Construction and Building Materials 167 (2018) 890–898

Contents lists available at ScienceDirect

Construction and Building Materials

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

Effect of casting methods and SCMs on properties of mortars prepared with fine MSW incineration bottom ash

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HIGHLIGHTS

- Different casting methods and SCMs were used for preparing mortars with MSWIBA.
- The dry-mixed method effectively reduced the expansion of these mortars.
- FA was the most effective in mitigating the expansion of these mortars.

ARTICLE INFO

Article history:
Received 10 October 2017
Received in revised form 6 January 2018
Accepted 14 February 2018

Keywords:
Fine incineration bottom ash
Metallic aluminium
Glass
ASR expansion
SCMs
Casting methods

ABSTRACT

Fine municipal solid waste incineration bottom ash (MSWIBA) contains more contaminants (e.g. metallic aluminium, glass and gypsum) that cannot be effectively removed by current recycling techniques and this thus limits its engineering application in concrete products. Instead of removing these contaminants, the objective of this research was to investigate the influences of using different casting methods and various supplementary cementitious materials (SCMs) on improving the properties of cement mortar prepared with the fine MSWIBA. In this study, the mortar bar specimens incorporating 100% fine MSWIBA as sand were prepared using the conventional wet-mixed method and a dry-mixed method. The SCMs applied were fly ash (FA), ground-granulated blast-furnace slag (GGBS) and waste glass powder (GP), with a replacement ratio of 30 wt% of ordinary cement in the mortar. The curing conditions of the specimens were in the 20 °C water, in the 80 °C water and in an 80 °C NaOH solution for 28 days, respectively. The experimental results showed that the dry-mixed method was an effective method to mitigate the expansion of the mortar prepared with MSWIBA as well as to enhance its mechanical properties after being subjected to the NaOH solution. The order of effectiveness of SCMs on the reduction in the expansion of the mortar prepared with MSWIBA was FA, GGBS and GP. It was indicated that FA was the most effective in mitigating the alkali-silica expansion as well as the alkaline-Al reaction.

1. Introduction

Currently, the waste-to-energy (WtE) incineration technology has been adopted as one of the most integral and effective options to manage the increasing amount of municipal solid waste (MSW) [1,2]. More and more MSW incinerators have been and are going to be built worldwide, especially in developing countries where the generation of MSW has been rapidly increasing in recent years. According to the energy conservation and emission reduction tasks of the "12th Five-Year Plan" (2011–2015) in China, the capacity of MSW incineration (MSWI) facilities has reached over 35% among all environmental benign MSW treatment capacity [3]. MSW is incinerated in the WtE plant at a temperature of around 700–1000 °C, after which the volume and the mass of the input solid waste would be reduced by approximately 80–90%. Meanwhile, recycled energy from the incineration in the form of heat or steam can be used to support the heating system or produce electricity [4].

Despite of these benefits of using the incineration technology to manage MSW, one of the downsides is the necessity to manage the incineration solid residues, such as incineration bottom ash (MSWIBA), MSW fly ash, air-pollution control residues, etc., among them MSWIBA is the major by-product (accounts for around 80% of all the solid residues) [5]. In general, MSWIBA can be described as heterogeneous solid granulates with a broad particle size distribution, consisting of glass, magnetic and paramagnetic metals, minerals, ceramics, slag/molten phase and unburned materials. According to this inherent feature and the suggestion from others' researches, the most widespread practice is to reuse MSWIBA as a

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https://doi.org/10.1016/j.conbuildmat.2018.02.077
0950-0618/

granular material or an aggregate substitute in the fields of construction and geotechnical engineering [6–8]. However, in practice, the reuse of MSWIBA is quite limited as it is subjected to stringent specification requirements [9].

When using MSWIBA as aggregates in concrete, several drawbacks derived from its chemical and physical characteristics have been realized. These include the potential chemical leaching (e.g.: heavy metals and salts) as well as the potential chemical attacks to concrete (e.g. metallic aluminium (Al), glass and gypsum) [10,11]. It has been found that the leaching of mortars incorporating fine MSWIBA can comply with the environmental legislation due to the binding effect of cement on the contaminants, which has proven that the use of cementitious materials to immobilize the contaminants in the fine MSWIBA is an efficient method to reduce its environmental risk [12]. However, in the concrete prepared with MSWIBA, expansion and induced cracks have been reported to progressively deteriorate the concrete products, which are commonly related to the hydrogen gas generation from the reaction of metallic Al or Al/Zn alloy in the alkaline medium of concrete, the alkali-silica reaction (ASR) between the alkali in concrete and the glass, and the excessive ettringite formation due to the rich sulphate content [11,13,14]. These chemical reactions can be expressed by the following equations. Therefore, it is necessary to investigate what are the impacts from metallic Al and glass in MSWIBA when it is used in cement mortars or concrete.

