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Oxygen ingress in mine waste: modelling, measurement and design implications for non-acid forming material encapsulation from a tropical environment case

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Abstract

Oxygen availability is a key constraint on sulphide oxidation and oxygen transport is often considered as the rate-limiting step in acid and metalliferous drainage/metal leaching (AMD/ML). Understanding the depth and continuity of the oxic zone is therefore fundamental to inform design decisions that can lower ARD/ML risk especially during the post-closure phase of a mine waste storage facility.

Reducing oxygen ingress is one of the few direct levers to mitigate the oxidation of pyrite, which produces ferrous iron, sulphate and acidity. Sulphide mine waste facility designs that achieve lowered oxygen ingress will conceptually have less long-term contaminant loads and should have more defensible closure performance criteria in closure plans, consistent with leading guidance (e.g. International Network for Acid Prevention 2020).

Two complementary approaches for estimating the oxidation zone extent are gas measurements and multiphase reaction and transport modelling, and ideally both should be applied. The objective of a multiphase model is typically to refine the conceptual understanding of oxygen supply mechanisms (diffusion versus advection), and once calibrated, allow screening of mitigation options and landform options before committing to expensive trials. Field measurements typically combine gas ports and oxygen sensors with suction and moisture content probes and lysimeters to capture coupled gas and moisture transport.

In a sulphide-rich mine waste facility, mitigation should target the dominant oxygen supply mechanism, which can include promoting water saturation in surficial layers to suppress oxygen diffusion, reducing air permeability to reduce advection, interrupting the development of thermal chimneys and managing heat with interim and final covers and landform designs.

The case study presented in this paper assesses an oxygen ingress–informed encapsulation design for a waste rock dump (WRD) at a mine in the tropical Asia-Pacific region.

Keywords: *oxygen, acid and metalliferous drainage, encapsulation, AMD, ARD*

1 Introduction

O*xygen availability is a key constraint on sulphide oxidation* and often considered as the rate-limiting step in acid and metalliferous drainage/metal leaching (AMD/ML). Understanding the depth and continuity of the oxic zone is therefore fundamental to inform design decisions to lower ARD/ML risk for all phases of the facility's life cycle, including closure and post-closure. Reducing oxygen ingress is one of the few direct levers to mitigate the oxidation of pyrite, which produces ferrous iron, sulphate and acidity.

Oxygen transport is influenced by several interacting processes, including gas diffusion, airflow, moisture distribution and geochemical reactions. These processes vary with site conditions such as climate, material

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properties and landform geometry. As a result, closure design requires a site-specific understanding of how oxygen moves through waste materials and how oxygen is consumed.

A preferred approach is to combine field measurements with numerical modelling. Field data provide direct evidence of oxygen behaviour, while modelling allows prediction of long-term performance under different conditions, including long-term climate change considerations. This combined approach enables closure design to define encapsulation thickness and cover performance based on oxygen flux rather than conservative assumptions.

This paper presents such an approach for a storage facility for mine waste rock in a tropical environment in the Asia-Pacific region. This case study shows the benefit of using site characterisation, monitoring and modelling to develop an encapsulation design that can act to reduce the longer-term geochemical loads from the stored waste rock.

2 Oxygen transport in mine waste

Oxygen is a key requirement for AMD generation, with diffusion dominating its migration through partially air-filled pores within waste facilities (Nicholson et al. 1989; Ritchie 1994). Oxygen transport in mine waste occurs through diffusion, advection and thermal convection, with the dominant mechanism dependent on material properties, moisture conditions and climatic influences.

Diffusion is the movement of oxygen down a concentration gradient and is typically the dominant mechanism in partially saturated waste rock as shown in Figure 1. Consumption of oxygen will lead to a gradient in oxygen fugacity in the material that initiates oxygen diffusion (flow from high concentration to low concentration). The oxygen concentration will be at its highest in material directly in contact with the atmosphere. Due to its consumption, the oxygen concentration will gradually become depleted within only a few metres. Initially, only the upper part of the material will be situated in the oxic zone, and the oxidation front will shift deeper into the material as sulphide minerals are depleted. According to the shrinking core model of Davis & Ritchie (1986), oxygen diffusion takes place through the pore space of the wastes, followed by diffusion into a moving reaction front within the particles. In other words, the front of the oxidation zone is at the reaction front within the pyrite grains, and no sharp oxidation front is present in the WRD itself (which creates a transition zone). Fully oxidised pyrite remnants may be present at the top of the oxic zone, partially oxidised pyrite exists deeper down, with unoxidised pyrite grains remain in the anoxic zone.

