REMEDIATION OF Cd, Pb AND Cr CONTAMINATED SOILS BY WASHING

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Abstract

The main objective of this study was to evaluate the effectiveness of soil washing to remove and reduce the leaching of Cd, Pb and Cr from two contaminated soil types designated as organic and inorganic. Contamination levels were in the range 500 mg/kg to 5,000 mg/kg. Four extraction solutions were used: EDTA, HCl, tap water, and detergent. The study demonstrated that EDTA was the most effective extraction solution, with removals exceeding 85% from the inorganic soil, and exceeding 50% from the organic soil. The leaching of metals from treated soils, as determined by the Toxicity Characteristic Leaching Procedure, TCLP, was reduced by 75% to more than 98% and generally below the TCLP concentration limits specified by the United States Environmental Protection Agency, USEPA.

Introduction and Background

With expanding industrialization, developing countries should benefit from the experience of industrial nations in the area of pollution control and prevention. In addition to existing contaminated sites, industrial activities and waste spills continue to contaminate soils. Accordingly, there is a constant demand for new and innovative pollution control technologies. Soil washing offers an alternative to competitive soil remediation technologies, including: stabilization/solidification, bioremediation and land disposal. The establishment of soil cleanup standards is necessary to advance the development of new soil remediation technologies. Asp(1) argued that the soil cleanup criteria adopted in some European countries promoted the development of a number of innovative full-scale cleanup technologies. In addition, it is essential to characterize the size and nature of the contamination problem to direct the scientific research and development activities towards the specific needs of the countries in the area.

Process Description

Soil washing involves contacting soils with aqueous wash solutions to remove soil-contained contaminants. Soil contaminants tend to associate with fine silt and clay particles due to the large available specific surface area (surface area per unit weight of soil). Larger soil particles tend to contain primarily surficial contamination(2). Soil washing is achieved through separating fine silt and clay fraction from the soil matrix, attrition scrubbing(2,3) which disintigrates soil aggregates releasing contaminated fines, scouring the surfaces of larger soil particles, and solubilizing and extracting soil-bound contaminants. Since soil washing techniques employ aqueous solutions, the leachibility of remediated soils is considerably reduced and washed soils may be replaced on site.

Soil washing employs two process variations: ex-situ and in-situ. In the ex-situ process, soils are excavated and subjected to variuos treatment and separation steps. Pretreatment consists mainly of debris segregating, size modification, and oversized soil particles washing and separation. The remaining soil is subjected to high energy contacting and scrubbing with the wash solution. Following washing, fine silt and clay fraction of the soil is separated, dewatered, and subjected to further treatment or disposal. The remaining soil is recovered as product and may be replaced on site or used as fill material. The separation of the contaminated fine soil fraction results in significant soil volume reduction. In-situ soil washing is a leaching process in which the washing solution is applied to the soil by injection(4) or flooding(1). The process aims at solubilizing and extracting soil-bound contaminants, and thus effective soil washing solutions are generally required. The applied wash solution percolates through soil reaching the water table, from where it is pumped back to the surface for treatment. The treated solution is recycled and the washing process is repeated until the contamination is reduced to the desired level. The basic ex-situ process involves the following general steps: Soil characterization, soil preparation, soil washing, size separation, solid-liquid separation, wastewater treatment, emissions collection and treatment, and residues handling. A brief description of the above steps is presented in the following sections.

Soil Characterization

The effectiveness of soil washing depends on the type and concentration of the contaminants and the characteristics of contaminated soils. Determination of the particle size distribution is essential for assessing the feasibility of the process. Different processes may specify different size limits for the fraction of the soil considered oversize, the fraction suitable for washing, and the fraction difficult to treat. The USEPA(5) specifies the following limits: over size (>2mm), effective soil washing size (0.25 mm to 2 mm), limited soil washing size (0.063 mm to 0.25 mm), and difficult soil washing size (<0.063 mm). Accordingly, most vendors(6) state a practical upper limit of 20% to 30% on the soil fine silt and clay fraction (<63 μm), above which the process becomes expensive due to the cost of fines separation and handling. The type and concentration of the contaminants is essential for selecting the proper wash solution and extent of treatment. Other soil characteristics(5) such as organic content, humus content, contaminant partition coefficient, pH and buffering capacity give important information on the compatibility of the wash solution and potential process effectiveness. In addition, the moisture content and other soil handling properties affect soil pretreatment and transfer requirements(5).

