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Optimization of the Stabilization Method for In-Situ Remediation of Lead (Pb) Contaminated Soil in Kabwe / Zambia

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Abstract

Lead (Pb) is a toxic heavy metal that has contaminated over one-third of Kabwe town in Zambia, primarily due to historical mining activities and other anthropogenic sources. Previous studies have reported elevated blood lead levels (BLLs) in more than 95% of children residing in affected areas, with concentrations exceeding 10 µg/dL. While chelation therapy and nutritional interventions may offer some benefit to exposed populations, long-term mitigation requires environmental remediation strategies to reduce ongoing Pb exposure and ensure sustained reductions in BLLs.

This study employed batch leaching experiments to assess the effectiveness of various soil amendments—slag, lime, char, and ash—for Pb immobilization in contaminated soils. Additionally, the study aimed to determine the optimal mixing ratios of these additives to enhance remediation efficacy. Among the tested materials, lime (1%) and slag (5%) demonstrated superior performance in reducing Pb mobility compared to char and ash. The most effective immobilization was achieved using a combination of slag and lime at concentrations of 2–3%, indicating the potential for synergistic effects in Pb stabilization.

1. Introduction

Lead (Pb) is a heavy metal known for its softness, malleability, ductility, and relatively low melting point. When freshly cut, Pb appears shiny gray with a bluish hue. Its distinct physical and chemical properties have supported its continued use in both industrial and domestic applications [1]. However, despite its economic and industrial significance, Pb is a toxic substance, and exposure can result in serious adverse health effects. Internal exposure typically occurs through the ingestion of Pb-contaminated soil, dust, or food. Inhalation is also a significant pathway, especially in dust-prone Pb hotspots.

Acute Pb poisoning is characterized by blood lead levels (BLLs) exceeding 45 µg/dL and presents with clinical symptoms such as constipation, abdominal pain, headaches, and vomiting. At higher exposure levels (>100 µg/dL), symptoms may progress to seizures, coma, and even death [2–4]. Children under the age of five are particularly vulnerable due to behaviors such as hand-to-mouth activity, increased absorption rates, and physiological susceptibility. As a result, they are more prone to severe outcomes, including developmental delays, neurological damage, and growth impairments [5].

The Kabwe lead mine operated for over 90 years and was Zambia's primary source of Pb and zinc (Zn) until its closure in June 1994 [6]. Earlier surveys identified widespread contamination of soils with toxic heavy metals in Kabwe, affecting a substantial area [6, 7]. Kabwe is currently considered one of the most polluted towns in the world, with more than 120,000 residents potentially impacted [8]. In many locations, soil Pb concentrations exceed the maximum allowable limit for residential areas (400 mg/kg) [9].

In 2015, studies reported elevated BLLs in children residing in townships surrounding the former mine site [10]. Stable Pb isotope analysis indicated that soil was likely the primary source of exposure [11]. One study found that over 95% of children living in highly affected areas had BLLs above 10 µg/dL, and approximately 50% had BLLs exceeding 45 µg/dL [12]. Consequently, heavy metal pollution in Kabwe has emerged as a major environmental health concern, affecting both humans and animals [4]. Numerous studies have demonstrated the severe health implications of Pb exposure in humans and other organisms [13–15].

Various pharmaceutical interventions exist for treating Pb poisoning. For example, one study documented the use of 3,180 courses of chelation therapy with dimercaptosuccinic acid (DMSA) in children (≤5 years) in Zamfara, Northern Nigeria [16]. Similarly, DMSA has recently been used to treat children (under 15 years) with elevated BLLs in Kabwe under the Zambia Mining and Environmental Remediation and Improvement Project (ZMERIP). However, medical interventions without concurrent environmental remediation are often ineffective due to the risk of re-exposure from contaminated environments.

Numerous methods have been reported for immobilizing bioavailable toxic metals in soil. Depending on contamination levels and site conditions, remediation may be performed in situ or ex situ, and either on-site or off-site. Remediation approaches include biological, physical, and chemical techniques, which may be applied independently or in combination for improved efficiency and cost-effectiveness. One widely used method is Stabilization/Solidification (S/S), which aims to improve soil structure and immobilize a broad spectrum of contaminants [17]. S/S commonly utilizes cementitious materials such as Portland cement (PC) and lime [18, 19]. The hydration products of these binders encapsulate contaminated material and chemically react with heavy metals, forming insoluble complexes through precipitation, often enhanced by the high pH environment [20].

However, the production of PC is energy-intensive and contributes approximately 5–8% of global anthropogenic carbon emissions [21]. Therefore, industrial by-products such as ground granulated blast furnace slag (from iron production), fly ash (from coal combustion), and slaked lime are increasingly being investigated as alternative or supplementary materials in remediation [22].

The current study explores the effectiveness of combining such additives for the immobilization of bioavailable Pb in contaminated soils.