Oxygen advection in waste rock relates to the bulk movement of air (including oxygen) through the pore spaces of the material, driven by pressure or density differences rather than concentration gradients (which drive diffusion). Heat generated by sulphide oxidation can enhance this process by promoting upward airflow, which in turn draws fresh oxygen into the system. This can establish convective cells, particularly in coarse, permeable waste rock.

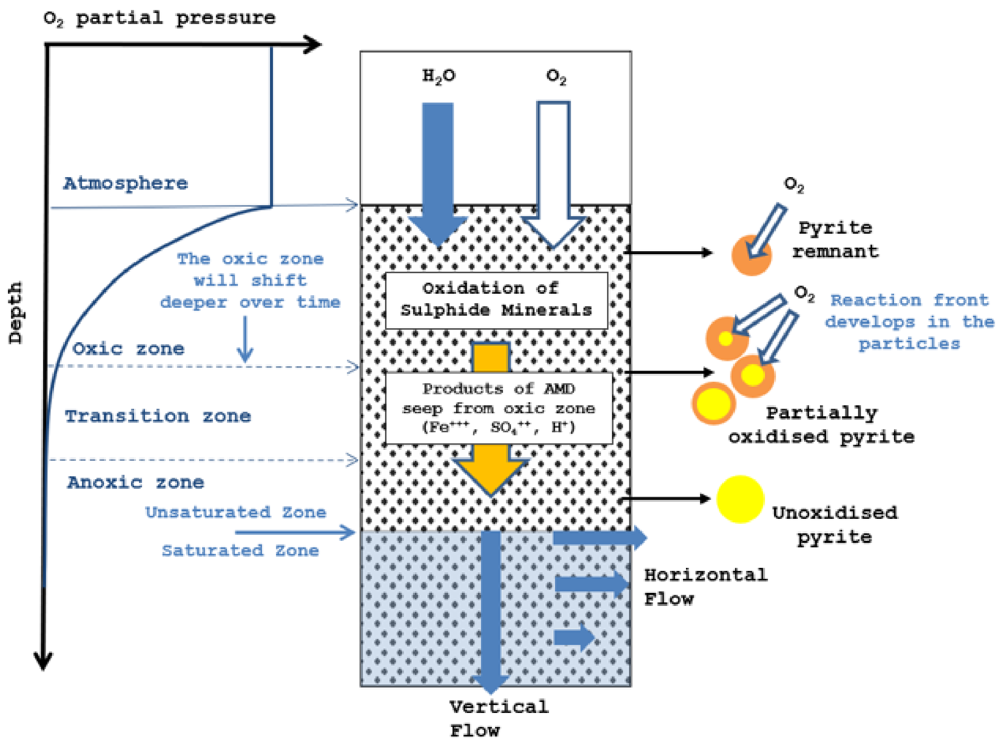


Figure 1 Conceptual model of the physicochemical process in the unsaturated zone (Fourie 2022)

