IJE TRANSACTIONS B: Applications Vol. 35, No. 02, (February 2022) 344-350

International Journal of Engineering

Journal Homepage: www.ije.ir

Design of Soil Remediation Techniques from Column Leaching Test Results

J. Sumalatha[a], C. L. Mahesh Kumar*[b], S. Prashant[a], K. G. Shwetha[b]

[a] *Department of Civil Engineering, M S Ramaiah Institute of Technology, Bangalore, India*
[b] *Department of Civil Engineering, Nitte Meenakshi Institute of Technology, Yelahanka, Bengaluru, Karnataka, India*

PAPER INFO

Paper history:
Received 11 October 2021
Received in revised form 14 November 2021
Accepted 17 November 2021

Keywords:
Column Leaching Test
Dispersion Coefficient
Elution Curve
Immobilization
Retardation Factor
Soil Washing

ABSTRACT

The soil remediation at a contaminated site requires knowledge of contaminant transport parameters and processes. This paper presents the determination of transport parameters from column leaching tests in context with two soil remediation techniques i.e., soil washing and immobilization. To evaluate the soil washing technique, the column leaching tests on the polluted soil were conducted with diluted acid solutions of hydrochloric acid, ethylene diamine tetraacetic acid and ferric chloride to evaluate the leaching efficiencies of the selected leaching solutions. It was observed that the efficiency of diluted ferric chloride solution was higher as it removed the higher percentage of metals from the soil. From these test results, the contaminant transport parameters i.e., retardation factor and dispersion coefficient were determined which are useful to calculate the volume of leaching solution that will be required for soil washing at a site. As part of immobilization study on this soil, the soil was mixed with the selected amendments (lime, sodium hydroxide and cement) to increase the pH of the soil to 10 and the retardation factors were estimated through batch leaching test results. The retardation factors of different metals obtained with lime addition were found higher than the other amendments. To analyze the long-term stability of the amended mixtures, the leaching tests were conducted on amended soil samples and the immobilization efficiencies were estimated. It was found that the immobilization efficiencies were higher with lime addition and also concluded that the immobilization effiencies are directly related to retardation factors.

doi*: 10.5829/ije.2022.35.02b.10*

1. INTRODUCTION

The pollution of soil may take place due to various reasons such as unregulated disposal of wastes, mining and industrial activities, modern agricultural practices, construction activities etc. [1–3]. The heavy metal pollution of soil may create health problems for living beings as they can enter into the living beings through several ways [4]. The pollution of groundwater due to migration of heavy metals from the contaminated soil is a serious problem as the ground water will be used for various purposes including spa treatments (medicinal thermal water) [5]. For the developing or residential areas a soil remediation is very much required and before planning the remediation, it is important to conduct a survey similar to work conducted by Ezirim and Okpoechi [6].

The various soil remediation techniques in practice are immobilization, chemical treatment, electrokinetic processes, biochemical processes, soil washing, incineration techniques and thermal desorption technique [7–9]. The two important and widely used soil remediation techniques are soil washing and immobilization. Diluted acids such as hydrochloric acid (HCl) and ethylenediamine tetra acetic acid (EDTA) can be used for soil washing treatment [10–14]. The soil washing technique is effective for granular soils as the textutre of the soil is more permeable. For less permeable soils such as clay, the soil washing is not very effective as the washing technique requires sufficient void spaces to wash out the pollutants from the soil. In such cases, immobilization is an alternate remediation technique where the migration of pollutants is restricted by converting the metals in soil to their stable hydroxide

*Corresponding Author Institutional Email: maheshkumar.cl@nmit.ac.in (C. L. Mahesh Kumar)

Please cite this article as: J. Sumalatha, C. L. Mahesh Kumar, S. Prashant, K. G. Shwetha, Design of Soil Remediation Techniques from Column Leaching Test Results, ***International Journal of Engineering, Transactions B: Applications,*** Vol. 35, No. 02, (2022) 344-350

form. The soil washing require treatment of wastewater after washing the contaminants from the soil and the extracted metals need to be disposed safely [15, 16].

The immobilization technique avoids excavation of the contaminated soil, treatment of wastewater, disposal of the contaminated fluid and provides relatively cost-effective solution to treat the contaminated soil [17]. The metal hydroxides formed after immobilization will not migrate because of their low soluble form and reduces the probability of contamination of nearby water bodies [18]. Various organic and inorganic additives can be used to restrict the mobility of contaminants in the soil using immobilization technique [19–25]. The additives such as clay, calcium hydroxide, cement, zeolites, hydroxyapatite, phosphates, organic compost, microbes, activated carbon, fly ash and lime are widely used materials to immobilize the metals in soil and sludge [26–33]. Long-term stability of the amended soils also depends on the solubility of metals in their converted form [34–36]. The selection of materials or chemicals required for these soil remediation techniques depends on the transport parameters of the contaminants in the soil to be treated. In the present study, it is proposed to demonstrate the determination of contaminant transport parameters through batch tests and column leching tests results. The one-dimensional advection-dispersion transport equation describes the rates of migration which is given in Equation (1) [37].