2. Materials and Methods

2.1. Study Site

Kabwe, the provincial capital of Zambia's Central Province, has a long history of Pb and Zn mining. Site assessment and soil analysis reports have shown that residential areas near the mine's tailings are highly contaminated, with Pb concentrations far exceeding acceptable levels for human habitation (Figure 1). In this study, two representative soil samples were collected from Chowa Township. The samples were labeled as KW-1 (Pb concentration: 5,473 mg/kg) and KW-2 (Pb concentration: 11,577 mg/kg).

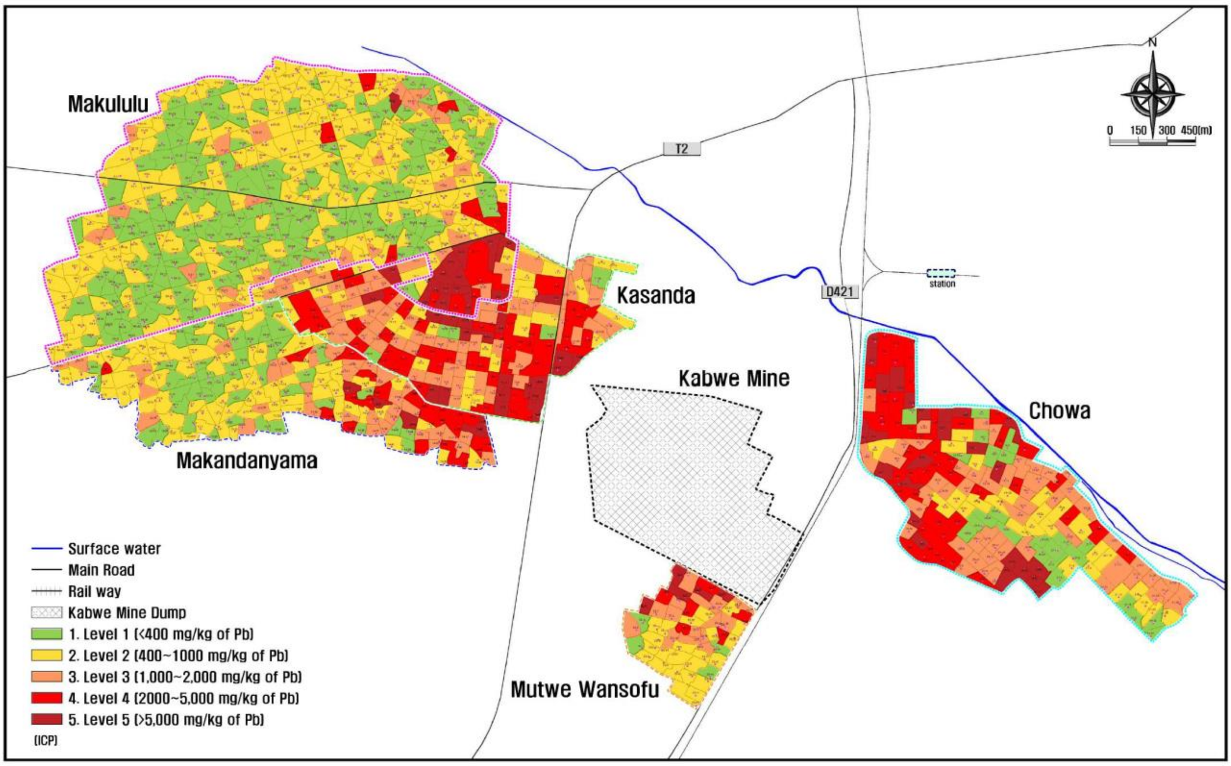

Figure 1: Classification of Pb contamination levels in five Kabwe townships based on ICP analysis. (Adapted from MIRECO, 2021).

2.2. Materials

Four types of additives—steel slag, coal ash (bottom ash), charcoal, and slaked lime—were evaluated for the remediation of Pb-contaminated soil in this study. Steel slag and coal ash were obtained from a scrap iron recycling plant located in Kabwe. The charcoal was locally produced and commonly used in Zambia.

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Slaked lime, composed of calcium hydroxide [$Ca(OH)_2$] with 95% purity, was supplied by Samchun Chemicals Co., Ltd., South Korea. The soil samples (KW-1 and KW-2) used in the experiments were collected from Chowa Township in Kabwe.

Table 1: **Type of Additives Used in the Experiments**

Additives	ID	Description
Steel slag	Slag	Obtained from a scrap iron recycling plant in Kabwe
Coal ash	Ash	Bottom ash from the same scrap iron recycling plant
Slaked lime	Lime	$Ca(OH)_2$, 95% purity, Samchun Chemicals Co., Ltd., South Korea
Charcoal	Char	Locally produced charcoal commonly used in Zambia

2.3. Experimental Design

To evaluate Pb leachability in contaminated soils treated with various additives, both batch and column leaching tests were conducted. Different mixing ratios were applied: 1%, 3%, and 5% for soil sample KW-1; and 5%, 10%, and 15% for sample KW-2 (Figure 2a).

