Journal of Advanced Concrete Technology

Materials, Structures and Environment

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Journal of Advanced Concrete Technology, volume 10 (2012), pp. 74-85

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Scientific paper

Effects of PFA and GGBS on Early-Ages Engineering Properties of Portland Cement Systems

Xiang Ming Zhou¹, Joel R. Slater², Stuart E. Wavell³ and Olayinka Oladiran⁴

Received 11 October 2011, accepted 20 December 2011

doi:10.315/jact.10.74

Abstract

A comprehensive study is presented on the effects of pulverised fly ash (PFA) and ground granulated blast furnace slag (GGBS) on early-age engineering properties of Portland cement (PC) systems. It has been found that partially replacing PC by PFA or GGBS resulted in longer setting times but better workability with PFA exhibiting more prominent effect than GGBS. As the replacement level increased, the setting of both PFA and GGBS pastes further delayed but workability of concrete was enhanced. PFA concretes exhibited consistently lower compression and splitting tensile strengths than PC ones. As the replacement level increased, strengths decreased. At the replacement level up to 30% by mass, GGBS concrete exhibited higher splitting tensile strength than PC concrete. However, as the replacement level further increased, it developed lower strength than PC concrete up to 21 days. Then, it managed to gain higher splitting tensile strength than PC concrete at the replacement levels up to 70% by mass at 28 days. Both PFA and GGBS can reduce drying shrinkage and the reduction effects became more significant as replacement level increased with GGBS performing better than PFA. Adding fibres into PFA concrete increased its splitting tensile strength and further reduced its drying shrinkage.

1. Introduction

The cement industry produces the world's second most used material, after water, and it contributes approximately 5 percent of the global carbon emissions. In many countries, legislation is now in place that specifies targets to reduce carbon emissions. This is due to the high energy intensive processes involved in Portland cement (PC) production, as on average 900 kg of carbon dioxide (CO₂) is emitted for every 1000 kg of cement produced. Construction industry has been looking for alternative binding materials/mineral admixtures to wholly or partially replace PC so that to reduce its negative environment impact for decades. Nowadays, mineral admixtures such as pulverised fly ash (PFA) and ground granulated blast furnace slag (GGBS) are becoming more and more widely used in concrete because they are able to improve durability and quality of concrete and also reduce negative environment impact of PC in terms of carbon emission and energy consumption (Lothenbach *et al.* 2011). For instance, the indicative embodied CO₂ (ECO₂) for PC CEM I, GGBS and PFA are 930, 52 and 4, respectively, kg CO₂/tonne on aver-

age as the main cementitious constituents of concrete used in the United Kingdom (UKQAA 2007). It should be noted that these figures are derived using data for the calendar year 2007 and they are 'cradle to factory gate' as they do not include the transport from the place of manufacture of the cementitious material to the concrete plant. Besides, the usage of these mineral admixtures eventually leads to economic benefit as most of them are industrial by-products.

Among various mineral admixtures, PFA is the combustion residue in pulverised coal-burning power plant, which flies out with the flue gas stream and is captured by electrostatic or mechanical precipitators, or bag filters. PFA itself is dust-like fine powder of mainly spherical and glassy particles. It has pozzolanic properties and consists essentially of SiO₂ and Al₂O₃ with the content of reactive SiO₂ being at least 25% by mass in order that it can be used as a type II addition for production of concrete conforming to EN 206-1. PFA has been used particularly in mass concrete applications and large volume placement to control expansion due to its low heat of hydration and also helps in reducing cracking at early ages. The main disadvantage of using PFA in concrete is that its strength development is significantly lower than that of PC resulting in a relatively low early strength. GGBS is a by-product from blast-furnaces of iron-manufacturing industry. It is a mixture of lime, silica, and alumina, the same oxides that make up PC, but not in the same proportion as PC. Though the compositions of GGBS may vary depending on the ores and other supplementary materials used in iron manufacturing, silicon, calcium, aluminium, magnesium, and oxygen constitute typically 95% or more of GGBS. EN 15167-1 specifies that as a type II concrete addition, the

¹Senior Lecturer, School of Engineering and Design, Brunel University, Uxbridge, Middlesex UK.
E-mail: Xiangming.Zhou@brunel.ac.uk

²Research Assistant, School of Engineering and Design, Brunel University, Uxbridge, Middlesex UK.

³Research Assistant, School of Engineering and Design, Brunel University, Uxbridge, Middlesex UK.

⁴Ph. D. student, School of Engineering and Design, Brunel University, Uxbridge, Middlesex UK.

chemical compositions of GGBS shall consist of at least 2/3 by mass of the sum of calcium oxide (CaO), magnesium oxide (MgO) and silicon dioxide (SiO₂) with the ratio by mass (CaO + MgO)/(SiO₂) exceeding 1.0. The remainder shall be mainly aluminium oxide (Al₂O₃). Concrete made with GGBS has many advantages, including improved durability, workability and economic benefits. Similar to PFA, the drawback in the use of GGBS concrete is that its strength development is considerably slower under standard 20 °C curing condition than that of PC concrete, although the ultimate strength is higher for the same water-to-binder ratio (Barnett *et al.* 2006).

