

Geochemical Safety of Enhanced Rock Weathering for Acid Mine Drainage Remediation in Japan and Zambia

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Abstract

Enhanced rock weathering (ERW) has recently been proposed as a strategy to couple mine drainage remediation with carbon dioxide removal. However, the geochemical safety of applying mafic rocks to acidic mine drainage systems remains insufficiently understood. This study evaluates the release and subsequent attenuation of nickel (Ni) and chromium (Cr) during basalt dissolution under acidic conditions representative of mine drainage. Batch experiments show that Ni and Cr concentrations initially increase but subsequently decline as pH rises, indicating natural sequestration through secondary iron mineral formation. In addition, tailings from Zambia were characterized to evaluate their potential suitability as carbon-reactive substrates, with basalt identified as a promising additive to enhance reactive Ca and Mg availability.

Keywords: Mine drainage, enhanced rock weathering, Ni, Cr, carbon dioxide removal, mine tailings

Introduction

Mine drainage from abandoned mines remains a long-term environmental challenge due to persistent acidity and dissolved metal release (Nordstrom, 2011). Although passive treatment systems such as wetlands and limestone drains are widely used because of their low operational requirements, they often provide limited alkalinity generation and do not contribute to climate-related goals such as carbon dioxide removal.

Enhanced rock weathering (ERW) has emerged as a promising approach for atmospheric CO₂ removal through accelerated silicate dissolution (Beerling *et al.*, 2020). While most ERW studies have focused on agricultural soils, acidic mine drainage systems may offer favourable geochemical conditions because low pH and high water–rock interaction rates can enhance silicate dissolution, consume acidity, and generate bicarbonate alkalinity. However, the use of mafic rocks such as basalt raises safety concerns because they may contain

elevated nickel (Ni) and chromium (Cr) concentrations (Flipkens *et al.*, 2021). Under acidic conditions, dissolution of these minerals may release trace metals into already impacted waters, making it essential to evaluate whether Ni and Cr remain mobile or become naturally attenuated through secondary mineral formation.

This study assesses the geochemical safety of basalt application in acidic mine drainage systems in Japan by examining the release and subsequent behaviour of Ni and Cr during basalt dissolution. In addition, because mine tailings storage facilities are increasingly being considered as potential carbon sinks due to their large volumes and reactive surface areas (Bullock *et al.*, 2022), Zambian mine tailings were characterized to evaluate their suitability for carbon sequestration. The study further investigates whether blending tailings with basalt can enhance carbonation reactions by increasing reactive Ca and Mg availability. The specific objectives are to: (i) evaluate Ni and Cr release during basalt dissolution



under acidic mine drainage conditions, (ii) determine whether natural geochemical processes promote their sequestration over time, and (iii) assess the potential of mine tailings for carbon reduction and the role of basalt in enhancing carbonation reactions.

Materials and Methodology

Basalt Characterization

Basalt samples from Hokkaido, Japan were crushed and sieved to approximately 75 μm particle size. Bulk mineralogy was determined using X-ray diffraction (XRD), while major element composition was measured by X-ray fluorescence (XRF). Surface morphology and mineral textures were examined using scanning electron microscopy (SEM) with energy dispersive spectroscopy (EDS). Basalt serves as the primary reactive material for the experimental dissolution study, both in the lab and in the field.

Batch Dissolution Experiments

Batch dissolution experiments were conducted to simulate basalt weathering under acidic mine drainage conditions (Figure 1). Basalt powders were reacted with deionized water adjusted to pH 3.5 with sulfuric acid, which represents typical acidic mine drainage conditions. Experiments were performed at a solid-to-liquid ratio of 1:8 and maintained at approximately 25 $^{\circ}\text{C}$ with constant agitation. Samples were collected periodically over a 50-day period. Filtered solutions were analyzed using ICP-MS to determine concentrations of Ca, Mg, Ni and Cr.

To validate the laboratory findings, field-scale trials were conducted by applying 1 tonne of basalt material to two separate river systems. In the field trials, basalt was applied as a passive reactive amendment. The material was placed directly in selected river systems, packaged in 5 kg nylon filter bags, allowing water-rock contact under natural flow conditions while minimizing environmental impacts (Figure 1). The crushed basalt had a coarser particle-size distribution (1~2cm) than the laboratory powders, reflecting practical field deployment conditions and reducing the likelihood of rapid downstream transport. Water samples were collected upstream of the application zone, immediately downstream of the amended zone, and at a downstream mixing point to distinguish basalt-related geochemical effects from background river chemistry. Flow rates at Shojin and Amemasu were ~ 0.19 and ~ 0.16 m^3/s , respectively. Conditions were monitored qualitatively during each sampling event, and the results are interpreted as field-scale geochemical trends under dynamic hydrological conditions.

