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Alkali-treated incineration bottom ash as supplementary cementitious materials

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HIGHLIGHTS

- Metallic aluminum in IBA is removed by alkali treatment.
- Pozzolanic properties of IBA is enhanced after alkali treatment.
- The alkali-treated IBA possesses pozzolanic reactivity similar to the coal fly ash.
- The resulting IBA blended cement mortar has comparable density and strength to the control.

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ABSTRACT

Municipal solid waste incineration bottom ash (IBA) contains metallic aluminum which generates gas when in contact with cement paste. To increase the utilization potential of IBA, alkali treatment for removal of metallic aluminum is proposed. This paper investigated the effects of alkalinity, reaction temperature, and alkali type on the properties of alkali-treated IBA and the resulting IBA blended cement mortars. Results showed that alkali treatment effectively removes the metallic aluminum in IBA and minimizes aeration in IBA blended cement mortars. Furthermore, alkali treatment enhances pozzolanic properties of IBA and the resulting alkali-treated IBA possessed pozzolanic reactivity similar to coal fly ash. The strength activity indices (SAI) of the resulting alkali-treated IBA blended cement mortars were above 75% of the control at the age of 28 days and beyond. In particular, the mix incorporating IBA treated with NaOH (pH = 14) at 25 °C has a strength comparable to that of control at the age of 90 days. The proposed method provides an effective, efficient, and fast means for the removal of metallic aluminum in IBA and the alkali-treated IBA can potentially be used as supplementary cementitious materials for concrete production.

1. Introduction

With economic development and population growth, generation of municipal solid waste (MSW) around the world has increased over the years. Compared to direct landfill of MSW, incineration provides effective means to reduce the mass and the volume of MSW by 80% and 90%, respectively [1] and to convert waste into green energy. The incineration ash residues, however, still need to be managed and are often disposed of by landfill. For land and resource scarcity cities or countries like Singapore, utilization of incineration ash residues to diverge them from landfill is of great interest and significance [2].

Two types of ash residues are commonly found after incineration, the incineration bottom ash (IBA) which is the non-combustible residue of combustion that falls on the bottom of incinerator [3] and the incineration fly ash (IFA) which is the fine residue that is driven out from the incinerator with flue gases [3]. Compared to IFA, IBA is much less hazardous [4] and is classified as a non-hazardous waste according to the European Waste Catalogue [5]. Furthermore, IBA represents about 75 ~ 80% of the total ash residue after incineration [6] while IFA only accounts for the remaining 20%. As such, IBA has much higher potential to be used for civil engineering applications [7] and successful use of IBA creates greater impact on resource creation and extension of lifespan of landfill.

Supplementary cementitious materials (SCMs) possess cementitious and/or pozzolanic properties [8], which are often used to replace cement in the production of concrete. SCMs contribute to

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the hardened properties of concrete and certain SCMs also improve the fresh properties [9] of concrete. SCMs greatly reduce the demand on cement and significantly lower the greenhouse gas emissions [10] associated with cement clinker production. Common SCMs such as coal fly ash, ground granulated blast-furnace slag, and silica fume are by-products from different industry sectors [11].

It has been reported that IBA possesses pozzolanic properties and can be a potential cement supplement and replacement [12,13]. However, IBA contains certain amount of metallic aluminium due to the presence of aluminium products, such as aluminium cans, foil, container, and packaging [14], in municipal solid waste. When IBA is mixed with cement, it reacts with hydroxide ions to generate hydrogen gas as follows [15].

$$Al + 2OH^- + H_2O \rightarrow [AlO(OH)_2]^- + H_2 \quad (1)$$

Generation of hydrogen gas may lead to aeration [7], expansion and cracking of concrete [15–17] and even explosion [18] in some extreme cases. Removal of metallic aluminium from IBA to prevent hydrogen generation is therefore crucial for the successful application of IBA as supplementary cementitious materials. Bertolini et al. [19] used wet grinding to remove metallic aluminium in IBA before it can be used as cement supplements. However, results showed that the removal efficiency is low and long rest time from days to months is required for the depletion of metallic aluminium in IBA.

In this paper, alkali treatment was proposed to remove metallic aluminium in IBA. X-ray fluorescence (XRF), X-ray powder diffraction (XRD), collection of gas over water, and saturated lime test were used to characterize chemical composition, mineralogy composition, gas generation, and pozzolanic reactivity of IBA, respectively, before and after alkali treatment. The alkali-treated IBA was then used to prepare IBA blended cement mortars in accordance with ASTM C311/C311 M for the determination of dry density, compressive strength, and strength activity index. The influence of alkali treatment conditions including alkalinity, temperature, and alkali type, on the properties of IBA and the resulting IBA blended cement mortars were reported.

