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An exploratory study on high-volume fly ash concrete incorporating silica fume subjected to thermal loads

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ABSTRACT

In this study, cement has been partially replaced with a Class F fly ash (FA) at a level of 70% to produce high-volume fly ash (HVFA) concrete (F70). F70 was modified by partially replacing FA with silica fume (SF) at levels of 10% and 20%, by weight. All HVFA concrete types were compared to the neat Portland cement (PC) concrete. After curing, the specimens were exposed to elevated temperatures ranging from 400 °C to 1000 °C with an interval of 200 °C. Weight and compressive strength before and after firing have been thoroughly explored. The various decomposition phases formed were identified using X-ray diffraction (XRD) and scanning electron microscopy (SEM). The results indicated higher relative strength of all HVFA concrete types. F70 exhibited the highest relative strength. The SF blends exhibited good fire performance up to 600 °C, then severe degradation in the residual strength was observed at 800 and 1000 °C.

1. Introduction

In view of the global sustainable development, it is recommended that supplementary cementing materials be used in place of cement in the concrete industry. The most worldwide available supplementary cementitious materials are FA and SF. It was estimated that around one billion t of FA is produced annually worldwide in coal-fired steam power plants (Bakharev, 2005), while the current global output of SF, at most, between 1 and 1.5 million t/y (Rashad and Khalil, 2013). Due to the rapid economic development and the growth in the world population consumption of energy over the world, FA and SF have significantly increased. Air and environment pollution has become a problem, thus, the idea of using waste materials has gained popularity. FA and SF are two of the most common concrete ingredients due to their benefit properties.

Cement plant has been always among industries which generate plenty of CO_2 (Benhelal et al., 2013). In 2009, according to Eurostat the cement industry in the European Union is responsible for 38.5% of the total European CO_2 emissions from industry (Vatopoulos and Tzimas, 2012). Understanding the environmental impact of cement manufacturing is therefore becoming increasing important (Huntzinger and Eatmon, 2009). Globally, more than 56% of CO_2 emission is caused by the thermal decomposition of calcium carbonate into calcium oxide and CO_2 during the sintering process of Portland clinker. For almost each t of cement produced about 1 t of CO_2 is emitted into the air, the cement industry accounts for about 7% of the 23,000 million t of CO_2 produced by mankind annually. Due to a world-wide increase in the demand for cement, cement production could represent nearly 10% of total anthropogenic CO_2 emissions in the close future (Habert et al., 2011; Yang et al., 2013). The cement industry is the second largest producer of this gas (Malhotra and Mehta, 2005). According to the European Cement Association, cement production was responsible for 2.83 billion t of CO_2 emissions worldwide in 2008 (CEMBUREAU, 2009). Not only CO_2 releases from cement manufacture, but also sulfur dioxide (SO_2), nitrous oxides (NO_x), methane (CH_4), etc (Valipour et al., 2014) that can cause the greenhouse effect and acid rain. In addition each tonne of cement might require input of 1.5–1.6 tonnes of raw materials, 3000–4300 MJ of fuel energy and 120–160 KWh of electrical energy (EIPPCB, 2013; Feiz et al., 2014). Resulting, cement is the most costly component of concrete. The air pollution and unit cost of concrete can be reduced by replacing part of cement with by-product materials such as FA and SF. Use of such additions makes waste management more efficient, reduces energy consumption during cement production and lowers CO_2 emissions. These properties will cause an increased demand for alternative cementitious materials, because in order to fulfil their future responsibilities cement and concrete producers need to have a high degree of flexibility in the selection and use of supplementary

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cementitious materials (Ponikiewski and Golaszewski, 2014; Benhelal et al., 2013). Huntzinger and Eatmon (2009) pointed out that the greenhouse gas impact calculated from blended cement is reduced as much as approximately 22% compared with that of neat PC. Yang et al. (2014) have reported that the value of CO_2 intensity decreased sharply as the substitution level of the supplementary cementitious materials increased up to approximately 15–20%, beyond which the rate of decrease gradually slowed. However, the utilization of FA instead of dumping it as a waste material can be used in concrete to reduce the environmental problems of power plants and decreases electric costs besides reducing the amount of solid waste, greenhouse gas emission associated with Portland clinker production, conserves existing natural resource, an economic grounds as pozzolan for partial replacement of cement. Although FA is a valuable mineral admixture for blended PC and concrete, only about 6% of the total available FA is used for this purpose (Malhotra and Mehta, 2002); whilst the most of the rest is land filled-and surface-impounded, with potential risks of air pollution, contamination of water due to leeching (Guerrero et al., 1999). Therefore, FA should not only be disposed of safely to prevent environmental pollution, but should be treated as a valuable resource.