$$R\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial Z^2} - v_s\frac{\partial C}{\partial Z} \quad (1)$$

where,
R = retardation factor = $1+\rho K/n$
ρ = dry density (g/cm^3)
K = distribution coefficient (c m^3/g)
n = porosity
D = dispersion coefficient (cm^2/s)
v_s = seepage velocity (cm/s)

As part of the investigation, a contaminated soil was studied to know the suitability of the soil washing and immobilization techniques. The column leaching tests were carried out with 0.1 normal chemical solutions of HCl, EDTA, and Ferric Chloride ($FeCl_3$) on the contaminated soil and found that $FeCl_3$ is effective in the removal of metals. The transport rates were anticipated via preparing the elution curves using trial values substituted in theoretical equation and matching them with elution curves of experimental values. The transport rates of contaminants during column leaching tests were modeled using the MATLAB programming for the analytical solution which is based on the Shackelford and Glade's [38] leaching mass ratio (LMR) approach. Since the column leaching tests represent the leaching process in the field during soil washing, the transport rates obtained by this method are useful in the field to estimate the volume of flushing solution needed to wash out the various contaminants. The immobilization studies were also conducted by mixing the soil with additives such as lime, sodium hydroxide and cement which increases the pH of soil and immobilize the metals in it. The amended samples were tested for their leachability to evaluate the efficiencies of additives and found that the leaching of metals from lime amended sample were less. The batch tests were performed on amended soil samples to estimate the retardation factors and found that the retardation factor of lime amended sample was higher. The values of retardation factors were compared with the efficiencies of amendments obtained from leaching tests and found that the retardation factors are useful to identify the best additive.

2. MATERIALS AND METHODS

The research methodology of the current research work is illustrated in the flow chart (Figure 1).

2. 1. Characteristics of Contaminated Soil The soil samples were collected from a dumping yard located at the outskirts of Bangalore, India. The composition of the soil was estimated to be of 34% sand, 12% silt and 54% clay. The soil is classified as low plasticity clay (CL) as per Indian Standard classification system. The plasticity and compaction characteristics of the contaminated soil are as given in Table 1. The quantities of metal ions presented in the contaminated soil were estimated by following the methods specified in USEPA [39] and the estimated quantities are given in Table 2. The maximum permissible limits of heavy metals in soil specified by World Health Organization (WHO) [40] are also presented in Table 2.

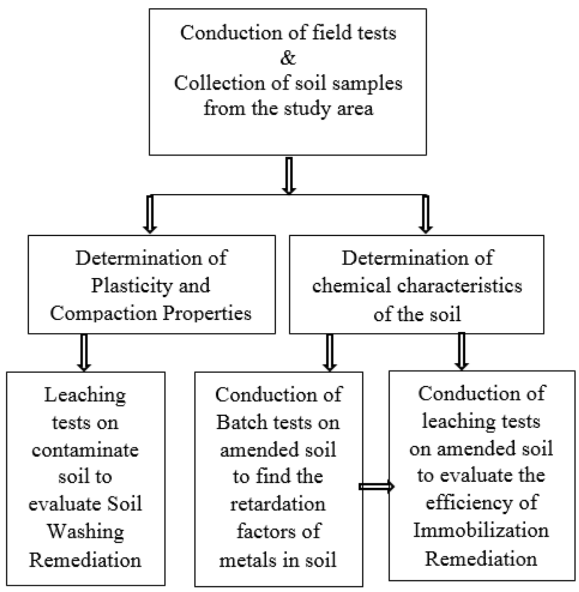

Figure 1. Flowchart of the research methodology

TABLE 1. Plasticity and compaction characteristics of contaminated soil

Specific gravity (G)	Maximum dry density (g/cc)	Optimum water content (%)	Liquid limit (%)	Plastic limit (%)	Shrinkage limit (%)	Plasticity index (Ip) (%)
2.69	1.62	24.6	56.2	24.8	13.6	31.4

TABLE 2. Heavy metals in contaminated soil

Metals in soil	Cu	Zn	Fe	Cr	Cd	Ni	Pb
Quantity of metals in soil (mg/kg)	112.8	148.6	198.7	18.9	1.2	44.6	4.8
Permissible limits of heavy metals in soil (mg/kg)	36	50	-	100	0.8	35	85

2. 2. Column Leaching Tests on Contaminated Soil The in-situ soil washing program was simulated by performing the column leaching tests with various leaching solutions. The diluted acid solution was permitted to flow through the soil column and the effluent concentrations were measured periodically. The effluent volume (V) and the mass of contaminant leached (Δm) were found periodically. For each time interval, the leached pore volumes of flow (T^1= V/Vv) were calculated. The LMR which is the ratio of leached mass of contaminant (Δm) from the soil to initial mass of contaminant (M_0) was computed periodically and the Cumulative LMR (LMR_m) was calculated with respect to time. These values were plotted with respect to their respective leached pore volumes (T^1). The plots, thus prepared are called experimental elution curves which are important to analyze the efficiency of leaching solution.

