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Synthesis and characterization of mortars with circulating fluidized bed combustion fly ash and ground granulated blast-furnace slag

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HIGHLIGHTS

- CFBC fly ash has the potential replacement of partial cementing materials.
- Addition of CFBC fly ash reduces the compressive strength and increases length change.
- GGBFS can be effectively used in reducing the length change.
- The amount of CFBC fly ash replacing cement was recommended to be limited below 20%.
- The amount of GGBFS replacing cement was no less than 70%.

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ABSTRACT

The purpose of this study to investigate the synthesis and characterization of cement-based composites with circulating fluidized bed combustion (CFBC) fly ash and ground granulated blast-furnace slag (GGBFS). Firstly, CFBC fly ash shall be examined to confirm to the chemical and physical requirements according to ASTM C821-09. Secondly, the properties of mortars mixed with cement, CFBC fly ash and GGBFS as cementitious materials were explored. Test results showed that CFBC fly ash does not comply with the chemical and physical requirements in ASTM C821-09 (Standard specification for lime for use with pozzolans), but accords with the requirements of ASTM C593-11 (Specification for fly ash and other pozzolans for use with lime for soil stabilization). Based on the test results, CFBC fly ash has the potential replacement of partial cementing materials and as an alternative of pozzolan. The initial setting time of mortars increases with an increasing amount of cement replacement by CFBC fly ash and GGBFS. The compressive strength of mortars with GGBFS and CFBC fly ash is lower than that of ordinary Portland cement (OPC) mortar. The more the CFBC fly replaces OPC, the less the compressive strength obtains. Meanwhile, CFBC fly ash would results in a higher length change when adding up to 30%. In terms of engineering property, environment and economic, the amount of OPC replacement by CFBC fly ash was recommended to be limited below 20%, while by GGBFS it was recommended to be limited below 70%.

1. Introduction

The construction materials industry is under growing stress to decrease the energy used in manufacture of Portland cement and the related greenhouse gas emissions [1]. To reduce the environmental impact of construction, the demand for using a greater proportion of industry by-products or developing several alternative binders to replace Portland cement has become urgently needed [2].

Circulating fluidized bed combustion (CFBC) is a much more efficiently clean and environmental-friendly coal combustion technique when comparing with traditional coal combustion [3,4]. This technology has many advantages, such as a wide-ranging fuel flexibility, low combustion temperatures, lower SO_2 and NO_x emissions, as well as a high combustion efficiency [5–7]. CFBC ash is different from most typical coal combustion by-products for high contents of f-CaO and SO_3 [3]. In addition, CFBC ash comprises mainly coarse and angular, flaky, and irregular particles with a broad particle size range [8,9]. Ground granulated blast furnace slag (GGBFS) is a by-product from the blast-furnaces of iron and it is a very beneficial in the mortar and concrete production [10–12]. GGBFS can be mixed with cement to produce a pozzolanic reaction and to form calcium silicate hydrate (C—S—H) gel, which is similar to clinker. However, this process is very slow

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unless the GGBFS is activated by an alkaline compound such as calcium hydroxide (CH) [13,14], which is luckily formed during the Portland cement hydration.

CFBC fly ash and GGBFS are promising admixtures for construction and building materials. The main hydration products of CFBC fly ash and GGBFS are hydrated calcium silicate (C—S—H), ettringite (AFt), gypsum and some portlandite [3,4,15]. These admixtures replacing partial cement can improve the properties of concrete and positively contribute to material cost savings and the recycling of waste resources. Previous research [16–18] found that increasing the replacement percent of GGBFS by cement is to prolong the setting times of concrete. Oner and Akyuz [19] tried to find the optimum level of GGBFS on the compressive strength of concrete and revealed that the compressive strength of concrete mixtures containing GGBFS increases as the amount of GGBFS increase. Substitution of GGBFS around 55% seems to be the optimum level for the desired compressive strength. After the optimum point, the addition of GGBFS does not improve the compressive strength. Chi and Huang [9] stated that CFBC fly ash has an optimistic influence on compressive strength, splitting tensile strength, and sulphate attack resistance of hardened roller compacted concrete. Shen et al. [3] found that CFBC fly ash had a little influence on the strength of the Portland cement when its content was under 20%, but the strength reduced meaningfully if the CFBC fly ash content was over 20%. Chen et al. [15] pointed out that 15–20 wt% CFBC fly ash and 10–30 wt% Type F fly ash (FA), as replacement of GGBFS, were the optimal values for the no-cement SFC (Slag-Class F fly ash-Circulating fluidized bed combustion fly ash) binder to obtain the best compressive strength. Nguyen et al. [20] confirmed the important role of CFBC fly ash to enhance the mechanical properties of the high-volume low calcium fly ash (HVFA) cement pastes. The main hydration products of the hardened paste are ettringite (AFt) and calcium aluminum silicate hydrate (C—A—S—H) gel [15].