In the batch experiments, the Synthetic Precipitation Leaching Procedure (SPLP), based on USEPA Method 1312 [9], was used to simulate the effect of acid rain on Pb leaching. A leachate solution (150 mL) was added to 30 g of the soil-additive mixture in a shake flask, agitated at 100 revolutions per minute (RPM) (Figure 2b). At intervals of 1, 6, 12, 24, 36, and 48 hours, the pH of the solution was measured. The suspension was then filtered using a 0.45 μm membrane, and the filtrate was analyzed for Pb concentration using Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES; VARIAN 720-ES).

(a) (b)

Figure 2: (a) Preparation of soil samples mixed with additives. (b) Batch leaching experimental setup.

A curing test was also conducted to assess the long-term immobilization potential of each additive. Soil, additive, and deionized water were mixed and cured in a saturated state for 14 days. The cured samples were then dried at 105°C, pulverized, and subjected to leaching using 0.1 N hydrochloric acid (HCl). For this leaching test, 10 g of the cured sample was mixed with 50 mL of 0.1 N HCl and stirred at 100 RPM for 1 hour.

Column leaching experiments were performed to simulate long-term leaching behavior under saturated conditions. Soil and additives were thoroughly mixed and packed into columns (5 cm diameter × 30 cm height) to a depth of 20 cm. The SPLP solution and deionized water were used as leachants, which were introduced from the bottom of the column at a flow rate of 110–130 mL/day (Figure 3). The experiment was run for 15 days, and leachates were collected and filtered through 0.45 μm membranes prior to analysis for Pb content.

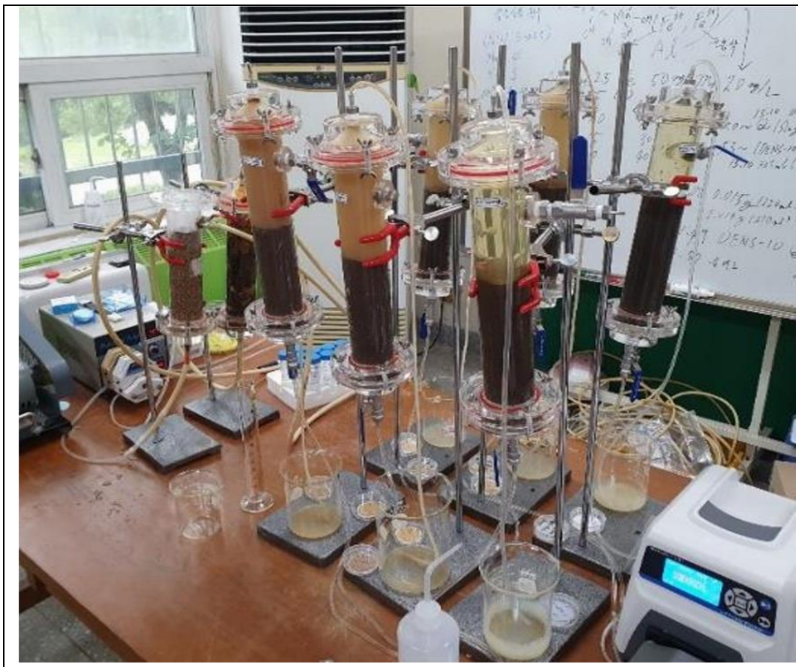


Figure 3: Column leaching setup for long-term evaluation of Pb leachability.

3. Results and Discussion

3.1. Initial Batch Leaching Experiments

Batch leaching experiments were conducted to evaluate the effectiveness of four additives—slag, lime, char, and ash—in stabilizing Pb in contaminated soil. For soil sample KW-1, additives were applied at mixing ratios of 1%, 3%, and 5%. For sample KW-2, higher ratios of 5%, 10%, and 15% were used. Lime was the exception; it was applied only up to 5% due to its tendency to increase the pH above 12, which can enhance Pb leaching instead of immobilizing it.

