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Capturing the overburden storage area construction and post-construction period in assessing the performance of alternate source control strategies

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Abstract

Acid and metalliferous drainage (AMD) risks are related to the geochemical characteristics of the waste rock, the physical environment in which the rock is placed and the mobilisation pathways which transport oxidation products to the receiving environment. Typical overburden storage areas (OSAs) are constructed using top-down placement with end-tipping or dozer push over a high tip face, which provides high airflow capacity and subsequently a supply of oxygen to facilitate sulphide oxidation within the waste rock. Proactive rehabilitation of OSAs focuses on reducing oxygen supply and utilises lower air permeability layers to impede advective and convective oxygen transport. This limits sulphide oxidation and the generation of stored acidity, with the desired advantage of a reduced reliance on the final cover system and/or duration for which water collection and treatment may be required.

An alternative OSA construction method utilising lower air permeability layers was compared to traditional top-down construction. With the implementation of proactive rehabilitation, sulphide oxidation over the 17-year construction period was reduced by 34% to 50% of the traditional top-down placement figure. Comparatively, when considering the post-construction period, there was a more substantial reduction in sulphide oxidation, with the ongoing annual rate 76% to 93% lower than traditional top-down placement. The simulated results highlight the need to assess both the construction and post-construction period in forecasting the stored and potential load of oxidation products on AMD risk reduction.

The numerical simulation method which semi-couples the sulphide oxidation/oxygen consumption rate (OCR) to the in situ physical environment simulated within the modelled OSA (i.e. in situ temperature and pore-oxygen concentration) provided an effective OCR generally 80% lower than the input value. Over the 26-year simulation period the effective OCR reduced for the proactive rehabilitation due to the lower internal temperature and depleted oxygen, while the effective OCR increased for the traditional top-down construction in parallel with an increase in the in situ temperature and pore-oxygen concentration. The results highlight an optimised strategy for developing informative OCRs in OSA assessment.

Keywords: *overburden storage area, source control, alternative construction method, proactive rehabilitation, progressive rehabilitation, waste rock storage facility design*

1 Introduction

Progressive rehabilitation (Australasia) or progressive reclamation (the Americas) in mine closure has inadvertently become a blanket term covering a range of activities progressively implemented over the life of mine. The Australian Government Department of Industry Innovation and Science defines progressive

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rehabilitation as 'a life of mine process that produces benefits that enable post-mining land-use objectives to be achieved'. In Western Australia, progressive rehabilitation is defined as 'the staged treatment of disturbed areas during exploration, construction, development of mine operations as soon as these areas become available, rather than undertaking large-scale rehabilitation works at the completion of planned activities' (Department of Energy, Mines, Industry Regulation and Safety [DEMIRS] 2023). In British Columbia, Canada, the Ministry of Energy and Mines defines progressive reclamation as 'the process of restoring land that has been mined to a natural or economic usable state in an ongoing manner over the life of mine' (EY 2017).

Mine closure practices specific to progressive rehabilitation for managing potentially acid forming (PAF) waste rock and associated acid and metalliferous drainage (AMD) focus on progressive cover system construction and revegetation. The idea is that by progressively implementing cover systems and revegetation, water infiltration and potential oxygen ingress can be managed, thus optimising the management of AMD in overburden storage areas (OSAs). Yet it should be realised that the effectiveness of managing oxygen ingress with the partial placement of a cover system would be limited due to the landform scale dominated advective and convective airflow through the OSA.

While cover system construction and revegetation are clearly activities defined under progressive rehabilitation there is not the same board consensus for where other AMD mitigation strategies, such as source control focused on alternative OSA construction methods, would be captured. Meiers & O'Kane (2018) proposed an alternate term of 'enhanced progressive rehabilitation' to capture alternate OSA construction methods with a focus on minimising the generation of stored oxidation products, during and following construction, through the implementation of layers of lower air permeability.

In the practical sense of mine closure, progressive rehabilitation through cover system implementation focuses on managing an existing risk. The PAF waste rock has been exposed to oxidative conditions over the OSA construction period, providing a load of oxidation products that can be mobilised to the receiving environment. Alternatively, OSA construction methods implemented to reduce airflow and sulphide oxidation during and post construction are primarily focused on a future or potential risk. Hence by nature they are considered proactive mitigation measures. Given the recent advancement in mine closure planning, strategies and frameworks of implementation developed over the past decade there is also a need to expand the current rehabilitation definitions to include proactive rehabilitation. Beyond proactive rehabilitation there may be additional considerations such as adaptive rehabilitation supported by ongoing monitoring and changing site conditions, and holistic rehabilitation focused on social, ecological and economic factors.