Soil Preparation

Soil preparation includes: excavation, size modification and separation of oversized objects(7). Various soil excavation equipment may be used for soil excavation and size reduction depending on the soil characteristics. Excavation equipment include bachoes, front-end loaders, bulldozers, draglines or clamshells, and dredges. Size modification equipment include a variety of jaw crushers, impact mills, hammer mills, ball mills, and other equipment. In the process, large material may be subjected to size reduction or segregation by screening. Crushed oversize particles are water washed then separated, usually using vibrating screens.

Soil Washing

Ex-situ soil washing involves high energy contacting and scrubbing of contaminated soils in liquid wash solutions. Washers, mixing units, oscillation/vibration units, water-knife units (rotary drum screen scrubbers), high-pressure water jets, bubble column floatation units, and other techniques are used in soil washing. The Biotrol® soil washing system(2) employs several stages of intensive scrubbing achieved by two opposing pitch propeller type impellers. Before washing, the soil (less than 2 mm) is passed through a froth floatation unit to separate hydrophobic contaminants. The process is applicable for organic and inorganic contaminants. The USEPA volume reduction pilot-scale process(8) utilizes a mini-washer unit. The pretreated soil fraction (<0.5 inch) is fed to the washer where the wash solution is added. The wash solution can be heated to a maximum temperature of 150 °C. The Harbauer soil cleaning system(9) involves mixing the soil with extractant solution (mostly biodegradable detergants) in a blade washer followed by extraction in a vibration unit. Clean soils between the sizes 15 µm and 12 mm are recovered following solid-liquid separation.

A wide range of contaminants can be treated using various extraction solutions. Many organic and inorganic wash solutions have been investigated including: surfactants, detergants, acids (HNO_3, HCl, H_2SO_4), bases (i.e., NaOH), chelating agents (EDTA), oxidizing and reducing agents (i,e., H_2O_2), electrolytes, heated solutions, solvent extractants, and others. Surfactants and detergants are effective for the removal of hydrophilic and hydrophobic organics. Acids and bases are effective for the removal of hydrophobic organic compounds and heavy metals(10). Chelating agents help solubilize and keep heavy metals in solution. The selection of washing solutions should be based on the characteristics of soils and contaminants, and the results of bench and pilot-scale testing. Sequential soil washing using various solutions may be necessary to achieve the desired contaminant removal(11).

Size and Solid-Liquid Separation

The purpose of size separation is to separate the contaminated fine silt and clay fraction from the clean soil. Solid-liquid separation is designed to separate the wash solution from the contaminated soil fraction. Post treatment size separation typically employs screens, spiral classifiers, and hydrocyclones. Solid-liquid separation can be achieved by gravity separation, straining, centrifugation, coagulation-flocculation, and filtration. Sedimentation facilities are typically used following screening. The underflow from the sedimentation step may be clean, or may require further treatment. The overflow from the sedimentation step carries the fine particles and requires further solid-liquid separation. The presence of humus and large quantity of fine clay may interfere with the separation process. Coagulation followed by floatation or sedimentation is typically used for fines separation. The USEPA pilot soil washing unit separates the cleaned soil into three fractions using two vibrating screens, 0.25 mm and 2 mm(8). Gravity sedimentation separates particles with sizes in the range 34 µm to 250 µm. Contaminated fines are separated by coagulation-flocculation followed by sedimentation and filtration. The lower limit of particle size separation achieved by the Harbauer system(9) is 15 µm. This separation is achieved by sedimentation followed by 5 stage hydrocyclones. The contaminated fines, <15 µm, are separated by coagulation-flocculation followed by countercurrent floatation.

Wastewater Treatment

The separated wastewater is usually recovered and reused for washing. Wastewater treatment technologies are widely available and well-established. Wastewater treatment include biological, physical-chemical, and thermal processes. The presence of surfactants and chelating agents in wash solutions may interfere with wastewater treatment. Wastewater treatment is an additional cost to the treatment process and should be included when evaluating the feasibility of the technology.

