15	200	straight	2	12.4	0.09
[71]	30	500	deformed, hooked	12	28	1.0–2.0

Under uniaxial tension, steel fiber-reinforced cementitious composites generally show strain-softening or slight strain-hardening behaviors [72]. Fiber volume and geometry pose substantial influence on the composite tensile performance. Table 6 lists tensile strength and strain capacity of steel fiber-reinforced composites reported in previous studies, showing that the composite tensile strain capacity is generally below 1.5% when the fiber volume is less than 3%. Naaman compared cementitious composites reinforced with steel fibers of different geometrical shapes (see Fig. 7) and concluded that polygonal twisted fiber (i.e., Torex fiber) demonstrated the highest promise for ensuring a strong fiber/matrix interfacial bond. With this fiber type, the tensile strain capacity achieved 1.0–1.5% and the tensile strength attained over 13 MPa at 2 vol% fiber inclusion [60]. Kim et al. [73] concluded that twisted fibers appear more effective than hooked in promoting the composite load carrying capacity, energy absorption capacity and multiple cracking behavior. Apart from fiber geometry, fiber volume also plays a critical role in tailoring tensile performance. Naaman and Homrich [71] achieved the composite tensile strength of 28 MPa and strain capacity of 2% by increasing fiber volume up to 12% (known as slurry infiltrated fibrous concrete, SIFCON). Under tension, SIFCON also displays multiple cracking character on material surface [74]. It should be pointed out that, with such a high volume fraction of steel fibers, the production process of SIFCON is changed, in which the fibers are first placed in the mold, followed by the infiltration of highly flowable cementitious slurry [71].

Steel fiber is alkali resistant. Application of steel fiber in alkali-activated materials has been addressed by Bernal et al. [75], who incorporated 1.5 vol% steel fiber into alkali-activated slag concrete. The tensile splitting and flexural strengths were found to increase by 24% and 38%, respectively, whereas compressive strength declined as fiber volume increased.

Due to the high fiber modulus and tensile strength, steel fiber can be combined with polymeric fibers, e.g., PVA and PE fibers, to form synergistic reinforcement in cementitious composites for enhancing crack width control. Studies in this category are discussed in Section 5: Fiber hybridization.

3.3.1. *Summary for steel fiber*

Steel fiber can be used to develop cementitious composites with high tensile strength (>13.6 MPa) and strain capacity (up to 1.25%) together with multiple cracking character. Its viability also extends to alkali-activated materials. Twisted steel fiber offers superior composite performance due to the enhanced bond with cementitious matrix. Steel fiber is also beneficial for the control of crack width and propagation.

3.4. PE fiber

Polyolefin fiber is a generic name of PE and PP fibers. Polyolefin fiber has been used to mitigate shrinkage-induced cracks in early studies [76]. With a chain structure of ethylene aligned along the fiber axis, the high-density PE (HDPE) fiber is commonly used for ductility development in cementitious composites. Table 7 shows tensile performance of ECC reinforced with PE and HDPE fibers at different fiber lengths and diameters. Due to high fiber modulus and elongation at break, PE-ECC normally exhibits high tensile strength and strain capacity, with the fiber inclusion ranging at 1.0–2.5 vol%. PE fiber is hydrophobic and tends to form weak fiber/matrix interfacial bond in normal-strength cementitious matrix. This essentially leads to the comparatively lower capability of crack width control in PE-ECC than PVA-ECC. To enhance tensile ductility and crack width control, carbon nanofiber (CNF) coating [77] is utilized for surface treatment of PE fiber, and is found to promote the fiber/matrix frictional bond by forming a "CNF-reinforced C–S–H layer" that densifies the ITZ. Alternatively, plasma coating can be employed to tailor fiber surface hydrophilicity to enhance the fiber/matrix chemical bond, and therefore to promote composite tensile strength and ductility [78,79].

In combination with high-strength matrix material, PE-ECC can achieve simultaneously high tensile strength (up to 20 MPa) and strain capacity (up to 8.7%) [25]. With the distinct multiple cracking behavior and residual crack widths below 100 μm, this formulation could be potentially useful for developing high-performance ECC as needed. Besides static loadings, PE fiber also enhances the composite impact resistance. Studies on dynamic behaviors of PE-ECC can be found in Refs. [85,88].

3.4.1. Summary for PE fiber

PE fiber forms robust reinforcement in ECC and leads to equivalent or even superior composite mechanical performance compared to PVA-ECC. PE fiber, however, is less efficient than PVA in controlling crack widths. By adopting fiber surface treatment, PE-ECC can gain enhanced crack width control ability, and can be used for developing high-performance ECC combining high-strength matrix materials.

3.5. Basalt fiber

Basalt fiber is derived from natural basalt rock, an assemblage of several inorganic silicate minerals, by heating the rocks into molten state at about 1450 °C and rapidly extruding the liquid through a die to form fibers [89]. Basalt fiber is considered sustainable. Its main feedstock, basalt rocks are among the most common and abundant deposits on the Earth surface. Basalt fiber is manufactured without additional chemicals or solvents, and can be potentially recycled through incineration. The high chemical resistance renders basalt fiber durable, hence achieving low life-cycle emissions and cost when used for infrastructure constructions.

Militky et al. [90] classified basalt minerals into three categories in terms of the silicate content, i.e., alkaline (>42%), mildly acidic (43–46%), and acidic basalts (>46%), amongst which only acidic basalt can be used for fiber production. Although holding a compositional similarity with asbestos fiber, which has been banned in many countries for carcinogenicity, basalt fiber is proven to be non-hazardous due to a different micromorphology [1]. Basalt fiber is highly resistant to alkalis, acids and has high tensile strength, modulus and melting temperature compared to PVA fiber. Basalt fiber has a low elongation at break, i.e., 2.85–3.15%, which appears less favorable for attaining high tensile ductility of such reinforced cementitious composites. Sim et al. [91] suggested that the alkali resistance of basalt fiber was between that of high-strength glass (i.e., S-glass) and carbon fibers, whereas the basalt fiber was found most stable when exposed to high temperatures [91].

Short basalt fiber has been used in conventional concrete [92] and alkali-activated concrete [93,94]. The inclusion of basalt fiber in concrete varies in the range of 0.1–3.0 vol%. Using high-volumes of basalt fiber causes difficulties in mixing and fiber dispersion. Basalt fiber was proven to enhance concrete abrasion resistance, flexural strength and toughness [95]. However, compressive strength was found to decrease by up to 26.4% even with 1 vol% fiber inclusion [94,95]. Additionally, Li and Xu [93,96] studied impact resistance of geopolymer concrete reinforced with basalt fiber, and concluded that 0.3 vol% fiber inclusion could significantly improve deformation and energy absorption capacities but led to no visible improvement in dynamic compressive strength. Concrete reinforced with basalt fiber also showed improved resistance to heat transfer [97]. Basalt fiber was also used in lime-based mortars as a repair material for masonry structure, in which the composite flexural strength and toughness could be improved [98,99].

As a preliminary study on basalt-ECC, Choi and Lee [100] investigated the fiber/matrix interfacial bond for basalt and PVA fibers using single fiber pullout test, and found that basalt fiber showed a chemical bond 1.9 times that of PVA fiber, but exhibited low fiber bridging capacity compared to PVA and PE fibers. Basalt fiber tends to display brittle failure at break. It seems unlikely for basalt-ECC to outperform PVA-ECC, particularly regarding tensile ductility and crack control. However, further investigations are needed for developing desirable formulations of basalt-ECC.

3.5.1. Summary for basalt fiber

Basalt fiber has been successfully used in conventional PC-based and alkali-activated concretes for enhancing flexural strength and toughness. It can also be used for developing heat resistance in cementitious composites. Basalt-ECC with high tensile ductility and crack control capability needs to be further investigated.