Proactive rehabilitation with a focus on OSA material source control minimises the generation of oxidation products. This approach increases the likelihood of meeting closure objectives with a reduced reliance on the final cover system and/or alternate mitigation measures such as collection and treatment. The conceptual AMD risk reduction achieved with progressive and proactive rehabilitation is illustrated in Figure 1.

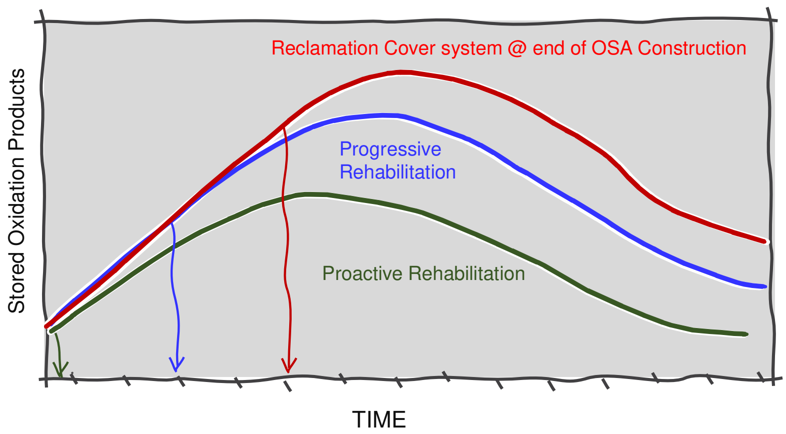

Figure 1 Illustrated acid and metalliferous drainage risk related to stored oxidation products and timing of the rehabilitation method

A key aspect in advancing and assessing alternative OSA designs is demonstrating performance through a quantitative assessment tool to enable informative operational and closure decisions. This paper provides a case study where alternative OSA designs were evaluated in a transient analysis with the predicted sulphide oxidation over the construction and post-construction period. A methodology was developed utilising Bentley software (Bentley Systems Inc 2020) and FlexPDE 7.19 (PDE Solutions Inc 2021) as a back-end solver for simulating performance. The assessment methodology was developed to include a key aspect of sulphide oxidation in that the sulphide oxidation rate is influenced by the physical environment imposed by the OSA itself. A blind case study is provided to demonstrate the risk reduction associated with an alternative construction method in limiting sulphide oxidation and heat generation.

2 Numerical simulation approach

AMD risks are known to be complex and interrelated, and strongly related to geochemical characteristics of the waste rock (Lottermoser 2010). However, the method and timing of waste rock placement and the physical environment in which it is placed have been shown to be more important in understanding AMD (Baisley & O'Kane 2017). As such, a key aspect in advancing a strategy of assessing alternative OSA designs is demonstrating performance through a quantitative assessment tool that accounts for the physical environment imposed by the OSA on sulphide oxidation. This aspect of the interrelated influence of in situ OSA temperature and pore-oxygen concentration on simulated sulphide oxidation and exothermic heat generation within an OSA was demonstrated by Meiers et al. (2022)

A methodology was developed utilising Bentley software (Bentley Systems Inc 2020) and FlexPDE 7.19 (PDE Solutions Inc 2021) as a back-end solver for simulating heat, water and air transfer as well as oxygen consumption. The software solves the partial differential equations for steady state and transient saturated-unsaturated seepage, heat, airflow and mass transport through a porous medium. The assessment included diffusive and advective oxygen transport. FlexPDE coding was implemented to couple exothermic heat generation and the sulphide oxidation rate to the simulated in situ temperature and pore-oxygen concentration, which in essence establishes a numerical simulation model that meets a key objective where the simulated in situ physical environment within the OSA influences sulphide oxidation.

2.1 Simulated sulphide oxidation

FlexPDE coding was implemented to link the OCR to in situ temperature and pore-oxygen concentration using the relationship by Jaynes et al. (1984) and the Arrhenius equation as illustrated in Figure 2. At oxygen concentrations below 1 vol.%, a linear decline curve is applied to the OCR from 1 vol.% to 0 vol.% oxygen.