Solid Residues Handling

Several options are available for the treatment and management of contaminated fine silt and clay fraction of the soil, including: incineration, stabilization/solidification, biological treatment, chemical treatment, heat desorption, and land disposal. In addition, the sludges generated from treating the wastewater should be handled according to their characteristics. The cost of handling the solid residues is an important factor in the overall feasibility of the process. Because of the additional cost, most vendors set the upper practical limit of fine silt and clay fraction of the soil to below 30%(6).

Emissions Control

Regulated volatile contaminants stripped during the various process activities should be collected and treated according to applicable standards and regulations. Vapor condensors and adsorption columns are examples of applicable emission control technologies. Vapors can be collected through the use of vacuum blowers. Emission control processes generate wastes that should be handled properly. For example, exhausted activated carbon require regeneration or disposal. Emissions control contributes an additional cost that should be considered in evaluating the overall feasibility of the process.

Performance and Applicability

Soil washing can be used alone or in combination with other treatment processes as a preprocessing step(5). Soil washing may be used for remediating soils contaminated with a wide range of organic and inorganic contaminants. According to the USEPA(5), the applicability of the technology for cleaning sandy/gravely soils contaminated with volatile organic compounds and volatile and non-volatile metals is good to excellent. Washing soils contaminated with semi-volatile organic compounds, PCBs, halogenated pesticides, dioxins, organic and inorganic cynides, organic and inorganic corrosives, and reactive oxidizers and reducers is suggested to have moderate to marginal applicability, depending on site specific conditions. The extraction of heavy metals from soils has been practiced for long by the metal mining industry, and thus soil washing development should benifit from the accumulated experience of the mining industry(12). The technology has been successfully applied to treat soils contaminated with a wide range of organic and inorganic contaminants at full scale remediation projects in Germany and the Netherlands. Other commercial operations are currently under development in the United States and Europe(1,5,10,13,14). During 1986-1989, soil washing was selected as a source remediation process at eight contaminated Superfund sites in the United States(15). The Harbauer soil cleaning system, during the period July 1987 to December 1988, treated approximately 11,500 tons of soil at an oil refinary site in Berlin(9). The cost of treating one ton of soil using soil washing is in the range $50 to $200 in the U.S. and Europe, including the cost of residues handling(5). Comparatively, the cost of landfilling is approximately $200 per ton, and incineration is approximately $500 per ton(1).

In-Situ Soil Washing

In-situ soil washing is a leaching process that does not require soil excavation. In the process the washing solution, applied to soil by flooding or injection, percolates through the soil solubilizing and attracting contaminants. The wash water then reaches the water table or the drainage system from where it is pumped, using withdrawal wells, to the surface for treatment. The process aims at solubilizing and extracting soil-bound contaminants, and thus the use of effective extraction solutions may be necessary. The treated water is then recycled and the process is repeated until contamination is reduced to the desired level. The effectiveness of the process depends on the type of soil and contaminant. The process is better suited for permeable soils (permeability(4) $>10^{-4}$ cm/sec). Accordingly, soils with high fine silt and clay content may not be suitable because of the limited permeability. Highly soluble contaminants are removed easier than insoluble or moderately soluble contaminants. In addition, freshly contaminated soils may be easier to clean than older sites. Depending on site specific conditions, the cost of in-situ soil washing may not exceed $100 per ton(1). The Waste-Tech Services, Inc.(1) conducted a field pilot study in southern Florida to clean a site contaminated with oil floating on the watertable. The soil was contaminated due to watertable fluctuations. In-situ soil washing achieved, using a propreitary alkaline polymer surfactant, approximately 75% soil oil removal and complete oil removal from the ground water.

Materials and Methods

The study presented in this paper includes batch, wrest-shaker experiments and soil-column experiments. To ensure accuracy, blanks and duplicate leachate samples were analyzed for each run. All used glassware and sample vials were properly acid washed and rinsed. Two clean soil types, an organic, agricultural silty soil, and an inorganic construction sandy soil were used. A summary of selected characteristics of the two soils is presented in Table 1. Selected sizes were separated from the soils and mixed according to Table 2. Portions of the prepared soils were contaminated with Cr ($K_2Cr_2O_7$), Cd ($Cd(NO_3)_2$), and Pb ($Pb(NO_3)_2$) at individual contamination levels of 500 mg/kg, 1,000 mg/kg, and 2,000 mg/kg. After contamination, the soil samples were oven dried, sieved, and thoroughly mixed.

