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Hydration and physical characteristics of ultrahigh-volume fly ash-cement systems with low water/binder ratio

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HIGHLIGHTS

- UHVFA-cement mortar with 80% FA obtains a 28-day compressive strength over 65 MPa.
- The total hydration heat of the UHVFA-cement mortar with 80% FA is reduced by 70%.
- The C3S exothermic peak of UHVFA-cement mortar with 80% FA is delayed by 21 hours.
- Aluminate gel content first increases and then decreases with increasing FA content.
- Morphological & micro-aggregate effects of FA maintain adequate strength of UHVFA concrete.

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ABSTRACT

Replacing Portland cement by fly ash in concrete has attracted extensive attention, as this approach is effective in controlling heat release rate, reducing material cost and enhancing greenness. However, only limited studies have been reported on the hydration and physical characteristics of ultrahigh-volume fly ash (UHVFA, fly ash/binder > 60 wt%) concrete. This study aims to explore these characteristics of fly ash–cement systems with low water/binder ratios and a wide range of fly ash replacement levels (from 20% to almost 100%). Even if 80% of the cement was replaced by fly ash, the 28-day compressive strength of the mortar reached over 65 MPa under normal curing conditions, and the total hydration heat was 70% less than that of conventional cement mortar. Moreover, the morphological and micro-aggregate effects of the fly ash were found to play important roles in maintaining adequate strength of the systems, especially for those cases with UHVFA. The findings of this study can support the future designs and applications of sustainable UHVFA concrete.

1. Introduction

To develop sustainable construction materials, incorporating supplementary cementitious materials (SCMs) in concrete has attracted extensive attention. As the most widely used SCMs, fly ash, or pulverized fuel ash, is the principal industrial waste of coal combustion in thermal power plants, and its proper disposal has become a challenge [1–3]. Replacing cement by fly ash in concrete brings several benefits. Firstly, this approach increases the greenness, reduces the material cost and decreases the hydration heat [4–6]. Specially, the temperature in concrete structures has an important effect on the construction schedule and safety, since cracking may occur due to non-uniform thermal expansion and contraction, especially for concrete construction involving large volumes [7]. Secondly, the addition of a suitable amount of fly ash can enhance the durability of concrete [8]. Thirdly, the micro-aggregate and morphological effects of the un-hydrated fly ash particles with small particle size and smooth spherical shape result in better workability, higher compactness in the interfacial transition zone and a finer pore structure of concrete [9–13].

To achieve the goal of cleaner production, ultrahigh-volume fly ash (UHVFA) concrete with more than 60% of cement replaced by fly ash has been developed to achieve a low carbon footprint and cost efficiency [3]. From the chemical viewpoint, since the pozzolanic reaction of fly ash is a relatively slow process, its contribution to concrete strength occurs mainly at later ages, so the early

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strength may be significantly reduced if a large amount of fly ash is used [14]. A summary of the 28-day compressive strength of UHVFA concrete with normal curing conditions and without chemical activation can be found in Yu et al. [4]. However, high early strength is not required in many applications, such as concrete dams, and researchers have explored different approaches for improving the situation.

Previous work of the authors has demonstrated that 28-day compressive strength of more than 60 MPa could be achieved even with 80% of the cement replaced by fly ash in concrete, by simply lowering the water/binder ratio to 0.2 and introducing an appropriate amount of silica fume [4,15]. To understand the mechanism of achieving such a high strength level in this UHVFA concrete, the hydration and physical characteristics should be evaluated; however, only limited studies on this topic for UHVFA concrete have been reported [16–22]. This study aims to evaluate the hydration and physical characteristics of FA-cement systems with low water/binder ratios and the Portland cement replaced by fly ash at five different percentages (20%, 40%, 60%, 80% and 98%). Compressive strength was measured at different ages (from 7 to 360 days), and the hydration heat release rate was studied for up to 7 days. To understand the physical and chemical changes during the hydration process, the FA-cement system was characterized using X-ray diffraction (XRD), scanning electron microscopy (SEM) and thermogravimetric analysis (TGA). The findings of this study can support the future design and wider applications of UHVFA concrete.