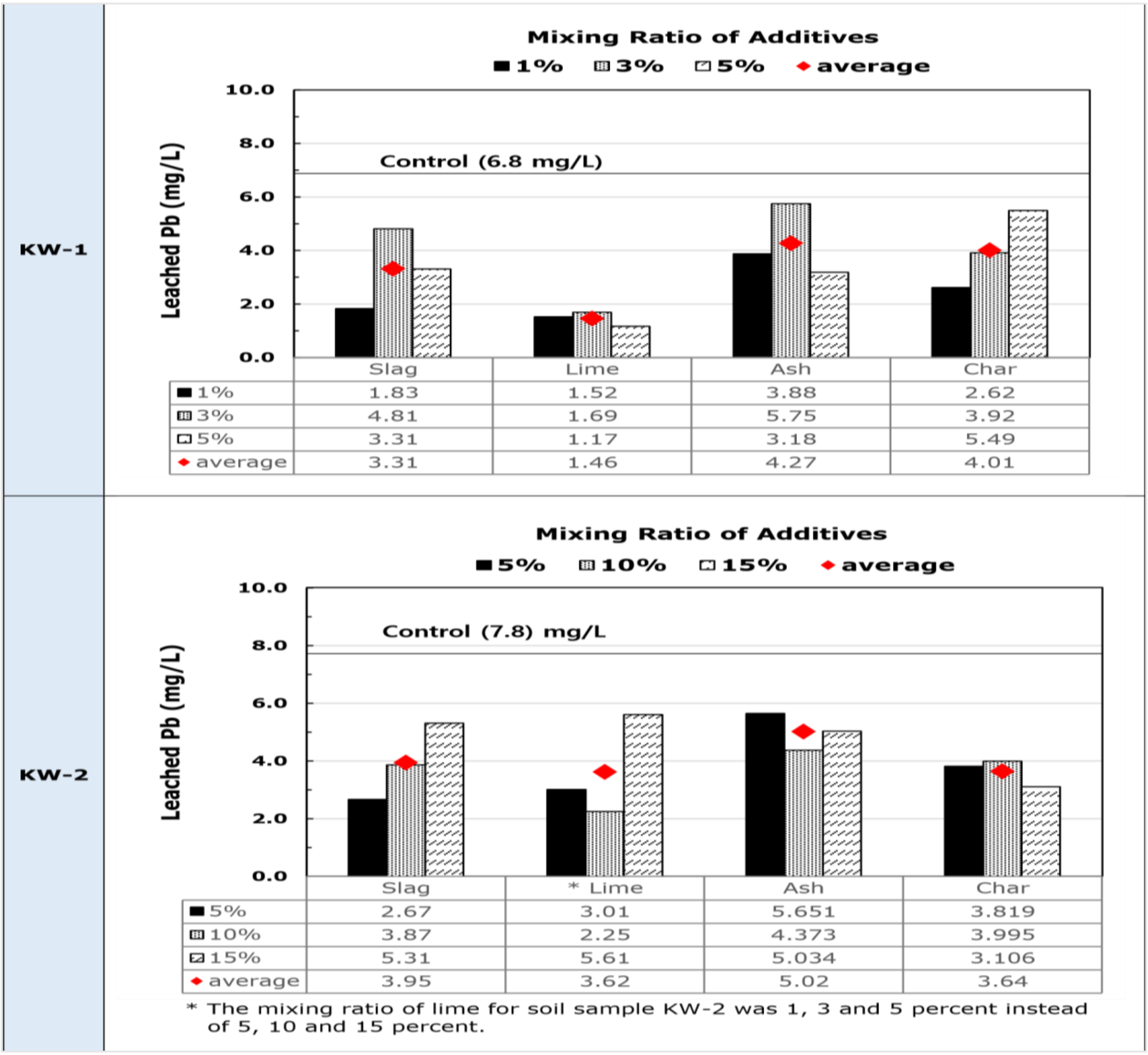
3.2. Pb Concentration in Leachate from SPLP Test (Figure 4)

Figure 4 presents the Pb concentrations in the SPLP leachate as influenced by different additives and their respective mixing ratios for samples KW-1 and KW-2.

For KW-1 (initial Pb concentration: 5,473 mg/kg), the control leachate had a Pb concentration of 6.8 mg/L. Among the tested additives, lime demonstrated the highest stabilization efficiency, reducing the average Pb concentration in leachate to 1.46 mg/L. In comparison, average concentrations were 3.3 mg/L (slag), 4.0 mg/L (char), and 4.3 mg/L (ash).

When 1%, 3%, and 5% of lime were mixed with KW-1, the corresponding Pb concentrations were 1.5, 1.7, and 1.2 mg/L, respectively. Slag at 1% yielded 1.8 mg/L, showing a similar performance to lime.

For KW-2 (initial Pb: 11,577 mg/kg), the control leachate had a Pb concentration of 7.8 mg/L. Lime again showed the best performance, with an average leachate Pb concentration of 3.62 mg/L. Slag (5%) achieved 2.7 mg/L, while char and ash were less effective, with concentrations of 3.6 mg/L and 5.0 mg/L, respectively.



with Pb-contaminated soil, Pb concentration in leachate solution was 2.7 mg/L. Lime (1 percent) and slag (5 percent) had high efficiency on Pb treatment compared to char and ash.**Figure 4**: Stabilized Pb concentration after 48 hours of SPLP batch leaching

3.3. Additive Performance Summary (KW-1 and KW-2)

The batch leaching experiments revealed that Pb stabilization efficiency did not follow a linear trend with increasing additive ratios. However, some consistent observations were made:

- **For KW-1**, lime and slag (both at 1%) exhibited the most effective stabilization performance.
- **For KW-2**, lime (1%) and slag (5%) also yielded low Pb concentrations in leachate, indicating high stabilization potential.

