Removal of Contaminants from Behshehr Landfill Using Permeable Reactive Barriers in Column Adsorption Test

Hamed Yekeh Dehghan[1], Reza Ziaie Moayed[2*]

[1] PhD Candidate, Faculty of Engineering, Imam Khomeini International University, Qazvin, Iran, dehhamed42@gmail.com
[2]Professor, Faculty of Engineering, Imam Khomeini International University, Qazvin, Iran, ziaie@eng.ikiu.ac.ir

ABSTRACT

Groundwater contamination by heavy metals, particularly cadmium (Cd) and zinc (Zn), is a serious environmental problem associated with landfill leachate and industrial activities. Due to their persistence, mobility, and toxicity, these metals threaten ecosystems and human health. Among available remediation methods, permeable reactive barriers (PRBs) have attracted considerable attention because of their long-term effectiveness, low maintenance costs, and minimal disturbance to subsurface environments. The performance of a PRB mainly depends on the characteristics of the reactive medium and its ability to remove contaminants under continuous groundwater flow. This study evaluated a reactive medium composed of 75 wt.% natural clinoptilolite zeolite and 25 wt.% recycled iron filings for removing cadmium and zinc from groundwater under laboratory column conditions representative of the Behshahr landfill site. A Plexiglas column (9 cm diameter and 40 cm height) was used to simulate contaminant transport through the PRB. Influent concentrations were 100 mg/L Zn and 5 mg/L Cd, based on measured landfill leachate concentrations. Effluent samples collected at different depths were analyzed using ICP–MS. Breakthrough curves were interpreted using the Thomas and Yoon–Nelson models to evaluate adsorption capacity, kinetic parameters, and breakthrough behavior. The experimental data were also used to estimate the required PRB thickness for different service lifetimes. The results showed that increasing the reactive-bed depth significantly delayed breakthrough and extended the effective service life of the barrier. Zinc exhibited higher adsorption capacity and longer breakthrough times than cadmium, whereas cadmium reached the regulatory limit earlier and therefore governed the PRB design. Both the Thomas and Yoon–Nelson models adequately described the experimental breakthrough curves, confirming their suitability for predicting contaminant transport in fixed-bed systems. The estimated PRB thickness increased with design lifetime and was consistently greater for cadmium than for zinc. Overall, the combined use of zeolite and recycled iron filings proved to be an efficient and sustainable reactive medium for groundwater remediation affected by landfill leachate.

KEYWORDS

Permeable Reactive Barriers, Column Adsorption Test, Landfill, Cadmium, Zinc

1. Introduction

Groundwater is one of the most important freshwater resources; however, rapid industrialization and improper waste disposal have increased the risk of heavy-metal contamination worldwide [1–3]. Cadmium and zinc are among the most common contaminants detected in landfill leachate. Cadmium is highly toxic even at low concentrations, while excessive zinc may adversely affect ecosystems and water quality [4]. Therefore, effective technologies are required to prevent the migration of these contaminants into groundwater.

Among the available remediation methods, Permeable Reactive Barriers (PRBs) have gained considerable attention because contaminated groundwater flows naturally through a reactive medium where pollutants are removed by adsorption, ion exchange, precipitation, and redox reactions [1–3,5]. The efficiency of a PRB mainly depends on the properties of the reactive material. Natural clinoptilolite zeolite possesses high cation-exchange capacity and chemical stability, whereas iron-based materials enhance heavy-metal removal through adsorption and reduction mechanisms [6,7]. Their combined use can improve both contaminant removal efficiency and hydraulic performance. This study evaluates the performance of a zeolite–iron reactive medium using laboratory column experiments under dynamic flow conditions. The breakthrough behavior of cadmium and zinc was analyzed using the Thomas and Yoon–Nelson models, and the required PRB thickness was estimated for different design lifetimes [9–12].

2. Methodology

A laboratory-scale fixed-bed column experiment was conducted to evaluate the performance of a permeable reactive barrier (PRB) containing a reactive mixture of 75 wt.% natural clinoptilolite zeolite and 25 wt.% recycled iron filings for removing cadmium (Cd) and zinc (Zn) from contaminated groundwater. Laboratory column tests were selected because they realistically simulate groundwater flow and contaminant transport under continuous-flow conditions and provide reliable data for field-scale PRB design [6,12]. The experimental setup consisted of a Plexiglas column with an internal diameter of 9 cm and a height of 40 cm (Figure 1). Approximately 2 kg of the mixed reactive medium was packed into the column to form a 40-cm reactive layer. Before introducing the contaminated solution, the column was saturated with clean water to establish uniform hydraulic conditions. Synthetic groundwater containing 100 mg/L Zn and 5 mg/L Cd, representing the maximum concentrations measured in the Behshahr landfill leachate, was pumped through the column at a constant flow rate of 2.5 $mL\ min^{-1}$ and a pH of approximately 7.0 [8]. Effluent samples were analyzed using ICP–MS. The breakthrough curves (C_t/C_0 versus time) were interpreted using the Thomas and Yoon–Nelson models to determine adsorption capacity, breakthrough characteristics, and service life of the reactive medium [9,10]. Finally, the experimental data were used to estimate the required PRB thickness for different design lifetimes [11,12].