3.6. Glass fiber

Glass fiber, also known as synthetic vitreous fiber, is derived from silicate glasses that contain over 50% SiO_2 on a molar basis. At the atomic level, glass fiber is built on a two-dimensional network of Si–O–Si bonds [101]. Most glass fibers are spun from melted glasses with different chemical compositions. Common types of glass fibers include E-glass, S-glass, alkali-resistant (AR) glass, etc. E-glass fiber is commonly adopted for general applications but has a low alkali resistance due to the weak Si–O–Si bond vulnerable to breakage at high pH. In this regard, AR glass fiber has been mostly used in cementitious materials for its high compatibility with the alkaline environment generated by PC hydration.

A number of standards and technical reports on practice of glass fiber reinforced concrete (GFRC, or GRC in Europe) are available through the International Glassfiber Reinforced Concrete Association (GRCA) [102]. Previous studies suggested that glass fiber at low volume fractions (V_f)

Table 7
Representative tensile performance of PE-ECC.

Ref	Fiber geometry		Fiber volume, %	ECC tensile performance	
	Length, mm	Diameter, μm		Strength, MPa	Strain capacity, %
[82]	12	24	2.2	10.8	2.4
[80]	6	12	1.5	10	2.8
[81]	12.7	28	2	14.5	3.4
[84]	12	24/38	1.0–2.5	4.2-5.3	2.5-5.0
[85]	12	20	2.1	6.5	5.7
[87]	18	12	1.75	8.8	7.2
[86]	18	12	1.75	13.1	7.5
[25]	18	25	2	17.8	8.5

Note: ascending order of ECC tensile strain capacity is followed.

could mitigate shrinkage and cracking in self-consolidated concrete (V_f < 0.26%) [103] and lightweight concrete (V_f = 0.25–0.5%) [104]. Higher fiber volumes are needed to promote the composite tensile strength and ductility. Ali et al. [105] conducted a parametric study on the effects of fiber length (10–40 mm) and volume (2.1–8.2 vol%). With 30 mm in length and 8.2 vol% addition, glass fiber-reinforced cementitious composites displayed strain-hardening behavior under uniaxial tension, showing tensile strength of 18 MPa and strain capacity of 0.8% [105]. Their applications, however, are limited to thinner elements due to the required spray process. It should also be noted that the continuing hydration of cement into the glass bundles could cause excessive increase in the fiber/matrix bond over time, which increases the possibility of fiber breakage when matrix cracks are formed. Embrittlement of GFRC over time has been observed [106]. Apart from the static composite behavior, the impact resistance of cementitious composites can also be enhanced when glass fiber is introduced [107].

In alternative binders, glass fiber has been incorporated into slag-based [108] and fly ash-based [109] alkali-activated composites. The use of glass fiber also extends to phosphate-based cementitious composites [110].

3.6.1. Summary for glass fiber

For applications in cementitious materials, glass fiber does not provide equivalent composite tensile ductility to PVA-ECC. Large volume fiber inclusions are normally needed for attaining tensile strain-hardening, but may raise potential concerns over fiber dispersion, material cost, etc. As the mechanical properties of glass fiber-reinforced cementitious composites would degrade over time, long-term composite performance need to be further investigated.

3.7. PET fiber

Polyethylene terephthalate (PET) fiber is a type of recycled fiber, which can be derived from waste plastic bottles. Macro-scale recycled PET fiber is usually used in concrete for shrinkage control [111] and as reinforcements for concrete flexural strength and toughness [112,113]. PET fiber could also be manufactured at micro scale for applications in concrete [114–129] or ECC [130,131]. The properties of macro and micro PET fibers are listed in Table 8.

Generally, the hydrophobic surface of PET fiber results in comparatively weak fiber/matrix interfacial bonds and virgin PET fiber is vulnerable to chemical degradation in the alkaline cementitious matrix [132,133]. To enhance the mechanical bond at fiber/matrix interface, PET fiber has been modified to various geometries such as hooked, twisted or crimped shapes [111,127]. A variety of chemical treatments have also been adopted to enhance the fiber surface hydrophilicity and the alkali resistance, such as plasma oxidization [134], alkali treatment [124] and hydrophilization treatment with maleic anhydride grafted polypropylene [121]. Recently, following the micromechanical guideline described in Section 2, Lin et al. [130] achieved the ECC tensile performance shown in Fig. 8 using the PET fiber modified with surface treatment. Although the PET-ECC attained tensile strain-hardening with the tensile strength of 2.63 MPa and strain capacity of 0.8%, the crack width control ability was poor [131].

3.7.1. Summary for PET fiber

For applications in cementitious materials, PET fiber does not provide equivalent composite tensile ductility or crack width control ability compared to PVA fiber. PET-ECC can be potentially useful for non-structural applications.

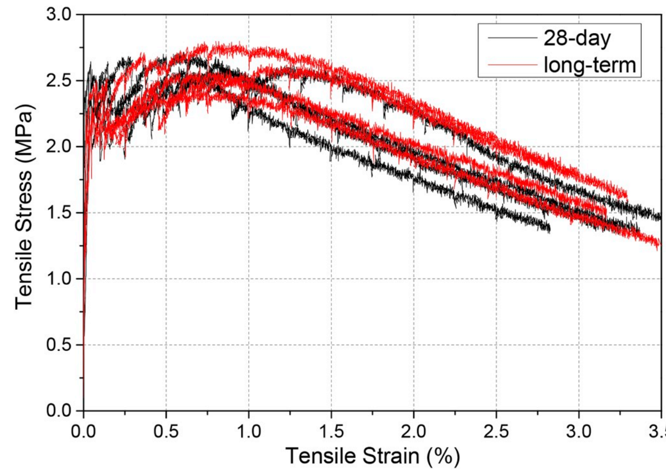

Fig. 8. Uniaxial tensile stress-strain relation of ECC with 2 vol% treated PET fibers (After [131]). The long-term patterns are obtained through accelerated aging of specimens, which are first cured in moisture room for 28 days and subsequently stored in 60 °C water for additional 5 weeks. This is to predict material properties after 13.5 years of natural weathering.

3.8. PP fiber

PP is the second most used fiber material after polyester, with an annual world consumption of 6 million cubic tons in 2010 [135–137]. Melt spinning is the most commonly adopted process for extruding PP fiber from PP at the industrial scale [138]. The PP granules are melted at 210–280 °C and the molten liquid is extruded through a spin head followed by an air quenching process. Tensile properties of PP fiber can be tailored through its manufacturing process. PP fiber currently used in concrete and ECC is derived from isotactic polypropylene (iPP), which has a high modulus and tensile strength compared to other PP texture, e.g., syndiotactic polypropylene (sPP). In reference to PVA, PP fiber shows lower modulus and higher elongation at break. These traits offer PP-reinforced cementitious composites generally high ductility. PP fiber has a good durability with strong resistance to acidic and alkaline environments. The aging effect of PP fiber caused by oxidization can lead to fiber embrittlement, which, however, can be largely improved by chemical stabilization of fibers through pre-treatments [139].

PP fiber has been used in conventional concrete, where compressive strength, splitting tensile strength and flexural strength are improved [140,141]. Incorporation of PP fiber also improves concrete shrinkage control and impact resistance [142–144], and is effective to delay crack growth in reinforced concrete [145]. The technical advantage led by PP fiber is limited by the volume fraction, i.e., overdosed fiber content could substantially decrease concrete workability, compressive strength and durability [146,147]. The volume fraction of PP fiber is normally kept below 1% in concrete in order to maintain its beneficial impacts on concrete performance. It should be mentioned that PP fiber is more hydrophobic compared to PVA fiber (see contact angles in Table 3). This hydrophobicity leads to a weak chemical bond at the fiber/matrix interface. Low frequency cold plasma treatment can be applied to PP fiber to improve flexural strength and toughness of PP fiber-reinforced concrete [148,149]. The plasma exposure changes fiber surface from

Table 8
Geometries and technical specifications of recycled PET fibers.