These findings suggest that relatively low additive ratios—particularly lime and slag—are sufficient to significantly reduce Pb mobility in both moderate and heavily contaminated soils. Ash consistently showed the lowest stabilizing efficiency in both samples, likely due to its lower calcium and carbon content, especially in bottom ash compared to fly ash [23, 24].

Although lime performed best, its cost is higher than industrial by-products like slag and ash. Therefore, economic considerations prompted further testing using slag-based combinations.

3.4. Optimized Additive Combinations (Table 2, Figure 5)

To identify optimal mixing conditions, a second set of batch leaching experiments was conducted. Given its poor performance, **ash** was excluded. Similarly, **lime**, due to its higher cost, was not used alone but in combination with **slag** in a 1:1 ratio. **Charcoal**, which also incurs moderate cost, was similarly paired with slag.

Table 2 outlines the new mixing conditions applied to samples KW-1 and KW-2, using lower additive concentrations to assess cost-effectiveness and stabilization performance.

In these optimized tests (Figure 5), the **Slag + Lime** combination consistently outperformed other treatments:

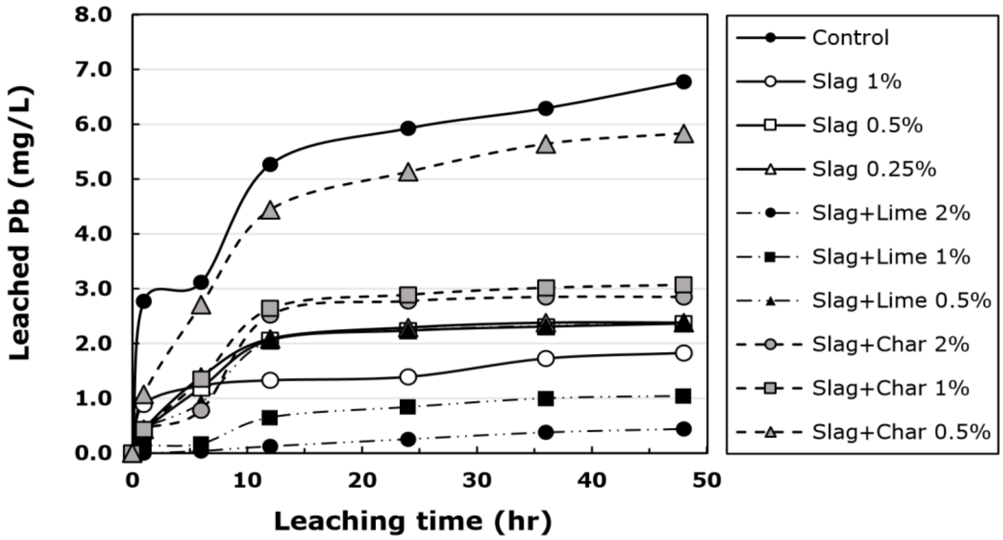
- **KW-1:** Average Pb in leachate was 1.3 mg/L (Slag+Lime), 2.2 mg/L (Slag), and 3.9 mg/L (Slag+Char).
- **KW-2:** Average Pb concentrations were 1.3 mg/L (Slag+Lime), 3.4 mg/L (Slag), and 3.5 mg/L (Slag+Char).

Results confirmed that mixing **Slag + Lime at 2–3% total** provides significantly better Pb immobilization than using slag or charcoal alone.

