Construction and Building Materials 156 (2017) 728–738

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Circulating fluidized bed combustion ash as controlled low-strength material (CLSM) by alkaline activation

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HIGHLIGHTS

- CLSM was fabricated using alkaline activation of CFBC ashes.
- CLSM satisfied the properties outlined in ACI 229.
- Ettringite was identified as a main reaction product.

ARTICLE INFO

Article history:
Received 25 May 2016
Received in revised form 1 August 2017
Accepted 1 September 2017

Keywords:
Controlled low-strength material
Circulating fluidized bed combustion ash
Alkali-activation
Calcium sulfate
Industrial by-product

ABSTRACT

The present study is aimed at providing a useful means of treating and utilizing the CFBC ash as controlled low-strength material (CLSM). The CLSM in this study was produced by activating a mixture of CFBC fly ash, bottom ash and blast furnace slag with sodium hydroxide (NaOH) solution. The characteristics of the CLSM were evaluated by the main factors such as flow, bleeding and compressive strength as stated in ACI 229, along with initial setting time and XRD patterns. The CLSM showed delayed strength development due to the reactivity of calcium sulfate in CFBC fly ash and bottom ash. This effect is evidenced by the XRD pattern of the CLSM at 7 and 56 d which showed the consumption of gypsum as a source of calcium sulfate, to produce the reaction product ettringite.

1. Introduction

Circulating fluidized bed combustion (CFBC) is a clean, advanced technology for the combustion of coal. It is capable of significant reduction in SO_2 and NO_x emission when burning fuels with high sulfur content [1,2]. The operating temperature of CFBC is 800–900 °C which is much lower than that of conventional pulverized coal combustion (PCC: ranging 1300–1700 °C) and therefore is particularly well suited for reduction in NO_x emissions [1,3,4]. The in situ removal of SO_2 in CFBC is achieved by the use of limestone without grinding or processing [4,5]. In addition, high efficiency, stable operation over a large loading range are the advantages that CFBC possesses over conventional combustion technology [5]. Consequently, the adoption of CFBC has been consistently increasing ever since its commercialization in the 1970s and has now become the most widely used fluidized combustion bed in the world [6].

However, treatment of the resulting by-product of CFBC power plants, ash, remains a challenge [7,8]. Despite the self-cementing property of CFBC ashes, large specific surface area leads to high consumption of water in comparison with that of PCC ashes. This is due to the relatively lower firing temperature in the CFBC boiler, its highly exothermic reaction with water, low content of SiO_2 and Al_2O_3, and excessive expansion and durability concerns for the final product due to the presence of anhydrite and free lime [1,9–11]. CFBC ash, therefore, has failed to satisfy European or North American standards for additives or components in concretes, owing to the aforementioned drawbacks and difficulties involved in its application as an additive in construction materials [11].

On the other hand, attempts have been made in previous studies to utilize the ashes as a construction material [12,13]. The self-cementing property of CFBC ashes was used as a binder in the production of ash water dense suspension (AWDS) in a study conducted by Anthony et al. [10], where the ashes were loaded into a spherical reactor and mixed with water at 170 °C and 0.5–0.85 MPa. Sheng et al. (2007) investigated means of utilizing

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http://dx.doi.org/10.1016/j.conbuildmat.2017.09.001
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the self-cementitious property of CFBC fly ash as an additive for cement [7,9]. While a decrease in the setting time was observed as the amount of CFBC fly ash was added increased, this was accompanied by expansion and water consumption [9]. These characteristics of CFBC ashes can be utilized as cement admixtures, for instance as a setting retarder replacing gypsum [14]. A number of studies focused on the utilization of bottom ash by means of alkali-activation [15–17]. In particular, synthesis of geopolymer (i.e., geopolymer brick) using CFBC bottom ash was attempted [1,18,19]. Nonetheless, an appropriate solution was provided for bulk treatment to utilize the characteristics of CFBC ashes that are disadvantageous for use as a construction material is provided.

