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Review on recent advances of sustainable engineered/strain-hardening cementitious composites (ECC/SHCC) with ultrahigh-volume pozzolan

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Abstract

Engineered Cementitious Composites (ECC, also known as Strain-Hardening Cementitious Composites or SHCC) are a family of high-performance fibre-reinforced cement-based materials. With the ultimate tensile strain of over 1% and the self-controlled crack width of less than 100 µm, ECC enables high damage tolerance and outstanding durability under various environments for infrastructure. Owing to the absence of coarse aggregates and the low content of fine aggregates, the cement content in conventional ECC can be over 600 kg/m^3, which is undesirable for low-carbon buildings and infrastructure. Ultrahigh-volume (over 60%) pozzolan has been explored to produce sustainable ECC. This article reviews recent advances of sustainable ECC with ultrahigh-volume Class F fly ash or limestone calcined clay. These sustainable ECC either match or surpass mechanical properties and durability characteristics of conventional ECC, while their carbon footprint and embodied energy are much lower than those of conventional ECC. This review article sheds light on fundamental and applied studies on sustainable ECC.

Keywords: Engineered Cementitious Composite (ECC); Strain-Hardening Cementitious Composites (SHCC); Fly Ash; Calcined Clay; Environmental Impact

1 Introduction

The construction sector is one of the main components of the global economy, directly accounting for 6% of the global GDP [1]. Portland cement concrete is the most important construction material, as it is essential for the fast urbanization and social development in the modern world. At about 25 giga tonnes (Gt) or around 3.5 tonnes per capita on an annual consumption basis [2, 3], it is being consumed at an ever-increasing rate. The consumption of materials in general, and construction material in particular, have driven the growth of the economy. An indicator of this growth is the consumption of cement [4]. Since 2010, the world consumption of cement has increased from 3.64 Gt to 4.65 Gt in 2017, while China's consumption has increased from 2.05 Gt per year to 2.35 Gt in the same period [5]. On the other hand, cement production contributes to 8-9% of the anthropogenic CO_2 and 2-3% of the energy consumed in the world [6], which makes the construction industry face considerable pressure towards the carbon peaking and carbon neutrality.

There are great efforts to make the entire construction sector achieve carbon neutrality by 2050 by using green materials and renewable energy in both the production of materials and operation of buildings [7, 8]. The construction industry has been facing the challenge of low productivity and lack of innovation. Being a conservative sector, the construction sector has been slow-moving regarding the introduction of new technology such as new materials use, design as well as automation. To address the various challenges, namely sustainability, resilience and durability, facing the construction industry in an effective manner, a paradigm shift in construction materials technology is required. The Integrated Structures and Material Design (ISMD) approach [9] to infrastructure systems construction illustrated in Figure 1 tries to address many of these interconnected challenges using a lifecycle analysis approach. This approach is similar to the circular economic model, which is being increasingly applied in different sectors of the economy.