Table 2: Mixing conditions for the additives Slag, Lime and Char

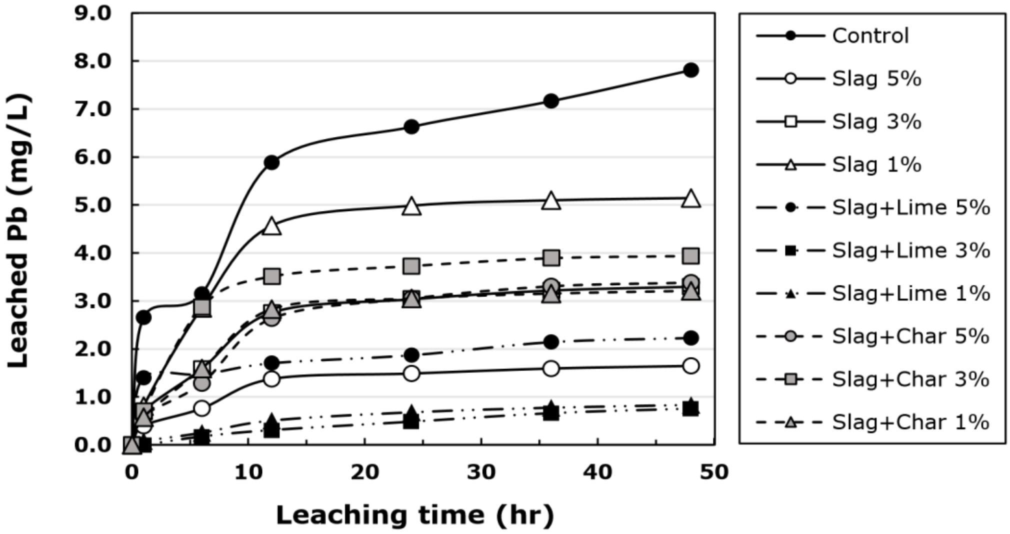
Soil	Additive	Mixing ratio with soil (by weight)
KW-1	Slag	1.0 percent
	Slag	0.5 percent
	Slag	0.25 percent
	Slag + Lime (1:1)	2.0 percent
	Slag + Lime (1:1)	1.0 percent
	Slag + Lime (1:1)	0.5 percent
	Slag + Char (1:1)	2.0 percent
	Slag + Char (1:1)	1.0 percent
	Slag + Char (1:1)	0.5 percent
KW-2	Slag	5.0 percent
	Slag	3.0 percent
	Slag	1.0 percent
	Slag + Lime (1:1)	5.0 percent
	Slag + Lime (1:1)	3.0 percent
	Slag + Lime (1:1)	1.0 percent
	Slag + Char (1:1)	5.0 percent
	Slag + Char (1:1)	3.0 percent
	Slag + Char (1:1)	1.0 percent

KW-1



Lead concentrations in leachate after 48-hours reaction (mg/L)			
Mixing Ratio	Slag	Slag+Lime	Slag+Char
2% (Slag 1%)	1.83	0.44	2.85
1% (Slag 0.5%)	2.37	1.05	3.07
0.5% (Slag 0.25%)	2.38	2.37	5.84
Average	2.19	1.29	3.92

KW-2



Lead concentrations in leachate after 48-hours reaction (mg/L)			
Mixing Ratio	Slag	Slag+Lime	Slag+Char
5%	1.65	2.23	3.38
3%	3.30	0.76	3.94
1%	5.12	0.83	3.21
Average	3.36	1.27	3.51

Figure 5: Batch leaching results for various additive mixing conditions

These results indicate that the **Slag + Lime** mixture had a significantly greater capacity to immobilize Pb than either slag or Slag + Char mixtures. The enhanced performance can be attributed to multiple chemical mechanisms:

- **Steel slag** contains iron, calcium, aluminum, and silicon, which promote Pb immobilization via adsorption and chemical bonding.
- **Charcoal**, composed primarily of carbon, provides Pb immobilization through its high surface area and adsorption properties.
- **Lime [$Ca(OH)_2$]**, when added to soil, induces pozzolanic reactions that form stable, cementitious compounds.

The key reactions include:

1. **Ca^{2+} + 2OH^- + soluble clay silica → Calcium Silicate Hydrate (CSH)**
2. **Ca^{2+} + 2OH^- + soluble clay alumina → Calcium Aluminate Hydrate (CAH)**

These compounds form rigid and stable matrices that encapsulate Pb particles, effectively reducing their mobility. Lime's superior performance is attributed to its ability to chemically bind Pb within these hydration products.

3.6. HCl Leaching After Curing (Figure 6)

Figure 6 presents Pb concentrations in leachate following curing and subsequent leaching with 0.1 N HCl (pH ≈ 2). Although the acidic environment resulted in higher overall Pb leaching compared to the SPLP tests, the observed trends remained consistent.

Notably, the **Slag + Lime** mixtures demonstrated the most effective Pb stabilization, with significantly lower Pb concentrations compared to other combinations. This indicates that the immobilization effects are chemically robust, even under aggressive acidic conditions.