Scale	Type	Cross-section Dimension, mm	Length, mm	Density, g/cm^3	Young's modulus, GPa	Strength, MPa	Elongation, %	Ref
Macro	Embossed	0.2 × 1.3	50	1.38	10.2	420.7	11.2	[117]
Micro	Chopped	0.038 diameter	12	1.37	11.5	1105	22.0	[130]

hydrophobic to hydrophilic, resulting in a stronger adhesion between PP-fiber and cementitious matrix.

PP fiber has been used as an alternative to PVA fiber for producing ECC. Comparable composite tensile ductility can be achieved between PP- and PVA-ECC. Despite the cost advantage of using PP fiber, PP-ECC show low tensile strength in general. Yang and Li [150,151] applied micromechanical modeling to tailor PP-ECC and achieved tensile strain capacity of 4% and tensile strength of 2.0–2.5 MPa. Through tuning matrix flowability, mixing procedure and curing condition for high tenacity PP-ECC, Felekoglu et al. [152] improved the tensile strength to 3.64–3.81 MPa and attained a strain capacity of 1.91–3.91%.

PP fiber can also be used to improve flexural strength and shrinkage resistance of alkali-activated materials [153]. Zhang et al. [154] applied PP fiber to metakaolin-fly ash geopolymer composites to improve flexural strength, toughness and impact resistance. Additionally, one-part geopolymer also demonstrates compatibility with PP fiber [155].

3.8.1. Summary for PP fiber

PP-ECC can achieve comparable tensile ductility but lower tensile strength than PVA-ECC. PP fiber is resistant to alkaline environments. The low cost and high chemical stability of PP fiber make it potentially attractive for PVA fiber replacement in certain applications.

3.9. Nylon fiber

Nylon is a largely produced and consumed synthetic polymer. Nylon fibers used as reinforcements of cementitious materials can be either virgin or recycled from nylon-made products. Common types of virgin nylon fiber used for cementitious composites include Nylon 6 and Nylon 66, whereas recycled nylon fibers can be of any generic type. In conventional FRCC, nylon fiber has been found to effectively mitigate autogenous shrinkage at early age [156,157]. Regarding mechanical performance, Song et al. [158] compared flexural behavior between concretes made with nylon and PP fibers, and concluded that the nylon-concrete outperformed PP-concrete in tensile strength, modulus of rupture and impact resistance. A similar comparative study was conducted by Pakravan and Latifi [159] on cementitious composites made with PP, nylon 66 and PAN-based carbon fibers, among which nylon 66 was found to induce the highest composite flexural strength and toughness. The effectiveness of nylon fiber can be further improved by irradiation treatment [160]. Spadea et al. [161] completed a series of studies that examined potential uses of recycled nylon fiber by repurposed fishing net nylon fiber in mortars at additions of 1.0 wt% and 1.5 wt% and with fiber lengths of 12.5 mm, 25 mm and 37.5 mm. The flexural strength and ductility were found to be optimized at 1.5 wt% in fiber addition and 37.5 mm in fiber length.

In the context of ECC products, nylon fiber was compared with other low-modulus fibers including PP and acrylic for composite flexural behaviors [162]. The ECC flexural ductility was found to improve with incorporation of nylon fiber but with a compromise in strength. Fig. 9 shows uniaxial tensile stress-strain relation of ECC made with 2 vol% nylon fiber at the ACE-MRL, University of Michigan. The test was conducted using M45 ECC matrix formulation and was tested at the age of 28 days with/without carbonation curing (procedure of carbonation curing can be found in Refs. [163,164]). The purpose of conducting carbonation curing on the nylon-ECC was to investigate potential alterations in matrix or fiber/matrix interface that might favor the composite tensile properties. Both carbonation-cured and non-carbonated nylon-ECC were found to achieve tensile strain capacities over 4%, which were comparable to conventional PVA-ECC. The residual crack widths of the nylon-ECCs ranged between 100 and 200 μm. Regarding fresh properties, nylon fiber inclusion up to 2.5 vol% has not been reported with dispersion issues. Nevertheless, longer fiber length and higher fiber addition tend to reduce workability of nylon fiber-reinforced mortars [161].

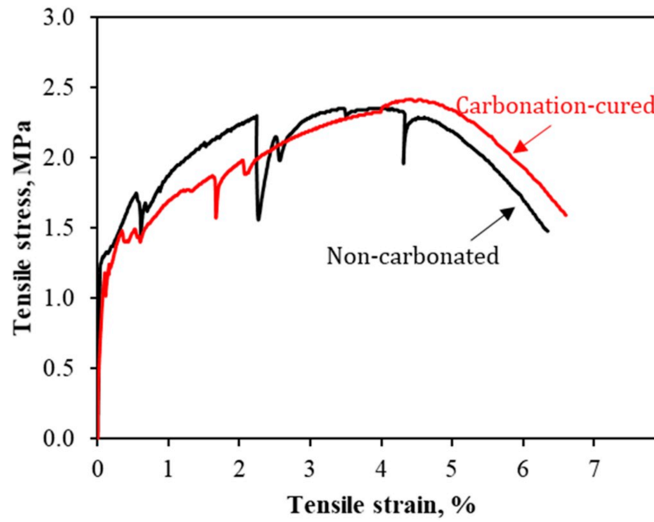

Fig. 9. Example of uniaxial tensile stress-strain relation of nylon-ECC (M45 matrix material, 2 vol% fiber addition, tested at 28 days at ACE-MRL, University of Michigan).

3.9.1. Summary for nylon fiber

Compared to PVA fiber, nylon fiber has low modulus but high elongation at break. These properties make nylon fiber more effective in establishing ductility than strength when used in ECC. Nylon fiber can be potentially recycled from waste nylon-made materials, which have abundant sources to feed infrastructure needs. Waste-derived nylon fiber appears to be a sustainable option for high-ductility ECC.

3.10. Other man-made fibers

Aramid is a synthetic polymer with high strength and thermal stability. Aramid fiber has been used in ultrahigh strength concrete as reinforcements for static [165,166] and dynamic loads [167]. Curosu et al. [27] compared aramid, HDPE and PBO fibers, and identified a stronger fiber/matrix interfacial bond and higher composite tensile strength for aramid than PE fibers [27]. Another man-made fiber used in ECC is acrylic fiber based on PAN polymer. Halvaei [162] compared flexural behaviors of ECC reinforced with acrylic, PP and nylon 66 fibers, and concluded that using acrylic fiber led to the highest ECC flexural strength, whereas PP and nylon 66 fibers appeared more amenable to improve ECC flexural toughness and ductility. Additionally, acrylic fiber has been used as a precursor for production of PAN-based carbon fibers.

Ceramic fibers synthesized with Al_2O_3 and SiO_2 have been used to establish thermal resistance and insulation for cementitious composites [168,169]. Ceramic fibers also exhibit high resistance to aging in alkaline environments. Bernal et al. [170] used alumina-silica-zirconia fiber in geopolymer composites and observed significant improvement in heat resistance. This fiber also showed ability to mitigate excessive shrinkage of cementitious composites at elevated temperatures [170].

3.11. Environmental and economic impact of man-made fibers

3.11.1. Cost

Costs of man-made fibers commonly used as reinforcements of cementitious composites are graphically compared in Fig. 10. It is recognized that fibers are usually supplied on a mass basis, whereas technical performance of composites is more commonly associated with volumetric proportion. Therefore, the volume-based costs presented in Fig. 10b tend to be more realistic in reflecting fiber cost in cementitious materials.

