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Treatability of volatile chlorinated hydrocarbon-contaminated soils of different textures along a vertical profile by mechanical soil aeration: A laboratory test

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A B S T R A C T

Mechanical soil aeration is a simple, effective, and low-cost soil remediation technology that is suitable for sites contaminated with volatile chlorinated hydrocarbons (VCHs). Conventionally, this technique is used to treat the mixed soil of a site without considering the diversity and treatability of different soils within the site. A laboratory test was conducted to evaluate the effectiveness of mechanical soil aeration for remediating soils of different textures (silty, clayey, and sandy soils) along a vertical profile at an abandoned chloro-alkali chemical site in China. The collected soils were artificially contaminated with chloroform (TCM) and trichloroethylene (TCE). Mechanical soil aeration was effective for remediating VCHs (removal efficiency >98%). The volatilization process was described by an exponential kinetic function. In the early stage of treatment (0–7 hr), rapid contaminant volatilization followed a pseudo-first order kinetic model. VCH concentrations decreased to low levels and showed a tailing phenomenon with very slow contaminant release after 8 hr. Compared with silty and sandy soils, clayey soil has high organic-matter content, a large specific surface area, a high clay fraction, and a complex pore structure. These characteristics substantially influenced the removal process, making it less efficient, more time consuming, and consequently more expensive. Our findings provide a potential basis for optimizing soil remediation strategy in a cost-effective manner.

Introduction

Volatile chlorinated hydrocarbons (VCHs), which are potential mutagens and carcinogens, are among the most commonly used industrial products. VCHs are introduced into the environment through their use as chemical intermediates. Such compounds are frequently found in contaminated soils in China and throughout the world (Wu et al., 2005).

Soil remediation technologies that are applied to sites contaminated with VCHs include soil vapor extraction (Albergaria

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et al., 2012), soil flushing (Kujawski et al., 2007), thermal desorption (He and Sulkes, 2011), bioremediation (Chang et al., Q4 Q3 2002; Williamson et al., 2009), microwaving (Acierno et al., 2001, Q5 Acierno et al., 2004; Jones et al., 2002), and bioventing (Fukue et al., 2006). However, economic constraints may restrict the use of these technologies in developing countries.

Mechanical soil aeration was developed as a low-cost and highly effective remediation technology for VCH-contaminated sites and was mentioned in an annual report on remediation technologies published by the United States Environmental Protection Agency (U.S. EPA, 2007). This technology facilitates the release of volatile organic compounds (VOCs) from the soil by plowing and forced cross-ventilation. The released VOCs are then collected and treated. The advantages of mechanical soil aeration include ease of operation, significant remedial efficiency, a short remediation cycle, and cost-effectiveness. However, there are some drawbacks associated with this technology (Zhang et al., 2015). First, handling of contaminated soils is associated with an increased risk of human toxic exposure. In addition, the excavation process may pose structural risks to neighboring buildings (Yang et al., 2013).

Mechanical soil aeration removes VOCs by volatilization induced by mixing, cutting, and flipping the soils. Our previous studies on soil remediation by mechanical soil aeration in the field and laboratory revealed that agitation frequency, soil temperature, and aeration affect the removal efficiency of VCHs (Shi et al., 2012; Ma et al., 2015a, 2015b). Heterogeneity and non-uniformity of soil media introduce many uncertainties into the remediation process. Remediation efficiency is strongly influenced by differences in soil characteristics.

In practice, mechanical soil aeration is commonly applied after excavation of soil for *ex situ* remediation, without considering the effects of different soil layers along a vertical profile. It may be more cost effective to treat each soil fraction (*i.e.*, clay, silt, and sand) separately to achieve optimal remediation efficiency, assuming that separate excavation of the soil texture types is feasible. The present study was undertaken to conduct a laboratory treatability study of three soils along a vertical profile of an abandoned chloro-alkali chemical site. Our approach aimed to investigate the response of different soil textures to mechanical soil aeration and analyze the remediation efficiency of different treatments. The results provide data to optimize decision-making for the remediation of sites contaminated with VCHs.

1. Materials and methods

1.1. Chemicals and reagents

Chloroform (TCM) and trichloroethylene (TCE) were used to simulate contaminated soils and were purchased from Sinopharm Chemical Reagent (Beijing, China), with purities of 99%. Methanol (Fisher Scientific, GC Resolv, America) was used to extract the above mentioned contaminants (TCM and TCE).

1.2. Preparation of contaminated soils

Original soil samples were collected from three soil horizons of a vertical profile in a contaminated site: horizon 2 (2.5–5.5 m deep), horizon 3 (5.5–8.1 m deep), and horizon 4 (8.1–10.7 m deep) (Fig. 1).

Prior to the experiment, large particles and plant residues were removed from the soil. The soil was air-dried for 20 days, ground, sifted using a #10 (2 mm) sieve, dried at 105°C for 12 hr, and stored for subsequent use (Ma et al., 2015a, 2015b). This pretreatment was performed to obtain a fraction of soil with uniform physical properties and without contaminants.

The artificially contaminated soils were prepared as follows. The contaminant solution was prepared by adding 15 mL of each of the two contaminants to 250 mL of methanol. Next, 2000 g of sieved soil was spread evenly on a polyethylene plastic sheet; 500 mL of high-purity water was added to maintain soil moisture content of 20% (W/W), and the mixture was stirred and pressed. We immediately added 50 mL of contaminant solution, covered the mixture with 1000 g of sieved soil and 100 mL of high-purity water, and immediately wrapped the mixture with plastic sheeting and sealed it with tape (Ma et al., 2015a, 2015b). The contaminated soils were sealed in airtight boxes and stored at 4°C for 4 days to ensure that the concentration of contaminants was even and stable (Shi et al., 2012).

1.3. Experimental procedure

We designed an apparatus to simulate mechanical soil aeration. This apparatus allowed contaminants to be removed via volatilization induced by mixing, cutting, and flipping of the soil by rotating coulters. The released VOCs were discharged after treatment with activated carbon. The apparatus consisted of a main body, a temperature control system, an automatic control system, and an exhaust gas treatment system (Fig. 2). The following operation parameters were fixed during the experiment: aeration rate (3 L/min), initial soil temperature (20°C), agitation interval (2 hr), mixing speed (200 r/min), and agitation time (10 sec).

Soil samples were collected every hour for the first 24 hr and every 2 hr between hours 25 and 48. Each group of samples included three replicates, and the final data were the average values of the three replicates. Soil samples collected for VCH measurement were placed in 40-mL closed glass vessels pre-filled with 10 mL methanol. Additional soil samples were collected from the area surrounding the VCH sampling sites and used to analyze water content. All samples were stored in a refrigerator at 4°C before analysis (Ma et al., 2015a, 2015b).

1.4. Analytical methods

The concentrations of VCHs in the soils were measured using a gas chromatograph (7890A GC, Agilent Technologies, USA) equipped with a mass spectrometer (5975C MS, Agilent, America), in accordance with the USEPA-8260C method. The GC was fitted with a DB-624 capillary column (60 m × 250 μm × 1.4 μm; Agilent) and was operated with helium as the carrier gas (flow rate, 1.2 mL/min). The oven temperature was programmed as follows: 40°C for 2 min, increased to 200°C at a rate of 20°C/min, increased to 250°C at a rate of 10°C/min, and maintained at 250°C for 3 min. The Method Detection Limits of target VOCs detected are presented in Table S1. The relative percent difference between replicate samples was ≤25%.

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