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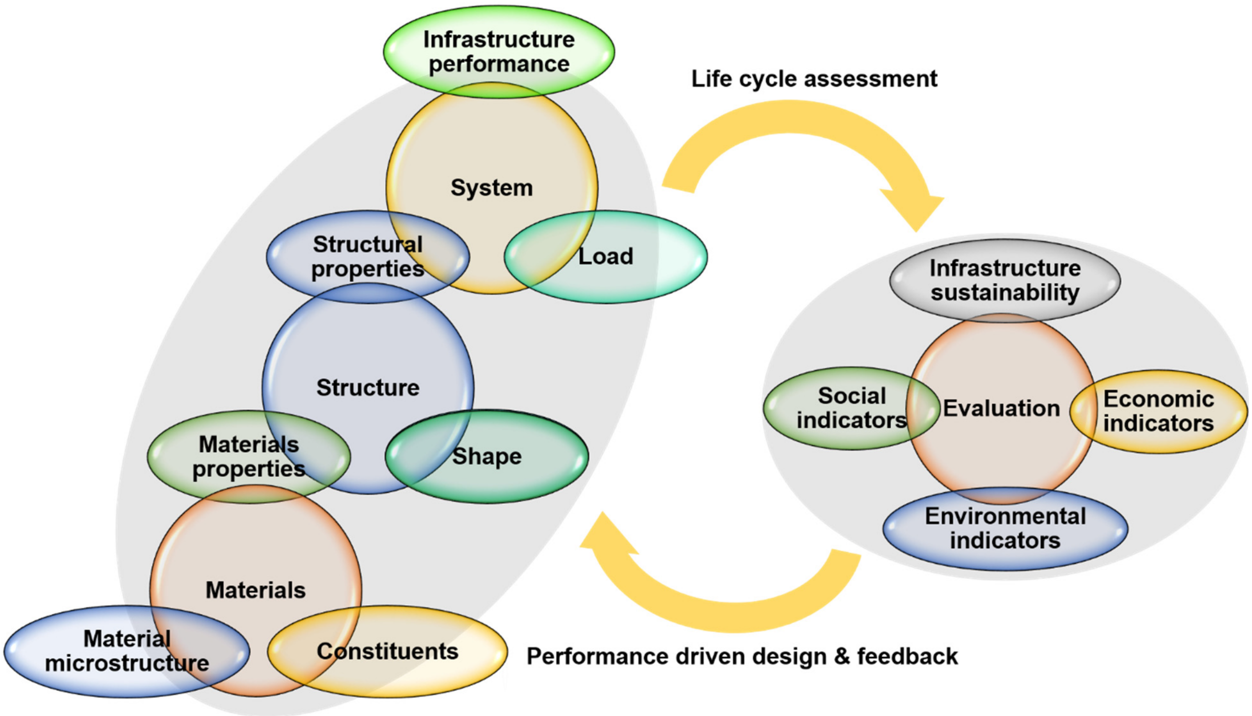

Figure 1. The Integrated Structures and Materials Design (ISMD) applied to Infrastructure Systems.

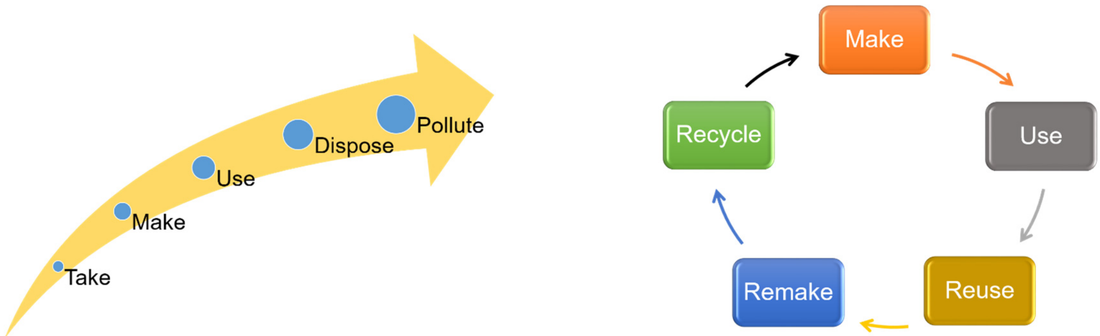

Figure 2. Schematic depiction of linear economic models (left) and circular sustainability models (right) [11].

2 Sustainability and Green Construction

As opposed to the closed economy, the idea of an open economy, a precursor to the concept of the Circular Economy, was first proposed by Boulding in 1966 [10]. The 'use and throw' model of the 'Linear Economy' was changed to the 'Make, Use and Re-use' model [11] (Figure 2) in the report by Stahel and Reday in 1976 [12]. The Organization for Economic Co-operation and Development (OECD) defines the circular economy as "a system which maximizes the value of the materials and products that circulate within the economy" [13]. As the circular economy model allows for sharp environmental footprint reduction and resource preservation, the model has attracted increasing attention from governments, industries, and researchers. Such an approach vastly reduces the huge number of discarded products going to landfill. It incentivizes the manufacturer to build the product to last as long as possible, design it for easy recycling and take responsibility for the product's whole life cycle.

The British Standards Institution (BSI) developed the 1st standard for Circular Economy (BS 8001 Framework for implementing the principles of the circular economy in organizations) in 2016. China's 14th five-year plan starting from 2021, included promoting the circular economy model as a national policy.

Most importantly, the Circular Economy can help to fulfil the emission reduction goal of the 21st Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change, COP 21 Paris Agreement. Since the greenhouse gas reduction commitments made by signatory countries are insufficient to limit the global warming to 1.5 °C, it is estimated that half of the additional emissions reductions (15 Gt CO_2 per year) must be delivered by Circular Economy [14].