2. 3. Estimation of Transport Parameters from Column Leaching Tests The analytical solution developed by Shackelford and Glade [38] is as given below (Equation (2)).

$$\text{LMRm} = \frac{\sum\Delta m}{M_0} = \frac{T^I}{R} - \frac{1}{2}\{\left(\frac{T^I}{R} - 1\right) erfc\left(\frac{R-T^I}{2\sqrt{\frac{T^I R}{P_L}}}\right) + (\frac{T^I}{R} + 1)\exp(P_L) erfc(\frac{R-T^I}{2\sqrt{\frac{T^I R}{P_L}}} \quad (2)$$

LMR_m = cumulative leaching mass ratio = $\sum (\Delta m / M_0)$
P_L=column Peclet number = $v_s L/D$;

To plot the theoretical elution curves, experimental values of T^1 and P_L along with trial values of transport parameters (D and R) were taken as input in the MATLAB program which was generated out of the above equation (Equation (2)). The theoretical elution curve was then coordinated with the experimental one to estimate the transport parameters.

2. 4. Batch Tests on Amended Soil Samples The Batch tests were conducted to find the distribution coefficients (K) as per ASTM specifications [41]. The distribution coefficient was then calculated from Equation (3):

$$K = \frac{(C_o - C_t)V}{M.C_t} \quad (3)$$

where,
C_o and C_t respectively are initial and final concentrations of the pollutants. M and V are mass of soil taken (g) and the volume of solution used (ml) respectively. The value of K will be zero for non-reactive solutes reducing R=1.

2. 5. Amended Soil Samples and Leaching Tests The contaminated soil sample of about 110 grams was taken in a container and the additive / amendment was added to the soil in such a way that the pH value of the mixture achieved the desired value. The samples were prepared with 3 inorganic additives, i.e., lime, cement and NaOH. Since the immobilization efficiencies increases with increasing pH value [27–31] and the effiencies were observed to be higher corresponding to a pH value of 10, each selected additive was added to adjust the pH of the mixture to maintain a pH value of 10. To evaluate the long-term stability of the soil mixtures, leaching tests were conducted by passing water through the soil placed in the containers and the effluent was collected in a container. The concentrations of heavy metals in effluents were found by Atomic Absorption Spectroscopy (AAS) to know the amounts of various contaminants leached out after solidification and to assess the capabilities of these solidifying agents. From the effluent concentrations estimated, the cumulative percentage leached and the immobilization efficiency were estimated for each metal ion (Table 3).

3. RESULTS AND DISCUSSION

3. 1. Column Leaching Tests and Analytical Method The removal efficiencies of leaching solutions studied with respect to each metal ion (copper, zinc, iron, nickel, cadmium, lead and chromium) in the sludge were analyzed. From the column leaching tests it was observed that with diluted HCl, EDTA and $FeCl_3$, the removal efficiencies of metals were around 30-50%, 50-70% and 70-80%, respectively. The removal efficiencies of $FeCl_3$ were observed high among the three solutions. The effiencies were in the sequence of $FeCl_3$ > EDTA > HCl which is similar to data reported in literature [42, 43]. The removal efficiencies were observed slightly lower than the reported data [43, 44]. This may be due to the presence of more clay fraction in the soil studied. Out of the metals studied, the removal efficiencies were in the following order which are similar to the studies conducted by Sumalatha et al. [45]. It can be observed that the removal efficiency of cadmium is the highest and that of chromium is the lowest.

Cd> Pb> Zn> Cu> Fe> Ni> Cr

The elution curves obtained by washing the soil with diluted acids are shown in Figures 2 to 4. The transport parameters were found with 0.1M $FeCl_3$ since the higher efficiencies were achieved with this solution. The elution curves (theoretical) plotted for copper and zinc are shown in Figures 5 and 6 along with their experimental values. Similar plots were prepared for other metals and their transport parameters are reported in Table 3. The parameters thus estimated can be substituted in the MATLAB program along with the field parameters to estimate the leached pore volumes of flow required in the field and thus the volume of leaching solution needed at the site to implement the in-situ soil washing program.