Table 1: Selected characteristics of raw soil samples from their respective sites.

Soil Parameter	Silty, High* Volatile Content Soil	Sandy, Low** Volatile Content Soil
Coarse Sand (%)	12.3	64.4
Fine Sand (%)	12.0	34.0
Silt and Clay (%)	75.7	1.6
Moisture Content (%)	1.8	0.6
Volatile Content at 550 °C (%)	6.1	0.9
pH (1 wt. soil:1 wt. water)	7.9	9.6

* Organic Soil

**Inorganic Soil

The following extraction solutions were prepared and used in the the batch experiments: EDTA (0.025 N, 0.05 N, and 0.1 N), 0.1 N HCl, Tap water, and 0.5% local detergent. The 0.025 N EDTA solution was used with the lowest level of contamination, 0.05 N used with the intermediate contamination level, and 0.1 N used with the highest contamination level. Batch experiments consisted of washing 10 g of soil in 100 mL extraction solution, in glass bottles, for 30 minutes. After washing, the contents of the bottles were centrifuged at 2000 rpm for 15 minutes, the liquid carefully separated, and the soil oven dried at 103 °C.

Table 2: Characteristics of contaminated soils used in the study.

Soil Parameter	Inorganic Soil	Organic Soil
Passing Sieve Retained On Sieve		
No. 4*....................No. 10	10%	0%
No. 10....................No. 40	40%	44%
No. 40....................No. 200	40%	44%
No. 200..................Pan	10%	12%
Contamination Levels:		
-Cr, Total (mg/kg)	(485),(1020),(1940)	(510),(980),(2100)
-Pb, Total (mg/kg)	(500),(1020), (2050)	(545),(1090),(1970)
-Cd, Total (mg/kg)	(490), (970), (2110)	(460), (930), (1950)

* ASTM (No. 4=4.75 mm, No.10=2mm, No.40=425μm, No.200=75μm)

In the TCLP test, the solids were added to individual extractor bottles and extracted with a volume of extraction fluid equal to 20 times the weight of the solids. The TCLP extraction fluid consisted of 5.7 mL glacial acetic acid and 64.3 mL of 1.0 N NaOH diluted to 1 L, with a pH of 4.93±0.05. The tightly closed extraction TCLP bottles were rotated in a rotary extractor at 30 rpm for 18 hours. After completion, the contents of the TCLP bottles were centrifuged for 15 minutes and the concentration of metals in the liquid phase measured. The concentrations of individual metals in all extraction solutions were measured using flame atomic absorption, FAA. All soil metals were determined using nitric acid digestion procedure, Method 302D(16).

Each glass column, 500 mm long and 50 mm in diameter, was filled with 50 mm graded gravel and on top of which, 500 g of the contaminated inorganic soil (Table 1) was added. Three columns, at a contamination level of 5000 mg/kg, were used for each metal. Each of the three columns was extracted with a daily 300 mL of 0.1 N HCl, 1 N HCl, or 0.1 N EDTA solution. The extraction solutions were drained the next day, after 24 hours of contact.

Results and Discussion

In this section, an evaluation of the effectiveness of soil washing in remediating the two treated types of contaminated soils is presented. Two treatment objectives were considered: (1) removal of the contaminant from the soil; and (2) reduction of contaminant leaching from the soil. The results are presented and discussed in terms of achieving the above established treatment objectives, and little attempt was made to explain the various reactions and mechanisms that lead to producing the observed results.

Cr-Contaminated Soils

Except for the low Cr removals from the organic soil (Table 3), achieved using HCl solution, the four tested extraction solutions: tap water; EDTA; HCl; and detergent, were approximately equally effective in achieving the treatment objectives. Accoring to the data presented in Table 3, Cr removals were in the range 77% to 97.3% from the inorganic soil, and 34% to 57.5% from the organic soil (excluding HCl removal results). For HCl, the removals achieved from the organic soil were in the range 4% to 35%. Even though the two soils have nearly similar size distribution, the results indicate that Cr removal from the inorganic soil was significantly higher than that from the organic soil, reflecting the higher degree of attachment of the dichromate ion to the organic soil particles. It should be noted that the organic soil contained significant amounts of calcium carbonate which reacted with the acidic solution releasing carbon dioxide.