So far, lots of researches have been conducted on PFA and GGBS concrete. However, there is little research on engineering properties of PFA and GGBS systems at early ages. Generally it is regarded that during this period PC systems possess properties superior to PFA and GGBS ones mainly in strength development since the pozzolanic reactions of PFA and GGBS rely on calcium hydroxide (CaOH) released by PC hydration (Lothenbach *et al.* 2011). However PFA and GGBS concrete do exhibit some properties superior to PC concrete, such as lower drying shrinkage, which was explored in this study. Drying shrinkage introduces characteristic problem in concrete members and, if not accurately accounted for at the design stage, can cause severe cracking which in turn leads to service life reduction and impair the structural reliability and durability. However, the information in the literature about the influence of mineral admixtures, such as PFA and GGBS, on the drying shrinkage of concrete is found to be somewhat contradictory (Güneyisi *et al.* 2010). Sahmaran *et al.* (2007) stated that incorporation of mineral admixtures such as PFA reduces the drying shrinkage of concrete. They also stated that a possible mechanism contributing to the reduction of drying shrinkage of concrete is the matrix densification due to PFA addition, which may prevent internal moisture evaporation thus reducing shrinkage of concrete. An alternative mechanism is that unhydrated fly ash particles serve as fine aggregates to restrain the shrinkage deformation of concrete (Bisaillon *et al.* 1994; Zhang 1995). Güneyisi *et al.* (2010) also supported their findings and reported that mineral admixtures such as PFA, GGBS and MK can reduce drying shrinkage of concrete, the higher the replacement level the higher the reduction in the shrinkage of concrete. However, Mokarema *et al.* (2005) concluded that the addition of mineral admixtures, fly ash, slag and microsilica in their case, into PC concrete resulted in greater drying shrinkage. Therefore, this research was also intended to investigate the effects of PFA and GGBS on drying shrinkage of concrete. Besides, most researches published so far were focusing on PFA and GGBS conforming to the relevant ASTM classifications. As most PFA produced by coal-burning power stations and GGBS produced by iron-manufacturing plants are consumed by local construction industry due to the dif-

ficulties in storing and transporting PFA and GGBS powders, it is therefore necessary to investigate the engineering properties of PFA and GGBS produced at local market conforming to relevant national and regional technical standards. In line with these, a comprehensive study was conducted in this research on the engineering properties of PFA and GGBS, which was by-products of relevant UK industries and are compatible with EN 450 and EN 15167, respectively, as a type II addition in the production of concrete at early ages up to 28 days. Cement pastes and concretes with different amounts of PC replaced by PFA or GGBS were prepared and tested to obtain their engineering properties at fresh and hardened states up to 28 days, which were compared with those of pure PC concrete. Besides, limited research work has been carried out concerning the influence of short discrete fibre addition in concrete with pozzolans (Atis and Karahan 2009). Again there is contradicting information from various researches on the effects of fibres on drying shrinkage of concrete. Toutanji (1999) reported that polypropylene fibres mitigate plastic and early drying shrinkage by increasing the tensile property of concrete and bridging the forming cracks. Karahan and Atis (2011) also found that addition of polypropylene fibres in concrete or fly ash concrete reduces drying shrinkage considerably. However, Kayali *et al.* (1999) reported that polypropylene fibre reinforcement is not able to reduce drying shrinkage of concrete containing fly ash. Aly *et al.* (2008) even found that concrete reinforced by polypropylene fibres show consistently higher drying shrinkage than that without fibres. Therefore, this research was also aiming at investigating the effects of short discrete fibres on engineering properties, including drying shrinkage, of PFA concrete at early ages.

2. Materials

2.1 Raw materials

CEM II Portland cement conforming to EN 197-1 used for this study was commercially available from LA-FARGE Cement (UK). PFA for this research came from HCCP Hargreaves Coal Combustion Products Limited (UK) which is compliant with EN 450-1 for use as a type II addition in the production of concrete. GGBS was obtained from Hanson Heidelberg Cement Group (UK) which is compliant with EN 15167-1 for use as a type II addition in the production of concrete. The specific gravity density and Blaine fineness of PC, PFA and GGBS were tested conforming to EN 196-6 and the results are shown in **Table 1**. It can be seen that PFA

Table 1 Gravity density and Blaine fineness of cement, fly ash and GGBS.

	Gravity density	Blaine fineness (m ² /kg)
PC	2.94	453
PFA	2.18	619
GGBS	2.93	512

Table 2a Chemical compositions (elements) of cement, fly ash and GGBS (% by weight).