Tailings Characterization

Mine tailings collected from Zambia were characterized using XRD and XRF to determine mineral composition and elemental content. Particular attention was given to minerals containing Ca and Mg that could contribute to carbonation reactions. To evaluate methods of enhancing carbonation potential, the tailings were conceptually

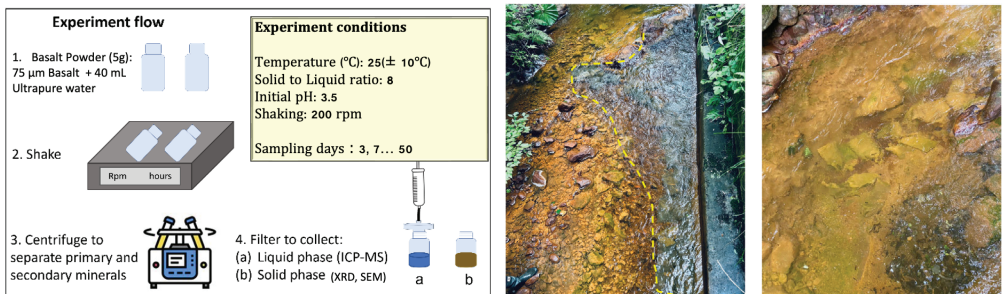


Figure 1 (a) Experiment conditions for the basalt dissolution and (b) pictures of the field-scale trial in one of the rivers, upon installation on the left, and one month later to the right.

assessed by mixing with basalt, a by-product rich in reactive Ca and Mg. In this study, carbon sequestration was assessed as a geochemical potential rather than directly quantified CO₂ removal. Therefore, the carbon-removal component is interpreted from mineralogical and geochemical indicators, particularly the availability of reactive Ca- and Mg-bearing silicates, pH evolution, and the potential for alkalinity generation during basalt dissolution.

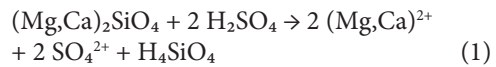
Results and Discussion

Basalt Dissolution and Acid Neutralization

Silicate rocks from Japan, including nineteen mafic rocks (basalt) and one ultramafic rock (harzburgite), were assessed for enhanced rock weathering (ERW) in acidic mine drainage systems. Whole-rock XRF results showed clear lithological differences in trace metals (Figure 2). The ultramafic sample contained very high Ni and Cr concentrations, exceeding 500 mg/L for both elements, while the basalts had much lower contents, with Cr below 250 mg/L and Ni below 150 mg/L. Because Ni and Cr may be released during dissolution under acidic conditions, the ultramafic rock was considered less suitable for direct ERW application. Basalt, however, is widely regarded as a suitable ERW feedstock due to its relatively rapid dissolution, lower trace-

metal risk, and ability to release Ca and Mg for neutralization and carbon sequestration (Linke *et al.*, 2024).

Batch experiments showed that basalt dissolution progressively increased pH from about 3.5 to approximately 7.5–8.5. This reflects proton-promoted dissolution of mafic silicate minerals such as olivine and pyroxene, during which acidity is consumed and Mg²⁺, Ca²⁺, and dissolved silica are released (Equation 1). These reactions act as a geochemical buffer and represent the main mechanism by which basalt can neutralize acidic mine drainage (Rimstidt *et al.*, 2012). The released Ca and Mg also support carbon sequestration by reacting with atmospheric or dissolved CO₂ to form bicarbonate alkalinity and, potentially, carbonate minerals or enhanced ocean alkalinity (Beerling *et al.*, 2020; Hartmann *et al.*, 2023). Thus, basalt weathering may provide a dual benefit by coupling AMD remediation with long-term carbon storage.



Environmental Risk Assessment: Nickel and Chromium mobility and attenuation

A primary environmental concern regarding the application of basalt for mine drainage

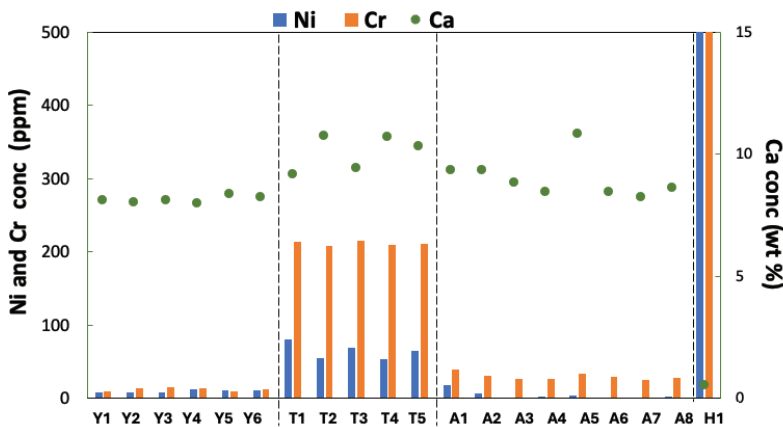


Figure 2 (a) Experiment conditions for the basalt dissolution and (b) pictures of the field-scale trial in one of the rivers, upon installation on the left, and one month later to the right.