Figure 3 illustrates the application of the circular system in the construction sector. It shows the difference between the traditional infrastructure life cycle model as opposed to the sustainable alternative. Every stage of the infrastructure life cycle, which starts with the sourcing of raw materials, maintenance, and operation, and ends with disposal of demolished structures at the end of life, is labour, energy and carbon-intensive. In this review paper, we will focus on the opportunity for the construction industry to reduce carbon footprint and energy content by replacing clinker with industrial wastes such as fly ash. The service life of concrete infrastructure will be enhanced by use of ECC with high volume fly ash and limestone calcined clay (LCC).

3 Material and Mix Compositions

Various pozzolans have been utilized to replace traditional Portland cement in concrete [15-17], such as fly ash, ground granulated blast furnace slag, silica fume, metakaolin, and rice husk ash. The pozzolanic reaction enhances the cementitious material by producing additional calcium silicate hydrate (CSH). This occurs after the oxides of silica (H_4SiO_4, SH) in them react with calcium hydroxide ($Ca(OH)_2$, CH), which is a by-product of cement hydration [18] as given by Eq. (1).

$$CH + SH \rightarrow CSH \tag{1}$$

The other major constituent in pozzolan is aluminate (A). It reacts with calcium hydroxide, limestone ($CaCO_3$, Cc) and water to form calcium aluminate hydrates (CAH) such as (C_4AH_{13}, C_3AH_6). In combination with silica, it can also form calcium aluminate hydrates (CASH), as shown in Eq. (2). Besides, the aluminate in metakaolin can also react with gypsum generating needle-like crystals of ettringite (AFt). The hydration products of calcium aluminate hydrates and ettringite can form as shown in equations (2)-(3) below.

$$S + (A) + CH \rightarrow C(A)SH \tag{2}$$

$$A + Cc + CH \rightarrow C_3A \cdot Cc \cdot H_{11} \tag{3}$$

These pozzolans in both reacted and unreacted forms are also known to densify the microstructure and help to improve the durability characteristics of concrete. In this review, we will focus on the role of two of the most important pozzolans. One is fly ash (FA, the most widely used industrial waste in concrete) and the other limestone calcined clay (LCC, a new type of pozzolan with a huge volume of availability and widely distributed around the globe) as far as addressing the carbon footprint of concrete [19]. The engineered cementitious composites (ECC) with high-volume fly ash or LCC are reported. With a large tensile strain capacity (up to several per cent) accompanied by multiple fine cracks with the crack width controlled to 100 μm or below, ECC is a promising material for significantly enhancing the resilience and durability of structures, thus making them more sustainable [19].

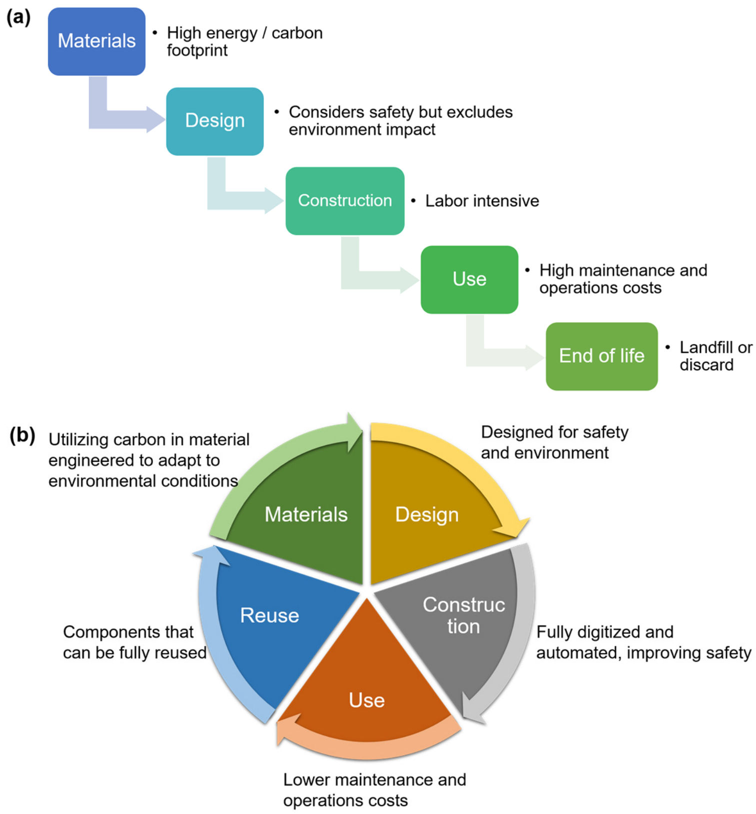

Figure 3. (a) traditional infrastructure life cycle, and (b) sustainable alternative life cycle [9].