	O	Si	Al	Ca	S	Na	Mg	Fe	K	Mn	Ti
PC	34.62	7.38	1.97	50.76	2.11	0.42	0.49	1.55	0.78	-	-
PFA	46.10	24.39	12.79	2.48	1.29	1.09	0.78	7.42	3.11	-	0.68
GGBS	40.06	15.45	5.47	32.37	0.96	0.23	3.99	-	0.59	0.52	0.40

Table 2b Chemical compositions (oxides) of cement, fly ash and GGBS (% by weight).

	CaO	SiO ₂	Al ₂ O ₃	FeO	K ₂ O	Na ₂ O	MgO	SO ₃	TiO ₂
PC	71.02	15.78	3.72	1.99	0.94	0.56	0.81	5.27	-
PFA	3.47	52.18	24.16	9.55	3.75	1.47	1.29	3.21	1.14
GGBS	45.29	33.06	10.34	-	0.71	0.31	6.61	2.39	0.67

Table 3 Mix proportions (kg/m³) of concrete mixtures.

Concrete	PC	PFA	GGBS	Water	Sand	Aggregate	Fibre	Total
100% PC	363	0	0	218	727	1091	0	2399
30% PFA	254.1	108.9	0	218	727	1091	0	2399
50% PFA	254.1	108.9	0	218	727	1091	0	2399
70% PFA	108.9	254.1	0	218	727	1091	0	2399
30% PFA + CF	254.1	108.9	0	218	727	1091	2.5	2401.5
50% PFA + CF	254.1	108.9	0	218	727	1091	2.5	2401.5
70% PFA + CF	108.9	254.1	0	218	727	1091	2.5	2401.5
30% GGBS	254.1	0	108.9	218	727	1091	0	2399
50% GGBS	181.5	0	181.5	218	727	1091	0	2399
70% GGBS	108.9	0	254.1	218	727	1091	0	2399

particles are the finest among the three and PFA also possess the lowest gravity density. The chemical compositions of the three binding materials were obtained through XRD analysis with the results shown in **Table 2a** in terms of elements and **Table 2b** in the terms of oxides, respectively. The percentages of free calcium oxide (CaO), tricalcium silicate (C₃S), dicalcium silicate (C₂S), tricalcium aluminate (C₃A), tetracalcium aluminoferrite (C₄AF) and gypsum (CaSO₄·2H₂O) were 17.94%, 54.03%, 8.40%, 10.75%, 5.34% and 3.26%, respectively, by mass for PC. It should be noted that the percentage of free CaO in the PC used for this research was much higher than normal for CEM II PC which may be because that limestone powder was inclusive in LAFARGE cement production as a mineral admixture. For PFA, the sum of the contents of SiO₂ and Al₂O₃ is 76.34% by mass, the total content of alkali calculated as Na₂O is 3.94% by mass and the content of MgO is 1.29% by mass which all satisfy the relevant requirement stipulated in EN 450-1. But it should be noted that the content of sulphuric anhydride, SO₃, is 3.21% by mass which does slightly exceed the limit, 3%, specified in EN 450-1. For GGBS, the contents of CaO, MgO and SiO₂ together are 84.96% by mass and the ratio by mass (CaO + MgO)/(SiO₂) is equal to 1.57 which both satisfy the relevant requirements specified in EN 15167-1. Therefore, both the PFA and the GGBS used for this study can be considered as type II addition of concrete, i.e., pozzolanic or cementitious materials, as per EN standards.

River sand with 4-mm nominal maximum grain size

was used as fine aggregate for preparing cement pastes and concretes. Its grading was obtained through sieve analysis and its fineness modulus was worked out as 2.64 both conforming to EN 12620-1. Gravel stone with 10-mm nominal maximum aggregate size was chosen as coarse aggregate for preparing concretes. Both sand and coarse aggregates were pre-heated in an oven with the temperature of 105 °C for 24 hours and then cooled down in air for 2 hours before they were mixed with other materials for making cement pastes or concretes. The mix proportions by weight for various concrete mixtures were kept constant as 1:2:3:0.6 (binder: sand: coarse aggregate: water) in which binder included PC, PFA and/or GGBS. In various concrete mixtures, PC was replaced by 30%, 50% and 70%, respectively, by mass by either PFA or GGBS. The mix proportions of various compositions of concrete mixtures in a constant volume unit (m³) are shown in **Table 3** as a common comparison basis. Cement pastes were also prepared accordingly in which the binder-to-water ratios were kept the same as that for the reference concretes, i.e., 0.60. However, there were no aggregate for pastes. It should be noted that in this study no cement or concrete chemical admixture, such as water reducing agents or superplasticizers, was added into cementitious pastes or concrete mixtures to avoid its effects coupled with those of PFA and GGBS on PC systems.

