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Utilization of circulating fluidized bed combustion ash in producing controlled low-strength materials with cement or sodium carbonate as activator

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HIGHLIGHTS

- High volume of CFBC fly ash and bottom ash were utilized in CLSM.
- The CLSM strength was significantly fluctuated by curing condition.
- CFBC ash led expansion of CLSM.
- Cement or sodium carbonate could be used as activator for CLSM.
- CLSM with CFBC fly ash could pass heavy metal leaching criteria.

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ABSTRACT

The present study investigates the fresh and hardened properties of controlled low-strength materials (CLSM) utilizing circulating fluidized bed combustion (CFBC) ashes, activated with cement or sodium carbonate. Engineering properties such as flowability, settlement, setting behavior, compressive strength, and hydration characteristics were evaluated. The results provided new insights, demonstrating that CFBC ashes can be effectively utilized in producing CLSM with suitable material design as the CLSM could achieve the required performances specified in the ACI 299R-13. The CLSM mixtures showed a self-destruction characteristic due to the formation of ettringite, while it showed stable strength development in a dry condition.

1. Introduction

Circulating fluidized bed combustion (CFBC) boilers are considered as a promising clean coal technology owing to their high combustion efficiency and low environmental footprint [1]. As a result, they are gradually replacing conventional boilers in thermal power plants [1]. In construction industries, recycling the coal ash generated from conventional pulverized coal combustion (PCC) is now becoming popular [2–10]; however, the use of by-products generated from CFBC boilers is only being discussed recently. The generation of CFBC ash is anticipated to become double that of conventional PCC ash given the same amount of electricity being generated, owing to the use of a low-grade coal and desulfurization agent [11]. Moreover, the rapid growth of CFBC technology implies that the generation of CFBC ash will simultaneously increase, urgently necessitating the development of various methods for recycling such by-products [11–25].

The chemical composition and characteristics of coal ash generated from CFBC boilers significantly differ from those of PCC boilers, as the coal is fired at a relatively lower temperature and a large amount of limestone is used for desulfurization [17]. Accordingly, CFBC ash is rich in free lime and anhydrite, has an irregular particle shape, and shows hydraulic reactivity [17,26]. On one hand, its hydraulic reactivity can be viewed as its potential to be a cementitious material; on the other hand, numerous technical concerns have been raised owing to the hydraulic reactivity of the ash. CFBC ash undergoes an exothermic reaction when mixed

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with water, inducing significant expansion during the hardening process [13,15,20]. Unlike PCC fly ash, which is spherical and has a narrow particle size range, CFBC ash has an irregular shape with a wide particle size range, implying that its use as an ingredient for concrete may cause difficulty in quality control of a final product [21,23]. In addition, it fails to satisfy the ASTM standard for additives of Portland cement owing to its high content of SO_3 [11]. Various alternatives for utilizing CFBC ash were investigated, for example, modifying the ash to mitigate its effect on the hydration of cement [16,21], recycling the ash in the production of special types of concrete such as roller compacted concrete used in road construction [11], autoclaved aerated concrete [25], and alkali-activated cement [17–19,27].

Controlled low-strength materials (CLSM), often used as cemented paste backfills, are one feasible application where a large amount of CFBC ash can be utilized [28–30]. The typical engineering properties required for CLSM are low strength for allowing future excavation and high flowability for self-compacting [31]. Moreover, utilization of non-standard materials in the fabrication of CLSM is highly recommended by the ACI Committee 229 [31]; thus, numerous studies were conducted in this respect [32,33,34]. For instance, the use of stockpiled CFBC fly ash was shown to be technically feasible for fabricating CLSM with a low content of cement [30]. In the study, CLSM mixtures in which cement is partially or fully replaced with CFBC fly ash showed a reduced setting time and increased strength; however, the flowability was decreased, requiring an engineered material design [30,35].

The present study investigated the fresh and hardened properties of CLSM utilizing CFBC ash (both fly ash and bottom ash) activated with cement or sodium carbonate. An experimental study was systematically designed to assess the feasibility of utilizing the CFBC ash in the fabrication of CLSM in terms of engineering and environmental aspects. The flowability, settlement, setting behavior, compressive strength, and hydration products of the CLSM were investigated to assess their engineering properties. For the environmental impact assessment, a heavy metal leaching test in accordance with the toxicity characteristic leaching procedure (TCLP) specified in the US EPA Method 1311 [36], along with pH measurement, was conducted by using hardened CLSM mixtures.