As shown in Fig. 10a, on a mass basis, fibers that potentially cost less than PVA fiber include acrylic, basalt, glass, nylon, PP and steel fibers,

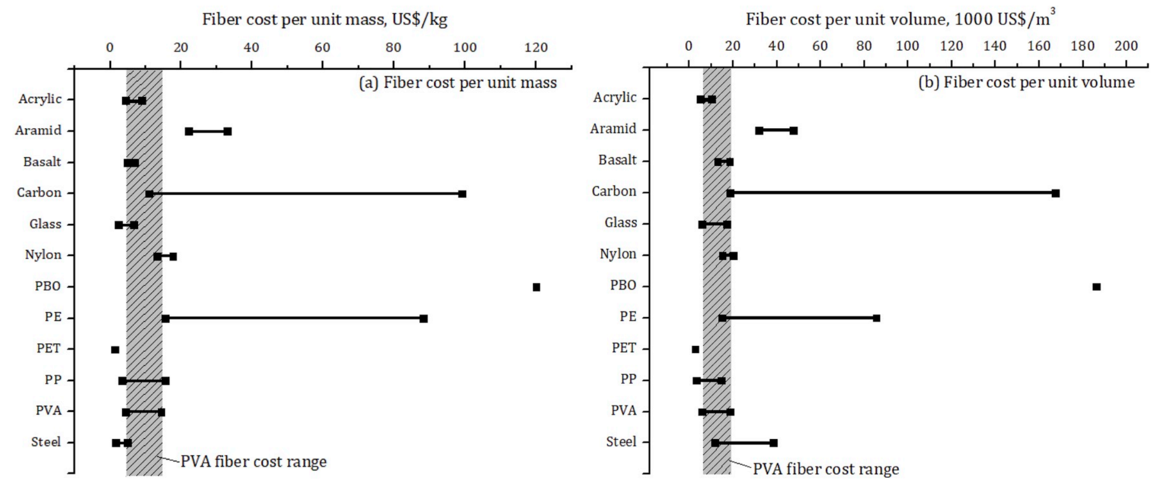

Fig. 10. Range of fiber cost (a) by unit mass, and (b) by unit volume. (Note: data may vary with manufacturers, suppliers and producing years). Data are sourced from unpublished quotations and communications with multiple suppliers of each fiber type.

amongst which glass, PP and steel fibers appear most appealing from technical perspectives as discussed earlier. On a volumetric basis, shown in Fig. 10b, however, the high densities of basalt and steel make them less attractive, whereas PP and acrylic remain viable, cost-effective options for replacing PVA fiber.

3.11.2. Embodied energy

Table 9 lists energy intensities of man-made fibers used in cementitious composites. Amongst all fibers surveyed, basalt and glass fibers demonstrate the lowest energy intensities, regardless of mass or volume basis. At the same volume, manufacturing of PP consumes less energy (108 GJ/m^3) than PVA (131 GJ/m^3), suggesting that PVA fiber could be potentially substituted by PP fiber for producing ECC with an equivalent to lower energy footprint. Steel fiber has low energy intensity per mass (30–60 MJ/kg), but shows a substantial energy intensity if measured on a volume basis (234–468 GJ/m^3). In designing ECC with a specific fiber volume, basalt, glass, PE and PP fibers are promising in reducing total energy consumption, whereas steel fiber seems not a sustainable option, particularly given the high volume addition needed for establishing desirable ductility as suggested in Section 3.3.

3.11.3. CO_2 emissions

Besides cost and energy consumption, fibers also contribute substantially to the CO_2 footprint of ECC through their manufacturing. Table 10 compares the quantity of CO_2 emitted based on unit mass and volume. Generally, high-energy fibers tend to embody high CO_2 emissions due to the intensive fuel consumption. Table 10 suggests that glass, PE, PET and PP fibers embody less CO_2 emissions compared to PVA fiber at the same volumetric basis, whereas applications of acrylic and carbon fibers may potentially be limited due to the significantly higher CO_2 emissions than PVA fiber. The CO_2 intensity of steel fiber is lower than PVA fiber on the same mass basis, but magnifies exceedingly if measured by volume. Due to the high fiber volume needed for establishing high tensile ductility in steel fiber-reinforced cementitious composites, it is not recommended to use steel fiber as the sole fiber type for ECC.

Table 9
Fiber embodied energy intensity.

Fiber	Energy intensity per unit mass (MJ/kg)	Energy intensity per unit volume (GJ/m^3)	Ref
Acrylic	133–175	157–207	[171, 172]
Aramid	–	–	–
Basalt	18	49	[173, 174]
Carbon	183–286	309–483	[175]
Glass	13–32	34–83	[175]
Nylon	250	285	[172]
PBO	–	–	–
PE	73–116	71–112	[176]
PET	39	53	[131]
PP	75–115	70–108	[172]
PVA	101	131	[177]
Steel	30–60	234–468	[175]

Table 10
Fiber embodied CO_2 emissions.

Fiber	CO_2 emission per unit mass (kg/kg)	CO_2 emission per unit volume (tonne/m^3)	Ref
Acrylic	33.5	39.5	[178]
Aramid	–	–	–
Basalt	–	–	–
Carbon	29.4	49.6	[179]
Glass	0.16	0.42	[180]
Nylon	–	–	–
PBO	–	–	–
PE[a]	2.0	1.9	[181]
PET[b]	0.81–3.4	1.1–4.6	[131]
PP	2.0	1.87	[181]
PVA	1.71	2.22	[182]
Steel	1.6	12.5	[183]

Note.
[a] : data is for low-density PE.
[b] : data is for virgin PET fiber.

3.12. Concluding remarks for man-made fibers

Ultrahigh tensile ductility and autogenous crack width control represent the most distinguishing features of ECC. Fig. 11 presents a comparative graph for tensile strain capacity of cementitious composites made with different man-made fibers. Clearly, only PE-ECC display substantially higher tensile ductility in reference to PVA-ECC. Fibers able to form comparable composite tensile ductility as PVA-ECC include nylon and PP, whereas glass and carbon fibers generally lead to composite tensile ductility of less than 1%.

A summary of effectiveness of different fibers and their recommended applications are presented in Table 11. Regarding PVA fiber, alternative fibers forming high tensile ductility for cementitious materials generally exhibit poor crack width control. In particular, typical crack widths in ECC made with nylon and PP fibers appear clearly larger than PVA-ECC (typically below 60 μm). PE fiber also leads to an increase

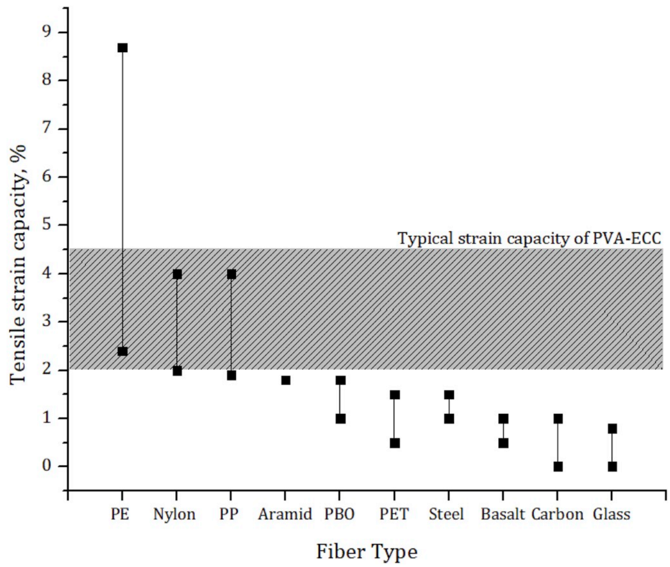

Fig. 11. Tensile strain capacity of cementitious composites made with different fibers. All literature data are obtained at the age of 28 days (nylon and basalt data are tested at the ACE-MRL, University of Michigan). Variation of tensile strain capacity for each fiber type is due to different mix proportions (matrix material and fiber volume) and/or different fiber manufacturers.

in crack width. The wide crack in reinforced concrete often means high permeability and shortened life cycle due to the accelerated ingress of external harmful species through the cracked pathways. Therefore, fibers leading to high tensile ductility but poor crack width control may potentially find applications in seismic design, where high energy absorption is desired, rather than in harsh and corrosive environments, where attaining adequately tight crack width and low permeability governs material design. If embodied energy and cost are also considered, PP fiber appears to be a potential candidate for producing ECC, whereas basalt, glass and PET fibers would deserve further investigation.