Table 1. Mix proportions (in kg/m^3) of ECC with ultrahigh-volume FA/LCC

Mix	Binder			Silica sand (s/b)	Water (w/b)	HRWR (Solid content)	PVA Fibre (vol.%)
	Cement	Fly Ash (% of binder)	LCC (% of binder)				
Conventional ECC (M45) [9]	588	705 (55%)	/	466 (0.36)	310 (0.24)	2.13	26 (2%)
UHV-FA ECC [31]	285	1141 (80%)	/	285 (0.20)	285 (0.20)	1.11	26 (2%)
UHV-LCC ECC-1 [19]	324	/	757 (70%)	432 (0.40)	432 (0.40)	3.31	26 (2%)
UHV-LCC ECC-2 [19]	234	/	937 (80%)	432 (0.40)	469 (0.40)	2.77	26 (2%)
UHV-FA/LCC ECC [33]	212	846 (69%)	172 (14%)	446 (0.36)	365 (0.30)	8.3	26 (2%)

In our previous studies, the ordinary Portland Cement (52.5N with 5% gypsum, BS EN 197-1 [20]) and siliceous fly ash (BS EN 450-1 [21]) were obtained in Hong Kong. The LCC pozzolan was brought from India, in which the weight ratio between calcined clay and limestone powder was 2:1. High-range water reducer (HRWR) was used to adjust the fresh property of ECC. For the fibre-reinforced composites, fine silica sand with the size of 120-180 μm was used. Similar to most of conventional medium-strength ECC, 2 vol.% of polyvinyl-alcohol (PVA) fibres were added. The PVA fibres reported in this article were from the same source, so the mechanical properties and environmental impacts of various ECC can be compared directly. The major difference between fly ash and LCC is the particle shape and content of oxides such as those of calcium and aluminium. The angular shape of LCC results in a lower workability and higher HRWR demand compared to fly ash.

Conventionally, most building codes have restricted the use of pozzolan to about 30-35% of the binder except for calcium-rich pozzolan like ground granulated blast furnace slag. However, research work in the last three decades shows that up to 50-60% replacement (high-volume pozzolan) and, more recently, up to 70-80% replacement (ultrahigh-volume pozzolan) is feasible [22-25]. This has been made possible by suitably reducing the water/binder ratio using high-performance superplasticizers. Due to the gradual phasing out of coal-fired thermal power plants and variability in fly ash characteristics, adequate amount of good quality fly ash is becoming unavailable at many locations. It is, therefore, necessary to search for alternative pozzolanic mineral admixtures. A green cement with LCC has been promoted in recent years by a group of researchers from Switzerland, India, and Cuba [26]. Given that limestone and clay are the same raw materials used to produce Portland cement, it is particularly suitable for this purpose. It has also been shown that relatively lower quality clay and limestone unsuitable for cement manufacture can be used to make LCC [26]. It is estimated that for a green LCC cement (LC^3-50) with 50% clinker, 30% calcined clay, 15% limestone and 5% gypsum, the carbon emission from cement production can be lowered by up to 30% [27, 28]. The use of higher volume fraction LCC as a mineral admixture in cement and concrete was successfully demonstrated by Yu and co-workers [29, 30]. Matrices with ultrahigh-volume fly ash or LCC have also been used to prepare ECC [31, 32]. Table 1 shows the mix proportions of conventional concrete and ECC mixes as well as mixes made with ultra-high volumes of FA and LCC. The mechanical properties, environmental performance and costs are compared so that conclusions can be drawn in terms of their potential as green construction materials from a sustainability perspective. All the mixes have been tuned to exhibit comparable workability by adding an appropriate amount of superplasticizer.