The other treatment objective, leaching reduction, was effectively achieved under all treatment conditions (Table 3). The TCLP regulatory limit for Cr in the TCLP extract is 5 mg/L. All contaminated soil samples exceeded, in terms of leaching, the TCLP limit. Under all conditions, the TCLP results from treated soil samples were below the TCLP limit. In addition, leaching reductions were in the range 87.5% to more than 98.9%.

Table 3: Chromium removal and soil leaching reduction.

Experimental Condition		Contamination Level = 500 mg/kg			Contamination Level = 1,000 mg/kg			Contamination Level =2,000 mg/kg		
Soil Type	Extraction Solution	(A)	(B)	(C)	(A)	(B)	(C)	(A)	(B)	(C)
Organic	None	8.0	0.0	0.0	23.0	0.0	0.0	53.0	0.0	0.0
Organic	Acid	<1.0	>87.5	4.0	<1.0	>95.7	18.0	<1.0	>98.1	35.0
Organic	EDTA	<1.0	>87.5	36.0	<1.0	>95.7	48.0	1.4	97.4	57.5
Organic	Detergent	<1.0	>87.5	34.0	<1.0	>95.7	47.0	1.1	97.9	50.0
Organic	Tap Water	<1.0	>87.5	38.0	<1.0	>95.7	47.0	<1.0	>98.1	55.0
Inorganic	None	22.0	0.0	0.0	47.0	0.0	0.0	88.0	0.0	0.0
Inorganic	Acid	<1.0	>95.5	86.0	1.5	96.8	86.5	2.0	97.7	93.8
Inorganic	EDTA	<1.0	>95.5	82.0	<1.0	>97.9	89.5	<1.0	>98.9	97.3
Inorganic	Detergent	<1.0	>95.5	77.0	<1.0	>97.9	86.0	<1.0	>98.9	77.3
Inorganic	Tap Water	<1.0	>95.5	77.0	<1.0	>97.9	82.0	2.8	96.8	86.0

(A) TCLP (mg/L).

(B) TCLP Reduction (%).

(C) Metal Removal Efficiency (%).

Pb-Contaminated Soils

Tap water was ineffective in removing Pb from both the organic and the inorganic soil types. Removals achieved using tap water (Table 4) were in the range from less than 1% to 5.5%. Both EDTA and HCl solutions were equally effective in removing Pb from the inorganic soil, with removals in the range 85.8% to 97%. However, only EDTA achieved removals in excess of 50% from the organic soil. The detergent solution removed 71.4% to 82.8% lead from the inorganic soil, but was ineffective in removing Pb from the organic soil. Washing was effective in reducing Pb leaching from the contaminated soils (Table 4). The TCLP regulatory limit for Pb in the TCLP extract is 5 mg/L. Untreated soil samples exceeded the TCLP limit at all levels of contamination. For treated soils, except for tap water treated inorganic soil, the TCLP results were below the TCLP limit. In addition, the achieved leaching reductions were in the range 87.5% to more than 98.9%.

Cd-Contaminated Soils

Cadmium removal results are presented graphically in Figures 1 and 2. The results indicate that only EDTA solution achieved significant Pb removals; in the range 58.5% to 62.3% from the organic soil, and 64% to 68.5% from the inorganic soil. Tap water and the detergent solution achieved low removals, below 7%, while HCl solution achieved a maximum removal of 18% from both soil types.

Table 4: Lead removal and soil leaching reduction.