4. Natural fibers

By their sources, natural fibers can be grouped into plant (cellulose/lignocellulose), animal and mineral fibers (see Fig. 12), amongst which plant fibers have been most used in formulations of cementitious composites. This section reviews the cementitious composites made with different natural fibers from the perspectives of mechanical properties, durability performance and environmental impacts.

4.1. Plant fibers

Plant fibers come in a broad variety of chemical compositions and microstructures. The basic compositions of plant fibers are cellulose, hemi-cellulose and lignin. In general, the fiber strength and stiffness are attributed to the presence of cellulose, which accounts for a high portion of plant fibers used in cementitious composites. Table 12 gives the ranges of physical properties of plant fibers commonly used in cementitious composites. With respect to PVA fiber, plant fibers generally exhibit lower tensile strength and Young's modulus. Elongations of most plant fibers are low, indicating reduced capacity for energy absorption under tension. By geometrical shape, cellulosic fibers in cementitious composites can be found in forms of strand, staple and pulp. As potential candidates to replace PVA fiber for producing ECC, staple plant fibers will be the focus of the following discussions. It is important to remember that plant fibers have high variations in mechanical properties, thus their reinforcing effects could differ depending on different sources and plant varieties.

4.1.1. Mechanical properties

To achieve desirable mechanical performance, plant fibers are usually used at higher volumes (i.e., 5–15%) than man-made fibers. The comparatively high dosage and high water absorption of plant fibers collectively lead to reductions in workability and poor fiber dispersions in fresh mixtures, hence may increase porosity and reduce compressive strength of the hardened cementitious composites. Studies on plant fiber dispersion and fresh mixture workability can be found in Ref. [184].

Incorporating plant fibers generally improves flexural strength and toughness of cementitious composites under static and dynamic loadings. Tensile ductility can also be improved by using plant fibers. Silva et al. [198] used sisal monofilament at a volume fraction of 10% together with 5% wollastonite fiber (diameter = 40 μm, length = 600 μm) to produce thin cement sheets. Under uniaxial tension, the averaged tensile strength and strain capacity achieved 10.56 MPa and 1.15%, respectively. The material also demonstrated multiple cracking behavior. However, this composite material was not strictly ECC due to the intentionally aligned orientation of the fiber filament. Recently, Soltan et al. developed a curaua fiber-reinforced ECC with 4.4 vol% fiber addition and achieved tensile strength of 2.2 MPa and tensile strain capacity of 0.8% (see Fig. 13) [193]. Although multiple cracks were well distributed during tension, the tensile strain capacity was not comparable to that of PVA-ECC, thus curaua fiber was proven to be unsuitable for structural applications. However, incorporating curaua fibers was found to create lightweightedness and low thermal conductivity of ECC, which appear potentially useful for special applications, such as building cladding and facade [193].

Table 11
Cementitious composite performance reinforced with different fibers.

Fiber type	Composite performance		Fiber economic and environmental impact		Recommended use
	Composite tensile ductility	Typical crack width, μm	Cost	Embodied energy	
Aramid	moderate	10–30	high	high	Structural, low ductility
Basalt	low	–	low	low	Structural, low ductility
Carbon	low	–	high	high	Structural, low ductility, self-sensing
Glass	low	–	low	low	Structural, low ductility
Nylon	high	>100	comparable to PVA	high	Structural, high ductility
PBO	moderate	10–30	high	high	Structural, high strength, low ductility
PE	high	50–150	high	comparable to PVA	Structural, high strength, high ductility
PET	moderate	150-200	low	low	Non-structural
PP	high	70–260	low	comparable to PVA	Structural, low strength, high ductility
PVA	high	<100	–	–	General structural applications
Steel	moderate	10-30	high	high	Structural, high strength, low ductility

Note: composite tensile ductility is classified according to tensile strain capacity in the context of ECC, i.e., low (<1%), moderate (1–2%), and high (>2%). Cost and embodied energy are in reference to that of PVA fiber.

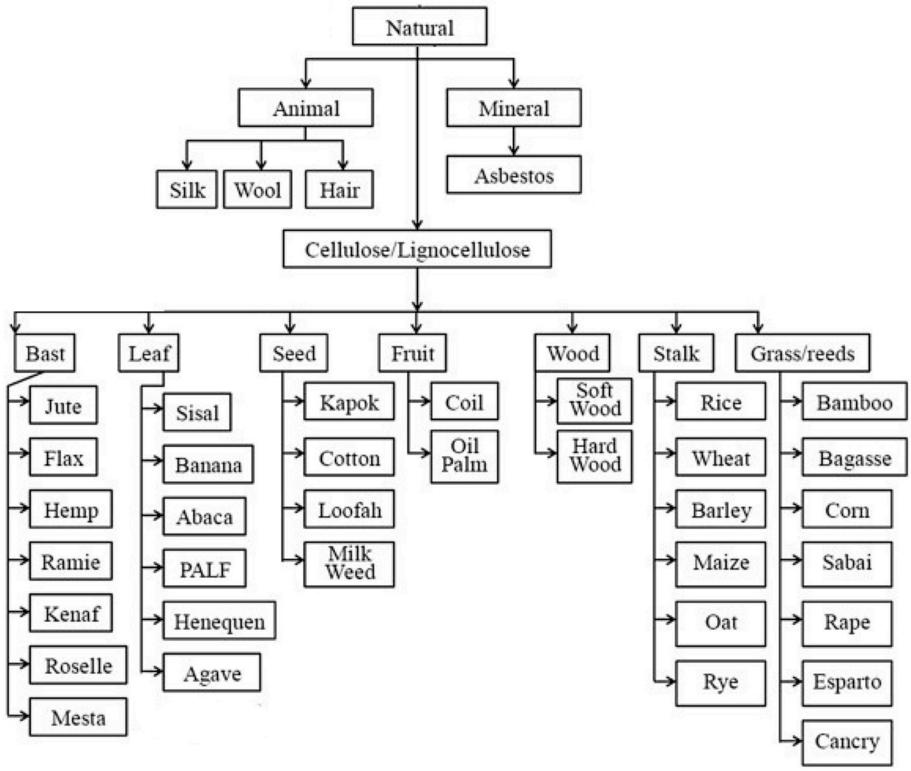

Fig. 12. Classification of natural fibers (after [185]).

Table 12
Technical specifications of plant fibers used in cementitious composites.

Fiber type	Density, g/cc	Tensile strength, MPa	Young's modulus, GPa	Elongation, %	Mechanical evaluation(s) of composites	Example studies
PVA	1.3	1600	42.8	6	Flexural/tensile	–
Bagasse	1.25	222–290	17–27.1	1.1	Flexural	[186]
Bamboo	0.6–1.1	140–800	11–32	2.5–3.7	Flexural	[187,188]
Banana	1.35	500	12	1.5–9.0	Flexural	[189]
Coir	1.15–1.46	95–230	2.8–6.0	15.0–51.4	Flexural	[190,191]
Cotton	1.5–1.6	287–800	5.5–12.6	3–10	Flexural	[188,192]
Curaua	1.42	488–752	31.8–51.6	–	Tensile	[193]
Flax	1.5	840–1800	50–100	1.8–3.2	Flexural	[194]
Hemp	1.5	690	70	1.6	Flexural	[195]
Jute	1.3	393–773	26.5	1.5–1.8	Flexural	[196,197]
Sisal	1.5	511–635	9.4–22	2.0–2.5	Flexural/tensile	[189,198]