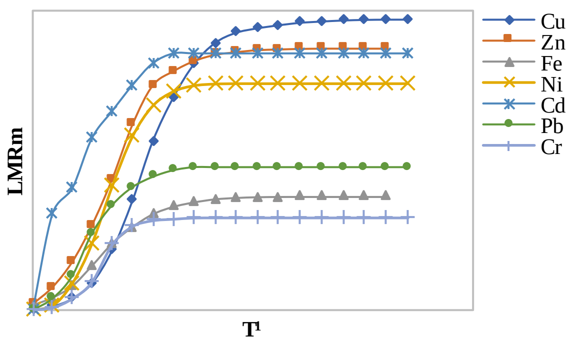

Figure 2. Elution curves (experimental) with diluted HCl

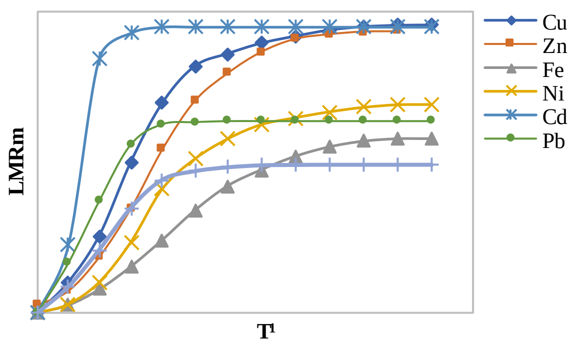

Figure 3. Elution curves (experimental) with diluted EDTA

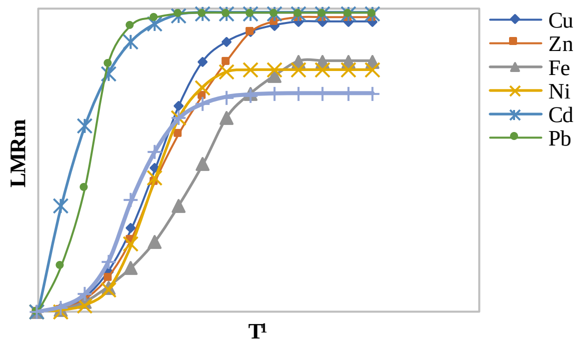

Figure 4. Elution curves (experimental) with diluted $FeCl_3$

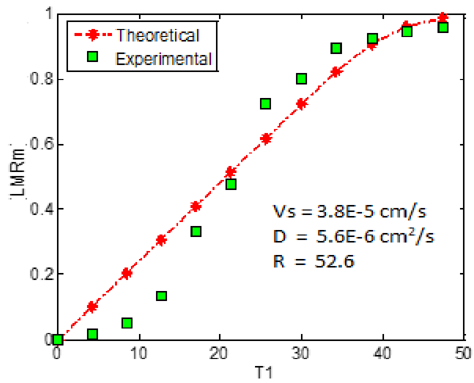

Figure 5. Elution curves of copper in soil

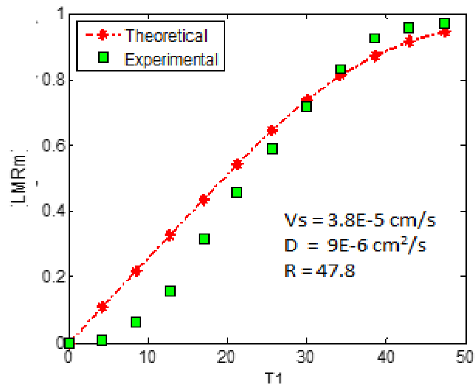

Figure 6. Elution curves of zinc in soil

TABLE 3. Transport rates of pollutants in soil

Pollutant	Dispersion coefficient (D) (cm^2/s)	Retardation Factor (R)
Copper (Cu)	5.6×10^{-6}	52.6
Zinc (Zn)	9.0×10^{-6}	47.8
Iron (Fe)	1.9×10^{-7}	67.7
Chromium (Cr)	1.1×10^{-6}	59.2
Cadmium (Cd)	7.0×10^{-5}	22.6
Nickel (Ni)	2.8×10^{-6}	62.8
Lead (Pb)	3.7×10^{-5}	28.4

3. 2. Batch Tests and Leaching Tests on Amended Soil Samples The retardation factors estimated from the batch tests on amended soil samples with respect to the additives used are given in Table 4. The immobilization efficiencies of the additives estimated through the results of leaching tests are summarized in Table 5. From these tables, it can be observed that the immobilization efficiencies of the additives are directly proportional to the retardation factors obtained from the batch tests. Hence it can be concluded that the retardation factors play an important role in selecting the suitable amendment for immobilization remediation. The immobilization efficiencies of metals with lime addition were higher than the other two additives. These results were similar to the data reported by Salihoglu [46]. The leachability of metals from the amended mixtures of this study were in the following order.

Cadmium> Lead> Iron> Nickel> Zinc> Copper> Chromium

The standard sequences of solubility of metal hydroxides with pH value are in the following order [47].