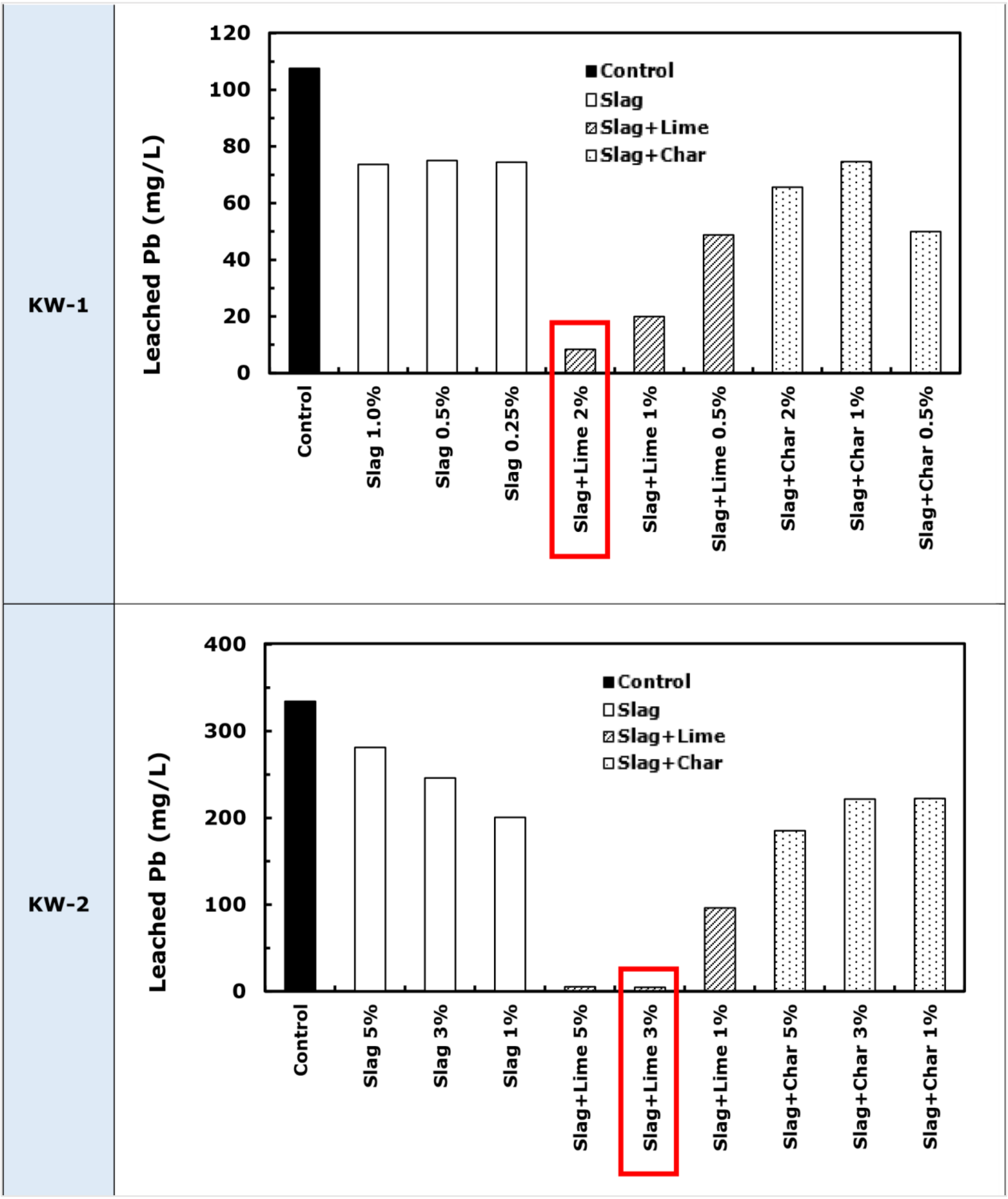


Figure 6: Concentration of eluted Pb at 0.1N HCl leaching after curing the soils

3.7. Column Leaching for Long-Term Evaluation (Figure 7)

To evaluate long-term Pb leachability, column leaching tests were performed using the optimized additive combinations determined from batch tests:

- **KW-1:** Slag (1%) + Lime (1%)
- **KW-2:** Slag (1.5%) + Lime (1.5%)

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Over the 15-day test period, cumulative Pb concentrations in leachate were significantly lower for the treated columns compared to controls. This confirms that the **Slag + Lime** mixture effectively immobilizes Pb over extended periods and under saturated flow conditions.

These results align well with batch and acid-leaching experiments, reinforcing the conclusion that low-ratio **Slag + Lime** combinations are suitable for in-situ Pb stabilization in contaminated urban soils.