In addition, short discrete fibres, Cemfiber in this case, from W R Grace (UK) Ltd. were used to reinforce concrete mixtures containing PFA. The mix proportions of fibre-reinforced PFA concretes in a constant volume

unit (m^3) are also shown in **Table 3**. The volume ratio of fibres in hardened concrete was 0.27%. The Cemfiber has the fibre length of 12 mm, individual fibre thickness of 18 micron, specific gravity density of 0.91 and specific surface area of $225 \text{ m}^2/\text{kg}$. Grace Cemfiber is a monofilament polypropylene fibre developed as a crack controlling additive for cementitious materials. It is normally used to inhibit the formation of small cracks which can occur through plastic shrinkage, premature drying and early thermal changes.

2.2 Mixing procedure and specimen preparation

Cement pastes were prepared using a bench-top mortar mixer. At the end of preparation, the ready mixed cement paste was transferred immediately to a lightly oiled Vicat mould for setting tests. Voids in the paste sample were gently removed. Concrete and fibre-reinforced concrete were produced using a stand-alone drum-type mixer. At the end of preparation, part of the ready mixed fresh concrete mixture was poured into a slump cone for slump test while the rest was poured into cylindrical and prismatic moulds, whose inner surfaces were coated with a thin layer of cream mould oil to prevent the concrete from adhering to them. All the moulds (cylinders and prisms) were filled with concrete in three layers and compacted with a rod after each layer was placed. The cylindrical specimens were 100 mm in diameter and 200 mm in length and were adopted for testing concrete compressive and splitting tensile strengths. The prismatic specimens were $75 \times 75 \text{ mm}^2$ in cross-section and 280 mm in length and were used for monitoring drying shrinkage of concrete. All the freshly prepared concrete prismatic and cylindrical specimens were immediately covered with plastic sheets to prevent moisture loss with water spraying on the top surface of the plastic sheet to keep a moisture environment and placed in normal laboratory environment with the temperature of $15 \pm 3^\circ\text{C}$ and relatively humidity of $50 \pm 10\%$. After 24 hours, all the concrete specimens were de-moulded. The concrete cylinders were then moved into a well-controlled curing cabinet with the temperature of $20 \pm 1^\circ\text{C}$ and relatively humidity of 95% till the age of testing. The prismatic concrete specimens with the dimension of $75 \times 75 \times 280 \text{ mm}^3$ were mounted into shrinkage measurement frames and allowed to dry from all exposed surfaces as per EN 1367-4 in a normal laboratory environment with the temperature of $15 \pm 5^\circ\text{C}$ and relatively humidity of $50 \pm 10\%$, but without designated temperature or relative humidity control, for monitoring drying shrinkage of concrete. Temperature and relative humidity of the laboratory environment were measured twice a day using a portable thermometer and humidity meter. It was found that the actual temperature varied between 12 and 18°C with the average of 15°C and relative humidity between 40% and 60% with the average of 50%.

3. Experimental procedures

3.1 Setting and slump tests

Initial and final setting times of various cementitious pastes were measured using a manual Vicat apparatus conforming to EN 196-3. Slump of fresh concrete mixtures was measured using a portable steel slump cone test set in accordance with EN 12350-2.

3.2 Compression and splitting tensile tests

Compressive and splitting tensile strengths of concretes were tested at the ages of 7, 14 and 28 days conforming to EN 12390-3 and EN 12390-6, respectively. Compressive strength was evaluated under a constant loading rate of 0.25 MPa/s while splitting tensile strength was tested under a constant loading rate of 0.06 MPa/s. Six cylindrical specimens were tested for each concrete mixture at each age, three for compressive strength and three for splitting tensile strength, to ensure repeatability. Cylindrical specimens for compressive strength measurement were capped conforming to EN 12390-3 using sulfur compound before testing.

3.3 Drying shrinkage test

Drying shrinkage tests were performed on the prismatic specimens in accordance with EN 1367-4. Longitudinal length change of the prismatic specimen was monitored using a dial-gage meter mounted on the top of the concrete prismatic specimen (see **Fig. 1**) with its de-moulded reading at 1 day as the reference. The readings of dial-gage were recorded twice a day and the average was taken as the representative value of that day. Then it was converted into shrinkage strain of concrete with

Fig. 1 Experimental set-up for drying shrinkage measurement.

respect to the original length of the prismatic specimen, 280 mm in this case. Three prismatic specimens were measured up to 28 days for drying shrinkage for each concrete mixture and the average was quoted to represent that of the concrete mixture.