$Cd(OH)_2$> $Pb(OH)_2$> $Zn(OH)_2$> $Cr(OH)_3$> $Fe(OH)_2$> $Ni(OH)_2$> $Cu(OH)_2$

The leachability orders of metals from this study were observed to be similar to these sequences with small variations. These variations may be due to the solid matrix created by cementing agents and cation exchange with soil.

TABLE 4. Results of batch tests on amended soil

Amendment	Retardation factors						
	Copper	**Zinc**	**Iron**	**Nickel**	**Cadmium**	**Lead**	**Chromium**
Lime	58.3	56.2	76.2	68.2	29.8	32.1	69.9
NaOH	54.8	52.4	69.6	63.8	23.9	29.8	61.2
Cement	55.7	55.8	71.3	64.4	25.6	30.9	64.7

TABLE 5. Results of leaching tests on amended soil

Amendment	% leached and % efficiency	Metals in soil						
		Copper	**Zinc**	**Iron**	**Nickel**	**Cadmium**	**Lead**	**Chromium**
Lime	% Leached	22.6	24.5	36.8	31.2	44.1	43.4	17.5
	% Efficiency	77.4	75.5	63.2	68.8	55.9	56.6	82.5
NaOH	% Leached	39.8	38.6	41.9	43.7	51.5	49.8	29.6
	% Efficiency	60.2	61.4	58.1	56.3	48.5	50.2	70.4
Cement	% Leached	31.6	32.5	39.8	38.1	47.5	44.2	20.1
	% Efficiency	68.4	67.5	60.2	61.9	52.5	55.8	79.9

4. CONCLUSIONS

The determination of transport parameters has been described through batch tests and column leaching tests. The usefulness of the transport parameters, thus determined is demonstrated in the design of soil remediation techniques such as soil washing and immobilization. The column leaching tests carried out with diluted acid solutions on a contaminated dump site soil were evaluated to assess the suitability of the chemical solutions for soil washing remediation. The contaminant transport parameters of the pollutants were estimated through elution curves and the importance of these parameters in selecting the type and quantity of leaching solution for soil washing was discussed. The immobilization efficiencies of three additives were studied corresponding to a pH value of 10. The retardation factors and long-term efficiencies of the amended soil samples were estimated through batch tests and leaching tests respectively. The results of these tests showed that the retardation factors are directly related to the immobilization efficiencies. Hence it was concluded that the retardation factors are useful to select suitable amendment for soil remediation using immobilization technique.

5. REFERENCES

1. Gebreyesus, S. T. "Heavy Metals in Contaminated Soil: Sources & Washing through Chemical Extractants." ***American Academic Scientific Research Journal for Engineering, Technology, and Sciences***, Vol. 10, No. 1, (2014), 54–60. Retrieved from https://www.asrjetsjournal.org/index.php/American_Scientific_Journal/article/view/730

2. Morais, S., e Costa, F. G., and Lourdes Pereir, M. de. "Heavy Metals and Human Health." In Environmental Health - Emerging Issues and Practice. InTech. https://doi.org/10.5772/29869

3. Shayler, H., McBride, M., and Harrison, E. Sources and impacts of contaminants in soils. Cornell Waste Management Institute.

4. Lin, C.-F., Lo, S.-S., Lin, H.-Y., and Lee, Y. "Stabilization of cadmium contaminated soils using synthesized zeolite." ***Journal of Hazardous Materials***, Vol. 60, No. 3, (1998), 217–226. https://doi.org/10.1016/S0304-3894(98)00092-2

5. Langer, P. "Groundwater Mining in Contemporary Urban Development for European Spa Towns." ***Journal of Human, Earth, and Future***, Vol. 1, No. 1, (2020), 1–9. https://doi.org/10.28991/HEF-2020-01-01-01

6. Ezirim, O. N., and Okpoechi, C. U. "Community-driven Development Strategy for Sustainable Infrastructure." ***Journal of Human, Earth, and Future***, Vol. 1, No. 2, (2020), 48–59. https://doi.org/10.28991/HEF-2020-01-02-01

7. Bolan, N., Kunhikrishnan, A., Thangarajan, R., Kumpiene, J., Park, J., Makino, T., Kirkham, M. B., and Scheckel, K. "Remediation of heavy metal(loid)s contaminated soils – To mobilize or to immobilize?" ***Journal of Hazardous Materials***, Vol. 266, (2014), 141–166. https://doi.org/10.1016/j.jhazmat.2013.12.018

8. Hamby, D. M. "Site remediation techniques supporting environmental restoration activities—a review." ***Science of the Total Environment***, Vol. 191, No. 3, (1996), 203–224. https://doi.org/10.1016/S0048-9697(96)05264-3