3 Tropical mine waste rock dump case study

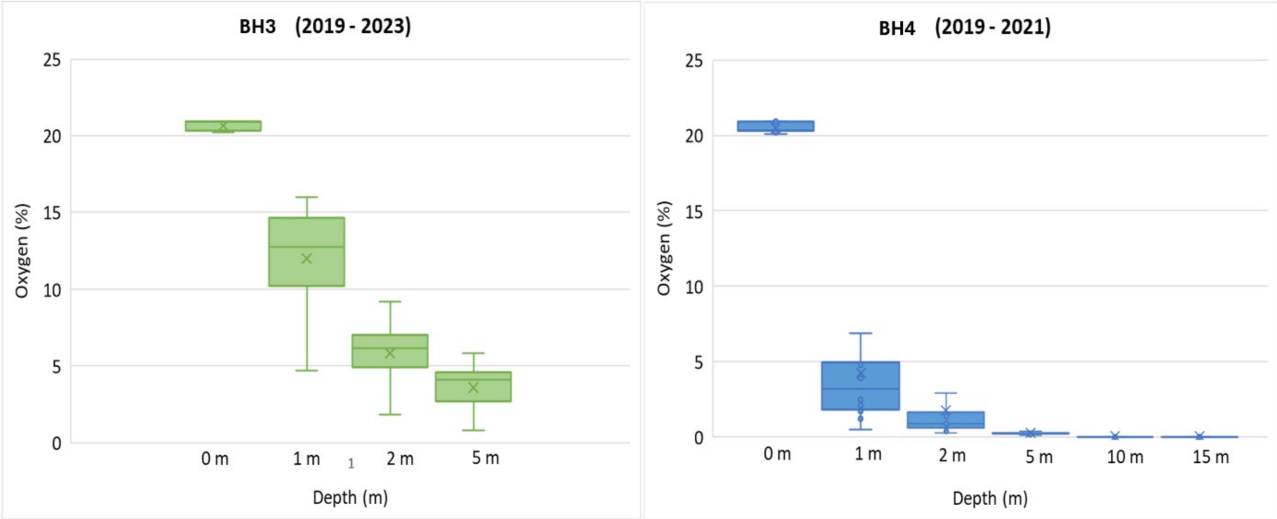
The case study considers a WRD at a mine in a tropical environmental, constructed using a bottom-up method with potentially acid forming (PAF) material encapsulated within non-acid forming (NAF) material. The closure design incorporates a 20 m-thick NAF encapsulation placed progressively during operations to form the final landform. The primary objective of this encapsulation is to limit oxygen ingress to the PAF core, thereby reducing sulphide oxidation and subsequent AMD generation.

The site is located in a tropical rainforest climate characterised by high rainfall and humidity, resulting in elevated moisture content within the WRD. These climatic conditions are favourable for reducing oxygen diffusion, as increased moisture reduces gas permeability and diffusivity. The conceptual design of the WRD cover considered material properties, moisture retention and oxygen consumption processes to limit oxygen transport to the more reactive PAF waste over the long term.

3.1 Field measurements

Field instrumentation included oxygen sensors, moisture probes and temperature sensors installed at multiple depths. Four operational oxygen monitoring sites with oxygen sensors were installed to depths between 5 and 15 m below surface. Field observations indicate that diffusion is the primary mechanism controlling oxygen transport. The temperature in the WRD was measured at <20°C, suggesting that the formation of convection airflow cells due to pyrite heat generation is not occurring.

Although there is variability in oxygen concentrations at some deeper (>10 m) monitoring locations, the overall interpretation for the dataset is that below the upper few metres of the facility, oxygen concentrations decrease sharply (Figure 2). This data implies that the waste rock material does not have an ongoing/readily available supply of oxygen below the upper few metres from the surface and provides a field-based confirmation that 20 m of encapsulation should be sufficient to limit oxygen transport. This information was used to provide inputs to the prediction modelling described in Section 3.4.



(a) (b)

Figure 2 Measured oxygen concentration; (a) Borehole 3 from 2019 to 2023; (b) Borehole 4 from 2019 to 2021

3.2 Oxygen consumption rate

Oxygen consumption rate (OCR) of the waste material can be calculated to provide input data for the oxygen diffusion model. Oxygen consumption within the WRD is driven by sulphide oxidation, and kinetic column leach testing was completed to calculate the rates of reaction. The results interpretation is based on the assumption that the initial release of sulphate in the columns is from the dissolution of reactive secondary minerals like gypsum since high initial concentrations are associated with elevated dissolved calcium (and, to a lesser extent, magnesium). After 50 weeks, the released sulphate approached equilibrium, with more consistent concentrations, and this is assumed to be derived from pyrite oxidation.

The column tests were performed on NAF and PAF samples, with total sulphur content ranging from 0.02% to 3.83%. The calculated OCR for the materials ranged from approximately 10^{-13} to 10^{-10} kg O_2/kg rock/s, with higher rates associated with PAF materials. For the oxygen diffusion modelling of the NAF material encapsulation, a conservative OCR of 7.73×10^{-12} kg O_2/kg rock/s was used; this value falls in the range of results from 2 column tests on NAF material with total sulphur contents of 0.25 and 1.26, respectively.

The relationship between oxygen consumption and sulphur content is shown in Figure 3, which plots calculated OCR against total sulphur content. The figure shows that higher sulphur content leads to higher OCRs within the waste rock.

