

# Preliminary Leaching Performance of Slag-Blended Cement for the Stabilization of Pyrite-Bearing Waste Rock

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## Abstract

This study explores slag-blended cement as an alternative to Ordinary Portland Cement (OPC) for stabilizing pyrite-bearing waste rock. Over a 64-day leaching experiment, OPC-treated waste rocks produced higher pH leachates and greater major ion release due to their faster reactivity and early cement hydrate phase dissolution. Slag-blend-treated waste rocks exhibited slower ion leaching, indicating the need for extended curing. Trace element concentrations (Cu, Mn, Ni, Pb) were slightly higher in leachates from untreated waste rock, reflecting cement's early-stage performance in metal(oids) immobilization. Further research is needed to assess slag's long-term effectiveness.

**Keywords:** Cement-based stabilization, Slag Cement, Portland Cement, Acid Rock Drainage, pyrite-bearing Waste Rock, Leaching Test

## Introduction

Acid Rock Drainage (ARD) is a widely recognized environmental issue at mine sites, where sulfide-bearing waste rock oxidizes, releasing acidic, metal-rich waters. If left untreated, this can cause severe ecological and health effects. Stabilization/Solidification (S/S) techniques, such as the use of Ordinary Portland Cement (OPC), are commonly employed to treat hazardous wastes (Wang *et al.* 2018). In the case of waste rock stabilization, OPC can form a cementitious barrier that may reduce ARD (Sephton and Webb 2017), but its long-term effectiveness remains uncertain. Gypsum ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ) in OPC can lead to the formation of expansive minerals like ettringite ( $\text{Ca}_6\text{Al}_2(\text{SO}_4)_3(\text{OH})_{12} \cdot 26\text{H}_2\text{O}$ ) and thaumasite ( $\text{Ca}_3\text{Si}(\text{OH})_6(\text{CO}_3)(\text{SO}_4) \cdot 12\text{H}_2\text{O}$ ), which weaken the barrier and expose sulfides to oxidation. Additionally, the high carbon emissions from cement production make OPC less ideal, highlighting the need for better alternatives.

This paper explores the use of an alternative cementitious material for stabilizing pyrite-bearing waste rock. Specifically, it investigates the potential of a supplementary cementitious material derived from granulated blast-furnace slag, which is currently used by Boliden AB in Sweden as a substitute for OPC in underground backfilling (Eriksson *et al.* 2018). Here, we compare slag-blended cement and OPC for their applicability in stabilizing waste rock in atmospheric conditions. Previous leaching tests for hazardous waste and standard leaching procedures for construction materials were conducted under saturated conditions (CEN 2015; ASTM 2018). However, in this study, we aimed to assess the leaching behavior of cement-encapsulated waste rock under atmospheric conditions rather than saturated. Thus, this study presents results from a new laboratory leaching set-up designed for monolithic cement-encapsulated waste rock. In the long term, this research seeks



to provide a comprehensive understanding of the geochemical interactions within the cemented matrix, contributing to the identification of the most effective and sustainable alternative material for stabilizing sulfidic waste rock.

## Methods

### *Encapsulation of Waste Rock by Cementitious Materials*

Waste rock samples were collected from a polymetallic Cu-Zn-Au-Ag mine in Northern Sweden. For this experiment, one rock type (andesite) was selected from the collected waste rock samples, which does not necessarily represent the entire waste rock volume but was selected to represent the average S value (11 wt. %). The waste rock sample (characterization from Butar Butar *et al.* 2025) is mainly composed of quartz (36.3 wt. %), smectite (25.7 wt. %), muscovite (12.3 wt. %), chlorite (10.9 wt. %), albite (7.0 wt. %), microcline (6.7 wt. %), and biotite (0.48 wt. %). Sulfur is principally associated with pyrite (0.61 wt. %), which is the most dominant sulfide in the rock sample. Most major elements (Al, Fe, K, Mg, Si) occur in rock-forming silicates, while trace elements like Co, Cu, Mn, and Ni are mostly associated with pyrite. Trace amounts of other metals (V and Zn) are also present in the sample.

