Soil Neutralization and Trace Metal Stabilization in Acid-Impacted Mine Soils Using a Composite Soil Stabilization System

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Abstract

Soils in abandoned mine areas are frequently affected by prolonged exposure to acid mine drainage (AMD), resulting in severe acidification, increased mobility of trace metals, and deterioration of soil physical structure. These acid-impacted mine soils can act as long-term secondary sources of contamination to surrounding surface water and groundwater. Effective remediation therefore requires not only rapid neutralization of soil acidity but also long-term stabilization of trace metals to prevent re-mobilization under variable environmental conditions.

This study evaluates a composite soil stabilization system designed to simultaneously achieve soil neutralization and trace metal immobilization in AMD-affected mine soils. The system integrates three functional material categories: inorganic alkaline components, mineral-based industrial by-products, and polymeric stabilizing agents. Laboratory experiments were conducted using soils collected from abandoned mine areas characterized by low pH and elevated concentrations of iron, manganese, and zinc.

Application of the composite stabilization system resulted in rapid neutralization of strongly acidic soils toward near-neutral pH conditions. Leaching-oriented tests demonstrated substantial reductions in the mobile fractions of trace metals. The improved performance is attributed to a combination of pH-induced precipitation, mineral-phase co-precipitation and incorporation of metals into solid matrices, and polymer-enhanced physical stabilization that reduces particle dispersion.

Repeated equilibration experiments under neutral and mildly acidic conditions indicated resistance to re-acidification and secondary metal release, suggesting improved long-term stability compared with conventional single-component alkaline amendments. By integrating multiple stabilization mechanisms within a single treatment framework using widely available materials, the proposed approach provides a practical and scalable solution for remediation of acid-impacted mine soils. The findings contribute to the development of sustainable mine land remediation technologies relevant to the objectives of the International Mine Water Association.

Keywords: Acid-impacted mine soils; soil neutralization; trace metal stabilization, composite soil stabilization, mine land remediation, trace metal immobilization, sustainable soil remediation

Introduction

Soils in abandoned mine areas are frequently subjected to prolonged exposure to acid mine drainage (AMD), resulting in severe acidification, enhanced mobility of trace metals, and progressive degradation of soil physical structure [1–3]. These acid-impacted mine soils represent a persistent source of secondary contamination to surface water and groundwater, particularly during rainfall events or changes in redox and pH conditions [4]. Effective remediation therefore requires not only neutralization of soil acidity, but also long-term stabilization of trace metals to prevent re-mobilization and recontamination.

Conventional soil remediation practices in mine-affected areas often rely on the application of alkaline amendments such as lime or other calcium-based materials to increase soil pH [5]. While such approaches can temporarily reduce acidity, numerous studies have shown that pH adjustment alone does not guarantee sustained immobilization of trace metals [6–8]. Under fluctuating environmental conditions, metals initially precipitated or adsorbed may be released again, undermining the long-term effectiveness of remediation efforts [9]. Furthermore, single-component soil amendments typically provide limited control over soil structure and fine particle mobility, which are critical factors influencing metal transport [10].

In response to these limitations, increasing attention has been given to composite and multi-functional soil stabilization systems that integrate chemical neutralization with physical and mineralogical stabilization mechanisms [11–13]. The International Mine Water Association (IMWA) has highlighted the importance of remediation technologies that are field-applicable, scalable, and capable of providing long-term environmental protection rather than short-term compliance [14].

Materials and Experimental Approach

Composite soil stabilization system

The composite soil stabilization system investigated in this study consists of three functional material categories: inorganic alkaline components, mineral-based industrial by-products, and polymeric stabilizing agents. These components were selected based on their complementary roles in soil neutralization and stabilization, as well as their widespread industrial availability.

The inorganic alkaline fraction provides rapid neutralization capacity, enabling efficient correction of soil acidity. The mineral-based components, derived from commonly available industrial by-products, contribute reactive surfaces and mineral phases that promote co-precipitation and incorporation of trace metals into relatively stable solid matrices. The polymeric component enhances microstructural integrity by binding fine soil particles and precipitates, thereby reducing dispersion and improving resistance to leaching.

Importantly, all components belong to material categories that are produced at industrial scales and are commercially available, allowing practical implementation in large-scale remediation projects without reliance on specialized or limited-supply reagents.

Soil samples and treatment procedure

Soil samples were collected from abandoned mine areas characterized by long-term AMD influence, exhibiting low pH and elevated concentrations of iron, manganese, and zinc. The soils were air-dried, homogenized, and sieved prior to treatment.

Composite stabilization materials were mixed with the soils at predetermined application rates. Treated soils were conditioned under controlled laboratory conditions to allow equilibration. Soil pH was monitored to evaluate neutralization performance, and leaching-oriented tests were conducted to assess changes in trace metal mobility.

To evaluate stability beyond immediate neutralization, treated soils were subjected to repeated equilibration cycles under neutral and mildly acidic conditions. This approach was designed to simulate environmental fluctuations and to assess resistance to re-acidification and secondary metal release.

Results and Discussion

Soil neutralization performance

Application of the composite stabilization system resulted in rapid neutralization of strongly acidic mine soils toward near-neutral pH conditions. For example, soil pH increased from approximately 2–3 to near-neutral conditions (pH 6–8) following treatment. Compared with untreated soils, which maintained persistently acidic pH values, treated soils exhibited stable pH levels after equilibration, indicating effective consumption of soil acidity by the alkaline fraction of the composite.