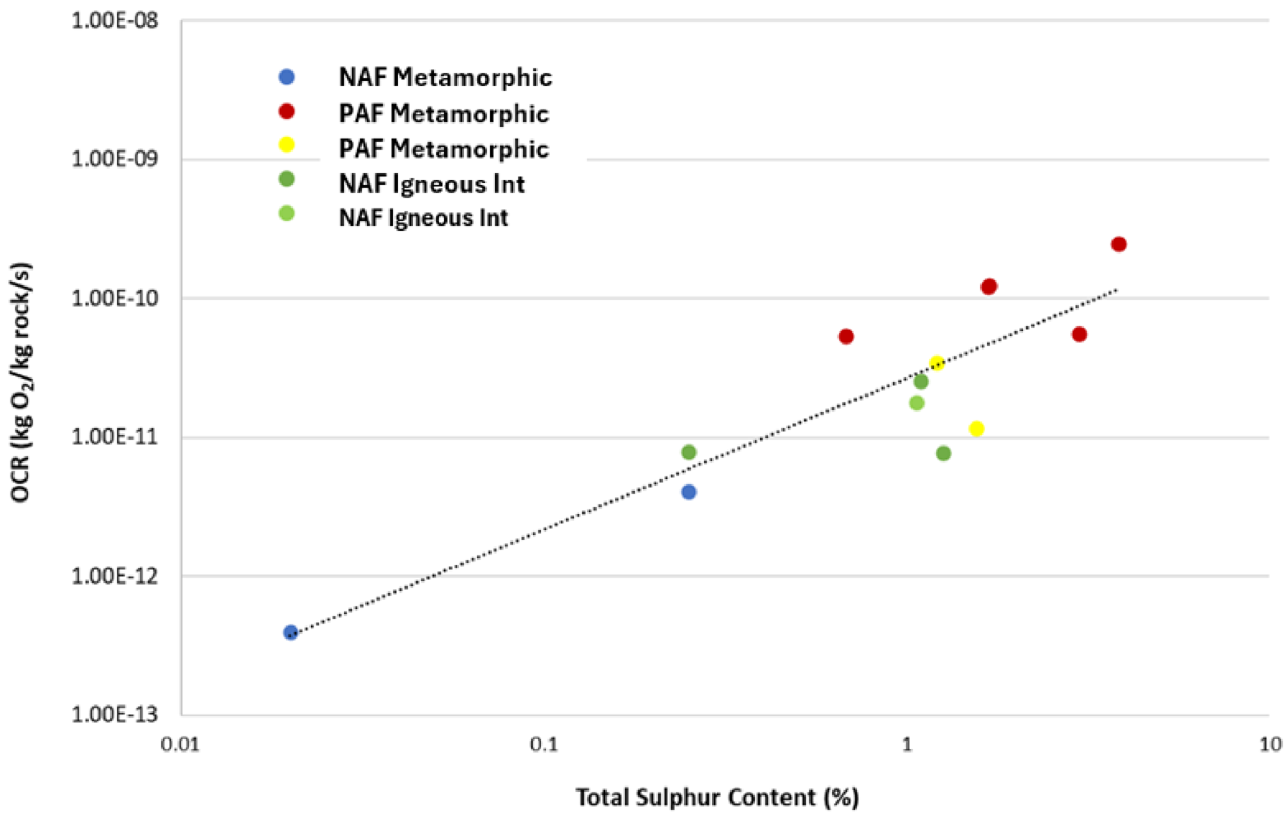


Figure 3 Calculated oxygen consumption rate versus total sulphur content for waste rock columns

3.3 Water balance and moisture modelling

Water balance modelling was conducted using SEEP/W from the GeoStudio suite of software to simulate infiltration, evapotranspiration and moisture distribution within the WRD cover. The results indicate that vegetation plays a significant role in modifying the water balance, with increased evapotranspiration reducing net infiltration and enhancing moisture retention within the upper layers. Deep infiltration is estimated to range from approximately 19% to 29% of mean annual precipitation, depending on vegetation.

Despite relatively high infiltration rates, the WRD remains largely unsaturated, with sufficient moisture retained in the pore space to significantly reduce oxygen diffusivity. The modelling confirms that moisture conditions are a key control on oxygen transport and that the presence of vegetation improves overall cover performance by reducing deep percolation and maintaining higher near-surface moisture contents.

These results were used as inputs to the multiphase modelling, ensuring that the coupled effects of water and gas transport were appropriately represented in the analysis.