The samples were cut into 3 cm × 3 cm × 3 cm specimens. Waste rock samples were encapsulated with 2 cm thick of both Ordinary Portland Cement (OPC) and slag-blended cement (50% OPC, 50% Slag) in duplicate. OPC was identified as type CEM I 52.5R from Cementa (Malmö, Sweden) while the slag was from Merox AB-Sweden (Oxelönd, Sweden). Additionally, each cement mixture was separately molded into 5 cm × 5 cm × 5 cm cubes as reference specimens. All specimens were cured for at least 28 days at 25 °C and 60% relative humidity. Determination of trace elements in solid materials was done using Inductively Coupled Plasma – Sector Field Mass Spectrometry (ICP-SFMS) by ALS Scandinavia in Luleå, Sweden.

### *Leaching Experiment*

For the leaching experiment, encapsulated waste rock samples (including a reference

untreated sample) were placed in transparent polycarbonate cells after curing. Seven cells were stored in a climate-controlled chamber at 25 °C and 60–80% relative humidity. Since no standardized leaching procedure exists for monolithic samples under atmospheric conditions, two standards were adapted: CEN/TS 15863:2015 (CEN 2015) for cell construction and experiment duration (64 days), and ASTM D5744-18 (ASTM 2018) for the weekly leaching procedure.

Milli-Q water served as the leachant, with volumes based on the sample surface area (500 mL for the reference and 600 mL for others). Cells were flooded weekly for 64 days, with water remaining in the cell for six hours before being emptied and sampled. The leachate was filtered (0.45 µm) and analyzed for main and trace elements (ICP-SFMS by ALS Scandinavia). Electrical conductivity (EC) and pH were measured immediately after sampling.

For one duplicate and the reference sample, leaching will continue beyond 64 days to assess long-term behavior and chemical interactions between the cemented matrix and waste rock. Microstructural analyses will follow after 64 days. This paper discusses results from the initial 64-day experiment.

## Results and Discussion

### *Chemistry of OPC and Slag-Mix Cement*

The initial composition of the cementitious materials and waste rock used in this study provides essential context for understanding the leaching behavior and stabilization performance using OPC and slag-blended cement. The background concentrations of major elements in OPC, slag, and waste rock are summarized in Table 1.

OPC is characterized by a high Ca content, primarily due to the presence of calcium silicates and calcium hydroxide, with smaller amounts of Si, Al, and Fe. Trace amounts of Mg, Na, K, and S are also present, reflecting the typical composition of clinker-based materials (Kothari *et al.* 2023). In contrast, slag exhibits a higher proportion of Si, Mg, and Al compared to OPC, while its Ca content is lower. This difference arises because slag relies on latent hydraulic phases rather than free lime for its cementitious properties (Chen 2007).

**Table 1** Background chemical composition (wt. %) for major elements in solid samples before leaching.

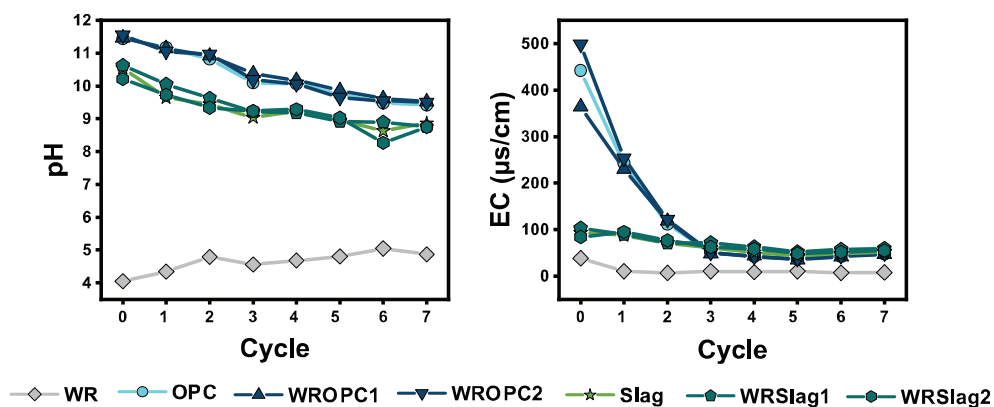
Sample	Al	Ca	Fe	Mg	K	Si	Na	S
Waste Rock	4.1	0.2	6.2	1.0	1.8	28	0.1	5.1
OPC	2.8	47	2.7	2.0	0.8	9.6	0.1	1.3
Slag	7.2	28	0.2	8.4	0.6	17	0.4	1.2
Aggregates	7.5	1.2	2.8	0.5	3.4	36	2.2	0.1