4 Mechanical Performance of ECC

The most important mechanical characteristic of conventional concrete is compressive strength which is usually correlated with other properties, such as flexural strength, shear strength, elastic modulus, abrasion resistance, and impact resistance. The most unique mechanical characteristic of ECC is the uniaxial tensile performance. Figure 4 (a) and (b) show the compressive strength, and Figure 5 shows the tensile behaviour of ECC mixes from Table 1.

A suitable matrix for ECC depends on its tensile first cracking strength and fracture toughness. Thus, ECC with ultra-high pozzolan contents can serve the purpose of ordinary concrete with additional benefits. These include improved energy absorption capacity (e.g., in the event of earthquake loading) or enhanced service life via crack width control, which restricts ingress of chloride ions, thereby delaying the onset of corrosion of steel reinforcement. The compressive strength of these mixes containing varying amounts of fly ash and LCC and different water/binder ratios follow the well-known trend of cementitious materials. Figure 4 (a) shows the increasing trend of compressive strength with curing time, while Figure 4 (b) shows the decrease in strength with increased water/binder ratio.

Figure 5 presents the typical tensile stress-strain behaviour of the ductile ECC mixes designed with high-volume fly ash or LCC respectively, which meet the fresh properties and compressive strength requirements of real-life construction. The strain capacity of ECC with ultrahigh-volume LCC is generally lower than similar fly ash-based mix. However, this can be overcome by a judicious combination of fly ash and LCC.

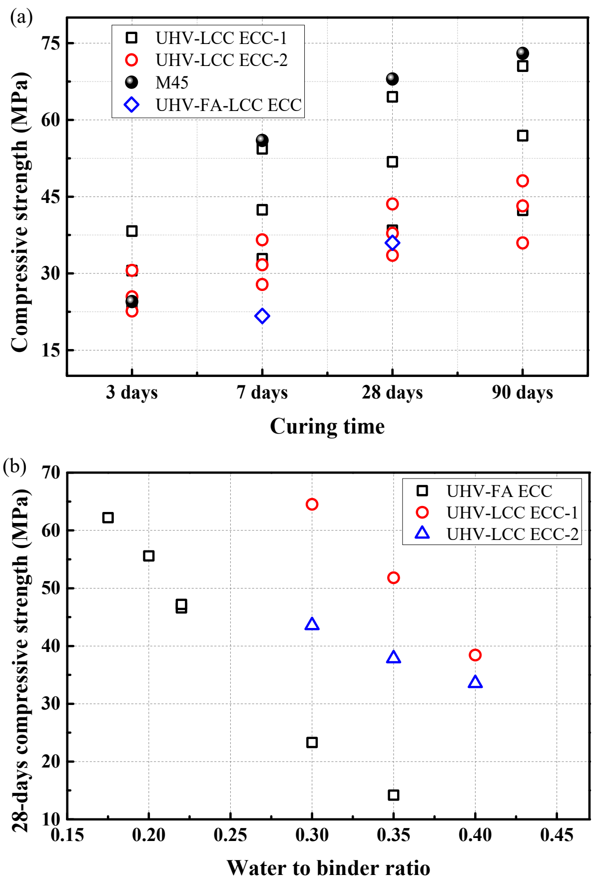

Figure 4. Compressive strength of ECC with different (a) curing time and (b) water-binder ratio.

5 Material Sustainability of ECC

Embodied carbon, embodied energy, and waste utilization are used as the Material Sustainability Indicators (MSIs) [34, 35] to quantify the sustainability of the ECC mixes. These MSIs are calculated based on the individual mix component values listed in Table 2, and mix proportions for the different composites discussed earlier. The cost of the mixes is also calculated based on the Hong Kong local prices.

Figure 6 shows the calculated material sustainability indicator, waste utilization and cost per unit volume of each of the mixes as per their mix proportions listed in Table 1. It can be observed from Table 2 that the PVA fibre and the superplasticizers have large values for material cost and embodied carbon, respectively. But fortunately, their dosages are of a small fraction of the mix.

