Neutralization and Metal Stabilization of Acid Mine Drainage Using an Inorganic–Mineral–Polymer Composite System

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Abstract

Acid mine drainage (AMD) remains a critical challenge in abandoned mine areas due to its low pH, elevated sulfate concentrations, and high mobility of dissolved metals. Conventional alkaline neutralization methods, typically based on lime or sodium hydroxide, provide rapid pH adjustment but are often associated with excessive sludge generation, limited long-term stability, and secondary environmental burdens. This study presents an inorganic–mineral–polymer composite system designed to achieve rapid neutralization of AMD while simultaneously promoting stabilization of dissolved metals.

Laboratory-scale experiments demonstrated that strongly acidic AMD (initial pH 2–3) was rapidly neutralized to near-neutral conditions (pH 6–8) within several minutes. Concurrently, significant reductions in dissolved iron, manganese, and zinc were observed compared to untreated AMD. The immobilization of metals is attributed to a combination of pH-induced precipitation, co-precipitation and incorporation into mineral phases, and physical stabilization within polymer-enhanced solid matrices.

Unlike conventional single-step alkaline treatment, the proposed system explicitly separates rapid neutralization from long-term stabilization within a single composite framework. Preliminary stability assessments under repeated equilibration conditions indicate reduced susceptibility to metal re-dissolution, suggesting improved long-term performance. The system is compatible with modular and mobile treatment configurations, making it particularly suitable for remote or inaccessible abandoned mine sites. The results demonstrate the potential of the composite approach as a practical and sustainable alternative for active AMD treatment, with clear relevance to the International Mine Water Association community.

Keywords: Acid mine drainage (AMD); AMD neutralization, metal stabilization, composite treatment system, mine water treatment, trace metal immobilization, sustainable mine water management

Introduction

Acid mine drainage (AMD) is one of the most persistent environmental problems associated with mining activities, particularly in abandoned mine areas where active management has ceased [1–3]. The oxidation of sulfide minerals generates acidic waters enriched with sulfate and dissolved metals, which can contaminate surface water and groundwater over extended periods [4].

Conventional AMD treatment relies primarily on alkaline reagents such as lime or sodium hydroxide to increase pH and induce metal precipitation [5]. While effective in the short term, these approaches often generate large volumes of hydroxide sludge with limited chemical stability [6]. Under fluctuating pH or redox conditions, metals immobilized as hydroxides may be re-dissolved, leading to renewed contamination [7].

Recent research has highlighted the potential of composite and multi-functional treatment systems that combine chemical, mineralogical, and physical stabilization mechanisms [8–10]. Such systems are increasingly considered promising alternatives for sustainable AMD management, particularly in remote or abandoned mine environments [11].

Conceptual Basis of the Composite AMD Treatment System

The composite system investigated in this study integrates three functional components: an inorganic alkaline fraction, mineral-based components, and polymeric stabilizing agents. Each component contributes a distinct function while operating synergistically within the overall treatment process.

The inorganic alkaline fraction provides immediate neutralization capacity, allowing rapid correction of AMD acidity. Mineral components supply reactive surfaces and phases that facilitate co-precipitation and incorporation of dissolved metals into solid matrices. The polymeric component enhances the physical integrity of the resulting solids by binding fine precipitates and reducing their susceptibility to dispersion and leaching.

A key feature of the proposed system is the explicit distinction between rapid neutralization and longer-term stabilization processes. While neutralization occurs almost instantaneously following application, stabilization mechanisms continue to operate as metals interact with mineral phases and polymer-enhanced matrices. This conceptual separation differentiates the composite system from conventional single-step alkaline treatments. The conceptual framework of the proposed AMD treatment system is illustrated in Figure 1. The composite approach distinguishes between two interconnected processes: rapid neutralization of AMD acidity and subsequent long-term stabilization of dissolved metals. While