Experimental Condition		Contamination Level = 500 mg/kg			Contamination Level = 1,000 mg/kg			Contamination Level =2,000 mg/kg		
Soil Type	Extraction Solution	(A)	(B)	(C)	(A)	(B)	(C)	(A)	(B)	(C)
Organic	None	8.3	0.0	0.0	20.5	0.0	0.0	48.0	0.0	0.0
Organic	Acid	<1.0	>88.0	37.8	<1.0	>95.1	25.2	3.0	>98.1	23.8
Organic	EDTA	3.3	60.2	71.0	4.1	80.0	74.0	4.2	97.4	73.0
Organic	Detergent	<1.0	>88.0	<1.0	<1.0	>95.1	<1.0	4.6	97.9	<1.0
Organic	Tap Water	<1.0	>88.0	<1.0	<1.0	>95.1	<1.0	<1.0	>98.1	<1.0
Inorganic	None	15.0	0.0	0.0	30.6	0.0	0.0	55.5	0.0	0.0
Inorganic	Acid	<1.0	>93.3	88.0	<1.0	>96.7	85.8	<1.0	>98.2	97.0
Inorganic	EDTA	<1.0	>93.3	88.2	1.1	96.4	90.2	2.1	96.2	95.5
Inorganic	Detergent	<1.0	>93.3	71.4	1.5	95.1	74.4	2.5	95.5	82.8
Inorganic	Tap Water	3.6	76.0	3.0	17.9	41.5	1.6	37.2	33.0	5.5

(A) TCLP (mg/L).

(B) TCLP Reduction (%).

(C) Metal Removal Efficiency (%).

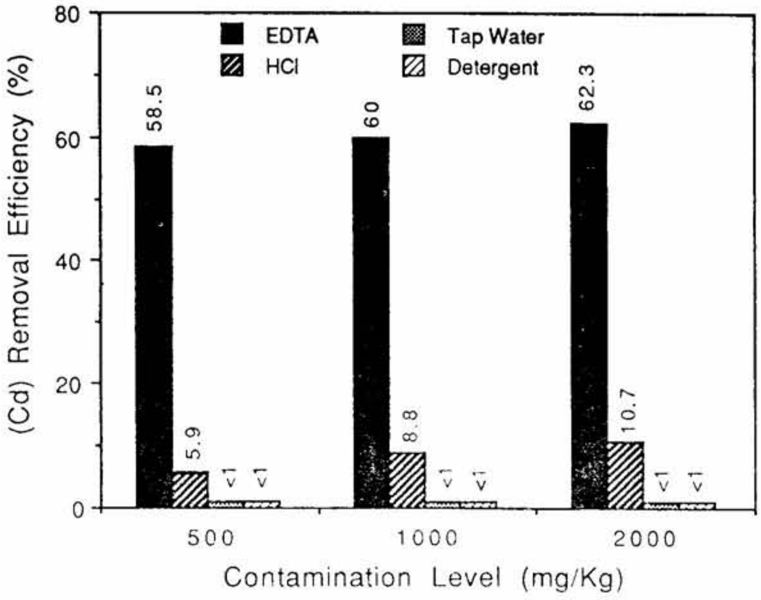

Figure 1: Removal of Cd from the contaminated organic soil.

In the sequential extraction column-experiments (Figure 3), designed to remove Cd at a contamination level of 5,000 mg/kg from the raw inorganic soil, the 0.1 N HCl solution achieved a higher cummulative removal (77%) than the 0.1 N EDTA solution (62%). The 1 N HCl solution achieved approximately 100% Cd cummulative removal. Most of the removals were achieved within five sequential extractions. Compared with the single extraction wrest-shaker experiments, the observed column results may indicate opposite EDTA and HCl removal trends. In this regard it should be noted that the following differences exist between both types of experiments: (1) in the single extraction experiments, the treated soil was prepared to have the characteristics presented in Table 2, while in the column experiments the raw soil (Table 1) was used; (2) the contaminatin level in the column experiments was 5,000 mg/L compared with the maximum contamination level of 2,000 mg/kg in the single extraction experiments; and (3) in the single extraction experiments, the concenmtations of EDTA, 0.025 N, 0.05 N, and 0.1 N, were respectively proportional to the contamination levels, 500 mg/kg, 1000 mg/kg, and 200 mg/kg. In addition, the wieght of extraction solution was 10 times that of the soil, while in a single column extraction, the ratio was at 0.6. According to the above differences, the opposite EDTA and HCl removal trends in both types of experiments may be related to the soil capacity to attach Cd in excess of 2,000 mg/L, the capacity of the extraction solution in a single extraction, and the extraction energy. More research is needed to further explain the observed trend.