$$2Al + 2NaOH + 6H_20 \rightarrow 2Na[Al(OH)_4] + 3H_2 \uparrow \quad (1)$$

$$Ca^{2+} + M^{+}(Na+, K+) + OH^{-} + SiO_2(glass) + H_2O \rightarrow M-A-S-H(gel) \quad (2)$$

$$6Ca^{2+} + 2Al(OH)_4^{-} + 3SO_4^{2-} + 4OH^{-} + 26H_2O \rightarrow Ca_6[Al(OH)_6]_2(SO_4)_3 \cdot 26H_2O \quad (3)$$

Proper pre-treatments have thus been investigated to reduce the environmental risk of MSWIBA, remove the harmful components and improve its engineering properties [15]. These pre-treatments include washing, weathering, carbonation, intensive separation of ferrous and non-ferrous metals, etc [10,16,17]. Generally, after these treatments, the obtained MSWIBA has much better properties, and lower leaching of heavy metals which can comply with environmental legislation. Also, the amount of metallic Al in the coarse MSWIBA can be reduced significantly [18]. However, these pre-treatment methods have a lower efficiency on removing contaminants in the fine MSWIBA particles below 2 mm [12]. For this fraction of MSWIBA, special pre-treatments/considerations or application methods which are environmental-friendly and economical are needed to be developed.

Instead of removal of these contaminants, other techniques such as the use of different concrete casting methods and supplementary cementitious materials (SCMs) can be considered. Traditionally, the wet-mixed method is used to produce cement based products, which have a good workability to aid casting into moulds. But the dry-mixed method is commonly used to produce pre-cast concrete elements such as concrete masonry, concrete pavement blocks and partition wall blocks using a precast molding machine which provides compaction and vibration at the same time [19]. Demoulding can be done immediately after casting so that one single set of mold can be used repeatedly for mass production of the precast products. In the literature, it has also been found that when the fine MSWIBA was used to produce cement bonded lightweight aggregates by a pelletizing technique, the pelletized lightweight aggregates had good engineering properties without cracks [20]. This shows that the preparation method would influence the properties of the product prepared with MSWIBA. Also, it has been reported that the use of SCMs can reduce the ASR expansion when the glass particles are used as aggregates in concrete [21]. The reduced pH value would also influence the H_2 gas generation from the metallic Al [22]. But there is less information about the effects of the use of different preparation methods (wet-mixed and dry-mixed methods) and SCMs (FA, GGBS and GP) on controlling the properties and potential cracking deterioration of concrete prepared with MSWIBA.

The aim of this study was to investigate the influences of using various casting methods and different SCMs on improving the mechanical properties and reducing the potential cracking risks of mortars prepared with the fine MSWIBA. A series of mortars were prepared with different types of SCMs and casting methods. The mechanical properties and expansion behaviour of the $25 \times 25 \times 285$ mm mortar bar specimens were then experimentally evaluated.

2. Materials and experimental methods

2.1. Raw materials

A water-quenched MSWIBA was collected from a Chinese MSWI plant. After incineration, it was delivered to Hong Kong and stored in the laboratory. But how long the IBA had been stored (aged) is unknown before it was delivered to Hong Kong. In this study, the fine MSWIBA with the size of <3.35 mm was oven dried before it was used in the experimental study. This fraction was used as sand for the preparation of mortar samples. Table 1 provides the oxide compositions of MSWIBA through X-ray fluorescence (XRF) analysis. The major oxides were SiO_2, CaO, Al_2O_3, P_2O_5, Fe_2O_3 and Na_2O. Based on the XRF and XRD results [23], it showed that the high content of SiO_2 was due to the presence of a lot of glass particles as well as quartz in the MSWIBA. In addition, a gas collection setup over water was developed to determine the amount of metallic Al in MSWIBA considering its chemical reaction with an alkaline solution (NaOH) as shown in Fig. 1 [12,23]. Due to the hydrogen generation from the Al reaction with the NaOH solution, the volume of gas collected was obtained. Based on the chemical reaction between Al and NaOH, the determined content of metallic Al in the fine MSWIBA was low (0.18 ± 0.2% by mass). This could be due to the aging effect, but also could be the size effect.

The Ordinary Portland cement (OPC) used was an ASTM Type I Portland cement in the reference mortar. SCMs adopted for the replacement of cement were fly ash (FA), ground-granulated blast-furnace slag (GGBS) and waste glass powder (GP) at a replacement ratio of 30% by mass of cement, which are commonly used in the preparation of concrete. The chemical compositions of cement, FA, GGBS and GP, determined by XRF, are detailed in Table 2.

The particle size distributions of the OPC, SCMs and MSWIBA are shown in Fig. 2, which indicate that FA, GGBS and OPC had similar particle size distributions. The FA had a Blaine fineness of 2900,

Table 1
Chemical compositions of MSWIBA.

Oxides (%)	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	Cl	K_2O	CaO	Fe_2O_3	Others	L.O.I
MSWIBA	2.29	1.49	6.64	37.34	5.20	1.65	1.22	1.70	21.28	2.91	1.97	16.31