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Research article

Decision support for environmental management of industrial non-hazardous secondary materials: New analytical methods combined with simulation and optimization modeling

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A B S T R A C T

Non-hazardous solid materials from industrial processes, once regarded as waste and disposed in landfills, offer numerous environmental and economic advantages when put to beneficial uses (BUs). Proper management of these industrial non-hazardous secondary materials (INSM) requires estimates of their probable environmental impacts among disposal as well as BU options. The U.S. Environmental Protection Agency (EPA) has recently approved new analytical methods (EPA Methods 1313–1316) to assess leachability of constituents of potential concern in these materials. These new methods are more realistic for many disposal and BU options than historical methods, such as the toxicity characteristic leaching protocol. Experimental data from these new methods are used to parameterize a chemical fate and transport (F&T) model to simulate long-term environmental releases from flue gas desulfurization gypsum (FGDG) when disposed of in an industrial landfill or beneficially used as an agricultural soil amendment. The F&T model is also coupled with optimization algorithms, the Beneficial Use Decision Support System (BUDSS), under development by EPA to enhance INSM management.

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1. Introduction

The generation and accumulation of industrial non-hazardous secondary materials (INSM), historically considered "waste," in large quantities may lead to risks for the environment. The proper management approach views these INSM as potential resources that could be put to beneficial use (BU) and lead to a better environment. Novel techniques, modeling, and quantitative decision support capabilities are tools that can be used to support decision-making on BU. The maximum use of the material with a minimum environmental and health impact and the lowest practical cost are essential components of an optimized INSM management approach. Even though the impact of beneficial uses of INSM on human and animal health is an important factor, this article focuses mainly on assessing the associated environmental release and cost.

As part of the proper INSM management approach, the Environmental Protection Agency (EPA) has identified significant beneficial uses of coal combustion residues, municipal solid waste, construction and demolition waste, mine tailings, and other materials that are often disposed in landfills. All of these applications involve the replacement of virgin/conventional materials by materials typically thought of as waste.

These INSM frequently contain constituents of potential concern (CPC) that are either toxic (e.g., As, Hg, Pg, Cd, Cr) or may have health consequences (e.g., Ba, Ni, Sr, Zn). The assessment of the extent to which these CPC might be released into the environment is of obvious importance to informed decisions regarding disposal or BU options. These CPC may accumulate in soils or be mobilized in pore water and groundwater, thereby posing risks to receptors.

Therefore, more realistic and sophisticated simulation and optimization techniques are essential to support decision-making on re-use of INSM. Several recent studies reported the use of simulation and optimization techniques and tools that can be used in solid waste management (Lu et al., 2009; Mir et al., 2016; Park, 2014; Park and Chertow, 2014; Puig et al., 2013). Among those, only few have considered the re-use applications of INSM. In some studies, the technical, economic and behavioral factors of INSM have been considered for optimization (Park, 2014), while some

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Abbreviations

INSM	Industrial non-hazardous secondary materials
BU	Beneficial use
EPA	Environmental protection agency
CPC	Constituents of potential concern
TCLP	Toxicity characteristic leaching protocol
SPLP	Synthetic precipitation leaching protocol
LS	liquid/solid
F&T	Fate and transport
FGDG	Flue gas desulfurization gypsum
SF	soil-FGDG mixture
NPC	Non-equilibrium partitioning coefficient
GEM	Generic environmental model
CCM	Conceptual compartment model
BUDSS	Beneficial use decision support system
MCL	Maximum contamination level
RSL	Regional screening levels
RCRA	Resource conservation and recovery act

have used life cycle assessment methodology (Puig et al., 2013). Park and Chertow (2014) introduced a new tool named “the reuse potential indicator” to identify the re-use potential of a waste material considering the properties of the materials and the associated cost. However, a study of combined fate and transportation modeling with the optimization algorithms is not reported to the best of our knowledge.

The toxicity characteristic leaching protocol ([TCLP] EPA Method 1311) has historically been the most common leaching test used in many environmental release assessments (Kim et al., 2005; Lincoln et al., 2007; Wang et al., 2014). However, TCLP represents a single scenario that was designed to mimic landfill leaching conditions, and may cause misinterpretation of element leaching when used in BU applications (Al-Abed et al., 2006). For example, TCLP underestimates the leaching of oxyanion-forming elements (Hooper, 1998). Other methods, such as synthetic precipitation leaching protocol ([SPLP] EPA Method 1312), or acid digestion procedures, are also not necessarily indicative of these varied applications. Recently approved Leaching Environmental Assessment Framework (LEAF) EPA Methods 1313–1316 developed by Kosson et al. (2002) provide detailed information about constituents release from materials. Among these, EPA Method 1314, which assesses the liquid/solid (LS) partitioning of constituents released from materials as a function of LS ratio, mimics actual field conditions.