4. Results and discussion

4.1 Setting times

The initial and final setting test results of various cement pastes containing PC, PFA and/or GGBS are shown in **Table 4**. It is clear from **Table 4** that the general effect of PFA and GGBS was to delay both the initial and the final settings of cement pastes which can be attributed to lower cement content available in the PC systems containing PFA and GGBS for gaining initial strength as part of the cement was replaced by PFA or GGBS. The hydration of cement and cement compounds, particularly tricalcium silicate (C_3S) which is responsible for the early strength of cementitious materials, was retarded due to lower amount of cement available in PFA and GGBS pastes. The setting of cement paste has been postulated to result from two fundamental steps: coagulation establishing contacts between cementitious grains and the formation of hydrates in the contact zones making the coagulation structure rigid (Brooks *et al.* 2000). For a binder with high cement content, the cement particles are expected to be more closely packed which could result in greater inter-particle contact and thus could speed up setting.

It can also be found from **Table 4** that PFA pastes exhibited much longer initial and final setting times than PC and GGBS ones indicating that the hydration process of PFA was slower than that of PC and GGBS. As the level of PFA replacement increased, both initial and final setting delayed. In a PFA and PC blended system, PFA can prevent cement particles from forming into blocks (Lee *et al.* 2003), hence delay its setting, which can be ascribed to the long setting time of PFA and PC blended system as observed in this study. This effect also increased as the percentage of PFA replacement increased. At the replacement level of 70%, the final setting of PFA paste was not even reached 7.5 hours after the test started. GGBS pastes also had longer initial and final setting times than PC one. It should be noted that both PFA and GGBS are latent hydraulic materials and their pozzolanic reaction relies on the calcium hydroxide released from PC hydration so that to develop strength (Sakai *et al.* 2005; Oner and Akyuz 2007). Therefore cement pastes containing PFA and GGBS exhibited longer setting times than PC paste. Compared with GGBS, the onset and rate of the pozzolanic reaction of PFA was even slower so PFA pastes had much

longer initial setting and final setting times than GGBS ones. It can also be seen that, at low GGBS replacement level up to 30%, its setting times were not much longer than those of PC paste. Similar to PFA, both initial and final setting times increased as the GGBS replacement level increased as less calcium hydroxide was available for its pozzolanic reaction.

4.2 Slump

The slump of various concrete mixtures is presented in **Fig. 2a** and **b** in which **Fig. 2a** is for plain and fibre-reinforced PFA concretes and **Fig. 2b** for GGBS concretes. It can be seen that replacing PC partially by PFA or GGBS led to a higher value of slump suggesting that both PFA and GGBS could enable concrete with better workability, which is ascribed to the smaller particles of PFA and GGBS filling in the gaps among sand, aggregates and cement grains in a blended cement system to facilitate better flow of fresh concrete thus better workability and greater slump. As the replacement level of

Fig. 2 Slump of fresh (a) plain (PFA) and fibre-reinforced PFA (PFA+CF) concretes; and (b) GGBS concretes (GGBS).

Table 4 Initial and final setting times in minutes of various cementitious pastes.

Setting	PC	30% PFA	50% PFA	70% PFA	30% GGBS	50% GGBS	70% GGBS
Initial setting	180	220	270	380	190	210	240
Final setting	240	330	340	-	250	280	300

PFA and GGBS increased, the slump further increased, indicating that better workability was resulted in. Compared with GGBS, PFA concrete had much greater slump, suggesting that it can bring much better workability to concrete. This prominent contribution of PFA in increasing workability of concrete is mainly due to (1) the density of PFA is smaller than that of PC. Accordingly, if PC is replaced with equal amount of PFA by mass, the paste volume of the mixture increases; (2) PFA prevents cement particle from forming into blocks; (3) PFA delays the hydration of cement; and (4) PFA particles are spherical in nature which is able to reduce friction between aggregate, sand and cement grains within concrete and smooth the concrete flow to increase fluidity. The spherical particles have ball-bearing effect which is able to improve consistence and fluidity of fresh concrete (Lee *et al.* 2003).

The effects of Cemfibres on the workability of PFA concrete is also shown in **Fig. 2a**. It is evident that slump decreased as short discrete Cemfibre was added into concrete indicating that workability reduced. The slump loss was found to be 21.5 mm for 30% PFA concrete, 20.5 mm for 50% PFA concrete and 17.5 mm for 70% PFA concrete, respectively. Fibres can form a network structure in concrete, which can restrain the segregation of aggregates in fresh concrete. Due to having larger specific surface area than aggregates, short discrete fibres need to absorb more cement paste to wrap around which increase the viscosity of fresh concrete mixture thus reduces its workability (Chen and Liu 2005).

GGBS when first mixed did not appear as watery as PFA. As can be seen in **Fig. 2b**, at 30% replacement level, GGBS concrete had almost the same slump as PC concrete. But it did become noticeably more watery than PC with increased percentages and thus brought better workability to concrete. The workability of GGBS is improved partly due to its larger fineness thus smaller particles sizes compared to PC. When the same amount of PC by mass was replaced by GGBS, more cement paste by volume is available to fit into voids among aggregate, sand and cement grains, which governs the workability of concrete. Besides, with its smoother texture and glassy surface, GGBS can have an improved mobility and therefore workability, which is demonstrated by the slump test results shown in **Fig. 2b**. The physical characteristics of siliceous by-products of GGBS are also accounted for the improvement of workability. The vitreous (glass) smooth and non-absorbing surface texture of these admixtures is in part responsible for better workability and lower water requirement of pastes and concretes containing siliceous by-products like GGBS (Mehta 1989).

