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Use of recycled glass powder to improve the performance properties of high volume fly ash-engineered cementitious composites

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HIGHLIGHTS

- Sustainable ECC with high volume fly ash and recycled glass powder was studied.
- Mechanical, physical, self-healing and microstructural investigation were carried.
- Incorporating RGP into HVFA-ECCs significantly improved their mechanical properties.
- Self-healing of HVFA-ECC was accelerated and recovery rate improved.
- Low Ca/Si ratio of new C-S-H structure was the outcome of RGP in HVFA-ECC.

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ABSTRACT

High-volume fly ash (HVFA) Engineered Cementitious Composites (ECC) show reduced strength and physical properties, especially at early curing ages. The goal of this study was to improve their strength characteristics by incorporating recycled glass powder (RGP) for enhanced material sustainability. Composites containing 15, 30, 45 and 60% RGP as a replacement for FA, with FA to cement ratio of 2.2, were studied in HVFA-ECC. Standard ECC mixtures with FA to Portland cement (FA/PC) ratio of 1.2, and HVFA-ECC with FA/C ratio of 2.2 without RGP were also produced as control mixtures. The experimental results confirmed that incorporating RGP into HVFA-ECC significantly improves compressive and flexural strengths, chloride ion resistance and electrical resistivity, and results in a comparable ductility to standard ECC, based on FA to cement ratio of 1.2. Furthermore, self-healing of HVFA-ECC was accelerated and final recovery rate of strength and physical properties improved. Microstructural analysis showed high portlandite consumption and the formation of low Ca/Si ratio in new C-S-H structures near C-Na-Al-S-H as the main outcome of the binary admixture in ECC.

1. Introduction

Engineered Cementitious Composites (ECC) is a new class of ultra-ductile fiber-reinforced concrete, developed in 1990s to improve the low tensile strength and especially ductility of concretes [1]. Through micromechanics-based design theory, ECC has been optimized with moderate fiber volume of no more than 2% to feature high damage tolerance and self-healing ability, with multiple micro-cracking behavior with crack widths of less than 100 µm. Although standard ECC costs more and is less eco-friendly due to its higher Portland cement (PC) content and the absence of coarse aggregates in its composition [2], using fly ash (FA) in place of Portland cement addresses economic and environmental concerns [3–5]. Indeed, many researchers have shown that increasing FA content in ECC with a FA/PC ratio of up to 2.8 is possible, and can even tighten crack widths and improve tensile strain ductility [6,7], with well-balanced performances at an FA/PC ratio of 2.2 [2,4]. However, using high volume fly ash (HVFA) has generally been associated with negative effects on compressive and tensile strength, especially at early ages. For instance, Yang et al. [6] studied the mechanical properties of ECCs prepared with FA/PC ratios of 1.2–5.6. They showed that the compressive and tensile

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strengths are reduced by around 40% and 15% respectively when FA to PC ratio is increased from 1.2 to 2. Wang and Li [7] also investigated the mechanical performance of ECCs prepared with various HVFA contents. The results showed the decrements of around 20%, 30% and 50% for the tensile strength, slip-hardening coefficient and the splitting force, respectively, when FA/PC ratios increased from 1 to 1.5. In accordance with these results, Lin et al. [8] recently indicated the reductions of around 35% in compressive and tensile strengths and 30% in the elastic modulus of self-compacting strain-hardening cementitious composites incorporating FA to PC ratios of 1 and 2. Furthermore, regarding the durability properties, Şahmaran and Li [9] confirmed that the chloride-ion permeability of HVFA-ECC prepared with FA/PC ratio of 2.2 is more than two times higher than that of ECC incorporated FA/PC ratio of 1.2. For these reasons, recent studies have focused on improving the strength of HVFA-ECC by incorporating new materials such as metakaolin [10], slag and silica fume [11], limestone powder [12], and nano-mineral additives [3] into ECC formulations.

In terms of sustainable management of waste materials, waste glasses have been widely used in different civil engineering fields as aggregates, fibers and powders, especially in concrete production [13,14]. Although recycled glass powder (RGP) has not gained the same industrial success as fly ash or slag [15], this recycled material has been proven to have high pozzolanic reactivity when the larger particle size is below 100 μm. This makes it a desirable mineral admixture to partially replace PC in concretes, and even enhance their mechanical and durability properties [16]. According to Siad et al. [17], using fine glass in cementitious materials has the potential to form a new pozzolanic C-S-H with very low C/S ratio and high amounts of alkalis (Na + K) and aluminum (Al), which could also result in denser structure and improved strength capacity. One of the major concerns regarding the use of waste glass in concretes is the alkali-silica reaction (ASR) risk, which can cause expansion and cracking. However, this has only occurred when the larger particle size (generally up to 0.3 mm) was used [18]; the finer RGP reduced ASR risk and expansion in concretes by up to 50% [19], especially when used in conjunction with fly ash or slag [20].