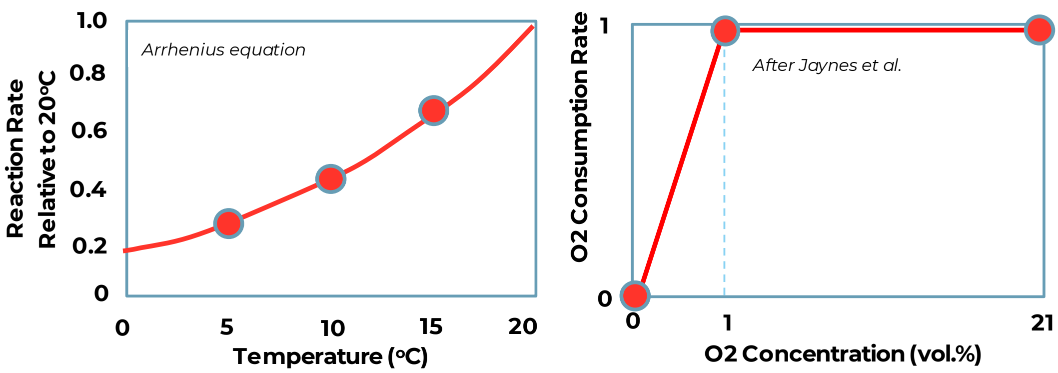

Figure 2 FlexPDE function to moderate oxygen consumption rate related to in situ temperature and pore-oxygen concentration

The thermodynamic conceptual model assumes that heat is generated due to the exothermic reaction of sulphide oxidation within the facility in the presence of oxygen and water. The heat source contributes to warming internal pore-air and results in a decrease in the pore-air density, which influences airflow.

The released heat from the sulphide oxidation is simulated as a heat source. The heat source generated in the chemical oxidation reaction is estimated according to the following equation:

Heat source (J/m^3/day) = exothermic generation rate (J/mol)/air molecular weight (kg/mol) × oxidation rate (kg/m^3/d).

The air molecular weight is 0.0288 kg/mol (Lahmira et al. 2014) and the exothermic generation rate is 400 kJ per mole of oxygen consumed.

3 Input parameters and geometry

3.1 Geometry of scenarios

Traditional OSA top-down placement and proactive rehabilitation using a celled structure of lower air permeability were assessed to demonstrate how sulphide oxidation can be limited during operations and post construction. The overall mesh geometry of the top-down and proactive rehabilitation are shown in Figures 3 and 4, respectively. The OSA has a height of approximately 210 m with a basal length of approximately 1,200 m. A 15 m-thick basal rubble zone extends over approximately 65% of the basal length. Proactive rehabilitation includes a 2 m nominally thick top cap across the horizonal surface and 15 m nominally thick end tipped layers on the outer slope creating three cells. The annual waste rock placement rate is approximately 8,000 m^3/yr over 17 years in the 2D cross-section. In the proactive rehabilitation each cell is completed over an estimated 5.5 years.

