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Recycling of municipal solid waste incineration by-product for cement composites preparation

Zhenzhou Yang [a], Ru Ji [c], Lili Liu [a], Xidong Wang [a], Zuotai Zhang [b,d,*]

[a] Beijing Key Laboratory for Solid Waste Utilization and Management and Department of Energy and Resource Engineering, College of Engineering, Peking University, Beijing 100871, PR China
[b] School of Environmental Science and Engineering, Southern University of Science and Technology of China, Shenzhen 518055, PR China
[c] School of Civil and Resource Engineering University of Science and Technology Beijing, Beijing 100083, PR China
[d] The Key Laboratory of Municipal Solid Waste Recycling Technology and Management of Shenzhen City, Shenzhen 518055, PR China

HIGHLIGHTS

- The effect of MSWI ash on the water demand and setting time of cement composites were explored.
- The effect of MSWI ash on the mechanical strength of cement composites were studied.
- The hydration characteristic of cement blended with MSWI ash was also studied.
- The benefit during the recycling of MSWI ash for the cement production were evaluated.

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ABSTRACT

In this study, the feasibility of application of municipal solid waste incineration (MSWI) fly ash and bottom ash as a supplementary cementitious material for the preparation of blended cement was evaluated. For this purpose, the cement composites with 10–50 wt% of cement replaced by the equivalent amount of washed MSWI fly ash and bottom ash were prepared, together with water needed for normal consistency, setting time for the blend, strength and hydration characteristics of MSWI ash-cement composites were investigated. The results show that the washed MSWI fly ash and bottom ash have some cementitious activity, but the activity is relatively lower than Portland cement. The behavior of the addition of composites of washed MSWI fly ash and bottom ash were observed to be different with respect to water demand and setting time. Addition of washed fly ash and bottom ash were found to have a deleterious effect on the mechanical strength of cement composites and the maximum replacement by washed MSWI fly ash and bottom ash should be limited to the range of 40 wt% and 20 wt%, respectively to ensure the mechanical properties of composites. Besides, the hydration characteristic of cement blended with washed MSWI fly ash and bottom ash was also measured by using X-ray powder diffraction (XRD) and scanning electron microscope (SEM). Finally, the environmental and economic impact of the as-derived cementitious materials was also evaluated. It was found that the recycling of MSWI fly ash and bottom ash for the cement production can achieve a significant economic and environmental benefit at the same time.

1. Introduction

Rapid urbanization in China results in enormous municipal solid wastes (MSW) generated and it was estimated that more than 260 million tons of MSW in China are generated per year, with an annual increasing rate of about 8 to 10 wt% [1]. Consequently, the timely and effective disposal of MSW has become a severe environmental issue that needs to be urgently solved. In China, landfill and agriculture are one of the most important ways for the disposal of MSW [2–4]. However, as the reduction of available land and the presence of pathogens and contaminants such as heavy metals, micro-pollutants and antimicrobial agents, the agriculture and landfill are limited [5]. By contrast, the incineration of MSW has been drawn much attention as it can reduce the quantity of waste, achieving the goal of heat recovery and easy operation [6–8]. Therefore, the incineration technology has been widely used to treat MSW in China and about 75 MSW incineration plants had

* Corresponding author at: School of Environmental Science and Engineering, Southern University of Science and Technology of China, Shenzhen 518055, PR China.

E-mail address: zhangzt@sustc.edu.cn (Z. Zhang).

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been built, which have 33,000 tons of MSW disposal capacity per day [9].

However, during the incineration process, two main by-products (municipal solid waste incineration (MSWI) bottom ash and fly ash) are produced. MSWI bottom ash is the residue from the bottom of incinerator while MSWI fly ash consists of the particles collected by the air pollution control devices installed with the incineration units. The production of MSWI fly ash and bottom ash accounts for 30–35 wt% of total MSW incinerated [10]. There are some differences between MSWI fly ash and bottom ash. Firstly, the bottom ash has coarser dimensions than the fly ash. Secondly, as compared to MSWI bottom ash, MSWI fly ash contains significant amounts of dangerous substances, such as heavy metals (e.g. Zn, Pb, Cu, Cr, Cd and Ni) and organic compounds [11,12]. In addition, due to the high levels of soluble salts of MSWI fly ash contains, e.g., KCl and NaCl, the chloride in the MSWI fly ash is also much higher than that in bottom ash [13,14]. Hence, the safe treatment of them has also posed a great challenge for the society.

Cement industry is well known for the absorbing and recycling of wastes of different kinds. In fact, this provides some of the interesting future development options such as increased use of industrial by-products and wastes defined as raw material, fuel and cement additives (blend cement) [15]. If the wastes have binding properties, it allows a reduction in the use of Portland cement, which is indirectly beneficial for the environment because of the reduction of CO_2 emissions as well as minimization of the consumption of natural materials associated with the manufacturing of Portland cement clinker [16]. The composition of MWSI fly ash and bottom ash compare well with that of coal fly ash and blast-furnace slag, which indicates that they have similar pozzolanic or hydrated properties [16,17]. Thus, in turn, it suggests that the addition of MSWI fly ash and bottom ash could be beneficial to the development of the microstructure of the hydrated cement paste. Hence, the MSWI fly ash and bottom ash can partially replace of cement to produce concrete in theory. It is worth mentioning that some pre-treatment is required before the utilization of MSWI fly ash and bottom ash for cement production, e.g., the MSWI bottom ash need to be ground into fine particles. Compared to MSWI bottom ash, fly ash is more difficult to handle because of the high chloride content, which could result in corrosion and clogging of the cement kiln and ancillary facilities during co-process, erode the reinforced concrete produced, and cause a more serious heavy metal pollution [18]. Therefore, the water-scrubbing step is necessary before the utilization of MSWI fly ash in cement industry.