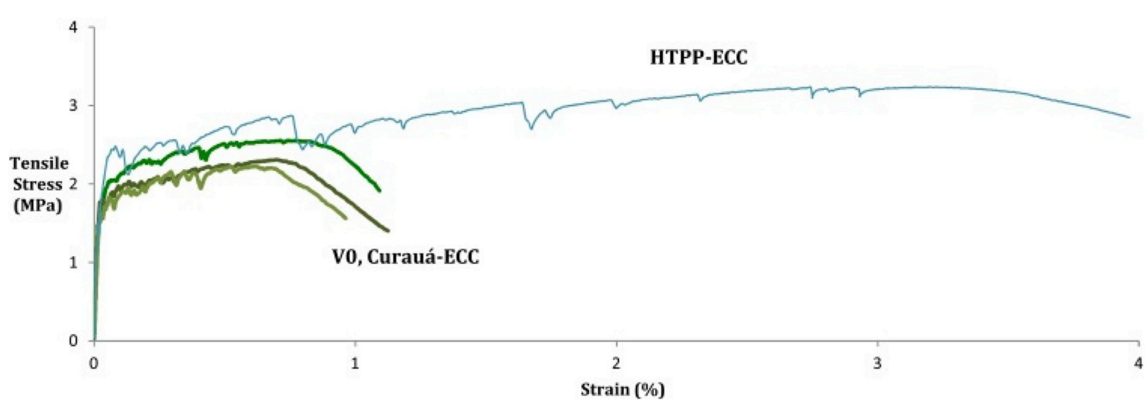

Fig. 13. Uniaxial tensile stress-strain relation of curaua-ECC (compared with high tenacity polypropylene fiber-ECC), after [193].

4.1.2. Durability performance

Extensive studies have addressed concerns on durability of plant fibers. Particularly, plant fibers are susceptible to aging and volumetric instability in the alkaline environment of hydrated cement. Calcium hydroxide formed during cement hydration can transport into fiber lumen and voids [199,200], and lead to fiber mineralization and depolymerization that cause loss of bond at the fiber/matrix interface as well as embrittlement of the fiber itself [201–203]. This aging effect can be accelerated by wet-dry cyclic exposure, which is therefore often used as the experimental condition for durability evaluation.

To improve the durability of cementitious composites made with plant fibers, two routes, i.e., fiber treatment and matrix modification, are commonly followed. Numerous methods for fiber treatment are available, including bleaching, hornification, alkaline treatment, polymer impregnation and silane coupling agents. These treatments generally aim to reduce fiber's hydrophilicity and improve water resistance [186,204]. Another route of improving durability of plant fiber-reinforced cementitious composites is to reduce the alkalinity of matrix material, through incorporating SCMs [205] or applying carbonation curing [206]. Although lower matrix alkalinity can effectively promote fiber's longevity, the low pH of pore solution raises concerns on steel corrosion and limits its use for reinforced applications.

4.1.3. Special attributes of plant fiber-reinforced cementitious composites

Although plant fibers are generally less durable and ductile compared to man-made fibers, some special attributes could be enabled by adding plant fibers to cementitious composites. Typically, the low density of plant fibers can derive lightweightedness for hardened cementitious composites. Most plant fibers also show low thermal conductivity, which can be used for establishing thermal insulation. Examples can be found in Ref. [207] for coir fiber and in Ref. [193] for curaua fiber.

4.2. Animal and mineral fibers

Animal fibers, e.g., wool, silk, are less used in cementitious composites compared to plant fibers. Li et al. used silk fiber in magnesium-bearing phosphoaluminate-hydroxyapatite bio-cement and reported a 22.2% increase in splitting tensile strength [208]. Recently, Fantilli et al. [209] applied wool and hemp fibers to mortars for enhancing flexural performance. Studies on uniaxial tension behaviors of cementitious composites reinforced with these fibers have not been found.

Asbestos is a typical mineral fiber formed naturally. The application of asbestos fiber was extensively studied in 1900s but has been banned in most countries as asbestos is considered a carcinogen. Akin to asbestos, wollastonite appears acicular shape at micro scale and has been proposed as a mineral fiber. Wollastonite crystallite has diameters of 25–30 μm and lengths of 400–2000 μm. Previous studies used wollastonite fiber in both PC-based [210] and geopolymer-based materials [211]. It was also used with silica fume as cement replacement up to 10%, where flexural strength of the cementitious composite could be improved by 40% [212].

4.3. Economic and environmental impacts of natural fibers

As the most used natural fibers, plant fibers are generally derived from byproducts of agricultural manufacturing and are renewable and biodegradable. The carbon footprints of plant fibers are commonly recognized to be close to neutral. The manufacturing costs are also marginal compared to most man-made fibers as shown in Fig. 14. In countries/regions where specific agricultural byproducts are easily accessible, the fiber costs could be negligible compared to that of other mixing components in cementitious materials, particularly cement [191]. The low cost and high renewability make plant fibers promising and sustainable candidates for replacing PVA fiber for non-structural applications.

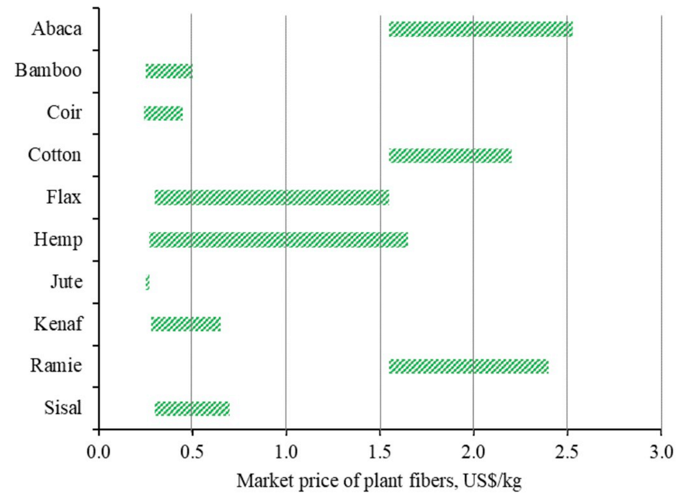

Fig. 14. Market price of commonly used plant fibers (per unit mass), (after [213]).

5. Fiber hybridization

5.1. Hybrid fibers in FRCC

Utilizing two or more different types of fibers to achieve synergistic fiber reinforcement has gained attention in FRCC [214]. Banthia and Gupta [215] classified the synergies into three groups, depending on the mechanisms involved:

1) *Hybrids based on fiber constitutive response*, where one fiber is stronger and stiffer and provides strength, and the other is more ductile or can readily undergo considerable slippage to provide toughness at high strains and crack openings.
2) *Hybrids based on fiber length scale*, where one fiber is small (micro- or meso-fiber) and provides micro-crack control at early stages of loading to arrest micro-cracks and delay their coalescence; the other fiber, at a larger length scale (macro-fiber), provides the bridging mechanism across macro-cracks, and induces toughness at high strains and crack openings. Additionally, the fiber/matrix interaction where one type of fiber may improve matrix performance, potentially increases the effectiveness of the other fiber type.
3) *Hybrids based on fiber function*, where one type of fiber induces composite strength or toughness (primary fiber), and the other type of fiber (processing fiber) provides desirable fresh properties.

These approaches are not mutually exclusive and may work in collective manners. The hybrid fiber system has the potential to improve the composite mechanical properties or to lower the composite cost while maintaining adequate technical performance compared to mono-fiber systems. A summary on hybrid-fiber reinforced cementitious composites (HyFRCC) is provided in Table 13, in which prior studies pertaining to composite tensile and flexural performance are particularly reviewed.

5.2. Hybrid polymeric/metallic fibers in ECC for performance improvement

Hybrid-fiber ECC (HyECC) have been developed following two methodologies: (1) incorporating additional fiber into an existing mono-fiber ECC system to generate a superimposed composite performance, i.e., $1 + x > 1$, and (2) partially replacing an existing fiber in ECC or use different fibers to form a new composite system while keeping a constant total fiber volume, i.e., $1 + 1 > 2$. The former methodology has been most adopted in HyECC, although the latter is more conforming to the concept of synergistic reinforcement by fiber hybridization. Following methodology (1), extensive studies were conducted on introducing steel fiber to PVA-ECC, by which composite ultimate tensile/flexural strengths and strain capacities could be improved [246–249]. The PVA/steel HyECC also attained a higher heat resistance by forming a

Table 13
Studies on hybrid-fiber reinforced cementitious composites (adapted from [269]).