2. Experimental program

2.1. Raw materials

Incineration bottom ash (IBA) was collected from a local Waste-to-Energy (WTE) incineration plant capable of treating 800 tons of solid waste daily and generating 22 MW of green energy. An advanced grate combustion system including a multi-stage grate furnace was designed and biofuel is used for waste incineration. Municipal solid waste is burned consistently without pre-processing. The burning temperature is between 800 and 1000 °C. Granular size of IBA ranges from micrometers to decimeters. Once collected from the incineration plant, the IBA was oven-dried immediately at 105 °C for 24 h. After that, the dried IBA particles without sieving and crushing were directly introduced into a ball miller at predetermined time span of 10 min with a rotation rate of 300 rpm. The planetary ball miller has 4 bowls and 100 g steel milling balls are used to grind 400 g IBA in each bowl (i.e., the mass ratio of milling balls to IBA is 1:4). Fig. 1 shows the gradation of the ground IBA. As can be seen, the ground IBA has an average particle size of around 30 μm with a maximum particle size of about 150 μm.

Laboratory grade pure sodium hydroxide solids or calcium hydroxide solid were used for the preparation of alkaline solution. Ordinary Portland cement (OPC, clinker content more than 80%), fine aggregates, tap water, and superplasticizer (SP) were used to

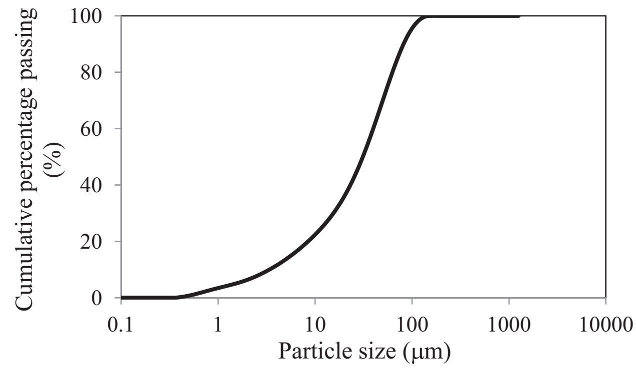

Fig. 1. Gradation of the ground IBA.

prepare IBA blended cement mortars. OPC conforming to the Singapore Standards SS 26 was used in this study. XRF test was carried out to reveal the chemical composition of OPC. Sequential X-ray spectrometer (Bruker S8 TIGER) was used in this study for XRF test and the chemical composition is showed in the form of weight percentage of oxidation (Table 1). Sample was weighed and mixed with 20 wt% of binding material CH_2O, pre-grind and mixed, and pelletized on an aluminum cup using a Herzog manual press at 15 tons for 20 s. After the measurements, all peaks in the spectra were carefully checked. The elements present in the sample are subjected to an evaluation process based on pre-calibrated element lines coming from a line library. Fine aggregates were normal river sand with particle size less than 5 mm. Water reducing admixture used in this study was a 3rd generation polycarboxylate-based superplasticizer (SP).

2.2. Alkali treatment of IBA

Table 2 summarizes the five treatment conditions investigated in the study where alkaline solution (sodium hydroxide or calcium hydroxide) was used at pre-determined alkalinity (PH = 12 or 14) to react with IBA at specific temperatures (25 or 70 °C) for a duration of 120 min. The first treatment condition in water was tested as the control. Alkaline solution was prepared by dissolving pre-determined amount of alkali into distilled water. A hot plate stirrer was used to condition the solution to the pre-determined temperature. After which, ground IBA was added into the solution with a solution-to-IBA ratio of 10 and stirred for a pre-determined duration of 120 min. Surface foaming as shown in Fig. 2a was observed when IBA was added into the alkaline solution due to gas generation from IBA via chemical reaction between metallic aluminum and alkali. With prolonged treatment duration (i.e., 2 h in the current study), the foaming was reduced and a clear solution can be obtained which suggests seizing of further gas generation from IBA as shown in Fig. 2b. The IBA solution was then centrifuged, followed by filtration to separate IBA from filtrate. IBA was washed 2–3 times to remove alkalis after treatment. The alkali-treated IBA was then oven dried at 105 °C for 2 h prior to further characterization and usage as cement supplements.

2.3. Mix design of IBA blended cement mortars

Table 3 summarizes the mix design of IBA blended cement mortars. In accordance with ASTM C311/C311M, 20% of cement in the control mortar should be replaced by the pozzolans of interest. A control mix without the addition of IBA (Mix 1) and another mix with the replacement of 20% cement by the original untreated IBA (Mix 2) were prepared for comparison.