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Magnetic and density characteristics of a heavily polluted soil with municipal solid waste incinerator residues: Significance for remediation strategies

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ABSTRACT

Physical separation methods are usually the preferred extraction methods for inorganic contaminants. However, successful remediation of inorganically contaminated sites requires proper knowledge of the contaminants. This paper describes the magnetic and density characteristics of a soil polluted with municipal solid waste incinerator residues, allowing the best separation method or combination of methods for remediating the 0.250–1 mm and the 1–2 mm soil fractions to be selected. Magnetic characterization was performed using a CARPCO high intensity magnetic separator with increasing magnetic fields from 0.04 to 0.7 Tesla. A second characterization using a factorial design was performed for three magnetic field intensities (0.08 and 0.4 and 0.7 Tesla) and three relative density fractions (light, intermediate and heavy). The results showed that As, Fe and Sn can be concentrated into the magnetic fraction using low intensity magnetism but not Cu, Pb, Sb and Zn. Moreover, high intensity magnetic separation was not appropriate for concentrating the contaminants present in our soil. The association of the contaminants with iron likely explained this finding, especially for Sn. A significant overlap exists in the removal yields for magnetic and density separation of the different inorganic contaminants, ranging from 29% to 72% depending on the contaminants and the soil fraction. Density separation alone should be preferred to magnetic separation alone because of the better removal efficiency and the lower soil mass in the contaminated fraction afforded by density separation.

1. Introduction

Improper disposal of municipal solid waste (MSW) incinerator residues have contributed to the contamination of numerous sites with inorganic and/or organic compounds (Mercier et al., 2002; Mercier et al., 2007). Contaminants commonly retrieved from these sites are arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), mercury (Hg), molybdenum (Mo), nickel (Ni), lead (Pb), antimony (Sb), tin (Sn) and zinc (Zn). The presence of a contaminant depends on the specific type of residue disposed on the site, such as bottom ash, fly ash or air pollution control residues (Chimenos et al., 1999) as well as the feed waste composition and incinerator technology and operation (Hjelmar, 1996). Organic compounds such as polycyclic aromatic hydrocarbons and dioxins/furans can also be present (Chung et al., 2010). These sites are normally characterized by high iron (Fe) contents, heterogeneous element speciation and extreme spatial variability in contaminant concentrations.

The selection of an appropriate decontamination method depends on the contaminants and the site characteristics (Mulligan et al., 2001). Of the available extraction methods, physical separation technologies, adapted from the mining and mineral industry, are usually considered the most economical remediation options (Blais et al., 2010). The most common physical separation technologies are screening, gravity concentration, hydrodynamic classification, froth flotation, electrostatic separation, attrition scrubbing and magnetic separation (Gosselin et al., 1999).

In the past, soils polluted by MSW incinerator residues have been treated by gravimetric separation (spiral) (Mercier et al., 2007) or a combination of gravimetric (Wilfley table and jig) and magnetic separation methods (Mercier et al., 2001; Muchová, 2010). Some soils have successfully been decontaminated either by gravity separation or by magnetic separation alone while some others have been decontaminated successfully using a combination of both.

Magnetic separation is achieved when magnetizable particles passing through a non-homogenous magnetic field are retained (Svoboda and Fujita, 2003). Magnetic force (F_m) is described by the following equation:

$$Fm = (1/\mu_0)\rho\chi V B \Delta B \quad (1)$$

where μ_0 is the magnetic permeability of a vacuum ($4\pi \times 10^{-7}$ N/A^2), ρ is the specific gravity (kg/m^3), χ is the volumetric magnetic

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susceptibility of the particle (m^3/kg), V is the volume of the particle (m^3), B is the external magnetic induction (T) and ΔB is the gradient of the magnetic induction.

Thus, magnetic force is proportional to the product of the external magnetic induction and the magnetic gradient. In a homogeneous magnetic field, no gradient is present, thus the magnetic force is zero. If a gradient is present, the particles will move in the direction of increasing magnetic field (Avens et al., 1993). Magnetization is achieved when particles are exposed to an external magnetic field (magnetic induction) and depends on the magnetic susceptibility of the material. A material with a high magnetic susceptibility will be magnetized in a low intensity magnetic field and will be easily moved by the magnetic force when subjected to a magnetic gradient.

In a magnetic separator, several competing forces can exist, such as gravity, inertial, surface and inter-particle forces (Svoboda and Fujita, 2003). Magnetic separation can be used on different soil particle sizes to separate contaminants based on their magnetic susceptibility. Soil particles have magnetic susceptibility varying from null to slightly negative for diamagnetic materials, slightly positive for paramagnetic materials to largely positive for ferrimagnetic and ferromagnetic materials (Dermont et al., 2008). Ferri/ferromagnetic materials can be removed with a low intensity magnetic separator (LIMS), while paramagnetic minerals can be removed using a high intensity magnetic separator (HIMS) (Oberteuf, 1973). Low intensity magnetic separation is often used to remove coarse metallic debris from soils using an electromagnet (Mercier et al., 2001).