2. Experimental procedure

2.1. Materials and mix proportions

The CFBC fly ash and bottom ash were obtained from the Gunsan Power Plant in South Korea. In the power plant, 100% petroleum coke is used as the coal source, and the annual production of ash is estimated as 200,000 tons. In this study, the CFBC fly ash was used as the binding material, and either Portland cement (type I) or sodium carbonate (98% purity) was added as the activator at a small dosage. River sand was used as aggregate for the CLSM. The specific gravities, water absorption, and fineness modulus of river sand were 2.65, 0.27%, and 2.95, respectively. The specific gravities of CFBC fly ash and bottom ash, which measured using ethanol instead of water due to their hydraulic reactivity, were 2.40 and 2.72, respectively. The particle size distribution of materials used in this study is shown in Fig. 1. The particle sizes of fly ash and bottom ash, cement were measured using by laser diffraction equipment (HELOS, Sympatec GmbH, Germany), while that of river sand was obtained by sieve analysis.

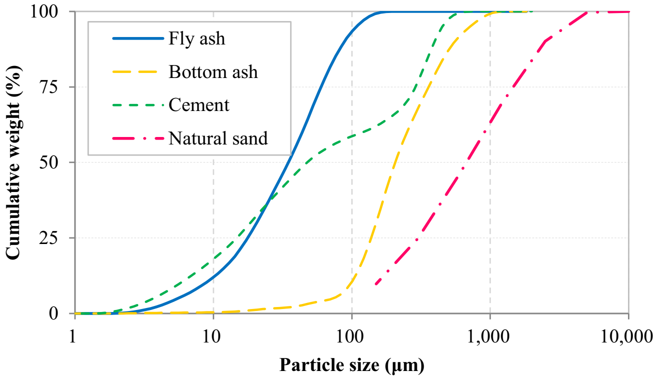

Fig. 1. Particle size distributions of materials used.

The chemical composition and the crystalline phases of the CFBC fly ash and bottom ash were analyzed using an X-ray fluorescence (XRF) spectrometer (RIX-2000, Rigaku Inc., Japan) and X-ray diffraction (XRD) spectrometer (X'Pert^3 Pro MRD, PANanlytical, Netherlands), respectively, and the results are presented in Table 1 and Fig. 2. The CFBC fly ash was rich in SiO_2, CaO, and SO_3, while the CFBC bottom ash was rich in CaO and SO_3. These results indicate that the CFBC ashes used in this study can be treated as a typical ash generated from CFBC boilers [37]. The loss on ignition (LOI) of the fly ash was much higher than that of the bottom ash. It should be noted that sulfur is mostly distributed around the surface of the ash because the desulfurization of the flue gas occurs on the surface of the calcium carbonate supplied into a CFBC boiler [37].

The XRD patterns of the CFBC ash showed that free lime (f-CaO), anhydrite ($CaSO_4$), and quartz (SiO_2) were present along with a small quantity of portlandite ($Ca(OH)_2$). In addition, the peak intensity of calcite was relatively lower, indicating that it was mostly consumed for desulfurization. In addition, this indicates that LOI of the ashes is attributed to the dehydration of portlandite and unburned carbon rather than decomposition of calcite. The crystalline phases present in the fly ash and bottom ash were similar, while a higher sulfate content in the bottom ash implies that it has a higher amount of anhydrite. The XRD patterns of the raw fly ash also showed peaks associated with the presence of ettringite, which was presumably formed upon contact with atmospheric moisture during storage.

The mix proportions of the CLSM mixtures are listed in Table 2, and are expressed in terms of the weight fraction of materials used per weight of fly ash. The mix proportions can be classified into two categories, S-series and B-series mixtures, in which sand and bottom ash, respectively, are used. The unit weight of water in the S-series mixtures was determined to satisfy the requirement of high flowability (flow diameter above 200 mm) specified by ACI 229R-13 [31] and was adopted in all mixtures. The weight fraction of the aggregate was determined based on a previous study

Table 1
Chemical composition of CFBC fly ash and bottom ash (wt%).

Material	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	K_2O	TiO_2	P_2O_5	LOI[a]
CFBC fly ash	23.2	29.7	13.8	6.6	1.6	6.9	1.5	1.0	1.1	14.7
CFBC bottom ash	51.1	11.0	6.8	4.5	1.3	19.9	0.3	0.5	0.9	3.7

[a] Loss on ignition measured by ASTM D7348 [38].

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