9. Mulligan, C. N., Yong, R. N., and Gibbs, B. F. "Remediation technologies for metal-contaminated soils and groundwater: an evaluation." ***Engineering Geology***, Vol. 60, No. 1–4, (2001), 193–207. https://doi.org/10.1016/S0013-7952(00)00101-0

10. Huang, K., Shen, Y., Wang, X., Song, X., Yuan, W., Xie, J., Wang, S., Bai, J., and Wang, J. "Choline-based deep eutectic solvent combined with EDTA-2Na as novel soil washing agent for lead removal in contaminated soil." ***Chemosphere***, Vol. 279, (2021), 130568. https://doi.org/10.1016/j.chemosphere.2021.130568

11. Ahn, Y., Pandi, K., Cho, D.-W., and Choi, J. "Feasibility of soil washing agents to remove fluoride and risk assessment of fluoride-contaminated soils." ***Journal of Soils and Sediments***, Vol. 21, No. 8, (2021), 2770–2777. https://doi.org/10.1007/s11368-020-02808-8

12. Xiao, R., Ali, A., Wang, P., Li, R., Tian, X., and Zhang, Z. "Comparison of the feasibility of different washing solutions for combined soil washing and phytoremediation for the detoxification of cadmium (Cd) and zinc (Zn) in contaminated soil." ***Chemosphere***, Vol. 230, (2019), 510–518. https://doi.org/10.1016/j.chemosphere.2019.05.121

13. Kaurin, A., Gluhar, S., Tilikj, N., and Lestan, D. "Soil washing with biodegradable chelating agents and EDTA: Effect on soil properties and plant growth." ***Chemosphere***, Vol. 260, (2020), 127673. https://doi.org/10.1016/j.chemosphere.2020.127673

14. Mohamadi, S., Saeedi, M., and Mollahosseini, A. "Desorption Kinetics of Heavy Metals (Lead, Zinc, and Nickel) Coexisted with Phenanthrene from a Natural High Buffering Soil." ***International Journal of Engineering, Transaction C: Aspects***, Vol. 32, No. 12, (2019), 1716–1725. https://doi.org/10.5829/ije.2019.32.12c.04

15. Chair, K., Bedoui, A., Bensalah, N., Sáez, C., Fernández-Morales, F. J., Cotillas, S., Cañizares, P., and Rodrigo, M. A. "Treatment of Soil-Washing Effluents Polluted with Herbicide Oxyfluorfen by Combined Biosorption–Electrolysis." ***Industrial & Engineering Chemistry Research***, Vol. 56, No. 8, (2017), 1903–1910. https://doi.org/10.1021/acs.iecr.6b04977

16. Satyro, S., Race, M., Marotta, R., Dezotti, M., Guida, M., and Clarizia, L. "Photocatalytic processes assisted by artificial solar light for soil washing effluent treatment." ***Environmental Science and Pollution Research***, Vol. 24, No. 7, (2017), 6353–6360. https://doi.org/10.1007/s11356-016-6431-9

17. Wuana, R. A., and Okieimen, F. E. "Heavy Metals in Contaminated Soils: A Review of Sources, Chemistry, Risks and Best Available Strategies for Remediation." ***ISRN Ecology***, Vol. 2011, (2011), 1–20. https://doi.org/10.5402/2011/402647

18. Basta, N. T., and McGowen, S. L. "Evaluation of chemical immobilization treatments for reducing heavy metal transport in a smelter-contaminated soil." ***Environmental Pollution***, Vol. 127, No. 1, (2004), 73–82. https://doi.org/10.1016/S0269-7491(03)00250-1

19. Abbott, D. E., Essington, M. E., Mullen, M. D., and Ammons, J. T. "Fly Ash and Lime-Stabilized Biosolid Mixtures in Mine Spoil Reclamation: Simulated Weathering." ***Journal of Environmental Quality***, Vol. 30, No. 2, (2001), 608–616. https://doi.org/10.2134/jeq2001.302608x

20. Cao, X., Ma, L. Q., and Shiralipour, A. "Effects of compost and phosphate amendments on arsenic mobility in soils and arsenic uptake by the hyperaccumulator, Pteris vittata L." ***Environmental Pollution***, Vol. 126, No. 2, (2003), 157–167. https://doi.org/10.1016/S0269-7491(03)00208-2

21. Clemente, R., Walker, D. J., Roig, A., and Bernal, M. P. "Heavy metal bioavailability in a soil affected by mineral sulphides contamination following the mine spillage at Aznalcóllar (Spain)." ***Biodegradation***, Vol. 14, No. 3, (2003), 199–205. https://doi.org/10.1023/A:1024288505979

22. Friesl, W., Lombi, E., Horak, O., and Wenzel, W. W. "Immobilization of heavy metals in soils using inorganic amendments in a greenhouse study." ***Journal of Plant Nutrition and Soil Science***, Vol. 166, No. 2, (2003), 191–196. https://doi.org/10.1002/jpln.200390028