### Leaching Behavior and pH Trends

Overall, there is minimal variation in major element concentrations between the leachate from the reference materials (OPC and Slag-blend) and the cement-treated waste rocks (see Fig. 2). A similar trend is observed regardless of whether the cemented matrix consists solely of reference materials (OPC and Slag-blend) or contains waste rock (WROPC and WRSslag). This suggests that geochemical interactions between the cemented matrix and the waste rock that can cause the mobility of elements have been limited so far. Additionally, the release of major elements from the reference untreated waste rock remains consistently lower than that from the cement-encapsulated waste rocks, indicating that, during the first 64 days of leaching, the primary source of element release is the cementitious materials (OPC and Slag) rather than the waste rock. This can also be linked to the lag time before the oxidation occurs in the waste rock, which is after 10 weeks of wet-dry cycle leaching of crushed (1–4 mm) waste rocks (Butar Butar *et al.* 2025).

The leachate from the OPC-treated waste rock consistently exhibited a higher pH compared to slag-blend-treated waste rocks throughout the 64-day observation period, ranging between 11.5 and 10. It can be observed that the leachate from the cement-encapsulated waste rocks had a higher pH compared to the reference untreated waste rock sample (4–5). It is important to note that this low pH may not be solely attributed to the waste rock itself, as the blank sample exhibited a similar pH trend (4–5). This may be due to the residual nitric acid in the tubes and cells from the acid-cleaning process. It is therefore recommended to rinse the tubes with MQ water several times before use.

The initially elevated pH of leachate from the OPC-treated waste rocks can be attributed to the dissolution of calcium hydroxide ( $\text{Ca}(\text{OH})_2$ ) from the cement (Sephton and Webb 2017), which provides an effective buffer against acidic conditions but may also lead to alkaline sulfide weathering (Butar Butar *et al.* 2025). In contrast, slag mix-treated waste rocks displayed a slightly lower pH range, decreasing from 10.5 to



**Figure 1** pH and electrical conductivity (EC) throughout the 64-day leaching experiment. One cycle represents one week except for cycle 2 to cycle 3 where there is a 2-week gap.



9.3 over the same period, probably due to the lower amount of OPC in slag-blended cement. This slightly lower pH trend may be associated with the slower activation of pozzolanic reactions, during which latent hydraulic phases react with water and Ca to form secondary binding phases (e.g., calcium silicate hydrates) (Chen 2007).

The leachate from OPC and OPC-treated waste rocks contained higher initial concentrations of Ca (Fig. 2), particularly during the first two leaching cycles, before declining to below 10 mg/L during cycles 3 and 4. The decline may be attributed to the dissolution of calcium-rich phases (during the early cycles) and the subsequent potential incorporation of Ca into stable phases, such as calcium silicate hydrates (C-S-H) (Scrivener *et al.* 2019). In contrast, leachates from slag-blend-treated waste rocks exhibited consistently lower Ca concentrations throughout the 64-day leaching period, although the concentrations became comparable to those of OPC-treated waste rocks during the final two cycles. This trend reflects the inherently lower total Ca content in slag compared to OPC. The higher initial Ca release from OPC may be due to its higher free lime content, which rapidly dissolves and releases Ca ions into the leachate. Curing time may also be a factor since slag-blended cement needs sufficient time to cure due to its slower reactivity (Wu *et al.* 1990)