Reference	Fibers	Major findings/comments
Larson & Krenchel, 1991 [216]	ST, PP	After 10 years of out-door exposure, fracture energy of hybrid composite increases by about 40%.
Banthia & Sheng, 1991 [217]	ST, C	Steel fiber contributes to strength and carbon fiber contributes to tougheness.
Feldman & Zheng, 1993 [218]	ST, PP	Stiff steel fiber improves the ultimate strength; ductile PP fiber improves post-peak strain capacity.
Soroushian et al., 1993 [219]	PP, PE	PE can be considered as the reinforcing fiber and fibrillated PP pulp is effective for processing. Hybrids are beneficial in impact loading and for improving flexural strength and toughness.
Komlos et al., 1995 [220]	ST, PP	HyFRCC with PP fiber show better post-crack responses and higher impact strength.
Mobasher & Li, 1996 [221]	PP, C, Al	Peak load is increased by 75% compared to composite containing only PP fiber.
Horiguchi & Sakai, 1999 [222]	ST, PVA	HyFRCC show greater first crack deflection for the same flexural toughness.
Qian & Stroeven, 2000 [223]	ST, PP	HyFRCC have a higher K_{IC} but the synergy disappears at a large displacement.
Peled et al., 2000 [224]	PVA, PP, G	Hybrid combinations (total of 5 vol%) of 40:20:40 and 40:0:60 G/PP/PVA provide comparable strength with 100% glass fiber reinforcement but with a significant improvement in toughness.
Ramanalingam et al., 2001 [225]	ST, PVA (micro and macro)	Hybridization provides significant increases to both ultimate load and post-peak ductility.
Stroeven et al., 2001 [226]	ST, PP, C	Hybridization improves the composite toughness and pull-out resistance of steel fibers.
Lawler et al., 2002 [227]	ST, PP	Hybridization improves both tensile and flexural performance, and reduces the permeability of HyFRCC under cracked conditions
Banthia & Gupta, 2004 [215]	ST, PP, C	High strength matrices are investigated for flexural toughness, and only in some cases synergy is noted.
Sujivorakul and Naaman, 2004 [228]	PVA, PE, C, ST (micro and macro)	The enhanced performance due to the micro-fibers is the result of their influence on mechanical properties of the matrix (micro-crack control) and bond with the macro-fibers.
Lawler et al., 2005 [229]	PVA, ST (micro and macro)	Macro-fibers are more likely to break in HyFRCC than in the same matrix containing macro-fibers alone, since the presence of micro-fibers increased the macro-fiber pull-out resistance.
Markovic 2006 [230]	ST (meso and macro)	Meso-fibers lead to small crack spacing, whereas macro-fibers take the role of crack bridging when bigger cracks developed. The volume of fully active fibers increases from 15% for the mono-fiber system to 32% for the hybrid-fiber system.
Banthia & Sappakittipakorn, 2007 [231]	ST (various diameters)	Partially replacing large diameter steel fibers with smaller ones results in a significantly higher toughness.
Yun et al., 2007 [232]	PE, PVA, ST	The addition of micro-fibers increases the snubbing strength of macro steel fiber. The hybridization improves the direct/splitting/flexural tensile strength, initial crack strength and energy absorbing capacity.
Hsie et al., 2008 [233]	PP (micro and macro)	Micro-fibers restrain cracks in primary stage. Macro-fibers have high elastic modulus and stiffness. High-volume micro-fiber functions in a similar way as steel fiber.
Blunt & Ostertag, 2009 [234,235]	PVA, ST	PVA and steel fibers provide micro- and macro-reinforcements, respectively. The hybridization promotes workability and flexural hardening.
Dawood & Ramli, 2010 [236]	N, ST	Partial replacement of steel fiber with palm fiber can significantly reduce the composite density and enhance the flexural strength and toughness.
Gao et al., 2011 [237]	ST (various lengths)	Short fibers increase the initial fracture toughness, and long fibers improve the unstable fracture toughness.
Park et al., 2012 [238]	ST (micro and macro)	The overall shape of tensile stress–strain curves is primarily dependent on the type of macro-fiber, although the addition of micro-fibers affects the strain-hardening and multiple cracking behaviors.
Ganesan et al., 2013 [239]	ST, PP	The hybridization significantly improves the tension stiffening effect and reduces the crack width.
Tosun-Felekoglu & Felekoglu, 2013 [240]	PVA, PP	Hybridization of PP and PVA fibers does not significantly affect flexural strength, toughness and multiple cracking performance.
Banthia et al., 2014 [241]	N, ST (Hooked-End and Double Deformed)	Adding cellulosic fiber does not change the toughness of matrix, but can contribute to toughness in the presence of steel fiber. Hybridized with cellulosic fibers, hooked-end steel fibers are more efficient in flexural reinforcement and double deformed steel fibers perform better in direct shear.
Banyhussan et al., 2016, 2018 [242,243]	PVA, ST (hooked-end) and Ny	PVA fiber can be partially replaced by nylon fiber without compromise in composite flexural strength or impact resistance. Adding PVA and nylon fibers to steel fiber-based FRCC enhances deflection-hardening behavior.
Demirhan et al., 2019 [244]	PVA, ST (hooked-end and brass-coated)	By hybridizing with hooked-end steel fibers, PVA fibers can be replaced by brass-coated steel fibers without compromise in composite flexural properties or impact resistance.
Yildirim, 2019 [245]	PVA, ST (hooked-end) and Ny	Hybridization of PVA and steel fibers significantly lowers drying shrinkage strains.Hybridization of PVA, steel and nylon fibers suppresses restrained shrinkage cracks.

Note: ST = Steel; PVA = Polyvinyl Alcohol; PE = Polyethylene; PP = Polypropylene; N = Natural; Ny = Nylon; Al = Alumina; G = Glass; and C = Carbon.

more robust crack control capability at elevated temperatures [250]. Recently, Ali and Nehdi [251,252] introduced 1 vol% nickel titanium shape memory alloy (SMA) fiber on top of 2 vol% PVA fiber, and found significant improvements in composite tensile and flexural performance. The shape restoration ability of SMA fiber also enabled rapid self-healing of micro-cracks in HyECC upon heat treatment [251]. Superior resistance to impact loading and projectile penetration of HyECC was demonstrated experimentally on hybrid PE/steel [253–256] and hybrid PVA/steel systems [257], and were numerically verified in Refs. [258, 259]. Durability of HyECC was also examined in Refs. [260–263].

Fewer studies have covered the concept of fiber synergy in HyECC following methodology (2). With the assistance of four-point-bending experiment, Ahmed et al. [264,265] examined the synergies of PVA/steel and PE/steel fiber systems in HyECC with a constant fiber volume of 2.5%. The flexural strength and deformation capacity were optimized by combining 1.5 vol% steel and 1.0 vol% PVA or PE fibers. Under uniaxial tension, the PE/steel HyECC could achieve higher ultimate tensile strength while maintaining comparable strain capacity as PE-ECC (see Fig. 15) [266]. These studies verified the synergy between metallic and polymeric fibers that, within certain ranges of volume proportions, polymeric fibers could contribute composite strain capacity and the formation of multiple cracks, whereas steel fiber promotes the development of composite tensile strength [265,266]. Steel fiber at small volume fractions could also reduce the intrinsic crack widths in PVA/steel HyECC (see Fig. 16, [267]), which, however, was found to slightly compromise tensile and flexural strain capacities [267]. This verified the feasibility of PVA/steel HyECC for enhancing load-carrying capacity under general structural conditions.

5.3. *Hybrid polymeric fibers in ECC for cost reduction*

Another motivation for fiber hybridization in ECC is to mitigate the composite cost through utilizing cost-effective fibers. In this context, recycled PET fiber was combined with PVA for producing ECC. The tensile stress-strain relations of the PVA/PET HyECC are shown in Fig. 17 [131], in which the composite tensile strength and strain capacity both decrease with PET fiber content. Table 14 shows the composite cost and environmental impact of the HyECC with respect to different fiber compositions. The fiber system with 1 vol% PVA and 1 vol % PET was concluded to be optimal at a trade-off between the technical and economic/environmental performance of the HyECC.