23. Walker, D. J., Clemente, R., and Bernal, M. P. "Contrasting effects of manure and compost on soil pH, heavy metal availability and growth of Chenopodium album L. in a soil contaminated by pyritic mine waste." ***Chemosphere***, Vol. 57, No. 3, (2004), 215–224. https://doi.org/10.1016/j.chemosphere.2004.05.020

24. Brunori, C., Cremisini, C., Massanisso, P., Pinto, V., and Torricelli, L. "Reuse of a treated red mud bauxite waste: studies on environmental compatibility." ***Journal of Hazardous Materials***, Vol. 117, No. 1, (2005), 55–63. https://doi.org/10.1016/j.jhazmat.2004.09.010

25. Guo, G., Zhou, Q., and Ma, L. Q. "Availability and Assessment of Fixing Additives for The in Situ Remediation of Heavy Metal Contaminated Soils: A Review." ***Environmental Monitoring and Assessment***, Vol. 116, No. 1–3, (2006), 513–528. https://doi.org/10.1007/s10661-006-7668-4

26. Kong, X., Ge, R., Liu, T., Xu, S., Hao, P., Zhao, X., Li, Z., Lei, X., and Duan, H. "Super-stable mineralization of cadmium by calcium-aluminum layered double hydroxide and its large-scale application in agriculture soil remediation." ***Chemical Engineering Journal***, Vol. 407, (2021), 127178. https://doi.org/10.1016/j.cej.2020.127178

27. Finžgar, N., Kos, B., and Leštan, D. " Bioavailability and mobility of Pb after soil treatment with different remediation methods." ***Plant, Soil and Environment***, Vol. 52, No. 1, (2011), 25–34. https://doi.org/10.17221/3342-PSE

28. Chuon Yi, O., and Chui Peng Cheong, A. Solidification of Industrial Waste Sludge with Incineration Fly Ash and Ordinary Portland Cement. Undergraduate Research Opportunities Program (UROP, 2002), Nanyang Technological University.

29. Kogbara, R. B. "A review of the mechanical and leaching performance of stabilized/solidified contaminated soils." ***Environmental Reviews***, Vol. 22, No. 1, (2014), 66–86. https://doi.org/10.1139/er-2013-0004

30. Martin, T. A., and Ruby, M. V. "Review ofin situ remediation technologies for lead, zinc, and cadmium in soil." ***Remediation Journal***, Vol. 14, No. 3, (2004), 35–53. https://doi.org/10.1002/rem.20011

31. Heidari, S., Basiri, H., Nourmoradi, H., Kamareei, B., and Omidi, Y. "Hexadecyl Trimethyl Ammonium Bromide-Modified Montmorillonite as a Low-Cost Sorbent for the Removal of Methyl Red from Liquid-Medium." ***International Journal of Engineering, Transaction A: Basics***, Vol. 29, No. 1, (2016), 60–67. https://doi.org/10.5829/idosi.ije.2016.29.01a.09

32. Ajemba, R. "Adsorption of Malachite Green from Aqueous Solution using Activated Ntezi Clay: Optimization, Isotherm and Kinetic Studies." ***International Journal of Engineering, Transaction C: Aspects***, Vol. 27, No. 6, (2014), 839–854. https://doi.org/10.5829/idosi.ije.2014.27.06c.03

33. Wen, D., Fu, R., and Li, Q. "Removal of inorganic contaminants in soil by electrokinetic remediation technologies: A review." ***Journal of Hazardous Materials***, Vol. 401, (2021), 123345. https://doi.org/10.1016/j.jhazmat.2020.123345

34. McGowen, S. L., Basta, N. T., and Brown, G. O. "Use of Diammonium Phosphate to Reduce Heavy Metal Solubility and Transport in Smelter-Contaminated Soil." ***Journal of Environmental Quality***, Vol. 30, No. 2, (2001), 493–500. https://doi.org/10.2134/jeq2001.302493x

35. Valipour, M., Shahbazi, K., and Khanmirzaei, A. "Chemical Immobilization of Lead, Cadmium, Copper, and Nickel in Contaminated Soils by Phosphate Amendments." ***CLEAN - Soil, Air, Water***, Vol. 44, No. 5, (2016), 572–578. https://doi.org/10.1002/clen.201300827

36. Zeng, G., Wan, J., Huang, D., Hu, L., Huang, C., Cheng, M., Xue, W., Gong, X., Wang, R., and Jiang, D. "Precipitation, adsorption and rhizosphere effect: The mechanisms for Phosphate-induced Pb immobilization in soils—A review." ***Journal of Hazardous Materials***, Vol. 339, (2017), 354–367. https://doi.org/10.1016/j.jhazmat.2017.05.038

37. Sharma, H., and Lewis, S. Waste containment systems, waste stabilization, and landfills: design and evaluation. John Wiley & Sons.