The concentrations of Al and Si in the leachate were consistently higher from the OPC-treated waste rocks compared to slag-

blend-treated waste rocks. The elevated levels of Al and Si in the leachate from OPC-treated waste rocks, particularly during the early stages, may be attributed to the dissolution of silicate phases in the cement. Interestingly, this higher release of Al and Si from OPC-treated waste rocks occurred despite the higher Al content in slag compared to OPC. This can be explained by the rapid dissolution of aluminate phases, such as tricalcium aluminate (C<sub>3</sub>A), in the OPC matrix (Hirsch *et al.* 2023), as well as higher pH in OPC-treated systems, which may enhance Al solubility. This trend is further supported by the higher EC values observed in the leachate from the OPC-treated waste rocks, indicating the rapid release of ions such as Al, Ca, and Si. Over time, EC in the leachate from OPC-treated waste rocks gradually decreased, consistent with the declining release of these ions. In contrast, leachate from slag-blend-treated waste rocks exhibited a more stable EC trend, likely reflecting the gradual release of major ions. This may be due to the slower reactivity of slag-blended cement which may lead to the late formation of soluble cement hydrate phases.

Both OPC- and slag-blend-treated waste rocks exhibited minimal leaching of Mg and Na, with concentrations remaining below 6 mg/L across all samples. However, leachate from slag mix-treated waste rocks demonstrated a gradual increase in Mg concentrations over time, likely due to the dissolution of Mg ions within the slag matrix which probably still has not reacted into a

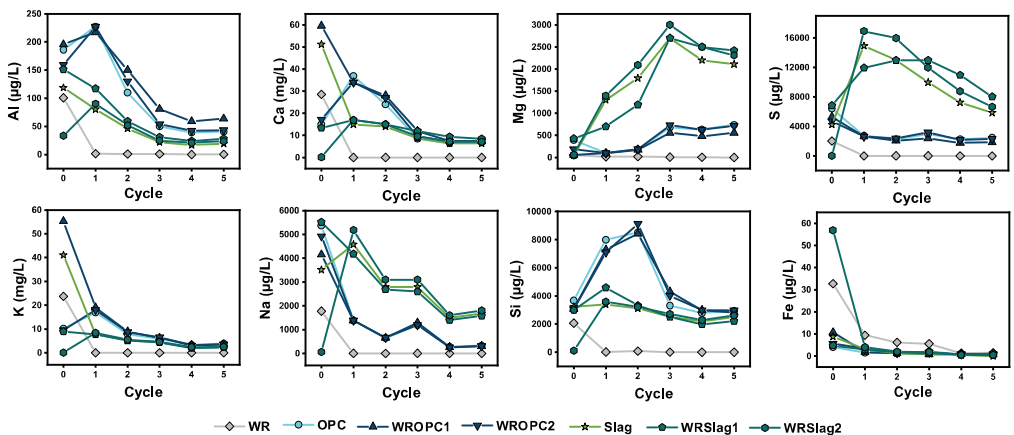


Figure 2 Leaching trends and concentrations of major elements throughout the 64-day leaching period. One cycle represents one week except for cycle 2 to cycle 3 where there is a 2-week gap.

stable phase (Zhai and Kurumisawa 2022). Additionally, slag-blend-treated waste rocks released higher concentrations of both Mg and Na compared to OPC-treated waste rocks, consistent with the higher initial Mg and Na content in slag. For S, slag-blend-treated waste rocks exhibited a higher release compared to OPC-treated waste rocks, despite the lower initial S content in the slag. This behavior may be attributed to the faster reactivity of OPC compared to slag facilitating the transformation of gypsum into ettringite (Sun *et al.* 2020), thereby stabilising S in the system. Due to the slower reactivity of slag, it is likely that during the early stages, gypsum in slag-blended cement still has not fully transformed to ettringite and may release S to the leachate (Ogirigbo and Black 2016). Furthermore, the release of S from the cemented waste rocks cannot be attributed to waste rock oxidation, as no evidence of oxidation has been observed in the reference waste rock yet. This interpretation is supported by the consistently low Fe release across all samples, which aligns with the absence of oxidation processes in the waste rock throughout the 64-day leaching duration.

Overall, the release of trace elements to the leachates across all samples is minimal, particularly for Cu, Mn, Ni, and Pb, with concentrations ranging from 0 to 5 µg/L per

cycle. However, Mo and V exhibit slightly higher release rates in cement-treated waste rocks, likely due to the increased mobility of these elements in alkaline environments. For some trace metals (Cu, Mn, Ni, Pb), the reference untreated waste rock releases slightly higher concentrations than the cement-treated waste rocks. Although the difference is small, this still demonstrates the early-stage performance of both OPC and slag-blended cement in immobilizing trace metals. However, it is important to note that this trend represents pre-oxidation conditions, and the behavior may change once oxidation progresses.