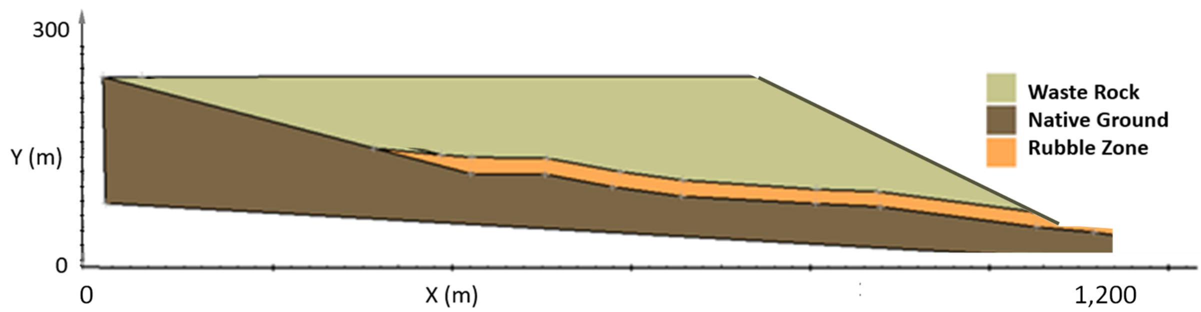

Figure 3 Traditional top-down overburden storage area geometry

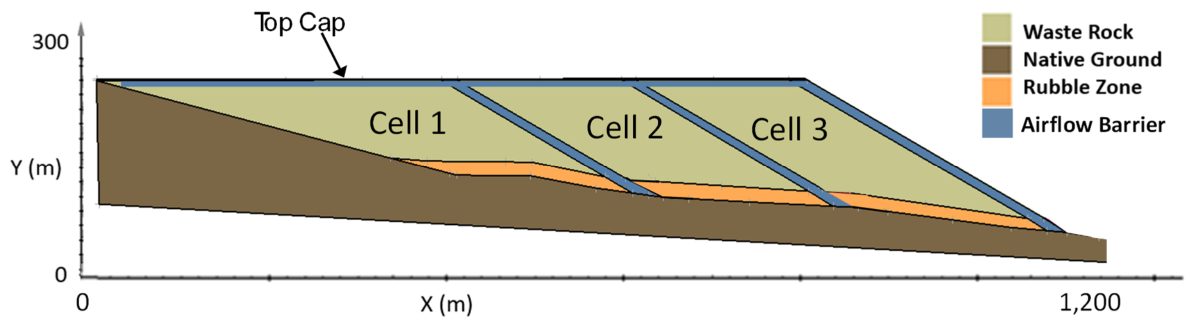

Figure 4 Proactive rehabilitation using celled construction with lower air permeability layers implemented over the construction period

3.2 Boundary conditions

Site-specific meteorological conditions were used to establish temperature and pressure boundary conditions for the simulation model. The upper boundary pressure conditions used a pore-air pressure of 0 kPa at the toe of the OSA and –2.30 kPa at the crest. Atmospheric oxygen concentration along the outer boundary is 280 g/m^3 (20.9 vol.% oxygen). A net infiltration rate of 600 mm/yr was applied as a constant seepage flux condition along the outer boundary.

3.3 Physical, hydraulic, pneumatic and thermal properties

Particle size distribution curves were used to establish hydraulic and pneumatic properties. In general, waste rock representing the bulk of the OSA volume is defined as having less than 10% silt- and clay-sized particles (fines referred to as < 0.076 mm), 5 to 35% sand-sized particles, and 60 to 95% gravel, cobbles and boulders, based on the Unified Soil Classification System. The material for constructing layers of reduced air permeability has a fines content of 20%.

The water retention curve (WRC) was developed for the waste rock using geotechnical index properties (void ratio, specific gravity and density), the SVSOILS database (Bentley Systems Inc 2020), information summarised in Fredlund et al. (2002) and engineering judgment. The hydraulic conductivity function (k-function) was developed according to the method described by Fredlund et al. (1994) using SVSOILS. The method uses the saturated hydraulic conductivity and WRC estimated through the continuous mathematical function developed by Fredlund & Xing (1994).

Air conductivity function (air-function) was developed for the waste rock using the SVSOILS database. The effect of the degree saturation on the air conductivity is evaluated using a coefficient of air relative permeability calculated using the van Genuchten (1980)–Mualem (1976) approach. The thermal properties of the waste rock were estimated based on values in the literature. Table 1 provides a summary of input parameters and Figure 5 shows the air-functions.

Table 1 Material properties used in the numerical simulation

Material property	Waste rock	Top cap	Diagonal layer
Porosity, m^3/m^3	0.3	0.35	0.35
Hydraulic conductivity, m/s	0.1	1e-4	3.5e-4
Thermal conductivity (J/day/m/°C)	60,000	60,000	60,000
Heat capacity (J/m^3/°C)	1,800,000	1,800,000	1,800,000