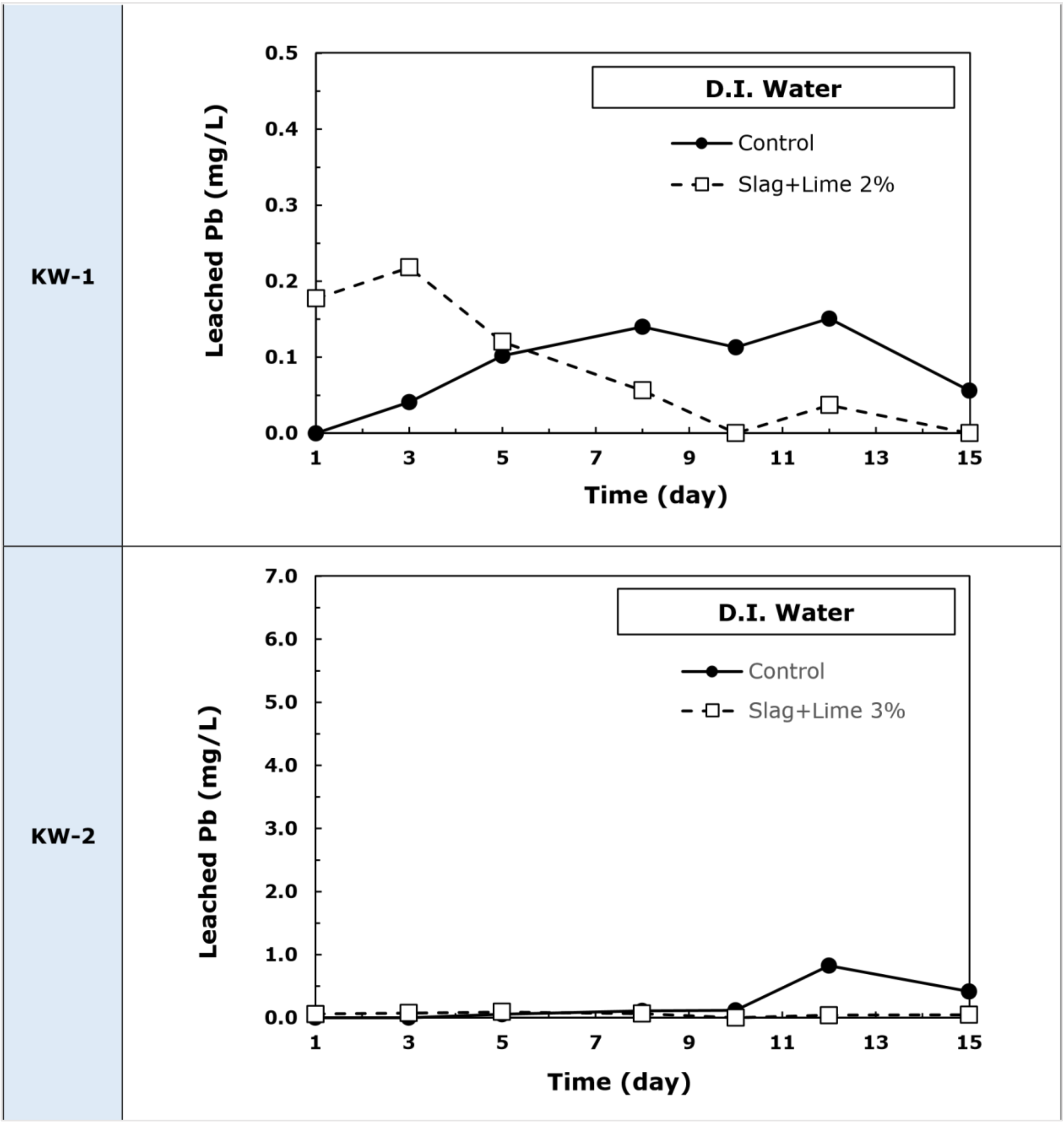

Figure 7: Column leaching experiments using deionized water

4. Conclusion and Recommendations

This study demonstrates that **environmental remediation is essential for sustainably reducing lead (Pb) exposure** in Kabwe, Zambia, where legacy contamination from mining has resulted in dangerously high Pb levels in residential soils. While medical interventions such as chelation therapy are crucial in managing elevated blood lead levels (BLLs), they must be complemented by **in-situ soil remediation strategies** to prevent continued re-exposure, especially in children.

The **stabilization technique**, using locally available and cost-effective materials, proved effective in significantly reducing Pb leachability in contaminated soils. Among the four additives tested—**slaked lime, steel slag, charcoal, and bottom ash**—lime and slag exhibited the highest stabilization performance.

Results from both **batch and column leaching experiments** confirmed that a mixture of **slag and lime** consistently produced the lowest Pb concentrations in leachates, across two different soil samples with varying contamination levels. The optimal immobilization was achieved using a total additive dose of **2–3% by weight**, with **slag and lime mixed in a 1:1 ratio**.

These findings support the following recommendations:

- **Adopt the slag-lime mixture (2–3%) for in-situ stabilization** of Pb-contaminated soils in Kabwe and similar high-risk areas.
- **Prioritize slag and lime over ash and char**, given their higher efficiency and favorable cost-performance balance.
- **Integrate soil remediation with medical and public health interventions** to ensure long-term reductions in lead exposure.
- **Leverage local industrial by-products** (e.g., slag from steel recycling) to reduce remediation costs and improve scalability.

By implementing this evidence-based approach, stakeholders can significantly mitigate the health risks associated with lead contamination, particularly for vulnerable populations such as young children.

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