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Mechanical properties of green structural concrete with ultrahigh-volume fly ash

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HIGHLIGHTS

- With a FA/binder of 80%, Grade 45 green concrete for structural use is developed.
- Adequate workability is maintained in green concrete for normal construction.
- Adding a small amount of SF can improve both mechanical and sorptivity performance.
- FA replacement level (FA/b ≤80%) has no obvious effect on FA cementing efficiency.
- Green concrete shows obvious superiority in environmental impact and material cost.

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ABSTRACT

Using a high dosage of fly ash in concrete is an effective approach to control the heat release rate, reduce the material cost and enhance the sustainability. However, ultrahigh-volume fly ash (UHVFA) concrete, with fly ash replacing over 60% of the binder by weight, often exhibits low compressive strength at an early stage, which limits the material to non-structural or semi-structural applications. Though different approaches have been proposed to increase the strength, the efficacy of some of the methods is debatable, because of the high energy consumption and/or low cost-benefit ratio. This study aims to increase the compressive strength of UHVFA concrete by the simple and practical method of reducing the water/binder ratio while adding super-plasticizers to maintain workability. Mortar samples were used to explore the influence of silica fume, and Portland cement was replaced with fly ash at five different percentages (20%, 40%, 60%, 80% and 98%). Mechanical properties up to 360-day age were recorded, and the cementing efficiency factor of the fly ash was studied. With a suitable mix proportion, even with 80% of the binder replaced by fly ash, the compressive strength of the mortar and concrete can reach over 40 MPa at 7-day age, and over 60 MPa at 28-day age. Compared to commercial Grade 45 concrete, the proposed green structural concrete shows a reduction in CO_2 emission of around 70%, a reduction in embodied energy of more than 60%, and a reduction in material cost of 15%.

1. Introduction

Fly ash (FA), or pulverized fuel ash (PFA), is a principal by-product of coal combustion in thermal power plants. These few years, around 600 million tonnes (MT) in China, around 220 MT in India and around 130 MT in the U.S. of fly ash is generated, and only approximately 70%, 60% and 50% of the fly ash is reused, respectively [1,2]. The large amount of remaining fly ash is disposed in landfills with the potential risks of air pollution and contamination of water due to leaching [3–5], not to mention that landfill space is becoming scarce in many urban neighborhoods. On the other hand, cement production is a highly energy intensive process that generates large amounts of CO_2, SO_2 and NO_x [6,7]. Since the early 1960s, many countries have started to incorporate fly ash into concrete as a pozzolanic material that may be used either as a component of blended Portland cement or as a mineral admixture in concrete. Substituting cement with fly ash in the mixture design of concrete brings a number of benefits. Firstly, replacement of cement by fly ash increases the environmental greenness and decreases the hydration heat as well as the material

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cost. Secondly, the addition of fly ash can enhance durability [8] and reduce drying shrinkage [5]. Thirdly, the morphological and micro-aggregate effects of 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 in the system [9–12].

Concrete with fly ash replacing 15–30% (hereafter, by weight) of the binder has been widely used, and researchers and engineers have developed the high-volume fly ash (HVFA) concrete, with 30–60% of fly ash in the binder. Desirable mechanical and durability properties of HVFA concrete has been achieved by careful selection of the mix proportions and the utilization of super-plasticizers [13]. Hence, there is wide interest in further increasing the replacement percentage of fly ash. This study focuses on ultrahigh-volume fly ash (UHVFA) concrete, defined here as the concrete with fly ash replacing more than 60% of the binder.

From the chemical viewpoint, in fly ash-cement systems, the highly amorphous silica and alumina phases in Class F fly ash react with the Portlandite to form additional calcium-silicate-hydrate (C-S-H) and/or calcium-aluminate-silicate-hydrate (C-A-S-H) phases [14–17], the so-called pozzolanic reaction. As the pozzolanic reaction of fly ash is a relatively slow process, its contribution to concrete strength occurs mainly at later ages, so the early strength (normally up to 28 days) would be significantly reduced if a large amount of fly ash is used [18,19]. The table in the Supplementary material summarizes the compressive strength of UHVFA concrete, with normal curing conditions and without chemical activation. Each column in the table gives the study reference, the mix composition, the strength at 28 days as well as the strength at other ages (with the curing days given in brackets). The results are mostly obtained for Class F fly ash, and those for Class C fly ash are explicitly stated in the first column. It should be noted that different studies utilized different specimen geometries for compressive testing, and the data was converted to the apparent strength of the cube specimen measuring 100 mm × 100 mm × 100 mm, based on the corresponding correction factor [20,21]. Fig. 1 illustrates the 28-day compressive strength versus the water/binder ratio, based on the data given in the Supplementary material. The figure indicates that only a small fraction of the mixes (9 out of 57) can reach compressive strength of over 40 MPa, and only 3 sets of data show compressive strength beyond 50 MPa at the 28-day age. This obviously limits the structural applications of UHVFA concrete. Researchers have explored different approaches for improving the situation, including: (i) lowering the water/binder ratio [14], (ii) substitution of a high-early strength Portland cement for ordinary Portland cement [22], (iii) replacement of a portion of the fly ash with a more reactive pozzolan such as silica fume or rice husk ash [22], (iv) chemical activation [23–25] (v) incorporating nano-materials (such as nano-SiO_2) [8], (vi) accelerated curing and autoclaving [26,27], and (vii) mechanical treatment (grinding) [28,29]. However, the efficacy of some of these methods is debatable because of the high energy consumption (Methods VI and VII) and/or the low cost-benefit ratio (Methods IV to VII). Hence, the first three methods may be more practical in general.