3.4 Multiphase modelling of oxygen ingress

A 2-dimensional multiphase modelling approach was applied to simulate coupled water flow and oxygen transport within the WRD over a 100-year period using GeoStudio software. The model incorporated site-specific parameters obtained from a site investigation and included hydraulic conductivity, moisture retention characteristics and OCRs. Boundary conditions were defined based on climatic data and infiltration rates derived from the water balance model.

The modelling results show that oxygen concentrations decrease rapidly with depth, with sub-oxic conditions typically achieved between 5 and 15 m below the surface as shown in Figures 4 and 5. These results are consistent with field measurements and provide validation of the understanding of the processes and of the numerical model. Under median climate conditions, modelling indicated that oxygen penetration is limited to the upper portion of the NAF cover, with negligible oxygen reaching the PAF core.

Sensitivity analyses indicated that increased rainfall results in higher moisture contents and reduced oxygen diffusivity, further limiting oxygen ingress. Conversely, reduced rainfall leads to slightly deeper oxygen penetration due to drier conditions; however, even under these conservative scenarios, oxygen ingress remains within the upper 20 m of the WRD. Vegetation was found to have limited influence on deep oxygen profiles at this site, as vegetation's primary effects are confined to near-surface moisture dynamics.

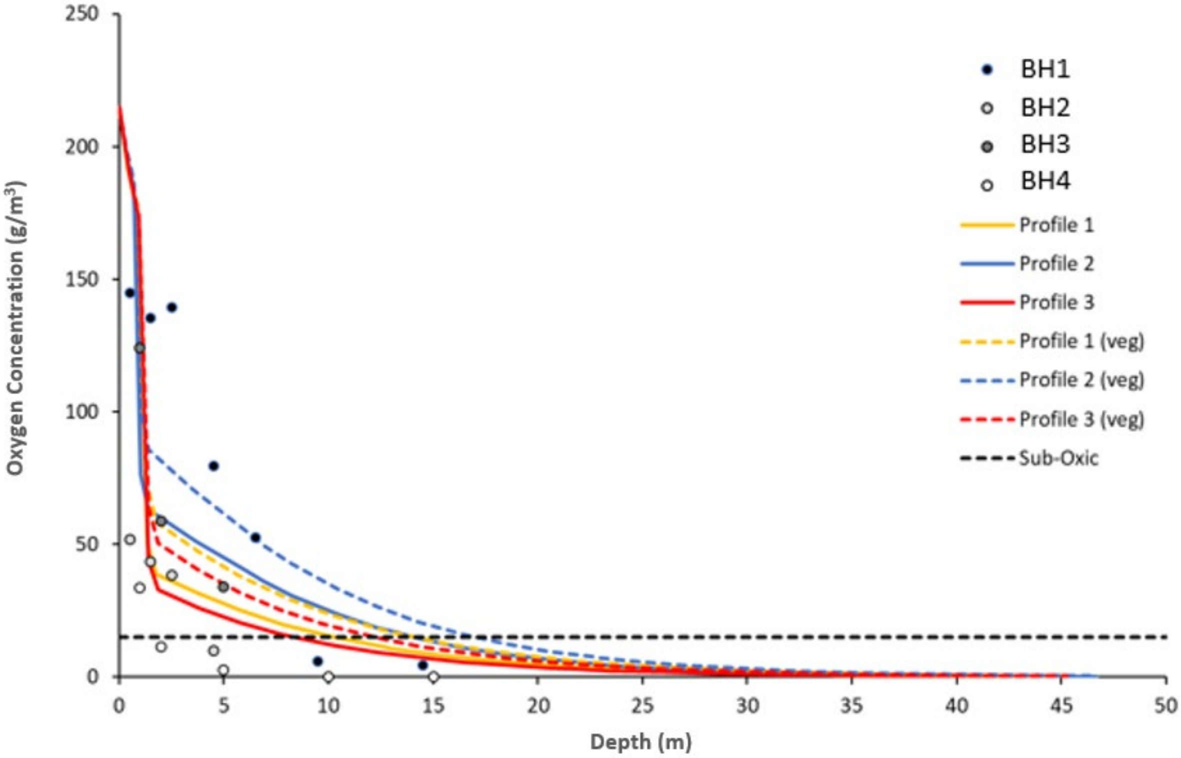


Figure 4 Modelled steady-state oxygen concentration in the waste rock dump (at profiles shown in Figure 5)