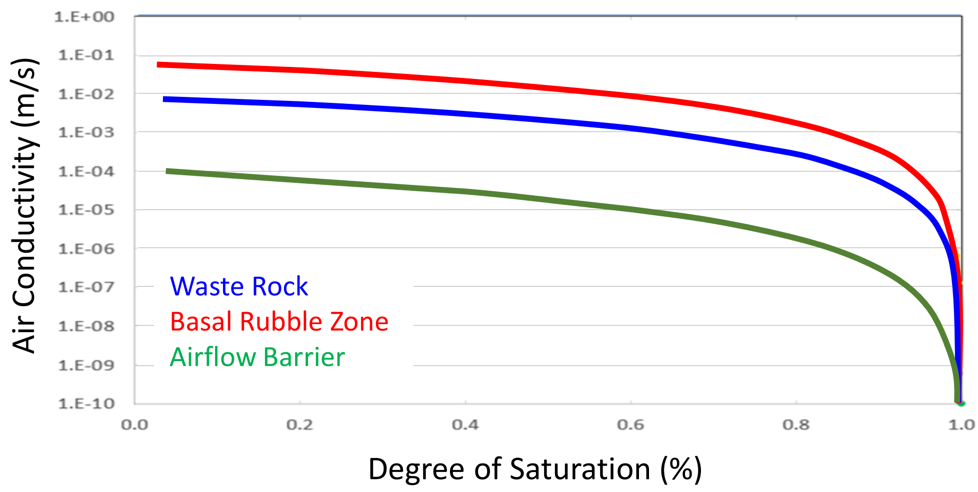

Figure 5 Air-functions used for assessing overburden storage area airflow

3.4 Oxygen consumption rate

Laboratory data pertaining to an OCR was carried out on the finer fraction of material (< 2 mm gain size). The finer fraction is considered as the reactive fraction, given the relationship between particle size and exposed particle surface area. A dry density of 1,863 kg/m^3 is used to estimate tonnage per cubic metre. A range of OCRs were developed for the waste rock and corrected for the entire grain size distribution, with a lower and upper bound of 0.25 g/m^3/day and 0.5 g/m^3/day, respectively.

4 Results

Results of the OSA assessment program are presented in the following sections.

4.1 Overburden storage area temperature and oxygen concentration profile

The simulated 2D oxygen concentration profile, using an OCR of 0.25 g/m^3/d, is shown in Figure 6 for the top-down placement and proactive rehabilitation at the end of construction (17-year period). The resupply of oxygen is sufficiently low for the proactive rehabilitation to generate waste rock with depleted pore-oxygen (i.e. 1 vol.%), primarily within Cells 1 and 2. Oxygen concentrations are higher for the simulated top-down construction, with depleted pore-oxygen limited to a small area further back from the outer slope. As a result, depleted pore-oxygen in the proactive rehabilitation will reduce sulphide oxidation and generate less heat on average compared to the traditional top-down construction.

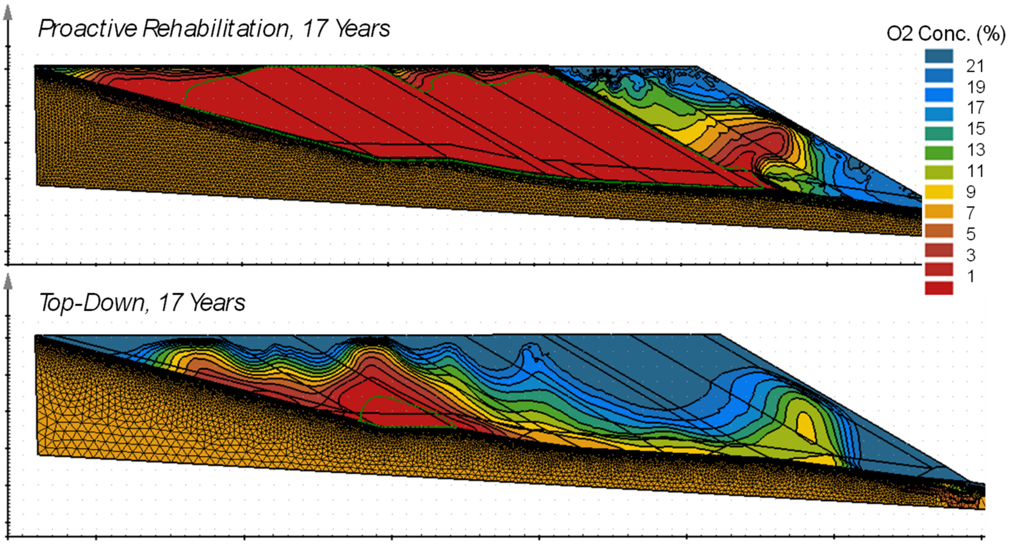

Figure 6 Simulated 2D pore-oxygen concentration using an oxygen consumption rate of 0.25 g/m^3/d

The simulated 2D temperature profile for the proactive rehabilitation is maintained at approximately 7°C over the construction period, as shown in Figure 7. In comparison, the temperature within the traditional top-down placement continues to increase given the observed higher temperature for waste rock in the back of the facility placed over a longer period. In general, the temperature is approximately 2°C higher for top-down placement.