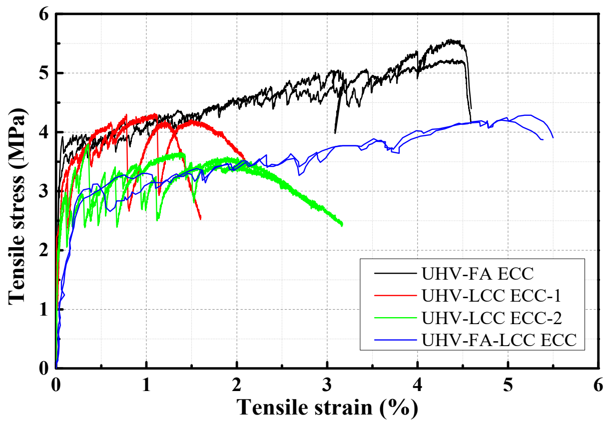

Figure 5. Tensile behaviour of ECC with ultrahigh-volume fly ash or LCC or both.

Table 2. Embodied carbon, embodied energy and cost of ingredients.

Material	Embodied Carbon (kg eq-CO_2/metric tonne)	Embodied Energy (MJ/metric tonne)	Cost (HKD/ metric tonne)
Portland Cement	912 [36]	5500 [36]	800
Fly Ash	8.0 [36]	100 [36]	400
LCC Pozzolan	210 [27]	3040 [27]	400
Silica Fume	8.0 [a]	100 [a]	3000
Water	1.0 [36]	100 [36]	7
HRWR (Powder)	1840 [37]	42670 [37]	23000
PVA Fibre	101 [38]	1710 [39]	160000

[a] Assumed to be identical as that for fly ash.

Though the sand/binder ratio varies among different ECC mixes, the results are compared in this study for discussion. A better comparison can be made if all the ECC mixes have the same paste/aggregate volume ratio. According to the results shown in Figure 6, using high-volume fly ash and LCC decreases the MSIs while also decreasing the cost of ECC. Therefore, there is a strong case for the construction industry to adopt these new types of ECC in practice starting with non-structural applications at the earliest. Further, the MSIs and costs are dominated by the PVA fibre. However, compared to conventional ECC (M45), the ECC mixes with high-volume fly ash and LCC show improvements in MSIs. The use of ECC in niche applications such as bridge decks, expansion joints, water-proofing repair, dampers in earthquake-resistant structures etc. is well established [9]. A service life-based design accounting for life cycle cost will be required for wider applications.