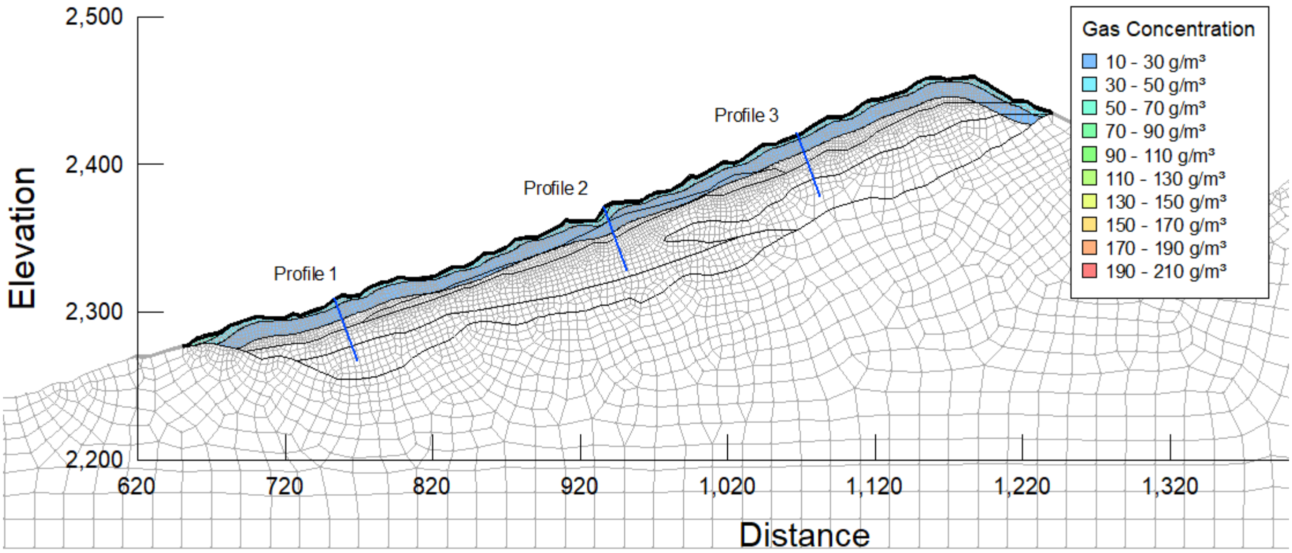


Figure 5 Modelled steady-state oxygen concentration in the waste rock dump

3.5 Encapsulation design and performance

The integration of field measurements and modelling results informed the design of the WRD encapsulation system. The selection of a 20 m-thick NAF cover is based on observed oxygen penetration depths, modelled oxygen profiles, and the need to provide a safety margin for variability in material properties and long-term landform evolution.

Field data indicate that oxygen is largely depleted within the upper 5–10 m of the WRD, while modelling suggests that oxygen penetration may extend not deeper than approximately 15 m with consideration of vegetation and typical climate conditions. The results from the field and modelling exercise support the selected cover thickness being sufficient such that oxygen would be attenuated within the NAF layer before reaching the more reactive waste placed in the PAF core of the facility.

The performance of the encapsulation system relies on several key mechanisms, including reduced diffusivity due to moisture, oxygen consumption within the NAF layer, and increased transport path length. Together, these processes limit the oxygen flux to the PAF material to levels insufficient to sustain significant sulphide oxidation. This approach follows a performance-based design philosophy, where encapsulation thickness is determined based on oxygen flux rather than prescriptive criteria.

The design also provides resilience to potential changes in climate, material properties and landform evolution, ensuring long-term stability and reduced environmental risk.

4 Conclusion

This paper demonstrates how oxygen measurement and multiphase modelling can be integrated to inform WRD encapsulation design. For a waste rock storage facility in a tropical environment mine, field measurements showed that rapid attenuation of oxygen occurred within the upper few metres of the surface of the WRD. Numerical modelling supported these observations, with simulations showing that oxygen penetration remains within the upper 20 m under a range of climatic conditions. These findings support the selection of a 20 m-thick NAF cover, which acts to limit oxygen ingress to the PAF core and reduces the risk of AMD generation.

The study highlights the value of combining monitoring and modelling to develop robust, performance-based closure designs that are resilient to uncertainty and changing conditions. This integrated approach represents best practice in mine waste management and provides a framework for improving closure outcomes at similar sites.

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