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Review

Soil washing for metal removal: A review of physical/chemical technologies and field applications

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Abstract

Soil washing is one of the few permanent treatment alternatives to remove metal contaminants from soils. This paper reviews the various technology types and pilot/full-scale field applications of soil washing applicable to soils highly contaminated with heavy metals. The physical separation technologies, the chemical extraction processes and the integrated processes that combine both physical and chemical methods are discussed separately. This paper reviews basic principles, applicability, advantages and limitations, methods of predicting and improving performance of each physical/chemical technology. The discussion is based on a review of 30 recent laboratory investigations and 37 field applications of soil washing systems which have been undertaken, mostly in the US, for the period 1990–2007. This paper also examines and compares the status of soil washing technology for remediation of soils contaminated with metals in the US, in Canada and in Europe.

Keywords: Heavy metals; Soil washing; Physical separation; Chemical extraction

Contents

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1. Introduction

In the United States, heavy metals are prevalent at almost all sites targeted by major remediation programs. For instance, metals are present in 77% of the Superfund sites (National Priorities List), in 72% of the Department of Defense (DOD) sites and in 55% of the Department of Energy (DOE) sites [1]. The USEPA estimates that over 50 million cubic meters of soil at current NPL sites are contaminated with metals [1].

The remediation of metal-contaminated sites has traditionally involved excavation of the contaminated soils, followed by the immobilization of metal contaminants by solidification/stabilization (S/S) technology prior to disposal of the materials treated in a permitted landfill site or on-site [2,3]. The remedial actions based on S/S technology are no longer considered a permanent environmental solution because of: (1) the metals are not removed from contaminated media; (2) the need for future monitoring of heavy metals on site; (3) questionable longevity of the solidified/stabilized materials; and (4) the long-term management of the solidified/stabilized materials is based on landfilling and requires soil caps to prevent erosion problems. Hence, there is a great need to promote effective soil treatment technologies that attempts to remove the metals from the soils. Soil washing, which uses physical or chemical processes, is one of the few permanent treatment alternatives to separate the metals from soils.

This paper provides a review of the soil washing methods (ex situ techniques) for soil contaminated with arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), mercury (Hg), nickel (Ni), lead (Pb), and zinc (Zn). Although arsenic is a metalloid, the term "metals" will be used to include all the elements under discussion. The discussion focuses on the remediation of soil matrices highly affected by industrial and military activities (e.g., soil contaminated by tailings/slags, brownfields, battery recycling site, and shooting range site). Soil washing processes related to organic contaminants and radioactive metals are not discussed here. Also, the discussion does not include in situ treatment (soil flushing). In this review, soil washing includes the following options: (1) physical separation based on mineral processing technologies; (2) chemical extraction based on leaching or dissolving process; and (3) combination of physical separation and chemical extraction.

This paper is organized in five sections: (1) soil washing background; (2) physical separation; (3) chemical extraction; (4) combination of physical separation and chemical extraction; and (5) status of soil washing in the US, in Canada and in Europe. The first purpose of this review is to present a technical description of the various technologies: principle, applicability, methods of predicting and improving performance are discussed. Several recent laboratory studies involving physical separation (seven examples) and chemical extractions (24 examples) are summarized. The physical separation technologies, the chemical extraction processes and the integrated processes that combine both physical and chemical methods will be discussed separately. The second purpose of this paper is to provide a review of the field applications of soil washing systems involved in the treatment of the metal contamination. The discussion is based on a collection of 37 case studies of pilot/full-scale remediation projects performed, mostly in the US, for the period 1990–2007. The third purpose of this paper is to review the implementation degree of soil washing technology relevant to the treatment of metal-contaminated soils, in the US, in Canada and in Europe.

2. Soil washing background

Soil washing, as discussed in this paper, refers to ex situ techniques that employ physical and/or chemical procedures to extract metals contaminants from soils. Fig. 1 presents a schematic diagram of typical options used in soil washing processes: (1) physical separation; (2) chemical extraction; (3) combination of both. Physical separation (PS) concentrates metal contaminants into a smaller volume of soil by exploiting differences in certain physical characteristics between the metal-bearing particles and soil particles (size, density, magnetism, and hydrophobic surface properties). Chemical extraction (CE) relates to techniques that try to solubilize the metal contaminants from the soil with an extracting aqueous fluid containing chemical reagents such as acids or chelating agents.

Soil washing systems are quite flexible in terms of number, type, and order of processes involved and other names are used for soil washing technologies: "soil separation", "soil recycling", or "volume reduction". The definition and use of the terms "soil washing", "physical separation" and "chemical extraction" can differ according to the authors. The degree to which chemical agent or physical separation techniques are used may affect the nomenclature to describe the washing process. In the US and in Europe, soil remediation processes based on mineral processing technologies are often referred as the broad term "soil washing" [4–6] although the term "physical separation" appears more accurate [7–9]. The term "soil washing" is also used in the literature for describing processes that involve chemical extraction processes [10–13]. FRTR [4] distinguishes "soil