38. Shackelford, C. D., and Glade, M. J. "Analytical Mass Leaching Model for Contaminated Soil and Soil Stabilized Waste." ***Ground Water***, Vol. 35, No. 2, (1997), 233–242. https://doi.org/10.1111/j.1745-6584.1997.tb00080.x

39. US Environmental Protection Agency (USEPA), Method 3050B. EPA 660 13-75-009, Acid Digestion of Sediments, Sludges and Soils, Washington, D.C., 1996.

40. World Health Organization. Permissible limits of heavy metals in soil and plants (Geneva: World Health Organization). Geneva, Switzerland, 1996.

41. ASTM, Standard test method for 24-h batch type measurement of contaminant sorption by soils and sediments, (D 4646-87), Annual book of ASTM Standards, American Society for Testing and Materials, Philadelphia, 04.04: 44-47, 1993.

42. Gitipour, S., Ahmadi, S., Madadian, E., and Ardestani, M. "Soil washing of chromium- and cadmium-contaminated sludge using acids and ethylenediaminetetra acetic acid chelating agent." ***Environmental Technology***, Vol. 37, No. 1, (2016), 145–151. https://doi.org/10.1080/09593330.2011.597784

43. Bilgin M, and Tulun S. "Heavy metals (Cu, Cd and Zn) contaminated soil removal by EDTA and FeCl3." ***Global NEST Journal***, Vol. 18, No. 1, (2016), 98–107.

44. Shi, J., Pang, J., Liu, Q., Luo, Y., Ye, J., Xu, Q., Long, B., Ye, B., and Yuan, X. "Simultaneous removal of multiple heavy metals from soil by washing with citric acid and ferric chloride." ***RSC Advances***, Vol. 10, No. 13, (2020), 7432–7442. https://doi.org/10.1039/C9RA09999A

45. Sumalatha, J., Naveen, B. P., and Malik, R. K. "Toxic Metals Removal from Industrial Sludge by Using Different Leaching Solutions." ***Journal of The Institution of Engineers (India): Series A***, Vol. 100, No. 2, (2019), 337–345. https://doi.org/10.1007/s40030-019-00361-3

46. Salihoglu, G. "Immobilization of antimony waste slag by applying geopolymerization and stabilization/solidification technologies." ***Journal of the Air & Waste Management Association***, Vol. 64, No. 11, (2014), 1288–1298. https://doi.org/10.1080/10962247.2014.943352

47. Snoeyink, V. L., and Jenkins, D. Water chemistry. Wiley. Retrieved from https://www.wiley.com/en-us/Water+Chemistry-p-9780471051961

Persian Abstract

چکیده

اصلاح خاک در یک سایت آلوده نیاز به آگاهی از پارامترها و فرآیندهای انتقال آلاینده دارد. این مقاله تعیین پارامترهای حمل و نقل از آزمایش‌های آبشویی ستون را در زمینه با دو تکنیک اصلاح خاک یعنی شستشوی خاک و بی‌حرکتی ارائه می‌کند. برای ارزیابی تکنیک شستشوی خاک، آزمایش‌های آبشویی ستونی بر روی خاک آلوده با محلول‌های اسید رقیق شده اسید هیدروکلریک، اتیلن دی آمین ترا استیک اسید و کلرید آهن برای ارزیابی کارایی آبشویی محلول‌های شستشوی انتخابی انجام شد. نتایج بدست آمده نشان می‌دهد که بازده محلول کلرید آهن رقیق شده بیشتر بود، زیرا درصد بیشتری از فلزات را از خاک حذف می گردد. از این نتایج آزمایش، پارامترهای انتقال آلاینده یعنی ضریب تاخیر و ضریب پراکندگی تعیین شد که برای محاسبه حجم محلول شستشو که برای شستشوی خاک در یک سایت مورد نیاز، مفید است. به عنوان بخشی از مطالعه تثبیت بر روی این خاک، خاک با اصلاحات انتخابی (آهک، هیدروکسید سدیم و سیمان) مخلوط شد تا pH خاک به ۱۰ افزایش یابد و عوامل تاخیری از طریق نتایج آزمایش آبشویی ناپیوسته برآورد شد. فاکتورهای تاخیری فلزات مختلف به‌دست‌آمده با افزودن آهک بالاتر از سایر اصلاح‌ها بود. برای تجزیه و تحلیل پایداری طولانی‌مدت مخلوط‌های اصلاح‌شده، آزمایش‌های آبشویی روی نمونه‌های خاک اصلاح شده انجام شد و راندمان تثبیت تخمین زده شد. مشخص شد که راندمان تثبیت با افزودن آهک بیشتر بوده و همچنین نتیجه گرفته شد که راندمان تثبیت مستقیماً با عوامل عقب ماندگی مرتبط است.