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Mobility of heavy metals and rare earth elements in incineration bottom ash through particle size reduction

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HIGHLIGHTS

- Physical and chemical characterization of incineration bottom ash (IBA) were performed.
- Particle size reduction of IBA using ball miller and fluidized bed were determined.
- Certain heavy metals were concentrated in specific size range after size reduction.
- Mechanisms of heavy metal mobility during particle size reduction were discussed.

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ABSTRACT

Incineration is an important municipal solid waste management process in Singapore. The incineration bottom ash (IBA) generated may contain heavy metals (HMs) and rare earth elements (REEs) that can cause environmental concerns upon reutilization. In this study, the particle size distribution, density, circularity, and chemical composition of the overall IBA as well as individual size ranges were determined. The particle size reduction characteristics and the mobility of HMs and REEs among different size ranges through ball milling and fluidization processes were examined. Certain HMs were found to present in high concentrations at particular particle size ranges. Mechanisms concerning the mobility of HMs and REEs were revealed.

1. Introduction

Singapore has been experiencing rapid population growth and economic development since 1970s. The amount of solid waste has increased by 7 folds, reaching 6.9 million tons per year (Khoo et al., 2012). Hence, incineration is necessary for a small island state as Singapore because it is able to reduce the solid waste volume by 90% and mass by 70% (Alba et al., 1997; Hjelmar, 1996; Kirby and Rimstidt, 1993). Incineration bottom ash (IBA) makes up to 80% of the incineration residues during the incineration process (Chimenos et al., 1999; Sabbas et al., 2003). IBA is widely reused as a secondary construction material like landfilling, road construction or cement production (Hjelmar, 1996; Chandler et al., 1997).

More than 80% of the heavy metals (HMs) such as Fe, Cu, Cr, Pb, Zn, As, Ni, Ti, etc, in municipal solid waste (MSW) were found to remain in IBA after incineration (Belevi and Langmeier, 2000; Belevi and Moench, 2000; Jung et al., 2004; Yao et al., 2010; Zhang et al., 2008). The high content of HMs in IBA may also exhibit environmental concerns in the long-term behavior of landfilling or reutilization (Ecke and Åberg, 2006). In addition, IBA consists of 15% non-combustible materials, the remaining 85% ash contains 25% opaque glass and 20% isotropic glass (Eighmy et al., 1994). Rare earth elements (REEs) are commonly used additives in these glass products (Schuler, 2011). A small percentage of MSW also contains such electronic products as color TV, car, computer, refrigerator, etc, in which they have relatively high REE such as color pigments (Eu, Yb, Gd), strong magnets (Gd), and catalysts (Ce) (Schuler, 2011; Bai and Sutanto, 2002). Therefore, it is beneficial to investigate the content of HMs and REEs in IBA from both environmental and economic aspects.

While a number of literatures have reported the physical and chemical properties of bulk IBA in several countries (Jung et al., 2004;

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Yao et al., 2010; Zhang et al., 2001), no study has examined the mobility of HMs and REEs during a particle size reduction process. Size reduction of IBA particles can happen throughout the transport, compaction and blending in re-utilization processes. The understanding of the mobility of HMs and REEs can help reduce the cost of the subsequent HM and REE removal process by excluding the fractions that contain low HM and REE contents of interests. The objective of the current study is to characterize the physical and chemical properties of IBA in Singapore during particle size reduction processes. Specifically, the particle size distribution, density, circularity, as well as the HM and REE contents of the bulk IBA are studied according to particular particle size ranges at different stages of a particle size reduction process. The mobilities of HMs and REEs among certain particle size ranges are compared between ball milling and fluidized bed particle size reduction processes.

2. Material and methods

2.1. Sample collection and pre-treatment

The IBA samples used in this study were collected from Tuas Incineration Plant (TIP), Singapore. TIP has a capacity of incinerating 1700 t of wastes per day. The IBA samples consist of primarily ash and residue from the combustion of domestic and industrial waste incinerated at a temperature 800–1000 °C for 2 h. The fraction of IBA having a size larger than 6 mm was removed before collection. A number of studies have found that IBA particles smaller than a typical range of 2.5–5 mm are the primary contribution to the total HM and REE contents (Chandler et al., 1997; Böni, 2013; Chen et al., 2008; Morf et al., 2013; Shim et al., 2003; Stegemann et al., 1995). The IBA samples collected were dried at 90 °C for 24 h in an oven prior to any experimentation.