Unlike conventional single-component alkaline amendments, the composite system maintained pH stability during subsequent equilibration cycles, suggesting that buffering capacity was not exhausted immediately after treatment. This behavior is particularly relevant for mine soils exposed to episodic acid inputs from residual sulfide oxidation or acidic pore water migration.

Reduction of trace metal mobility

Leaching-oriented analyses demonstrated a relevant reduction in the mobile fractions of iron, manganese, and zinc following treatment. The decrease in trace metal mobility cannot be attributed solely to pH increase. Instead, the results indicate the combined influence of multiple stabilization mechanisms.

The initial rise in pH reduced metal solubility and promoted precipitation reactions. Simultaneously, mineral components within the composite provided surfaces and reactive phases that facilitated co-precipitation and incorporation of metals into solid matrices. The polymeric stabilizer further enhanced retention by physically binding fine particles and precipitates, reducing their susceptibility to transport.

This multi-mechanistic stabilization contrasts with conventional treatments, where metals are often immobilized primarily as loosely bound hydroxide precipitates that may dissolve under changing conditions. The conceptual stabilization mechanisms of the composite system are illustrated in Figure 1. The system integrates three complementary functional components: an inorganic alkaline fraction responsible for rapid pH adjustment, mineral-based materials that promote co-precipitation and incorporation of metals into solid phases, and polymeric stabilizers that enhance microstructural integrity and reduce particle dispersion. Through the interaction of these mechanisms, trace metals become incorporated into stable soil matrices, substantially reducing their mobility and susceptibility to re-leaching.

Long-term stability and resistance to re-acidification

A key concern in mine soil remediation is the potential for recontamination following environmental changes. In this study, treated soils subjected to repeated equilibration under neutral and mildly acidic conditions exhibited sustained reductions in leachable metal concentrations. No abrupt increases in iron, manganese, or zinc mobility were observed during these cycles.

These findings suggest that trace metals were not merely temporarily precipitated but were incorporated into more stable solid phases and physically constrained within the soil matrix. The polymer-enhanced microstructure appears to play an important role in limiting particle dispersion and maintaining metal immobilization even when external conditions become less favorable.

Implications for field-scale application

The use of industrially available alkaline materials, mineral by-products, and polymeric stabilizers offers clear advantages for large-scale implementation. The composite system can be adapted to site-specific soil conditions by adjusting application rates, while maintaining the same fundamental stabilization mechanisms.

From a sustainability perspective, the incorporation of mineral by-products aligns with circular economy principles and reduces reliance on virgin materials. The ability to achieve both neutralization and stabilization within a single treatment framework simplifies field operations and reduces the likelihood of performance decline over time.

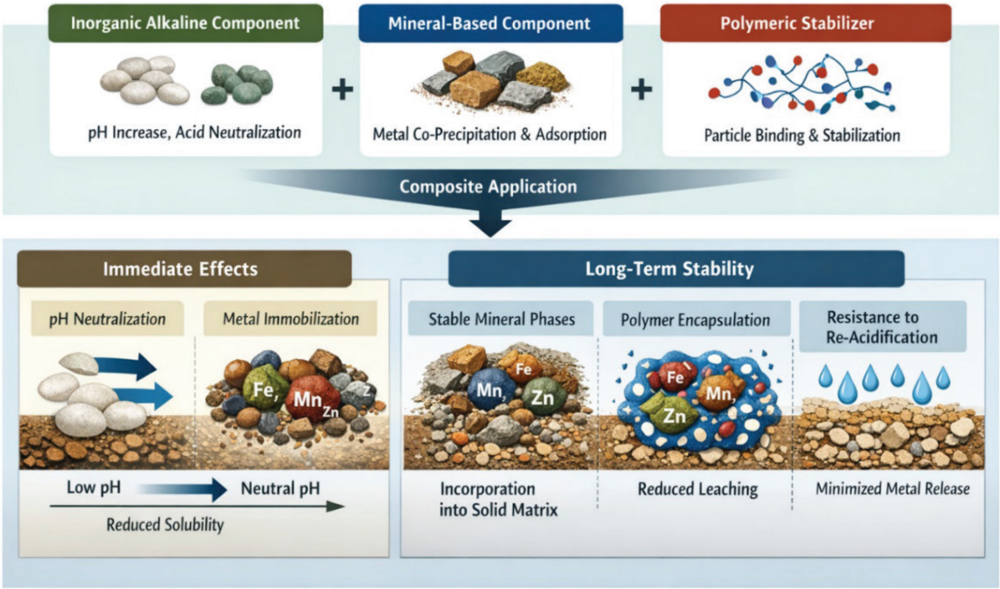

Figure 1 Composite soil stabilization mechanism for acid-impacted mine soils. Conceptual stabilization mechanism of the composite soil stabilization system for acid-impacted mine soils.

Conclusions

This study demonstrates that effective remediation of acid-impacted mine soils requires an integrated approach that combines soil neutralization with long-term trace metal stabilization. The composite soil stabilization system evaluated here successfully neutralized acidic mine soils while substantially reducing the mobility of iron, manganese, and zinc.

The observed performance is attributed to the synergistic action of pH-induced precipitation, mineral-phase co-precipitation, and polymer-enhanced physical stabilization. Importantly, the treated soils exhibited resistance to re-acidification and secondary metal release during repeated equilibration, indicating potential for long-term environmental protection.

By utilizing widely available material categories and integrating multiple stabilization mechanisms within a single framework, the proposed system offers a practical, scalable, and sustainable solution for the remediation of acid-impacted mine soils. The findings are directly relevant to the objectives of the International Mine Water Association and provide a solid foundation for further field validation and long-term monitoring studies.

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