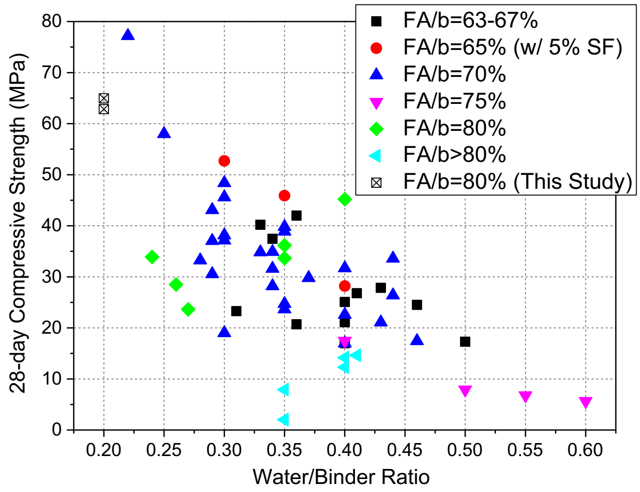

Fig. 1. 28-Day compressive strength vs water/binder ratio of UHVFA concrete.

2. Research objective and significance

This study aims to improve the compressive strength of ultrahigh-volume fly ash (UHVFA) concrete with a practical approach. Since UHVFA incorporation might lead to low early strength, a target of 40 MPa for 7-day-old concrete was set to avoid delays in the construction process due to insufficient strength gain, and a target of 55 MPa for 28-day-old concrete was set for attaining comparable strength to Grade 45 structural concrete. According to the data summarized in Fig. 1, 28-day compressive strength of over 50 MPa was reported in studies with no more than 70% of Portland cement replaced by fly ash. However, previous work of the authors on fiber reinforced pseudo-ductile cementitious composites (with very high binder ratio and only a small amount of sand in the mix) demonstrated that such strength is achievable even if 80% of the binder is replaced by fly ash, in conjunction with a low water/binder ratio and a very small amount of silica fume [30,31]. Hence, the target weight replacement fraction of the fly ash in the binder was set as 80%, and the water/binder ratio was kept as 0.20. Mortar samples were first employed to explore the effect of binder composition, where Portland cement was replaced with fly ash at five different percentages (20%, 40%, 60%, 80% and 98%). Mechanical properties up to 360-day age were recorded, and the cementing efficiency factor of fly ash was studied. Based on the findings, a green concrete with very high fly ash content was developed and compared to commercial Grade 45 concrete in terms of strength, cost as well as environmental impact. This research extends the use of UHVFA concrete in civil engineering applications, and widely promotes the concept of sustainability to the community. For countries like China and India, this technology can play an important role in meeting the huge infrastructure demands in a sustainable manner [22].

3. Experimental program

3.1. Materials, mixing and curing

The materials used in this study included cement, fly ash (FA), silica fume (SF), river sand, granite gravel and super-plasticizers. Type One 52.5 N Portland cement was manufactured by Green Island Cement Co., Ltd in Hong Kong, and met all the requirements of BS EN 197-1 [32]. Both Class F and Class C fly ash were provided by China Power and Light Co., Ltd in Hong Kong, and their SEM images are shown in Fig. 2. The silica fume was Microsilica 920U, provided by Elkem Co., Ltd in Norway. Table 1 lists the chemical compositions of the cement, fly ash and silica fume, while Fig. 3 presents their particle size distributions. The maximum size of the granite gravel was 20 mm. To ensure sufficient workability of the mix with a low water/binder ratio, the ADVA 105 polycarboxylate-based super-plasticizers, provided by Grace Construction Products in Hong Kong, was utilized to adjust the rheological properties of the mixes.