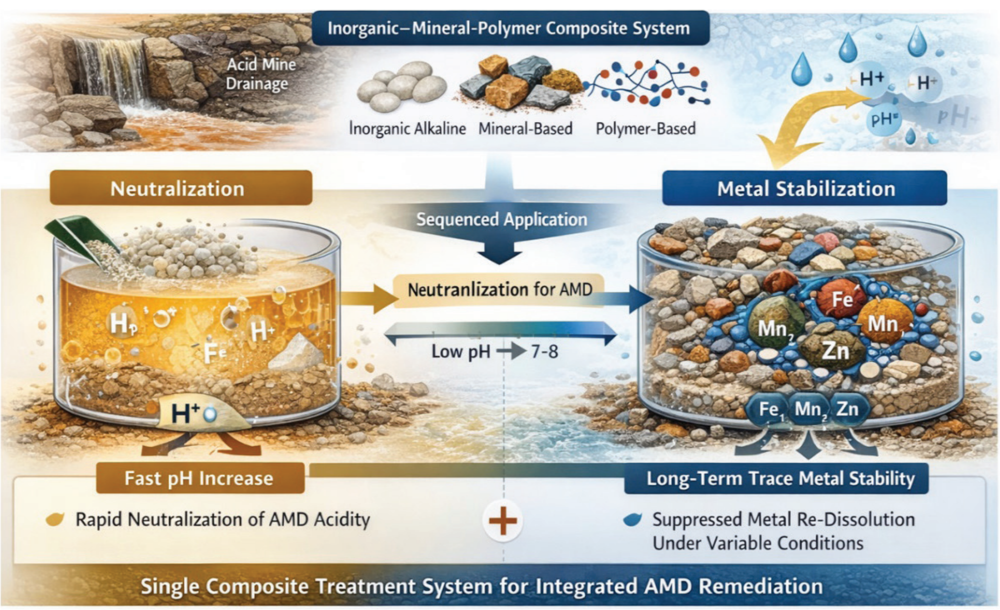

Figure 1 *Conceptual separation of AMD neutralization and metal stabilization processes using an inorganic–mineral–polymer composite system. The composite treatment system achieves rapid pH neutralization of acid mine drainage while simultaneously promoting long-term stabilization of dissolved metals through mineral-phase interactions and polymer-enhanced solid matrices.*

the alkaline fraction induces immediate pH elevation, mineral-based components promote co-precipitation and incorporation of metals into solid matrices. Simultaneously, polymeric stabilizers enhance the structural integrity of the resulting solids, reducing particle dispersion and suppressing metal re-dissolution under variable environmental conditions.

Experimental Approach

AMD characteristics and treatment procedure

AMD samples were obtained from abandoned mine settings characterized by strongly acidic conditions and elevated concentrations of dissolved iron, manganese, and zinc. The AMD exhibited initial pH values in the range of approximately 2–3.

Composite treatment materials were applied under controlled laboratory conditions. AMD samples were mixed with the composite system and monitored for pH evolution to assess neutralization kinetics. Following neutralization, treated waters were allowed to equilibrate, and dissolved metal concentrations were analyzed to evaluate removal performance.

Assessment of stabilization behavior

To investigate stability beyond immediate neutralization, treated AMD samples were subjected to repeated equilibration under neutral and mildly acidic conditions. This procedure was intended to simulate environmental fluctuations that may occur in field settings and to evaluate susceptibility to metal re-dissolution.

Results and Discussion

Rapid neutralization performance

The composite system achieved rapid neutralization of AMD, increasing pH from strongly acidic levels to near-neutral conditions within minutes. This rapid response is comparable to conventional alkaline treatments and satisfies operational requirements for active AMD management, particularly in high-flow or episodic discharge scenarios.

Importantly, pH levels remained relatively stable during subsequent equilibration, indicating that the neutralization capacity was not immediately exhausted and that buffering effects were present.

Metal removal and immobilization

Following treatment, dissolved concentrations of iron, manganese, and zinc were substantially reduced. While pH elevation played a critical role in decreasing metal solubility, the observed reductions cannot be explained solely by hydroxide precipitation.

Mineral components within the composite promoted co-precipitation and incorporation of metals into solid phases, while the polymeric fraction enhanced physical stabilization by binding precipitates and limiting particle mobility. This multi-mechanistic immobilization contrasts with conventional treatments, where metals are often retained as relatively unstable hydroxide solids. The composite system also exhibited reduced sludge-generation tendencies compared with conventional lime-based treatment systems.

Stability under repeated equilibration

During repeated equilibration under neutral and mildly acidic conditions, treated samples did not exhibit significant increases in dissolved metal concentrations. This behavior suggests resistance to re-dissolution and indicates that metals were stabilized within more robust solid matrices rather than being temporarily precipitated.

Such stability is essential for long-term AMD treatment, where treated waters may be exposed to varying chemical conditions over time.

Implications for field application

The composite system is compatible with modular and mobile treatment configurations, allowing deployment at remote or inaccessible abandoned mine sites. The use of widely available material categories supports scalability and reduces dependence on specialized reagents.

By integrating rapid neutralization with stabilization mechanisms in a single system, the proposed approach simplifies operational requirements while enhancing environmental protection.

Conclusions

The inorganic–mineral–polymer composite system evaluated in this study provides an effective approach for the treatment of acid mine drainage. Rapid neutralization of strongly acidic AMD was achieved alongside substantial reductions in dissolved iron, manganese, and zinc.

The improved performance relative to conventional alkaline treatments is attributed to the combined effects of pH-induced precipitation, mineral-phase co-precipitation, and polymer-enhanced physical stabilization. Preliminary stability assessments indicate resistance to metal re-dissolution under variable conditions, highlighting the potential for long-term effectiveness.

Overall, the composite approach represents a potentially practical and sustainable alternative for active AMD treatment, with strong relevance to abandoned mine remediation and the objectives of the International Mine Water Association.

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