4.3 Compressive strength

The compressive strengths of various concrete mixtures at early ages up to 28 days are shown in **Figs. 3 and 4**, in which **Fig. 3** is for plain and fibre-reinforced PFA

concretes and **Fig. 4** for GGBS concretes. Compressive strength of PC concrete is also shown in **Figs. 3 and 4** for comparison purpose. It can be seen that PFA concretes exhibited significantly lower compressive strengths than PC ones due to the relatively slower pozzolanic reaction of PFA which is often referred as 'a latent hydraulic binder'. The hydration of PC comes from the production of portlandite crystal ($\text{Ca}(\text{OH})_2$) and amorphous calcium silicate hydrate gel ($\text{C}_3\text{S}_2\text{H}_3$) (C-S-H) in high quantities which can be expressed as follows (Taylor 1997):

PFA consists essentially of silicon dioxide (SiO_2) and aluminium oxide (Al_2O_3) which reacts with the lime ($\text{Ca}(\text{OH})_2$) released during PC hydration with its pozzolanic reaction being expressed as follows (Mehta 1983):

Fig. 3 Compressive strength of plain (PFA) and fibre-reinforced PFA (PFA+CF) concretes (a) absolute strength; and (b) relative strength.

Fig. 4 Compressive strength of GGBS concretes: (a) absolute strength; (b) relative strength.

It then forms a stable calcium-silicate-hydrates (C-S-H) and calcium-aluminate-hydrates (CAH) which makes concrete gain strength. Since the pozzolanic reaction of PFA is slow and depends on the calcium hydroxide availability, the strength gain takes longer time for the PFA concrete. Though strength development of PFA is slower at early ages, it can last for a longer period than PC. Therefore PFA concrete may eventually develop higher strength than PC concrete at longer period (Papadakis 2000; Papadakis and Tsimas 2002), but it is not the focus of this study. As the amount of PC replaced by PFA increased, concrete compressive strength further decreased. For instance, the average compressive strengths of concretes with 30%, 50% and 70%, respectively, PC replaced by PFA were 15.06, 7.68 and 3.06 MPa, respectively, at 7 days compared with 25.83 MPa for PC concrete at the same age. Up to 28 days, PFA concretes always exhibited lower compressive strengths than PC ones at the same age. With the addition of short discrete fibres, there was a slight increase in the compressive strength. Except for 30% PFA concrete, there was a slight decrease of the compressive strength at 28 days when fibres were added. Presence of fibres makes the cement matrix more dense thus increases the com-

pressive strength. Similar findings were also reported by Topcu and Canbaz (2007) who found that compressive strength of PFA concretes with plastic propylene fibres were increased compared to those without fibres. However, Siddique (2004) reported contradicted information that generally presence of sunn hemp fibre induces porosity into PFA concrete thus reduces its compressive strength.

GGBS concretes also possessed lower compressive strength than PC ones at early ages as shown in Fig. 4. Similar to PFA, as the replacement level increased, compressive strength of GGBS concrete decreased. For instance, compressive strengths of concrete with 30%, 50% and 70%, respectively, PC replaced by GGBS exhibit 12%, 18% and 42%, respectively, lower than that of PC one at 14 days. However, it can be seen from Fig. 4 that the GGBS concrete at 30% replacement level gained a compressive strength of 31.91 MPa at 28 days which is greater than that of PC concrete at the same age, which is consistent with the findings from Babu and Kumar (2000) who reported that the 28-day compressive strengths of concrete containing GGBS up to 30% replacement level were all slightly higher than that of PC concrete but at the replacement level greater than 30% the strengths were lower than that of PC concrete. It should be noted that the pozzolanic reaction of GGBS is similar to that of PFA which also relies on the calcium hydroxide released by PC hydration so that it takes longer time to develop its strength particularly at high GGBS replacement level (Oner and Akyuz 2007).

Compared to PFA, GGBS concrete consistently demonstrated much higher compressive strength at all replacement levels. For instance, at 50% replacement level, the compressive strength of GGBS concretes are 118%, 158% and 93%, respectively, higher than those of PFA concretes at the ages of 7, 14 and 28 days, respectively. However, as can be found from Figs. 3b and 4b, PFA concrete gained strength faster than GGBS concrete. It can also be found from Figs. 3 and 4 that the variations in compressive strength due to the difference in replacement level of mineral admixture were smaller for GGBS than for PFA which is consistent with the findings from Babu and Kumar (2000) who concluded that the variations in compressive strength due to the different percentages of slag replacement were smaller than the corresponding variations in the case of fly ash.