Contaminants commonly retrieved in soil such as As, Cu, Pb, Sb, Sn and Zn are diamagnetic. However, contaminants can form paramagnetic minerals, especially when the Fe and manganese (Mn) content in the soil is high (Svoboda, 1987). Rikers et al. (1998a) demonstrated the efficiency of magnetic separation for various contaminated soils containing Pb, Cu and Zn. The explanation lies in the association between contaminants and Fe. Indeed, contaminants can be bound to Fe because of a corrosion protection treatment such as metal plating with Zn, Pb and Sn or as part of an alloy with iron. Contaminants can also be associated with iron because of the sorption of contaminants by iron oxyhydroxides. This effect is well known and is called the "scavenging" effect of amorphous iron or iron minerals. The scavenging effect of iron is particularly important when Fe remains under oxidizing conditions and originates from anthropogenic activities (Rikers et al., 1998b).

Gravity separation methods separate particles based on their relative density but also on their size and shape (Iskandar, 2001). Density misclassification caused by size classification and particle shape can lead to significant losses in efficiency. These misclassifications can be reduced by narrowing the feed size interval (Manser et al., 1991). The degree of liberation of the contaminants is also an important characteristic when using gravity separation methods. The degree of liberation is the percentage of the surface area of a particle occupied by a contaminant compared to the total surface of the particle (Duchesne and Mercier, 2003). This definition is different from the one usually used in the mineral industry but is more relevant for gravity separation in a remediation context. The most used gravity separation pieces of equipment are the spiral, the shaking table and the jig. Dense media (DM) allow a separation based on density only, without size and particle shape effects. This technology is considered the perfect density separation technique and is used as a predictive method for gravity separation efficiency (Mercier et al., 2001).

For soils with complex contamination, more than one remediation technology (technology train) may be needed. However, the chosen remediation methods must have little overlap to justify economically the use of successive treatment methods on a single soil fraction. Rikers et al. (1998b) concluded that magnetic separation has little overlap with density separation according to the average density of specific magnetic fractions.

The objective of this study was to characterize the magnetic and density properties of the coarse fractions (0.250–1 mm and 1–2 mm) of a soil polluted by MSW incinerator residues to precisely evaluate the separation efficiencies and the overlap between both separation methods.

2. Material and methods

2.1. Soil sampling

Soil heavily polluted with Municipal Solid Waste (MSW) incinerator bottom ash containing arsenic (As), copper (Cu), lead (Pb), antimony (Sb), tin (Sn) and zinc (Zn) was collected from a brownfield located in Québec City (Québec, Canada). Over 160 kg of soil were excavated using a backhoe-loader from a single trench at a depth of 0.3 m to 1 m and transported to the research facility into plastic containers. The soil was wet sieved using a mechanical 75-cm diameter Sweco™ to characterize the granulometric distribution and to isolate the two soil fractions (0.250–1 mm; 1–2 mm) used for this experiment. These two soil fractions were chosen because they usually represent a large proportion of the contaminated soil in brownfields and because these fractions can be treated using gravimetric and magnetic methods. The 0.250–1 mm fraction represented 39% of the soil and the 1–2 mm fraction represented 22% of the soil. The remaining 39% was the proportion of the fraction <0.250 mm. Initial inorganic contaminants contents were characterized by randomly collecting six samples of approximately 120 g from each fraction during the sieving operation.

2.2. Microanalysis

The composition and morphology of representative soil particles were studied using a Scanning Electron microscope (SEM, Carl Zeiss EVO® 50) equipped with an X-ray energy dispersion spectrometer (EDS, Oxford Instrument, INCAx-sight EDS). Polished thin sections (26 × 46 mm) of soil were coated with gold using a SPI™ sputter coater module. Soil particle images were generated with a Quadra-Pole Backscatter detector with a 20 kV accelerating voltage and a current beam of 100 μA. The carrying phase and the liberation of Pb and Sn were determined from these images. The liberation of contaminants (%) was obtained by calculating the ratio of the surface occupied by the contaminant to the total surface of the particle. Minerals were identified by X-ray diffraction (XRD) analysis using a Siemens D5000 diffractometer with Cu Kα radiation. Scans were taken for 2θ over 5° to 80° at 0.02°/s.

2.3. Magnetic separation

Magnetic separation was performed using a CARPCO 3 × 4 L high intensity magnetic separator (Outokumpu technology, Jacksonville, Florida, USA). Soil samples of approximately 350 g were exposed to an increasing magnetic field (induction) generated from a magnetic coil. Variations in the intensity of the magnetic field were obtained by using a variable transformer to control power input. Dry soil samples were dropped over the magnetic separation chamber using a vibratory feeder (Laborette 24 model, Fritsch GmbH, Idar-Oberstein, Germany) at a rate of 150 g per minute. Soil particles were brought close to the separation chamber walls (distance <0.5 cm) using an inversed V shape wooden block (Fig. 1). Non-magnetic particles passed through the separation chamber and were collected in a pan underneath the separation chamber, while magnetic particles were attracted and retained on the chamber's walls. Magnetic particles were collected from underneath the apparatus in a different pan by reducing the input power to zero. This operation was repeated three times for each input power to ensure complete separation. Each soil sample was subjected to an increasing magnetic field generated by input currents of 0.2, 0.5, 1.0, 2.0, 3.0, 4.0, 5.0 and 6.0 A (400 - 800 - 1,500 - 3,000 - 4,000 - 5,000 - 6,000 and 7,000 G, respectively) resulting in nine soil fractions including the final non-magnetic fraction. The magnetic flux