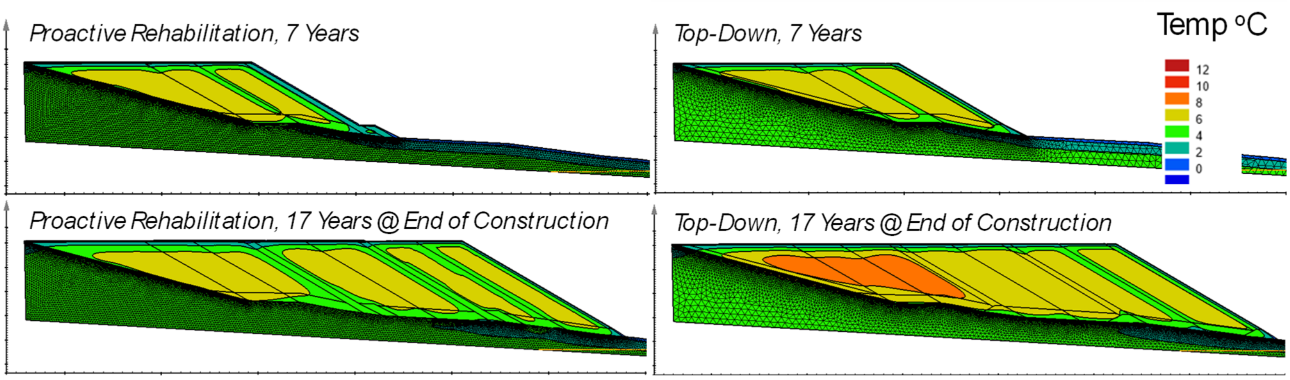

Figure 7 Simulated 2D temperature profile using an oxygen consumption rate of 0.25 g/m^3/d

4.2 Effective oxygen consumption rate

The OCR is linked to the in situ physical environment simulated in the OSA. In essence, where oxygen becomes depleted (< 1 vol.% oxygen) and in situ temperature is lower than 20°C the OCR will decrease, providing an effective OCR. The effective OCRs for the top-down placement and proactive rehabilitation using an input OCR value of 0.25 g/m^3/day are summarised in Table 2. The effective OCR was calculated from the ratio of the oxygen consumed to that of the theoretical maximum at each stage of the transient analysis.

Table 2 Effective oxygen consumption rate (OCR) for the simulation period using the 0.25 g/m^3/d

Period (years)	Waste rock (m^3)	Top-down construction		Proactive rehabilitation	
		Effective OCR	Effective OCR/OCR ratio	Effective OCR	Effective OCR/OCR ratio
2	1.5e+4	0.036	0.142	0.036	0.142
4	2.8e+4	0.035	0.142	0.035	0.142
7	4.5e+4	0.037	0.157	0.034	0.134
9	6.2e+4	0.038	0.150	0.032	0.130
12	8.2e+4	0.031	0.124	0.033	0.131
14	1.0e+5	0.034	0.134	0.029	0.092
17	1.2e+5	0.034	0.132	0.023	0.085
Construction ends					
21	NA	0.042	0.167	0.019	0.077
26	NA	0.051	0.205	0.020	0.078

The effective OCR fluctuates over the simulation period but is primarily less than 20% of the input OCR value. The simulated effective OCRs were deemed reasonable based on observed field-measured OSA temperature, pore-oxygen concentration and percentage of sulphide oxidation. Over the initial seven years of waste rock placement the effective OCR is similar for top-down and proactive rehabilitation, and in year nine the effective OCRs start to diverge. The effective OCR for top-down placement remains relatively constant over the construction period and there is a gradual decrease in the effective OCR for proactive rehabilitation. Differences in the in situ temperature and pore-oxygen concentration are illustrated in Figures 6 and 7.

In the post-construction period the effective OCR starts to increase for traditional top-down placement after remaining relatively constant over the construction period; likely due to an increase in the in situ temperature and oxygen resupply of the traditional top-down placement. Comparatively, the effective OCR for proactive rehabilitation decreases in the post-construction period. The analysis highlights the influence of the simulated in situ physical environment on the OCR over the assessment period and, in particular, the in situ heat generation.

4.3 Sulphide oxidation

The simulated cumulative oxygen consumption and associated acidity generated from sulphide oxidation for the 0.25 g/m^3/yr and 0.5 g/m^3/d OCRs are shown in Figure 8. The simulation was completed to assess the OCR over the construction period and early post-construction period.