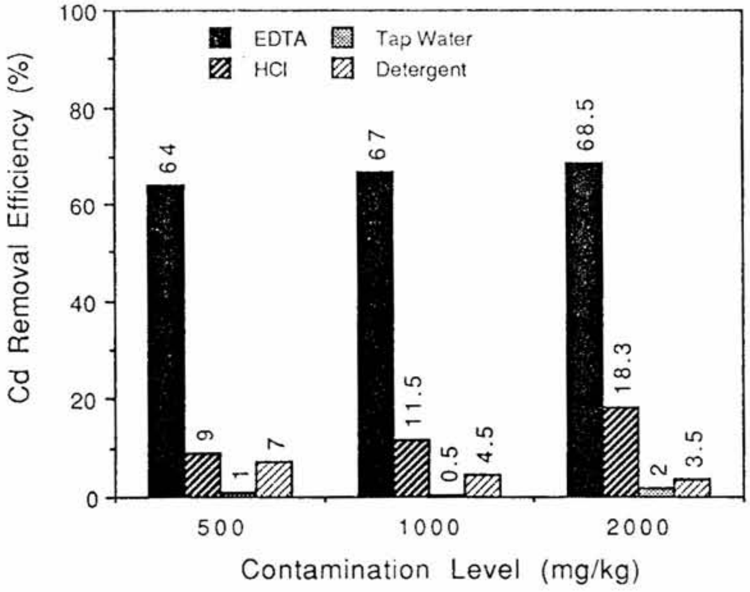

Figure 2: Removal of Cd from the contaminated inorganic soil.

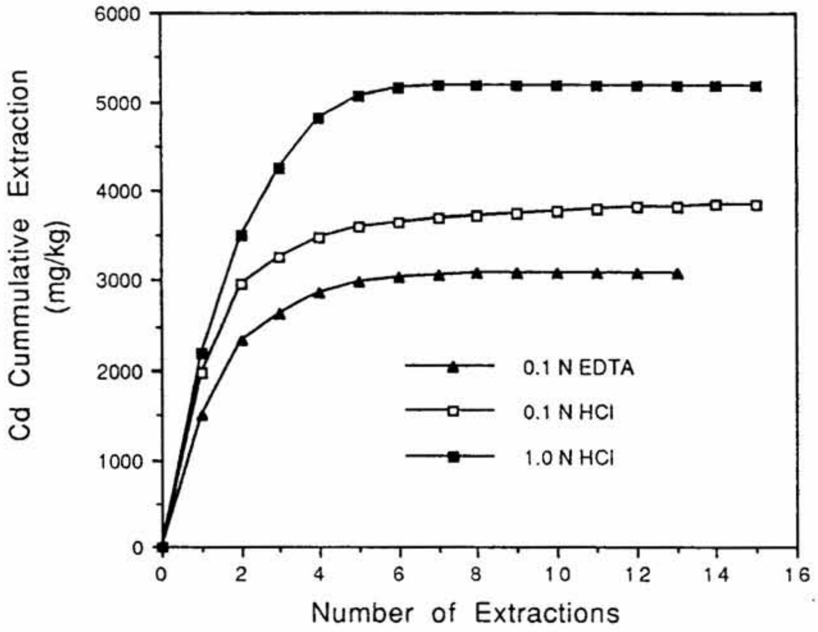

Figure 3: Removal of Cd from the contaminated inorganic soil-column using EDTA and HCl solutions.

The TCLP data presented in Table 5 indicate that none of the treated Cd contaminated soil samples achieved the TCLP limit of 1 mg/L in the TCLP extract. Nevertheless, significant leaching reductions were achieved. Additional extractions may be necessary to achieve the TCLP limit. The results presented in this paper indicate that the technical effectiveness of the process is depenedent on the nature of contaminant-soil relationship, and on the alteration of this relationship and the compitition achieved by the extraction solution and extraction energy. EDTA was the most effective extration solution used in the study.

Table 5: Cd Toxicity Characteristic Leaching Procedure (TCLP) results in mg/L.