4.4 Splitting tensile strength

Splitting tensile strengths of various concrete mixtures at early ages up to 28 days are shown in Figs. 5 and 6, in which Fig. 5 is for plain and fibre-reinforced PFA concretes while Fig. 6 for GGBS concretes. It can be found that PFA concretes had significantly lower splitting tensile strength than PC and GGBS concretes. As the amount of PFA replacement level increased, the splitting tensile strength of PFA concretes further decreased (see Fig. 5a) indicating the slow hydration and thus strength development process of PFA. Relative

Fig. 5 Splitting tensile strength of plain and fibre-reinforced PFA concretes: (a) absolute strength; and (b) relative strength.

splitting tensile strengths of plain and fibre-reinforced PFA concrete in percentage of its corresponding 28-day value are presented in **Fig. 5b** with respect to age. It can be seen that PFA concrete gained tensile strength faster than PC concrete due to its pozzolanic reaction. For instance, at 7 days, PFA concrete only gained 90%, 59% and 79%, respectively, of its corresponding 28-day tensile strength at the replacement level of 30%, 50% and 70%, respectively. These values increased to 93%, 75% and 82%, respectively at 14 days while, during the same period, the splitting tensile strength of PC concrete only increased from 97% to nearly 100% of its 28-day value.

The splitting tensile strengths of various PFA concretes with short discrete fibres are also shown in **Fig. 5a**. It can be seen that, when fibres were added into PFA concretes, in general, there is an increase in splitting tensile strength. Overall the splitting tensile strength increment varied from 1% to 44% for the three PFA concrete mixtures at 30%, 50% and 70%, respectively, replacement level at all the three ages investigated, except that at 7 days the splitting tensile strength of fibre-reinforced 70% PFA concrete was found to be 8% lower than that of plain PFA concrete at the same age. This may be because of the acceptable variation of concrete

Fig. 6 Splitting tensile strength of GGBS concretes: (a) absolute strength; and (b) relative strength.

properties as the splitting tensile strength for both mixtures were very low, i.e., 0.65 MPa for plain PFA concrete and 0.60 MPa for fibre reinforced PFA concrete, at this very early age and that the blended PFA and PC matrix may not be strong enough for the fibres to take effective. Topcu and Canbaz (2007) also found that PFA concrete with polypropylene fibres exhibited higher splitting tensile strength than the reference PFA concrete without fibres. Siddique (2004) also reported that there was an increase in splitting tensile strength of PFA concrete when san fibres was added compared to that without fibres. Both of their findings are consistent with this research. As the age increased, this strength increment effect due to the addition of fibres generally became more prominent. For instance, the splitting tensile strength increased 18%, 27% and 1%, respectively, at the PFA replacement level of 30%, 50% and 70%, respectively, at 14 days compared with their corresponding reference PFA concrete without fibres. These values increased to 20%, 26% and 42%, respectively, at 28 days. As the age of concrete increases and hydration of cement progresses, the bond between fibres and cement matrix strengthens and fibres become more efficiency in resisting tensile stress. Thus a higher splitting tensile strength is resulted in.

Fig. 7 Drying shrinkage of PFA concretes.

Fig. 8 Drying shrinkage of fibre-reinforced PFA concretes.

As far as GGBS concrete, it exhibited different behaviour from PFA ones. As can be seen from **Fig. 6** the concrete with 30% PC replaced by GGBS possessed consistently higher splitting tensile strength than the reference PC one. But as the replacement level increased to 50% and 70%, GGBS concrete gained lower splitting tensile strength than PC concrete at the age younger than around 21 days but they managed to gain higher tensile strength than PC concrete beyond this age to 28 days. Similar to PFA, GGBS concrete also developed splitting tensile strength faster than PC (see **Fig. 6b**).

Compared with PFA concrete, the splitting tensile strength of GGBS concrete was much higher. For instance, GGBS concrete developed splitting tensile strength 32%, 34% and 33%, respectively, higher than that of PFA concrete at the ages of 7, 14 and 28 days, respectively, at the replacement level of 30%. As the replacement level increased, the difference became even greater. At 50% replacement level, the splitting tensile strength of GGBS concrete was 109%, 102% and 80%,

respectively, higher than that of the corresponding PFA ones at 7, 14 and 28 days, respectively. These strength increments further increased to 226%, 266%, and 269%, respectively, at 70% replacement level indicating that GGBS has faster pozzolanic reaction thus strength development than PFA.

4.5 Free shrinkage

The results of drying shrinkage tests are presented in **Figs. 7, 8** and **9**, respectively, for plain PFA, fibre-reinforced PFA and GGBS concretes, respectively, at early ages up to 28 days. **Figures 7** and **9** indicate that in general replacing PC partially by PFA or GGBS reduced drying shrinkage of concrete. The reduction in shrinkage induced by PFA additions in the concrete is predominantly due to the reduction in pore size as a result of their finer particle size. The loss of free water causes little to no shrinkage but the loss of water from the capillaries, held by hydrostatic tension, causes significantly larger shrinkage (Güneyisi 2010). The addition of PFA and its smaller pore size will reduce shrink-

Fig. 9 Drying shrinkage of GGBS concretes.

age as drying shrinkage is directly associated with the pore size (Mokarema 2005).