remediation is the potential mobilization of trace elements, specifically nickel (Ni) and chromium (Cr), which are inherent to mafic minerals. As shown in the 50-day batch experiments (Figure 3), dissolved Ni and Cr concentrations exhibited a distinct peak and decline trend across all samples (A1, T1, Y1, and H1).

During the early stages of the batch experiment (Days 3–28), dissolved Ni and Cr concentrations increased markedly, with sample H1 reaching peak values of approximately 65 $\mu\text{g/L}$ Ni and 125 $\mu\text{g/L}$ Cr. This initial release is attributed to the rapid proton-promoted dissolution of primary basaltic silicate minerals, including olivine, pyroxene, plagioclase, augite, and smectite, in which Ni commonly substitutes for Mg and Cr may occur within the mineral lattice (White, 2017). However, between Day 28 and Day 50, both Ni and Cr concentrations declined sharply, returning to near-baseline levels. This pattern suggests that trace-metal release during basalt dissolution was transient and became increasingly controlled by natural attenuation as silicate weathering consumed acidity and increased solution pH toward circumneutral to alkaline conditions.

To assess environmental relevance, measured concentrations were compared with selected international water-quality guidelines. The maximum dissolved Ni concentration in the batch experiment, approximately 65 $\mu\text{g/L}$, remained below the WHO drinking-water guideline value of 70 $\mu\text{g/L}$. In contrast, the maximum total Cr concentration of approximately 125 $\mu\text{g/L}$ exceeded both the WHO guideline value

of 50 $\mu\text{g/L}$ for total Cr and the Japanese environmental standard of 20 $\mu\text{g/L}$ for Cr(VI). However, this Cr peak occurred under closed-system, high water–rock interaction conditions and declined substantially by Day 50. Importantly, field monitoring over 78 days in two rivers, River S and River A, and at a downstream mixing point showed that these elevated batch concentrations were not reproduced under dynamic environmental conditions. Ni concentrations in River S remained relatively stable at approximately 20 $\mu\text{g/L}$, while River A showed very low concentrations. At the downstream monitoring point, Ni remained consistently low, below 5 $\mu\text{g/L}$, throughout the monitoring period. Chromium concentrations were negligible across all field sites and remained below 10 $\mu\text{g/L}$, indicating that dilution and geochemical attenuation effectively limited trace-metal accumulation in the river system.

The observed decline in dissolved Ni and Cr concentrations in both laboratory and field settings suggests that trace-metal release during basalt dissolution is transient and partly self-limiting. During the early reaction stage, proton-promoted dissolution of primary basaltic minerals such as plagioclase, pyroxene, and augite likely promoted the release of divalent cations and trace elements hosted within the mineral structure. However, as basalt dissolution progressed, acidity was consumed and solution pH increased toward circumneutral to alkaline conditions. Under these conditions, Fe released from basaltic minerals can hydrolyse and precipitate as secondary Fe-bearing phases, which provide high-surface-area sites for trace-

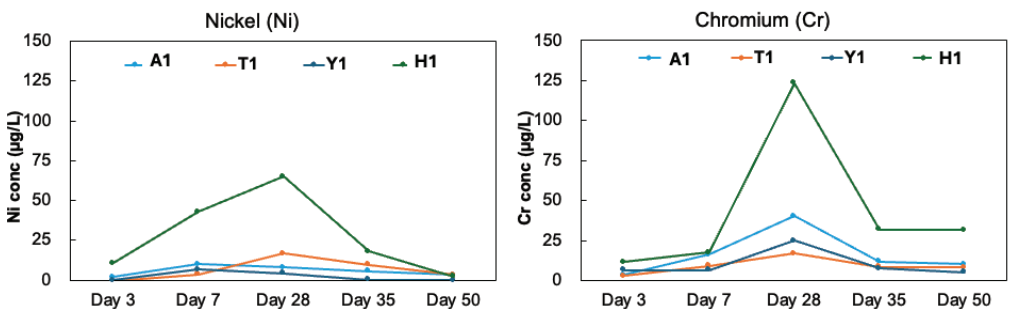


Figure 3 Trends of Ni and Cr during batch experiments for a 50 day period.