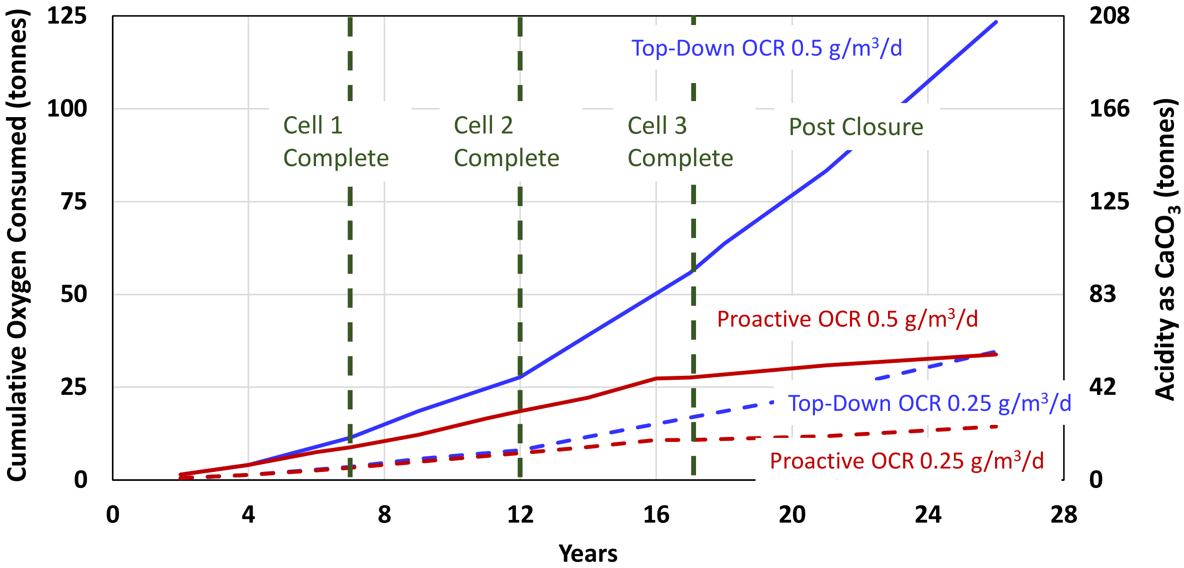

Figure 8 Simulated acidity generated over the overburden storage area assessment period

The implementation of proactive rehabilitation reduces sulphide oxidation over the construction period by approximately 50% and 33% for the input OCR values of 0.5 g/m^3/d and 0.25 g/m^3/d, respectively. The greater reduction in sulphide oxidation for an OCR of 0.5 g/m^3/d, is due to a greater proportion of waste rock with depleted pore-oxygen. The results may highlight that source control could be less effective in waste rock with a lower OCR unless a greater reduction in oxygen supply can be achieved.

Post construction (years 17 to 26) there is an increase in the ongoing rate of sulphide oxidation for traditional top-down placement due to ongoing increases in in situ temperature which increases the effective OCR and resupply of oxygen through airflow gradients. The rate of sulphide oxidation reduces in the post-closure period for the proactive rehabilitation scenarios; primarily related to the completion of the Cell 3 encapsulating all waste rock with the low air permeability layers. The ongoing rate of sulphide oxidation is 76% and 93% lower for proactive rehabilitation using an OCR of 0.25 g/m^3/d and 0.5 g/m^3/d, respectively. The analysis highlights the transient nature of the sulphide oxidation over the construction and post-construction periods and the need to access both periods for evaluating alternative OSA construction methods.

5 Conclusion

The numerical simulation method incorporates the timing of waste rock placement, internal temperature and pore-oxygen concentration on sulphide oxidation rate and heat generation. The simulation method provides an initial step in incorporating the physical environment imposed by the OSA construction method on sulphide oxidation as opposed to traditional numerical simulation assessment methods which simply assess airflow rates or the oxygen supply rate.

The OSA assessment program highlights the benefit of proactive rehabilitation in reducing AMD risk at closure. While there is a reduction in sulphide oxidation over the construction period with proactive rehabilitation, there appears to be greater benefit realised in the post-construction period. This long-term reduction in sulphide oxidation highlights the importance of considering both periods when assessing alternative OSA construction methods to forecast AMD risk. By minimising sulphide oxidation, proactive rehabilitation not only enhances closure outcomes but also offers substantial economic and environmental benefits. These findings underscore the importance of integrating proactive rehabilitation into standard mining practices.

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