Because of the recent satisfactory results of standard ECC incorporating glass powder [21] and the economic and environmental benefits of this new cementitious material, using RGP in composites containing HVFA may be advantageous for enhancing their technical, economic and environmental properties. However, considering the high ductility and self-healing ability of ECC containing HVFA, replacing FA with RGP can create a potential challenge to achieving these technical qualities. In this study, FA was partially replaced in ECC2.2 (FA/PC ratio of 2.2) by 15, 30, 45 and 60% by mass of RGP, in an attempt to enhance the mechanical and physical properties of HVFA-ECC. The effects of these replacements on the mechanical (compressive and flexure strengths), physical (rapid chloride permeability (RCP) and electrical resistivity (ER)) and self-healing capability of ECC mixtures were investigated. Scanning electron microscopy (SEM) and X-ray diffraction (XRD) analyses were conducted on the outer and inner parts of healed crack lines to determine any possible change in the self-healing product characteristics.

2. Experimental program

2.1. Materials

The materials used to prepare ECC mixtures were: Portland cement (PC) conforming to ASTM C150 [22], Class-F fly ash (FA) complying with ASTM C618 [23], silica sand (SS) with average and maximum particle sizes of 150 μm and 400 μm, respectively, polyvinyl alcohol (PVA) fibers, and high range water reducing admixture (HRWRA). Recycled glass powder (RGP), provided by a sorting center, had an average grain size of 20 μm and maximum gradation of 100 μm. The physical and chemical properties of PC, FA and RGP are provided in Table 1 and their particle size distributions are shown in Fig. 1. In addition to its high amounts of SiO_2 (74.8%) and Na_2O (7.2%), a significant amorphous content of around 90% can be reported in RGP.

2.2. Mixture proportions and specimen preparation

RGP was systemically introduced as FA replacement at 0, 15, 30, 45 and 60% in five different HVFA-ECC mixtures produced with a controlled mineral admixture (FA + RGP) to PC ratio of 2.2, SS to cementitious materials of 0.36 and water to binder ratio of 0.27, as summarized in Table 2. Moreover, a standard ECC mixture with FA to PC ratio of 1.2 was produced to match the most commonly used composition in literature. All ECC mixtures were prepared using the same 50-L planetary-type mixer. The volume of high range water reducing admixture (HRWRA) was adjusted gradually during casting to adequately satisfy the required workability determined by mini slump flow test [24]. During the casting of different compositions, a truncated conical mold with a height of 7.6 cm and bottom and top diameters of 9.2 and 4.4 cm respectively, was used to define the slump flow deformation in compliance with the test method recommended by Al-Dahawi et al. [25]. The amount of HRWRA was taken after ashiving a similar slump flow diameter of around 16 ± 0.5 cm.

Several specimens were prepared to test the mechanical, physical and self-healing properties of each mixture. 50 mm cubic specimens were used to determine compressive strength at 7, 28, 56, 90 and 120 days, and 360 × 75 × 50 mm prisms were used to measure flexural strengths and mid-span beam deflection capacities under four-point flexural load. Ø100 × 200 mm cylinders were used to investigate the effect of RGP replacement level on rapid chloride permeability test (RCPT) and electrical resistivity (ER) results. After 24 h of casting, specimens were demolded, cured in sealed bags for six days at 23 ± 2 °C and 95 ± 5% RH and kept in a laboratory environment at 23 ± 2 °C and 50 ± 5% RH.

2.3. Pre-cracking and self-healing testing

Since the type and volume of mineral admixtures have a high influence on the cracking behavior and self-healing ability of cementitious materials [26], this study assessed the rate of recovery of pre-cracked ECCs with and without RGP replacement. At the age of 28 days, three sound prisms from each composition were preloaded up to failure under flexural tensile loading, and the ultimate deformation capacities at ultimate loads were measured. Thereafter, prisms used to evaluate the self-healing rate were pre-

Table 1
Chemical and physical characteristics of PC, FA and RGP.

Chemical composition, %	PC	FA	RGP
SiO_2	19.5	57	74.8
Al_2O_3	5.1	21	2.0
Fe_2O_3	2.92	4.2	0.4
MgO	2.5	1.8	1.3
CaO	61.8	9.8	13.6
Na_2O	0.30	2.2	7.2
K_2O	1.11	1.5	0.6
Loss on ignition	2.5	1.3	0.5
$SiO_2 + Al_2O_3 + Fe_2O_3$	27.52	82.2	76.5
Physical properties			
Specific gravity	3.1	2.6	2.5
Blaine fineness (m^2/kg)	408	325	382