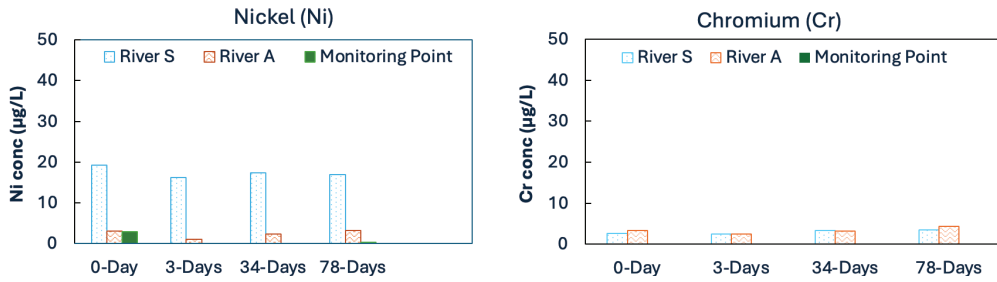


Figure 4 Long-term field monitoring of Ni and Cr concentrations ($\mu\text{g/L}$) in River S, River A, and the downstream mixing point.

metal attenuation through adsorption, co-precipitation, or structural incorporation. Secondary Fe minerals formed during AMD neutralization are widely recognized as important controls on trace-metal mobility because they can scavenge metals from solution and limit their downstream transport (Nordstrom, 2011; Baleeiro *et al.*, 2018).

The increase in pH alongside declining dissolved Ni and Cr indicates that basalt weathering neutralized acidity while promoting trace-metal sequestration. Fe released during dissolution likely precipitated as secondary Fe-bearing phases, providing sites for Ni and Cr removal through adsorption, co-precipitation, or structural incorporation. Post-reaction XRD (Figure 5) supports this mechanism, showing the persistence of basaltic minerals and increased clay mineral formation. As Fe oxyhydroxides are common in AMD systems, secondary Fe minerals can retain trace metals and have been shown to adsorb Ni(II) and Cr(VI), depending on pH, ionic strength, and competing ions (Kim and Kim, 2021; Zhao *et al.*, 2022).

Overall, the laboratory and field results indicate that Ni and Cr release during basalt-enhanced weathering is initially enhanced under acidic conditions but becomes partly self-limiting as pH increases and secondary Fe-bearing minerals form. Nevertheless, because Cr was measured only as total dissolved Cr, future work should distinguish Cr(III) from Cr(VI), particularly because Cr(VI) is more mobile and toxic under oxidizing conditions. In addition, since XRD may not fully resolve poorly crystalline Fe phases such as ferrihydrite, complementary SEM-EDS,

selective extraction, or spectroscopic analyses would further strengthen confirmation of the trace-metal attenuation mechanism.

Potential of Tailings Ponds as Carbon Sinks

Beyond basalt use in mine drainage, Zambia's mine tailings were evaluated as potential substrates for carbon sequestration. XRD analysis showed that the tailings are mainly composed of silicate minerals with minor sulfide remnants, while XRF results identified measurable Cu and Co, reflecting the original ore signature. Their fine-grained nature provides a high reactive surface area, but limited Ca- and Mg-bearing phases may constrain carbonation.

To improve carbonation potential, blending tailings with basalt was considered because basalt supplies reactive Ca and Mg silicates that dissolve to generate alkalinity. This hybrid approach could support both

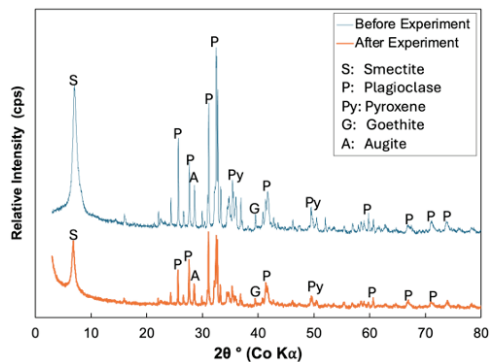


Figure 5 XRD patterns of basaltic material before and after the batch dissolution experiment.



metal stabilization and carbon sequestration, allowing tailings storage facilities to act as long-term carbon sinks when combined with water management systems that enhance water–rock interaction (Bullock *et al.*, 2022).

Conclusions

This study shows that basalt can effectively neutralize AMD while releasing Ca and Mg that may support carbon sequestration. Although Ni and Cr were initially released during dissolution, their concentrations declined as pH increased, suggesting transient and self-limiting metal mobility through secondary Fe-phase adsorption or co-precipitation. Zambian mine tailings also showed potential as carbon sinks, especially when blended with basalt to enhance reactive Ca and Mg availability. Overall, basalt-enhanced weathering offers a promising approach for combined mine water remediation, mine waste management, and carbon removal.

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