### Evaluation of New Leaching Set-Up

In this study, we tested a new leaching setup by adapting two existing standard procedures (CEN/TS 15863 and ASTM D5744). This modified setup allowed full exposure of all surface areas of the monolithic samples. The release of major elements was already evident as early as Week 0 to Week 1, providing insights into the initial performance of the cementitious materials. However, the 64-day duration is insufficient to observe sulfide oxidation in the reference waste rock sample, making it impossible to further interpret the data in terms of ARD. Therefore, the leaching duration will be extended. Additionally, a key limitation of this setup is its inability

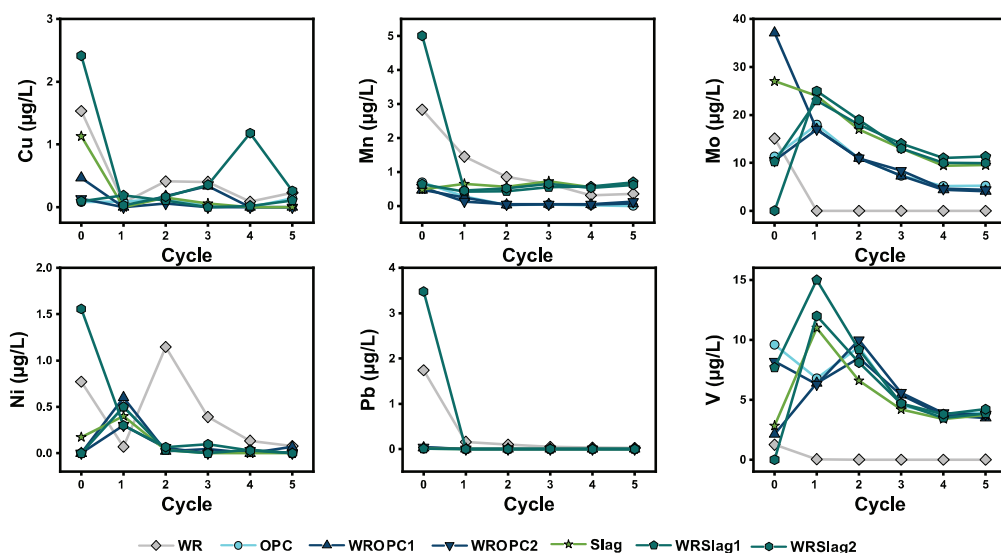


Figure 3 Leaching trends and concentrations of major elements throughout the 64-day leaching period. One cycle represents one week except for cycle 2 to cycle 3 where there is a 2-week gap.



to evaluate and calculate the diffusion coefficient, as diffusion calculations require a saturated leaching setup.

## Conclusions

This study evaluated slag-blended cement as a potential alternative to OPC for stabilizing pyrite-bearing waste rock and mitigating ARD. While the preliminary data were inconclusive regarding ARD prevention, the leachate chemistry provided valuable early-stage insights into the performance of slag-blended cement as a potential replacement for OPC. The results highlight the importance of cement chemistry, particularly during the early stages, in identifying suitable replacements for OPC.

Leachates from both OPC- and slag-blend-treated waste rocks maintained consistently high pH levels, with OPC-treated waste rocks exhibiting slightly higher pH values. OPC-treated waste rocks also released higher concentrations of ions, likely due to the dissolution of soluble cement hydrate phases. In contrast, slag-blend-treated waste rocks exhibited a slower release of some major ions (e.g., Al, Ca, Si), which is likely a result of its slower reactivity and delayed formation of soluble hydrate phases. This suggests that slag-blended cement may require a longer curing period compared to OPC.

After 64 days of leaching, it's still unclear if slag-blended cement is a viable alternative to OPC for mitigating ARD, as the waste rock has not yet oxidized. However, the experiment provided valuable early data. Future research will focus on longer leaching tests and microstructural analyses to assess cement-waste rock interactions, long-term performance, and the effects of sulfide oxidation.

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