The results seem to suggest that at 30% replacement level the drying shrinkage of PFA and GGBS concretes at certain ages was greater than that of PC one. However, this may be due to the acceptable measurement error. The resolution of the dial-gage is 0.001 mm which corresponds to 3.6 micro strains of the prismatic specimen. This resolution was not high enough to differentiate the small change in the drying shrinkage in one-day period. **Figures 7 and 9** also indicate that as the replacement level increased, the drying shrinkage further decreased. These results suggest that though PFA and GGBS concrete had lower strength than PC concrete at early ages but they also possessed lower drying shrinkage than PC concrete at the same age which could be a benefit of using these mineral admixtures in concrete. Compared with PFA, GGBS had more prominent effect in reducing drying shrinkage of concrete, particularly at high replacement level. For instance, at 50% and 70% replacement levels, the drying shrinkage of plain GGBS concrete was 3.4% and 16.9%, respectively, lower than those of plain PFA concrete at 28 days.

Addition of short discrete fibres into PFA concrete further reduced its drying shrinkage as can be seen from **Figs. 7 and 8**. For instance, PFA concrete at 30%, 50%, and 70%, respectively, replacement level with fibres exhibited 6.9%, 3.4%, and 6.5% reduction in drying shrinkage when compared to the corresponding reference PFA concrete without fibres at 28 days even at this very low fibre dosage with the volume ratio of 0.27%. When short discrete fibres is added into concrete mixtures, they are distributed in a randomly manner. Some of the fibres are distributed parallel to shrinkage strain. When concrete shrinks, these fibres parallel to shrinkage strain restrain the movement of concrete, thus reduce drying shrinkage.

5. Conclusions

This study investigated the effects of PFA and GGBS, as CEM Type II addition for making concrete, on PC systems at early ages. The examined properties included setting times, slump, compressive and splitting tensile strength, and free shrinkage. The following conclusions can be drawn:

- (1) Partially replacing PC by PFA or GGBS results in much longer setting times with PFA the longest among the three. As the replacement level increased, the setting of both PFA and GGBS pastes further delayed. But at the replacement level up to 30%, the initial and final setting times of GGBS paste were comparable to those of PC one;
- (2) Partially replacing PC by PFA or GGBS can significantly increase the workability of concrete with PFA having more prominent effect than GGBS. But addition of short discrete fibres into PFA concrete significantly reduced its workability even at a very low fibre dosage;
- (3) While PFA concrete exhibited significantly lower compressive and splitting tensile strengths than PC and GGBS ones, it gained strength faster than PC ones. As the level of PFA replacement increased, strengths of PFA concrete decreased. Addition of short discrete fibres into PFA concrete resulted in a slightly increased compressive strength but a significantly increased splitting tensile strength. As the age increased, this splitting tensile strength increasing effect due to fibre addition became more prominent;
- (4) At the replacement level of 30%, GGBS concrete exhibited higher splitting tensile strength than PC concrete up to 28 days and higher compressive strength at 28 days. As the replacement level further increased, strengths of GGBS concrete decreased and became lower than those of PC concrete. However, it managed to gain higher splitting

tensile strength than PC concrete at 28 days at the replacement level up to 70% due to pozzolanic reaction; and

- (5) Partially replacing PC by PFA or GGBS reduced drying shrinkage of concrete. As the replacement level increased, the free shrinkage of PFA concrete decreased indicating that PFA was able to reduce shrinkage of concrete at early ages. Compared with PFA, GGBS had more prominent effect in reducing drying shrinkage of concrete. By incorporating discontinuous fibres into PFA concrete, free shrinkage of concrete was further reduced suggesting the great benefit of using fibre reinforcement in PFA concrete.

Acknowledgement

The financial support from Brunel Research Initiatives and Enterprise Fund (BRIEF) under the grant LBK909 (904/2009) and Engineering and Physical Sciences Research Council (EPSRC) under the grant EP/I031952/1 is greatly appreciated. The authors would also like to thank United Kingdom Quality Ash Association (UKQAA) and HCCP Hargreaves Coal Combustion Products Limited (UK) for providing PFA, Cementitious Slag Makers Association (CSMA) UK and Hanson Heidelberg Cement Group (UK) for providing GGBS, and W R Grace (UK) Ltd. for providing Grace Cemfibre fibres to this research. The authors would also like to thank Lorna Anguilano at Experimental Technique Centre at Brunel University who helped conducting chemical analysis for PC, PFA and GGBS samples to this research.

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