As pozzolanic reaction of FA is a slow process, its contribution to strength occurs only at later ages, the early strength of concrete will be significantly reduced if a large amount of FA is used. This limits the wide use of HVFA concrete by engineers. Different approaches are used to accelerate the pozzolanic reaction of FA and therefore increase the early strength of the concrete containing FA. These approaches include mechanical treatment (Paya et al., 1995), accelerated curing (Maltais and Marchand, 1997) and blended FA with other materials such as SF (Rashad et al., 2014). Improving some properties of HVFA concretes with the inclusion of SF can be summarized as following: Yazıcı (2008) reported that the incorporation of 10% SF in HVFA SCCs modified the freezing-thawing resistance and chloride penetration resistance. Hariharan et al. (2011) reported that the inclusion of 6% or 10% SF in HVFA concretes showed gain in early strength. Xiaosheng et al. (2007) reported that the inclusion of 5% SF in HVFA concretes can effectively compensate for the loss of early strength and can accelerate the FA reaction. Turgut (2012) reported that in bricks manufacturing from limestone and FA, adding SF at levels of 5%, 10% and 20%, by FA weight increased the compressive strength. The compressive strength increased with increasing SF content.

There are few researches available in the literature regarding to the performance of FA concretes at elevated temperatures. Some of these researches can be summarized as following: Diederichs et al. (1989) reported an increase in the compressive strength of concrete containing Class F FA after exposure to 200 °C and 250 °C. Tang and Lo (2009) reported that both NSC and HSC containing 25% FA showed better performance in residual mechanical and fracture properties at both normal and after exposure to elevated temperatures of 27, 200, 400, 500 and 600 °C for 1 h Balendran and Martin-Buades (2000) found that the incorporation of FA could reduce the fire damage on NSC. Seleem et al. (2011) incorporated FA, SF, slag and metakaolin (MK) in concretes in two ratios of 10% and 20% in the form of either cement replacement or as an addition without affecting the cement content. They exposed the concrete specimens to 200, 400, 600 and 800 °C for 3 h. The results indicated that FA concretes exhibited the highest relative strength after exposure to 600 °C and 800 °C. Poon et al. (2001) studied the effect of elevated temperatures on HSCs containing FA, slag and SF as cement replacement. The replacement levels were 20%, 30%, and 40% by FA; 30%, 40% by slag and 5%, 10% by SF. The specimens were exposed to 200, 400, 600 and 800 °C for 1 h. They concluded that the FA concretes showed the best performance at elevated temperatures followed by slag, PC and SF concretes. 30% FA replacement exhibited the maximum relative residual strength. Aydın and Baradan (2007) reported an improvement in elevated temperature resistance of pumice mortars by partially replacing cement with FA at levels of 20%, 40% and 60%. The inclusion of 60% FA exhibited the best performance.

The effect of elevated temperatures on concrete containing high levels of FA (more than 50%) has not been investigated in details in the literature. At the same time, the effect of elevated temperatures on HVFA concretes containing SF has not been investigated. This paper presents the weight loss and the residual strength properties of the neat PC concrete, HVFA concrete and HVFA concretes containing SF in which 10% and 20% of FA was replaced with SF. Because waste materials as FA and SF replaced PC up to 70%, this means that the PC was eliminated from 100% to 30%. Consequently, the CO_2 emission caused by thermal decomposition during sintering process of Portland clinker will be reduced and the consumption of natural raw materials (limestone and sand) required will be reduced. In addition, the disposal of FA and SF will be eliminated. Therefore, this study aims to respond extra four issues: the lower emission of pollutants into atmosphere, reduction in consumption of natural resources, eliminate the disposal of FA and SF and produce HVFA concrete and blended HVFA concretes with SF that able to resist elevated temperatures. Extending to those purposes, the present study focuses on new material which can resist thermal loads. This investigation will therefore add a valuable knowledge to this area.

2. Experimental details

2.1. Materias

2.1.1. Cementitious materials

Commercially available PC, CEM I, 42.5N, of Blaine surface area 335 m^2/kg and conforming to the Egyptian Standard specifications (ES 4756-1/2007) was used. The FA was obtained from disposal waste resulting from the combustion of pulverised coal in the coal-fired furnaces. It complies with the requirements of BS3892: Part 1 (BSI 1992) and classified as low calcium Class F FA in ASTM-C618. The specific gravity and Blaine specific surface area was 2.4 and 400 m^2/kg. The SF was obtained from disposal waste resulting from the ferro-silicon alloys industry. The specific gravity and Blaine specific surface area was 2.32 t/m^3 and 20,200 m^2/kg. The relevant chemical composition of all cementitious materials was evaluated by X-ray fluorescence (XRF) spectrometry and the results are shown in Table 1. Fig. 1 shows the diffractograms of the raw FA and SF samples analyzed by X-ray diffraction (XRD).

Table 1
Oxide composition of PC, FA and SF (% by mass) after calculation from XRF results.

Composition	PC	FA	SF
CaO	63.47	4.76	0.98
SiO_2	20.18	55.95	95.2
Al_2O_3	4.83	23.3	–
MgO	2.47	1.85	0.431
Fe_2O_3	3.16	4.84	1.0
SO_3	3.26	0.65	0.02
K_2O	0.52	1.82	1.03
Na_2O	0.16	0.91	0.91
TiO_2	0.3	1.03	–
MnO	0.22	0.05	–
P_2O_5	0.09	0.73	–
$CaCO_3$	–	–	–
Cl^-	–	–	–
L.O.I.	2.18	3.47	0.429