Experimental Condition	Contamination Level = 500 mg/kg		Contamination Level = 1,000 mg/kg		Contamination Level = 2,000 mg/kg	
Parameter	Organic	Inorganic	Organic	Inorganic	Organic	Inorganic
$TCLP_{Initial}$	8.4	13.3	14.4	21.9	36.4	48.0
$TCLP_{Limit}$	1.0	1.0	1.0	1.0	1.0	1.0
$TCLP_{Final}$						
-EDTA	4.5	1.5	6.6	3.2	8.3	5.0
-HCl	3.1	1.0	6.2	2.0	8.8	4.5
-Tap Water	4.3	2.5	6.9	4.6	7.5	6.0
-Detergent	5.2	3.3	6.3	5.0	9.0	7.0

References

1- Asp, J. "Technology Update: Soil Washing, a cost effective remedial technology". Environmental Information (EI) digest, Environmental Information, Ltd, (1990)

2- Valine, S.B., D.D. Chilcote, and T.J. Chresand "BioTrol Soil Washing System". Presented at USEPA second forum on innovative hazardous waste treatment technologies: domestic and international, Philadelphia, Pennsylvania, May 15-17, (1990)

3- Valine, S.B. "Biotrol soil washing systems for removal of organic contamination at wood treating sites". Presented at workshop on the extractive treatment of ecavated soil. USEPA, Edison, New Jersey, (1988)

4- Nash, J., and R. P. Traver "Field evaluation of in situ washing of contaminated soils with water/surfactant". Results of work conducted under sponsership of USEPA contracts number 68-03-3113 and 68-03-3203 and US Air Force through agreement #RW 57931283-01-0 with the USEPA. USEPA Risk Reduction Engineering Laboratory, Cincinati, Ohio, (Not Dated)

5- USEPA "Soil Washiong Treatment". Engineering Bulletin, EPA/540/2-90/017. USEPA Office of Emergency and Remedial Response, Washington, D.C., and Office of Research and Development, Cincinnati, OH, (1990)

6- USEPA "Summary of the workshop on extractive treatment of excavated soil". Sponsered by USEPA Risk Reduction Engineering Laboratory, Cincinati, Ohio, December 1-2.(1988)

7 Beers, W.F. "Investigation of feedstock preparation and handling for mobile onsite treatment technologies. Draft report. EPA contract No. 68-03-3450. USEPA Risk Reduction Engineering Laboratory, Cincinati, Ohio, (1987).

8- Masters, H, and B. Rubin "EPA's mobiule volume reduction unit for soil washing". Presented at the seventeenth annual hazardous waste research symposium, Cincinnati, OH, April 9-11, (1991).

9- Brown, M. "Harbaur Soil cleaning system". Presented at the seventeenth annual hazardous waste research symposium, Cincinnati, OH, April 9-11, (1988)

10- Raghavan, R., D.H. Dietz, and E. Coles " Cleaning Excavated soil using Extraction agents: A state-of-the-art review". Project summary, EPA 600/2-89/0345, USEPA, (1988).

11- Ellis, W.D., T.R. Fogg, and A.N. Tafuri "Treatment of Soil contaminated with heavy metals". (Not Dated) In USEPA. Overview: Soil washing technologies for Site remediation. Compiled by Foster Wheeler Enviresponse, Inc, (1990).

12- Schmidt et al. "Hydrometallurgical treatmenyt of soil". Presented at workshop on the extractive treatment of ecavated soil. USEPA, Edison, New Jersey, (1988)

13- Nunno, T.J., and J.A. Hyman. "Assessment of intrnational technologies for superfund applications-technology review and trip report results". EPA/540/2-88/003, USEPA Risk Reduction Engineering Laboratory, Cincinati, Ohio, (1988).

14- Nunno, T.J., J.A. Hyman, and T. Pheiffer "Development of site remediation technnologies in European countries". Presented at workshop on the extractive treatment of excavated soil. USEPA, Edison, New Jersey. (1988)

15- USEPA ROD Annual Report, FYI1989, EPA/540/8-90/006, (1990).

16 APHA, AWWA and WPCF, Standard Methods for the Examination of Water and Wastewater. 17th Ed., Washington, D.C., (1989).