CFBC fly ashes as cement or concrete mineral admixtures have been reported due to its good pozzolanic activity and binding property [21,22]. Shen et al. [36] pointed out that anhydrite in CFBC ash can be used as an effective setting retarder but result in lower mortar compressive strength. The influence is harmless to bulk stability of cement paste with appropriate anhydrite addition. However, high swelling behaviour of CFBC fly ash was found to be harmful because of relatively high sulphate and lime contents [23]. Thus, the utilization percent of CFBC fly ash remains limited.

Blondin and Anthony [24] indicated that CFBC fly ash meets neither North America nor European Standards for components or additives in concrete. For an admixture used in cement and concrete, the SO_3 content should be kept within limits to provide resistance against severe swelling and cracking of hardened cement mixtures. ASTM 618 [25] limits the SO_3 content of CFBC fly ash to 5% when the ash is to be used as a pozzolanic material. In this study, CFBC fly ash shall be examined to confirm to the chemical and physical requirements according to the ASTM C821-09 [26] and the properties of mortars mixed with less OPC, CFBC fly ash and more GGBFS as cementitious materials were investigated.

2. Experimental program

2.1. Materials

ASTM Type I ordinary Portland cement (OPC), GGBFS, and CFBC fly ash were used in this study. Their chemical compositions and physical properties are listed in Table 1. A natural river sand was used as a fine aggregate in the manufacture of mortars. The sand had a fineness modulus of 3.10, a bulk density of 2620 kg/m^3, and an absorption of capacity of 2%.

Table 1
Chemical compositions and physical properties of OPC, GGBFS and CFBC fly ash.

	OPC	GGBFS	CFBC fly ash	Lime
Chemical compositions (%)				
CaO	63.8	40.67	56.8	55.42
SO_3	2.20	0.56	32.4	–
SiO_2	20.6	34.58	5.22	3.28
Fe_2O_3	3.20	0.44	0.58	0.52
Al_2O_3	5.40	13.69	2.21	1.47
Na_2O	0.32	0.15	–	–
MgO	1.98	7.05	2.06	1.08
K_2O	–	–	0.53	–
L.O.I.	1.0	1.13	–	40.7
Physical properties				
Specific gravity	3.05	2.88	2.78	2.71
Specific surface area (cm^2/g)	3640	4350	3000	3150
Initial setting time (min)	150	–	–	–
Final setting time (min)	230	–	–	–

2.2. Mixture proportion and specimen preparation

Mixing of OPC mortars and blended cement mortars with 526 kg of binder per cubic meter according to ASTM C 192 [27] was designed. The liquid/binder ratio was kept at a constant of 0.5. Twelve different blended cements were prepared to study the effects of cement replacement with various proportions of OPC, GGBFS, and CFBC fly ash. The selected replacement levels of GGBFS and CFBC fly ash were 60%, 70%, and 80% and 10%, 20%, and 30% by weight of OPC, respectively. Within mixture designation SxCy, x represents the level of replacement (in wt%) of GGBFS and y represents the level of replacement (in wt%) of CFBC fly ash as OPC. The mix proportions are shown in Table 2.

All mixtures were prepared by following steps: the OPC, GGBFS, CFBC fly ash, and sand were mixed in a laboratory mixer for 2 min to ensure that the dry materials are uniformly blended, then 70% water was added to the mixer over a period of 2 min while the mixing continued. And then the remaining water was poured into the mixer and the mixture was mixed again for an additional 1 min. The specimens were cast and kept in steel molds for 24 h, and then they were demolded and moved into a curing room at a relative humidity of 80% RH and 25 °C until test ages.

2.3. Methods

This study was divided into two parts. In the first part, CFBC fly ash shall be examined to comply with the chemical and physical requirements as listed in Table 3 according to the ASTM C821-09

Table 2
Mix proportions and calculated molar ratios for mortars.

Mix No.*	Cement/GGBFS/CFBC ash (mass ratio)	Water (kg/m^3)	Cement (kg/m^3)	GGBFS (kg/m^3)	CFBC fly ash (kg/m^3)	Fine aggregate (kg/m^3)
OPM	10/0/0	263	526	–	–	1441
S6C0	4/6/0	263	210	316	–	1432
S7C0	3/7/0	263	158	368	–	1428
S8C0	2/8/0	263	105	421	–	1426
S6C1	3/6/1	263	158	316	53	1428
S6C2	2/6/2	263	105	316	105	1425
S6C3	1/6/3	263	53	316	158	1422
S7C1	2/7/1	263	105	368	53	1425
S7C2	1/7/2	263	53	368	105	1423
S7C3	0/7/3	263	–	368	158	1420
S8C1	1/8/1	263	53	421	53	1423
S8C2	0/8/2	263	–	421	105	1420

* Within mixture designation SxCy, x represents the level of replacement (in wt%) of GGBFS and y represents the level of replacement (in wt%) of CFBC fly ash as cement.