In this context, the utilization of CFBC ashes for the fabrication of controlled-low strength material (CLSM) may provide a valid alternative in terms of engineering properties and environmental perspective. CLSM is a cementitious material with low strength and with self-compacting ability. It is used in place of conventional compacted fill [20]. The American Concrete Institute states that CLSM is in a flowable state at the time of placement and has compressive strength of 8.3 MPa (at most) at 28 d [21]. The engineering property of CLSM is far below that of conventional structural materials. Development of low strength CFBC ashes due to its high consumption of water may be desirable for CLSM in this respect. Furthermore, expansion and low durability due to the high content of sulfur of CFBC ashes are of less concerned applications of CLSM as a structural or void fill that does not act as a main structural component. From an environmental perspective, solidification of hazardous materials such as heavy metals was achieved using CLSM [22]. The leaching potential of the materials immobilized by a cementitious matrix is known to be low [23,24] and thus the environmental issues in this respect are of less concern. The use of industrial by-products such as mine tailings or coal ash in the production of CLSM were investigated in previous studies, which showed that the leaching potential of heavy metals incorporated in the materials is less of concern [25,26]. Accordingly, a large amount of industrial wastes are used as a constituent material in CLSM, i.e., as an aggregate [27,28] or cementitious binder replacing Portland cement [29,30]. Meanwhile, an alkali-activated material, or also known as geopolymer, consists of aluminosilicate phase [24,31], which is reported to possess higher heavy metal immobilization capacity in comparison with that of calcium silicate hydrate phase [32]. Recent studies of alkali-activated materials showed that these materials are effective for immobilization of hazardous ions [33,34], and exhibit excellent durability performance [31,35,36]. In addition, the carbon emission that accompanies production of geopolymer is less than that from cement [37], providing another environmental benefit. The ease of controlling the strength of alkali-activated CLSM without use of cement was evidenced by Lee et al. [38]. In particular, while the strength of CLSM made with cement can be controlled by the amount of cement, water and aggregate, there are more options to modify the characteristics of CLSM made by alkali-activation, such as the concentration of the alkali-activator. Accordingly, the alkali-activation of CFBC ashes is high potential not only to result in a material with low strength that is well suited for CLSM, but which could also provide a solution for bulk treatment of CFBC ashes. To the best of authors' knowledge, alkaline activation of CFBC ashes has not been investigated as means of developing sustainable cementitious material which can be utilized as CLSM.

A recent increase in the adoption of circulating fluidized bed combustion (CFBC) in coal power plants has inevitably triggered concerns about the mass generation and disposal of CFBC ashes around the world. The present study provides a useful means of treating and utilizing the CFBC ashes in CLSM. The CLSM was produced by activating a mixture of CFBC fly ash, bottom ash, and blast furnace slag, with NaOH. The characteristics of the CLSM were evaluated by the main factors such as flow, bleeding and compressive strength as stated in ACI 229 [20], along with initial setting time and XRD pattern. In particular, the XRD pattern analysis revealed the reaction components of the raw material and the reaction products to elucidate the development of strength in CLSM. Finally, correlation was made with the results in the previous studies and that recommended by ACI 229 [21].

2. Experimental program

2.1. Materials

CFBC fly ash and bottom ash obtained from a CFBC power plant in South Korea were used as a binder and fine aggregate, respectively. Blast furnace slag (BFS) obtained from a steel plant was also used as a binder to replace the CFBC fly ash and to enhance the mechanical properties of the final product. The XRD pattern of the CFBC fly ash, bottom ash, and slag is shown in Fig. 1. Table 1 shows the chemical composition of CFBC fly ash and bottom ash, and BFS measured by X-ray fluorescence (XRF) spectrometry. NaOH of a pellet type with a specific gravity of 2.13, was mixed with distilled water to make an alkali-activator of a designated molarity. Fig. 2 shows the particle size distribution of the raw

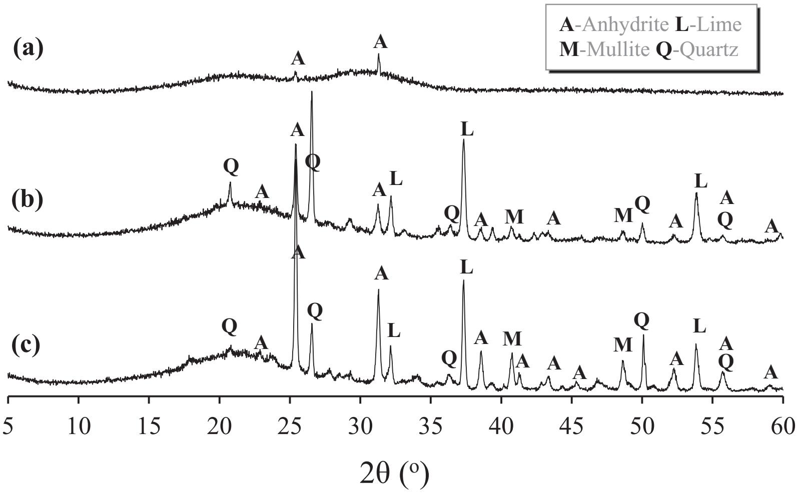

Fig. 1. XRD patterns of raw materials (a) blast furnace slag; (b) CFBC fly ash; (c) CFBC bottom ash.