With the availability of EPA Method 1314, it becomes feasible to estimate chemical partitioning behavior in a variety of in situ environmental scenarios reflecting beneficial land applications and disposal options. With a combination of this experimentally determined behavior data and chemical fate and transport (F&T) modeling algorithms, it then becomes feasible to realistically simulate long-term environmental releases of chemicals in BU as well as disposal scenarios of potential interest. Finally, by combining optimization algorithms with EPA Method 1314 data and F&T predictive models, it becomes possible to assess tradeoffs among alternative BU and disposal scenarios with regard to long-term direct environmental releases, indirect releases (e.g., greenhouse gases), costs, and other criteria of management interest.

Recently, Koralegedara et al., 2017 evaluated the leaching characteristics of trace elements in flue gas desulfurization gypsum (FGDG) and a soil-FGDG (SF) mixture under different environmental conditions of pH and LS using the recently approved EPA Methods 1313–1316. The present study explores EPA Method 1314 and TCLP data obtained for FGDG and SF by Koralegedara et al. (2017), and management uses of the LEAF data for EPA Method 1314 (LS ratio) for FGDG and SF materials, in combination with chemical F&T simulation and optimization algorithms. The objective of this paper is to demonstrate the methodologies and encourage similar applications to improve environmental management and BUs of INSM through F&T simulation coupled with optimization, using realistic model parameterization.

2. Methodology

2.1. Input data (EPA method 1314 and TCLP results) for the fate and transport model

Koralegedara et al., 2017 describe EPA Method 1314 performed for FGDG, soil, and SF. Briefly, commercially available FGDG, soil collected from an agricultural farm, and SF prepared by mixing soil:FGDG at 71:29 wt percent was used in an EPA 1314 column leaching test. Then deionized (DI) water was used as the extraction fluid and leachate was collected at different time intervals as a function of LS ratio. The same materials were used in a TCLP experiment. The extraction fluid was prepared by acidifying DI water with glacial acetic acid to reach the pH 2.88. The LS of 20 was used and the leachate was collected after 18 h. All the leachates were filtered through 0.45 μm polypropylene membrane filters, acidified with 5% HNO_3 and analyzed for dissolved elements by ICP-AES analysis (EPA Method 6010 B using an IRIS Intrepid Inductively Coupled Plasma-Atomic Emission Spectrometer, Thermo Electron Corporation, CA). Among the several targeted CPC, we looked for those that were leached from at least both FGDG and SF, and ideally soil as well. Using this criterion, we selected selenium (Se) and boron (B) to be used in the F&T model. Leachate concentrations of Se and B measured during EPA Method 1314 and TCLP for the FGDG SF and soil are presented in Tables S1–S3, respectively (supplementary information). Se was not detected in the native soil sample above the method detection level.

2.2. Development of non-equilibrium partitioning coefficient (NPC (LS)) models

The F&T simulation modeling presented subsequently requires the actual liquid-solid partitioning at various LS ratios. The liquid-solid partitioning coefficients calculated at different LS ratios using EPA-method 1314 data (Fig. 1&2) were used in the F&T simulation model. These liquid-solid partition coefficient values obtained under non-equilibrium conditions herein named as NPC were calculated for each sampling event considering the total content of each element available in the system (after adjusting the amounts removed from the system at each sampling event) and the concentration of each element in the leachate at that time (A calculation example is given in supplementary information (S.1)). The NPC of Se and B in all the materials is increased as the LS ratio increases, but at a decreasing rate (Figs. 1 and 2), except for B in FGDG. A regression model based on a power function was used to predict the partitioning of Se and B beyond the maximum LS ratio of the experiment.

2.3. Development and evaluation of chemical F&T model

To enable long-term simulation and comparison of expected environmental releases for the landfill disposal option and the agricultural field BU option, we used the Generic Environmental Model (GEM), a numerical, chemical F&T model. The GEM sets up and numerically solves the classical, advective/dispersive, partial