6. Conclusions and recommendations

In advancing sustainable developments of ECC through incorporating alternative fibers, three approaches have been surveyed, including substitution of PVA fiber with alternative man-made fibers, substitution of PVA fiber with natural fibers, and fiber hybridization.

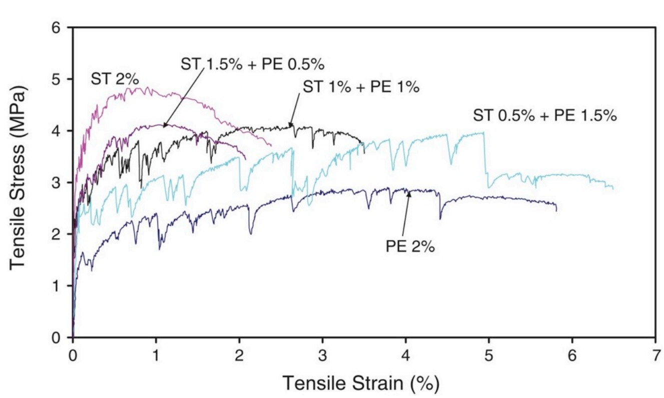

Fig. 15. Tensile stress-strain relation of HyECC with PE/steel(ST) fibers (after [266]).

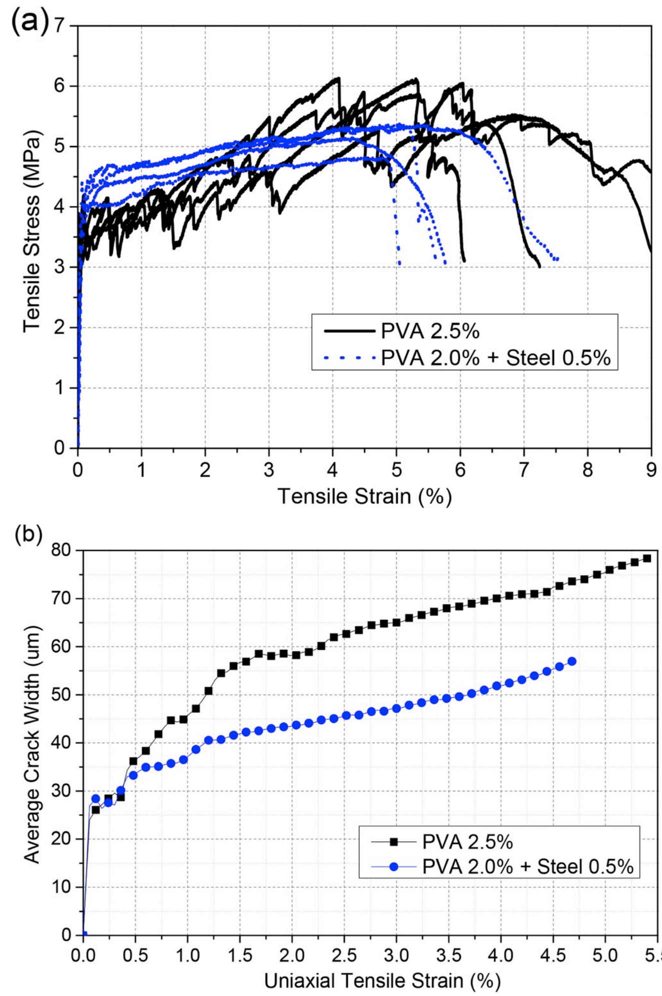

Fig. 16. Tensile performance of HyECC with 2.5 vol% PVA/steel fibers (after [267]): (a) tensile stress-strain relation, and (b) development of average crack width with increasing tensile strain.

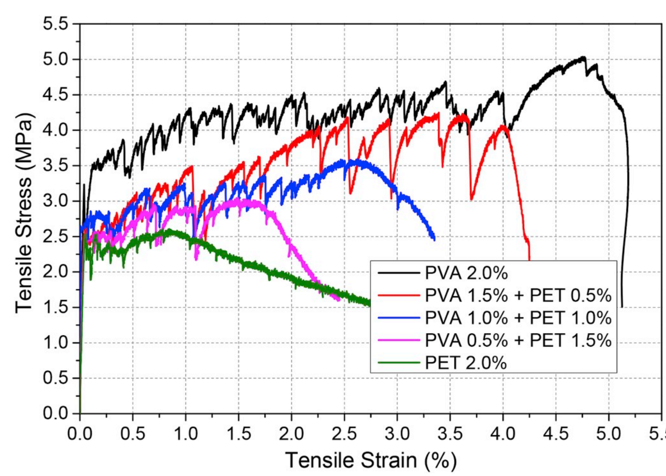

Fig. 17. Tensile stress-strain relation of HyECC with 2 vol% PVA/recycled PET fibers (after [131]). All mixes show strain-hardening behavior.

Amongst man-made fibers, PP fiber appears promising in attaining desirable composite technical performance under tensile and flexural loads, and embodies lower energy and cost compared to PVA fiber. The PP fiber-reinforced ECC can satisfy general structural requirements and

Table 14
Material sustainability indicators and cost comparison for HyECC with 2 vol% PVA/recycled PET fibers (after [131]).

Mixture	Embodied Energy (GJ/m^3)	Embodied Carbon (kg/m^3)	Solid Waste (kg/m^3)	Material (Matrix + Fiber) Cost (USD/m^3)	Fiber Cost (USD/m^3)
Commercial Grade 45 Concrete [268]	2.76	450	0	75	0
PVA 2.0%	4.17	293	−996	570	497
PVA 1.5% + PET 0.5%	3.78	287	−1,003	459	386
PVA 1.0% + PET 1.0%	3.39	282	−1,010	348	275
PVA 0.5% + PET 1.5%	3.00	276	−1,017	236	164
PET 2.0%	2.61	271	−1,024	125	52

represents a potential alternative to conventional PVA-ECC. Another alternative akin to PP fiber is nylon, which leads to high tensile ductility and comparable tensile strength of ECC. However, virgin nylon fiber is costly compared to PVA and consumes more energy at manufacturing. Waste-derived nylon fiber with adequate technical properties could be used as an alternative. PE fiber leads to the most outstanding ECC technical properties by simultaneously attaining high composite tensile strength and ductility. However, PE fiber is less cost-effective compared to PVA, and is not amenable to scale up for large-volume applications. It may still be useful for developing high-performance ECC, in which ultrahigh composite strength and ductility are simultaneously needed under various loading conditions. Although widely used in UHPC, steel fiber appears less favorable for ECC due to the high unit volume cost and high volume fraction needed to achieve the composite tensile strain-hardening. Other cost-effective fibers, such as basalt fiber, form lower composite tensile ductility but higher tensile strength and could be useful for low-ductility structural applications. Their implementation in producing ECC should be further investigated. Compared to most man-made fibers, plant fibers form low mechanical and durability performance for ECC and are not capable to fully displace PVA fiber for general applications. Plant fiber-reinforced ECC, however, is sustainable and useful as non-structural materials and can establish special attributes, e.g., lightweightedness and thermal insulation. Besides reinforcements with mono-fiber system, fiber hybridization could potentially achieve comparable composite performance at lower total cost and environmental impact. Viability of fiber hybridization should be validated on a case-by-case basis.

Applying alternative fibers for producing ECC is mainly driven by the desire to develop sustainable and cost-effective materials for the construction industry. In light of the continuing advancement of fiber technologies, including man-made and natural fibers, the potential for delivering greener and more durable ECC is substantial. Appropriately tailoring properties of fiber and fiber/matrix interfacial bond represents the main challenge and is the key pathway for the development of green-fiber ECC.

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