2.2. Physical property measurement

2.2.1. Particle size distribution

150 g IBA sample was separated into 9 particle size ranges using sieves of mesh sizes 0.212 mm; 0.6 mm; 1.0 mm; 1.4 mm; 1.7 mm; 2.8 mm; 4.0 mm; 5.6 mm (Tyler Equivalent) by a sieve shaker (Retsch, AS 200, Germany). The particle size distribution of each sample was measured 5 times.

2.2.2. Particle shape

Circularity is used to characterize the particle shape of IBA samples. Circularity is defined as

$$\text{Circularity} = 4\pi \frac{\text{Area}}{\text{Perimeter}^2}. \tag{1}$$

The area and perimeter of individual particles were obtained from analysis of photographic images of IBA using ImageJ image processing program (Wayne Rasband, v1.46r, National Institute of Mental Health). Each IBA sample was placed evenly on a flat horizontal surface including a known scale. Photographic images were taken by a digital camera (Canon, 450D) equipped with a 50 mm lens mounted perpendicular to the horizontal surface on a tripod stand. Sufficient images were taken at different areas of each sample to ensure the sample size for number of particles was sufficiently large.

2.2.3. Particle density

The density of these pre-dried samples was determined for different particle size ranges by a pycnometer (Quantachrome Ultra-Pycnometer 1000) in 15 runs each.

2.2.4. Particle size reduction by ball milling/fluidization

Due to the unfavorable energy requirement to fluidize large IBA particles and large particles do not contribute to the accumulation of HMs (Chen et al., 2008; Shim et al., 2003), only IBA particles less than 1.7 mm were used in the particle size reduction process.

The ball milling process was performed in a ball mill (Fritsch, Planetary Mill Pulverisette 5, Germany) consisting four grinding bowls. Each grinding bowl is 80 mL and five agate grinding balls of 10 mm diameter were used in each bowl. 100 g of IBA was divided equally into each grinding bowl and the ball mill was operated at a constant rotational speed of 300 rpm. Particle size distribution of the entire IBA sample used was determined at different milling time.

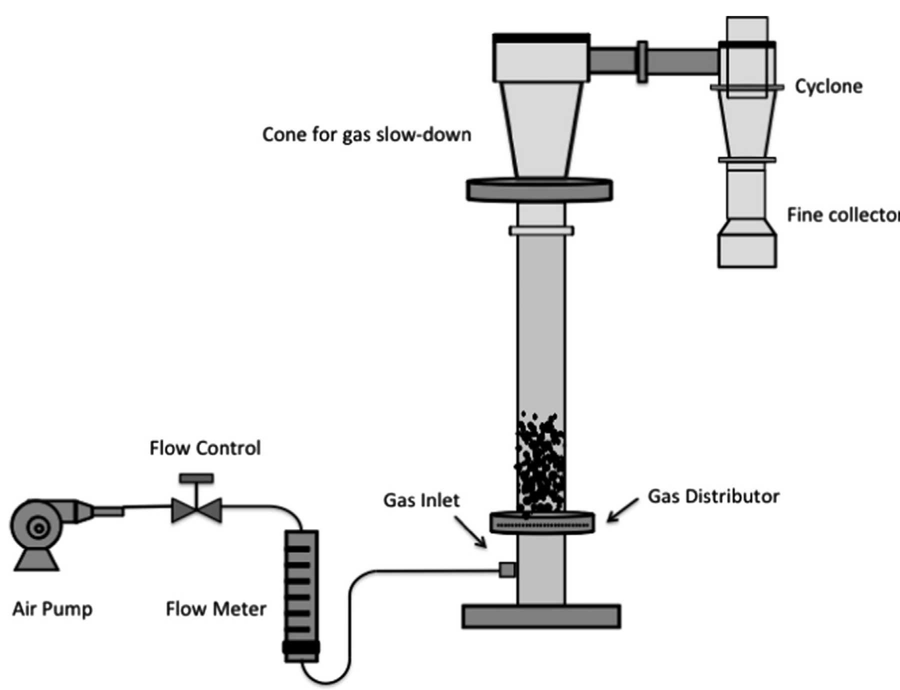

Fig. 1. Experimental setup of fluidized bed.