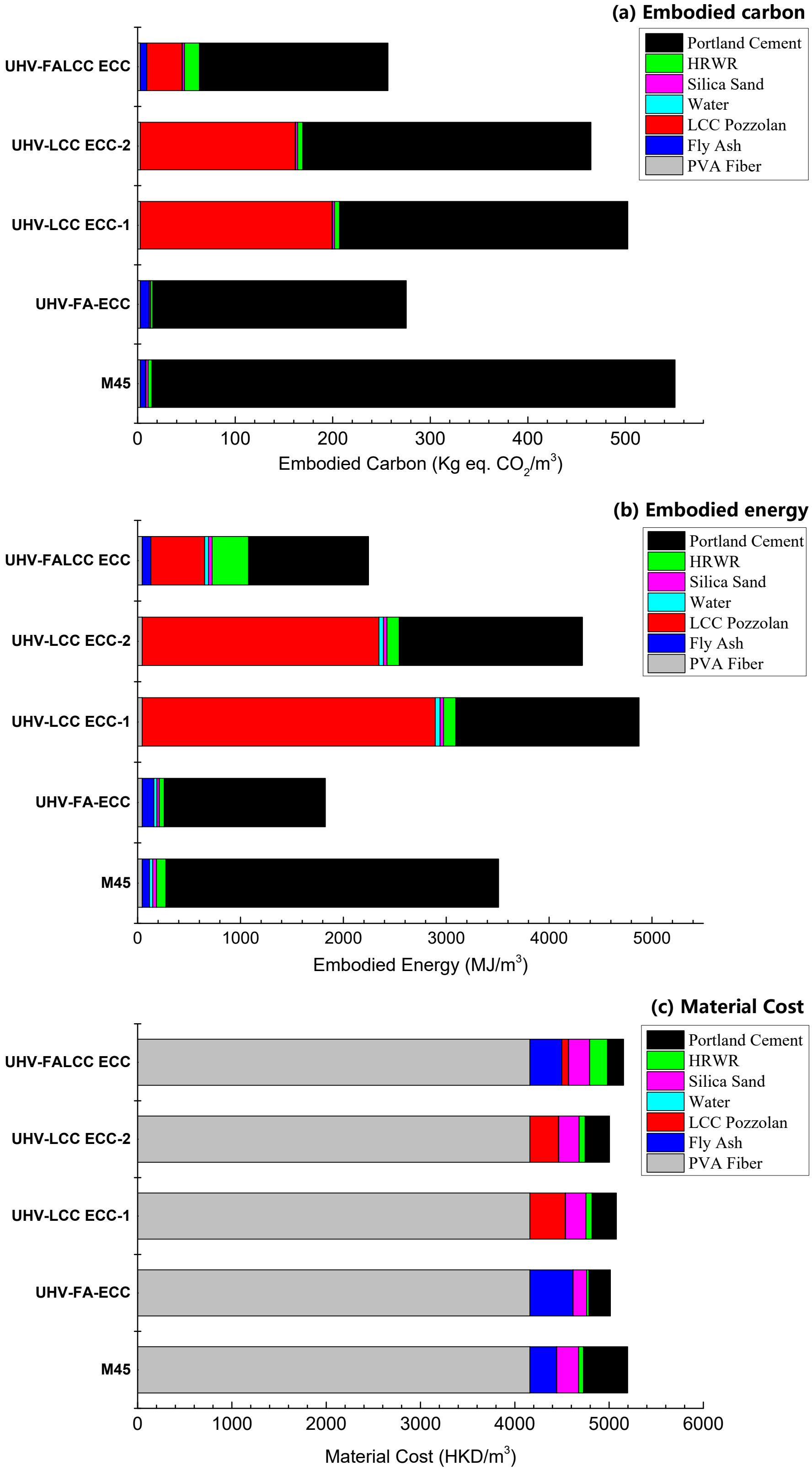

Figure 8. Comparison of Material Sustainability Indicators (MSI) of different ECC mixes: a) Embodied carbon; b) Embodied Energy; c) Material cost.

6 Prospects

The review of recent advances in ECC with ultrahigh-volume pozzolan reveals the advantages of carbon footprint, energy intensity, and initial material cost. It should be noted that the high initial material cost can be offset by the long service life and low maintenance cost [40]. To gain maximum benefits of these materials, fine aggregates from construction and demolition waste, and recycled polymeric fibres need to be deployed [41]. The tailorability of ECC at the material design level lends it toward the prescribed sustainable performance [19, 42]. Even though the durability of ECC has piqued the interest of many researchers [43, 44], the existing model to characterize deterioration and accurately predict its whole service life warrants more investigation. In a recent paper by Bao and Li [45], Lego blocks inspired construction has been proposed. Mechanically interlocking ECC blocks have been proven to be re-usable in different structural configurations. It enables both robotic construction and reuse of materials furthering circular economy. Such an approach would result in significant savings in embodied carbon, energy intensity and cost while increasing waste utilization, thereby accelerating the drive to achieve the climate goal set by the Intergovernmental Panel on Climate Change (IPCC) [46].

7 Summary and Conclusions

In light of the impending climate crisis, the sustainability and circular economy approach must be adopted in all sectors of the economy to achieve the goal of 2015 Paris climate agreement and limit the temperature increase to 1.5°C. This would require the construction industry to ensure significant reduction in its projected emission of greenhouse gases. Cement production, one of the major sources of greenhouse gas emission must bear a major responsibility to achieve the above target by reducing clinker factor, energy consumption and switching to low carbon fuel besides using carbon capture and storage.

This review paper explains the demand for sustainability in construction materials and application of circular economy principles. Several practical examples of engineered cementitious composites with ultrahigh-volume fly ash or limestone calcined clay (LCC) pozzolan have been discussed to illustrate the recent advances in this direction. The following conclusions and recommendations can be made. Ultrahigh-volume fly ash and LCC concrete are found to have similar/higher compressive strength compared to conventional concrete mixes. They are good examples of enhanced sustainability and a circular economy-based approach toward meeting the IPCC's goals. The use of ultrahigh-volume fly ash and LCC in the Engineered Cementitious Composites maintains the desirable tensile ductility while making the material greener with a lower carbon footprint. It is recommended that a circular economy-based approach with emphasis on service life-based design must be made mandatory for use in the construction industry in order to drive innovation and help avoid the climate crisis.

Authorship statement (CRediT)

DK Mishra: Writing – original draft.

H Wu: Writing – original draft, Visualization.

J Yu: Conceptualization, Writing – review and editing, Project administration.

CKY Leung: Supervision, Writing – review and editing.

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