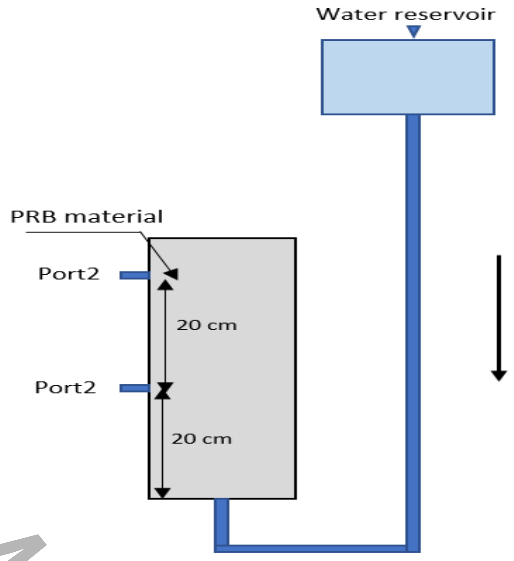

Figure 1.column test schematic

3. Results and Discussion

The experimental results demonstrated that the zeolite–iron reactive medium effectively removed cadmium and zinc from contaminated groundwater. Compared with clean sand, the reactive mixture significantly delayed contaminant breakthrough and maintained metal concentrations below environmental standards, confirming its suitability for PRB applications [8].

Increasing the reactive-bed thickness improved adsorption performance by extending the hydraulic residence time of groundwater within the barrier. Zinc exhibited a slower breakthrough and remained below the permissible limit longer than cadmium. In contrast, cadmium reached the breakthrough concentration earlier, indicating that it is the critical contaminant controlling PRB design [6,7,11]. The Thomas model successfully described the breakthrough behavior of both contaminants and provided reliable estimates of adsorption capacity and kinetic parameters [9]. Likewise, the Yoon–Nelson model showed good agreement with the experimental data, accurately predicting breakthrough time and adsorption performance [10]. The consistency between the experimental and predicted results confirms that both models are suitable for evaluating fixed-bed PRB systems. Based on the breakthrough analysis, the required PRB thickness increased with the desired design lifetime and was consistently greater for cadmium than for zinc. These findings demonstrate that the combined use of natural zeolite and recycled iron filings provides an efficient and environmentally sustainable reactive medium for groundwater remediation and offers practical engineering parameters for the design of field-scale PRB systems [1,5,11,12].

4. Conclusion

The results demonstrate that the zeolite–iron reactive medium is an effective and sustainable material for removing cadmium and zinc from groundwater contaminated by landfill leachate. Increasing the reactive-bed thickness improved adsorption efficiency and delayed contaminant breakthrough. Cadmium was identified as the controlling contaminant for PRB design. Furthermore, the Thomas and Yoon–Nelson models successfully predicted breakthrough behavior, providing reliable parameters for the design and optimization of field-scale permeable reactive barriers.

5. References

[1] C. M. Mayacela-Rojas, A. Molinari, J. L. Cortina, O. Gibert, C. Ayora, A. Tavolaro, et al. “Removal of transition metals from contaminated aquifers by PRB technology: Performance comparison among reactive materials.” International Journal of Environmental Research and Public Health 18(11) (2021): 6075.

[2] S. Bilardi, P. S. Calabrò, N. Moraci. “A review of the hydraulic performance of permeable reactive barriers based on granular zero valent iron.” Water 15(1) (2023): 200.

[3] M. Lawrinenko, S. Kurwadkar, R. T. Wilkin. “Long-term performance evaluation of zero-valent iron amended permeable reactive barriers for groundwater remediation–A mechanistic approach.” Geoscience Frontiers 14 (2023): 101494.

[4] J. Godt, F. Scheidig, C. Grosse-Siestrup, V. Esche, P. Brandenburg, A. Reich, D. A. Groneberg. “The toxicity of cadmium and resulting hazards for human health.” Journal of Occupational Medicine and Toxicology 1 (2006): 22.

[5] M. Sakr, H. El Agamawi, H. Klammler, M. M. Mohamed. “A review on the use of permeable reactive barriers as an effective technique for groundwater remediation.” Groundwater for Sustainable Development 21 (2023): 100914.

[6] L. C. C. Rocha, L. V. Zuquette. “Evaluation of zeolite as a potential reactive medium in a permeable reactive barrier (PRB): Batch and column studies.” Geosciences 10(2) (2020): 59.

[7] M. Sprynskyy, B. Buszewski, A. P. Terzyk, J. Namieśnik. “Study of the selection mechanism of heavy metal (Pb2+, Cu2+, Ni2+, and Cd2+) adsorption on clinoptilolite.” Journal of Colloid and Interface Science 304 (2006): 21–28.

[8] F. Hossein Zadeh, A. A. Momeni, R. Bagheri. “Investigation of heavy metal contamination in soils around the Behshahr landfill.” New Findings in Applied Geology 12(24) (2018): 77–88. (In Persian).

[9] H. C. Thomas. “Heterogeneous ion exchange in a flowing system.” Journal of the American Chemical Society 66 (1944): 1664–1666.

[10] Y. H. Yoon, J. H. Nelson. “Application of gas adsorption kinetics I. A theoretical model for respirator cartridge service life.” American Industrial Hygiene Association Journal 45 (1984): 509–516.

[11] D. Zhou, Y. Li, Y. Zhang, C. Zhang, X. Li, Z. Chen, et al. “Column test-based optimization of the permeable reactive barrier (PRB) technique for remediating groundwater contaminated by landfill leachates.” Journal of Contaminant Hydrology 168 (2014): 1–16.

[12] A. Gavaskar, N. Gupta, B. Sass, R. Janosy, J. Hicks. Design Guidance for Application of Permeable Reactive Barriers for Groundwater Remediation. AFRL-ML-TY-TR-2000-4547 (2000).