At present, most of domestic and overseas researches on MSWI fly ash and bottom ash stress on the safe disposal of these two by-products. For example, various methods such as melting, solidification/stabilization, acid extraction, vitrification and sintering have been used to solidify/stabilize MSWI fly ash [19–24]. Besides, MSWI bottom ash is also usually used as lightweight aggregates and road base materials [25,26]. However, few studies focus on recycling these two wastes as supplementary cementitious materials. Therefore, the aim of present study is to explore the viability of using the water-washed MSWI fly ash as well as ground bottom ash as supplementary cementitious materials for the cement production. The results obtained in the present study are expected to provide the basis clue for the safe utilization of the MSWI by-products, contributing to the sustainability of the cement industry.

2. Materials and method

2.1. Materials

Raw MSWI fly ash, washed fly ash and bottom ash used in this study were obtained from a MSW Incineration Plant in Beijing, China. The incineration temperature was between 850 and 1000 °C with the MSW capacity of 650 ton/day. To control the air pollution, the incinerator is equipped with a cyclone, an adsorption reactor and a fabric filter. The raw fly ash is captured by a bag-filter while the bottom ash is quenched in water. After that, bottom ash is magnetic separated and then collected. The sample-collecting period lasted 10 days and about 10 kg of raw fly ash and 10 kg of bottom ash were obtained to ensure the representative samples. The raw fly ash sample is pretreated successively via washing, separation and drying, i.e., the ash gathered was transported to the agitator tank and mixed with water for 0.5 h at a solid to liquid ratio of 1 g: 10 mL. The sediment was then separated from water and dried at about 200 °C. The bottom ashes obtained were ground in order to reduce their particles sizes into less than 154 μm. Then, the washed MSWI fly ash and bottom ash were stored in desiccator for further analysis. The class 42.5 Ordinary Portland Cement (OPC) was obtained from Beijing cement plant and the sand was the China standard sand produced by Xiamen ISO Standard Sand Co., Ltd. Tap water was used to prepare curing cement composites while ultrapure water was used for leaching test.

2.2. Experimental methods

2.2.1. Raw materials characterizations and sample preparation

The chemical composition and the crystalline mineral phase of raw materials were determined by the X-ray fluorescence spectrometer (XRF, S4-Explore, Bruker) and X-ray powder diffraction (XRD, D/Max 2500, Rigaku), respectively. In addition, information on the morphology of washed MSWI fly ash and bottom ash were obtained by scanning electron microscopy (SEM, S4800, Hitachi ltd of Japan). The heavy metal contents in the MSWI fly ash and bottom ash were measured by inductive coupled plasma-atomic emission spectrometry (ICP-AES, Prodigy XP, Leeman) after digestions. The water demand for normal consistency and setting time were tested according to Chinese National Standard GB/T 1346–2001. For the mechanical properties of blended cement measurements, the cement composites with the 10–50 wt% of cement replaced by the equivalent amount of washed MSWI fly ash and bottom ash. The mixing was carried out in a standard laboratory mixer under the same flowability condition, and then, they were cast into molds of 40 mm × 4 mm × 160 mm cubes. Finally, they were demolded and stored in a curing room with a temperature of 20 ± 2 °C and relative humility of 90 ± 5% for different aging interval exceeding 24 h.

2.2.2. The characterizations of products

The cement composites at different curing ages firstly undergo the flexural and compressive strength tests according to ASTM C39-72. Then, the crystalline mineral phases and morphology in the hydration products were investigated by XRD and SEM, respectively. The elemental compositions of each phase could be identified by energy dispersive X-ray spectrometry (EDS), which is coupled with SEM. In order to determine the potential leachability of heavy metals in raw materials and blended cement, Toxicity Characteristic Leaching Procedure (TCLP) method of the US Environmental Protection Agency (US-EPA) was applied to the cement composites at 28 days curing age. The extracting solution used was 0.1 M acetic acid at pH 4.93 and the heavy metals in leachate were quantified by ICP-AES.

3. Results and discussion

3.1. Characteristic of MSWI fly ash and bottom ash

The chemical composition of raw MSWI fly ash, washed fly ash and bottom ash are shown in Table 1. It can be seen that the major chemical compositions of MSWI fly ash and bottom ash are CaO, Al_2O_3 and SiO_2, which is similar with the common pozzolanic mineral admixture used in the cement-based materials. Compared with MSWI bottom ash, the loss on ignition (LOI) of MSWI fly ash is very high, indicating the presence of large amounts of carbonaceous materials in MSWI fly ash, which might be from the unburned carbon particles. Calcium oxide content in the MSWI fly ash is notably high, which is a result of $Ca(OH)_2$, rejected into the semi-dry gas cleaning tower to purify the flue gas in the power plant. In addition, the chloride content in the washed MSWI fly ash sample is about 1.2 wt%, which is much lower than the average content of chloride (5–35 wt%) in MSWI fly ashes in China [27–30], and the content of chloride (16.6 wt%) in raw fly ash in our study. This is due to the water-washing pretreatment conducted in this study that removed most chlorides in the raw fly ash sample. The heavy metals contents in MSWI fly ash and bottom ash are also listed in Table 2.The results show that the MSWI fly ash contains high contents of heavy metals, especially for those volatile elements such Zn, Cd and Pb. Compared to MSWI fly ash, bottom ash contains higher contents of no-volatile elements such as Cr