2. Experimental program

2.1. Materials, mixing and curing

The Type I 52.5N Portland cement was produced by Green Island Cement Co., Ltd in Hong Kong, which met all requirements of BS EN 197-1:2011 [23]. The Class F fly ash was provided by China Power and Light Co., Ltd in Hong Kong. The silica fume was Elkem™ Microsilica 920U. Table 1 lists the chemical compositions (determined by X-ray fluorescence) of the cement, fly ash and silica fume, and their particle size distributions (tested by Beckman Coulter™ LS230 laser particle analyzer) can be found in Yu et al. [4]. Medium river sands (commercial sands in Hong Kong) with the fineness modulus of 2.47 and the maximum size of 4.75 mm were used as the fine aggregates.

The proportions for all the mixes are listed in Table 2. The sand/binder ratio was fixed at a 2.0, which is a general value for conventional cement mortars [24]. The Mortar-Conventional series (Table 2) was designed as the control, in which the binder constituent was the same as that of typical commercial concrete. Based on a mix with the FA/binder ratio of 80%, SF/binder ratio of 2% and water/binder ratio of 0.2, which achieved the best mechanical performance among the UHVFA mixes explored by the authors in a previous study [4], the Mortar-FA series (Table 2) was designed to study the impact of the fly ash replacement level (from 20% to almost 100% by weight) on the hydration and physical characteristics. Specifically, the mixing amounts of cement for mortars FA20, FA40, FA60, FA80 and FA98 were 600 kg/m^3, 439 kg/m^3, 282 kg/m^3, 131 kg/m^3 and 0 kg/m^3, respectively. The workability of the mortar was measured in terms of the flow diameter according to ASTM C1437 [25]. To achieve similar workability (flow diameter of 200 mm) in the Mortar-FA series, different amounts of polycarboxylate-based super-plasticizers were added for different fly ash dosages. In addition, a Mortar-W/SP series (Table 2) was designed to evaluate the effect of water and/or super-plasticizer content on the hydration heat, where the binder composition was kept as the same as FA20 (Table 2). The reason for performing experiments of Mortar-W/SP series is further discussed in Section 3.2.

A Hobart™ HL800 mixer was utilized to prepare the mortars. All the specimens were cast in greased steel molds on a vibrating

Table 1
Chemical composition of cement, fly ash and silica fume.

Materials	LOI (%)[a]	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	CaO (%)	MgO (%)	SO_3 (%)	Na_2O (%)	K_2O (%)	Na_2Oeq (%)[b]	Active SiO_2[c] (%)
Portland Cement	1.17	20.15	4.38	3.37	63.85	2.13	4.66	0.11	0.38	0.36	–
Fly Ash (Class F)	2.49	49.83	18.94	11.43	9.27	3.57	2.13	1.55	1.80	2.73	70
Silica Fume	1.03	93.43	0.69	1.07	0.42	1.21	0.41	0.95	1.17	1.72	98

[a] LOI: Loss on ignition.
[b] Equivalent alkali: $Na_2Oeq = Na_2O + 0.658\ K_2O$.
[c] The fraction of SiO_2 that is soluble after treatment with hydrochloric acid (HCl) and with boiling potassium hydroxide (KOH) solution (BS EN 197-1 [23]).

Table 2
Mix proportion (by weight).

Series	Mix ID	Binder (B)			Sand/B	Water/B	SP[a]/B (%)
		Cement	Fly Ash	Silica Fume			
Mortar-Conventional	M45	1.00	0	0	2.0	0.45	0.00
	M42FA	0.75	0.25	0	2.0	0.42	0.36
Mortar-FA	FA20	0.78	0.20	0.02	2.0	0.20	1.92
	FA40	0.58	0.40	0.02	2.0	0.20	1.68
	FA60	0.38	0.60	0.02	2.0	0.20	1.44
	FA80	0.18	0.80	0.02	2.0	0.20	1.29
	FA98	0.00	0.98	0.02	2.0	0.20	1.21
Mortar-W/SP	W2SP2	0.78	0.20	0.02	2.0	0.20	2.00
	W2SP3	0.78	0.20	0.02	2.0	0.20	3.00
	W2SP4	0.78	0.20	0.02	2.0	0.20	4.00
	W2SP5	0.78	0.20	0.02	2.0	0.20	5.00
	W3SP2	0.78	0.20	0.02	2.0	0.30	2.00
	W4SP2	0.78	0.20	0.02	2.0	0.40	2.00
	W5SP2	0.78	0.20	0.02	2.0	0.50	2.00

Note: The specific gravity of each material: Cement = 3.14; Fly ash = 2.30; Silica fume = 2.20; Sand = 2.65.
[a] Grace™ ADVA 105 polycarboxylate-based super-plasticizers in solution form (with 30% solid content).