Progressive Management of AMD Risk During Construction of an Integrated Waste Storage Landform – A Case Study at Martabe Gold Mine, Indonesia

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Abstract Progressive encapsulation methods to mitigate the risk of acid mine drainage (AMD) offer significant advantages (such as a higher safety factor in design) compared to the more commonly implemented "final cover" closure strategies, which are typically vulnerable to single failure modes or events. This paper provides a case study of a progressive encapsulation strategy for the mitigation of acid mine drainage risk being implemented by PT Agincourt Resources at the Martabe Gold Mine, Sumatra, Indonesia, as part of ongoing construction of an integrated waste rock and tailings storage facility (TSF). Data provided includes that collected form an installed instrumentation network.

Key words Integrated waste storage facility, oxygen ingress rates, sealing layer, progressive rehabilitation

Introduction – Progressive Management in Context

Acid mine drainage (AMD) is arguably the most significant liability that mining companies retain post closure with global AMD management costs estimated at approximately $US 1.5 billion per annum (Harries 1997). These liabilities have resulted in part due to the fact that impacts from AMD may only become apparent at later stages of mine development, and that in many cases planning decisions are made during operational periods without fully addressing the nature of the risk related to AMD with respect to long term storage of waste.

The consequence of these and other factors, such as cost, has seen the proliferation of final cover systems to manage AMD risk, rather than progressive solutions that can be implemented during waste dump construction. Best practice would suggest that AMD prevention is better than mitigation, however many of the most commonly adopted strategies such as implementation of a final cover system do not meet this test, particularly when implemented in response to emerging AMD issues later in the LOM (Pearce 2014).

Progressive management solutions such as focusing on waste placement design concepts, use of internal encapsulation layers, and/or co disposal of waste have been implemented as alternative to end-of life-solutions, however the practice is still not wide spread. Reasons for the practice not being widespread are varied and in many cases site specific, but in general progressive management solutions are typically 1) More expensive than a "containment cell", 2) Not fully compatible with the mine schedule, 3) Too complicated to build as a result of logistical constraints (such as materials availability).

This paper attempts to demonstrate how progressive management strategies can be successfully achieved during the construction of an integrated waste rock storage facility (WRSF) and TSF given an understanding of integrated mine operations and closure planning.

Martabe Mine Setting

The Martabe gold and silver mine in the Province of North Sumatra is operated by Agincourt Resources. The mine is situated approximately 3 kilometres north of the township of Batangtoru and approximately 40 km south of the port of Sibolga The mining operations include two open pits, an integrated tailings storage facility (TSF) and an active valley-fill type waste rock storage facility (WRSF) located south of the main tailings impoundment. The primary WRSF area is integrated into and being developed as the main downstream containment structure of the TSF. The WRSF will include all mine waste, including potentially acid forming (PAF) waste rock, from the open pits. There are currently two active pits, and over time additional pits are expected to be brought on line as exploration and resource development activities are progressed. The complex mineralogy of the site requires detailed waste rock modelling and scheduling as the basis for WRSF design and waste management.

Waste Rock Management and Characterisation

A detailed waste rock management plan has been developed by OKC and Agincourt Resources technical teams (mine geology, exploration, mine planning, TSF) for the Martabe mine. The plan provides technical guidance for specific aspects of waste rock management during the development and operational phases, and an overall framework for the management of waste materials during the construction of the TSF.

Agincourt Resources have developed a significant materials characterisation database through geochemical characterisation of the waste rock at the Martabe mine site. Several sources of geochemical data was available to develop the risk-based waste rock classification process flow methodology for operational use in characterising blocks of waste rock.

Waste classification and subsequent modelling into discrete class system in the reserve model and schedule have been designed to take into account the broad characteristics of the deposit and translate this into a means of identifying material based on predicted AMD risk, potential utility for use in construction (soft materials are more amenable to compaction for example), and potential acidity buffering potential (presence of carbonates such as calcite).

The waste classification system and generation of waste schedules for the site are important as materials need to be identified that can be preferentially used in the construction of the sealing layers over the LOM. Bulk waste and internal waste are identified in the model which is an important aspect of waste scheduling as during mining operations grade control drilling is carried out. This activity results in ongoing updates to the model in which internal waste may be re-classified as ore, or may be present in to small volumes to separate out.

Waste Rock Schedule

The waste placement of materials within the TSF embankment is carried out according to a design specification. A detailed mine waste schedule has been developed for the site, which is based on the waste classification system and identifies the sources of materials over LOM to ensure that the build plan can meet the design specification. It is therefore important that the mine schedule and LOM build plan reference each other to ensure the succesful management of waste requiring management as it exits the pit. Scheduling is important to be carried out over LOM because design specification indicates that construction of of sealing layers require a source of low risk (with respect to AMD) finer textured lower risk materials, and criteria for compaction is based on particle sizing.

The Progressive Encapsulation Method and Oxygen Ingress Assessment

The conceptual model for assessing AMD risk assumes that oxygen availability to PAF waste rock within the WRSF is predominately restricted to a gas transport regime dominated by diffusion rather than advection. This results from a combination of the site's high rainfall and associated infiltration rates, and the placement of fine textured waste on the embankment outer slopes during each embankment raise. This scenario of waste placement and climate is favorable to create and maintain an "engineered tension saturated layer" across the surface of the embankment which limits oxygen ingress and thus AMD production and release.

Figure 1 shows the engineering concept, with PAF material being progressively encapsulated during construction on a lift by lift basis, where lifts constructed as part of the embankment raise are 10m in height, and waste is placed in 1m thick compacted layers.

OKC completed a detailed modelling study of convective and advective airflow within the WRSF LOM design using numerical modeling tools coupled within the GeoStudio (Geo-Slope International, 2012) software suite: TEMP/W, AIR/W, and SEEP/W (Pearce 2016). Surface infiltration seepage rates were calculated using VADOSE/W. The objective of the numerical modelling program was to develop guidelines for waste placement. It was anticipated that an easy-to-measure metric (such as in-place dry density) would be required in the field to guide materials placement.

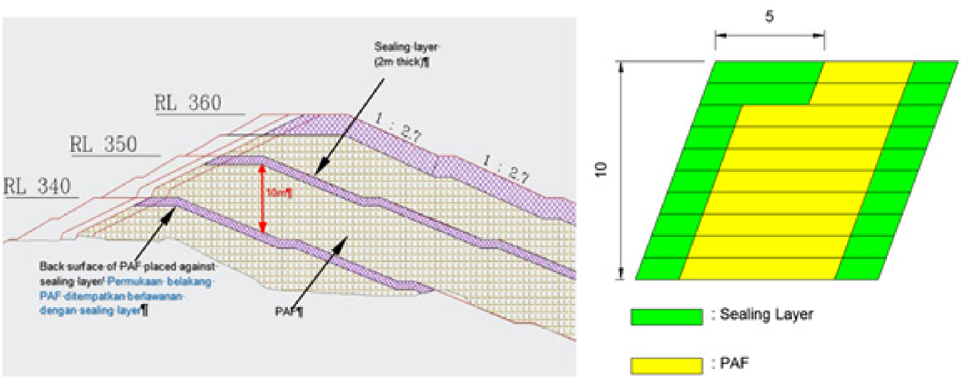

Figure 1 *PEM design used as basis for modelling assessment*

Density dependent convective airflow is a well-documented process, and has been observed in waste rock piles (Lu 2001). Convective airflow is initiated when a temperature induced density gradient exists between air within waste rock piles and ambient conditions. The presence of a convective cycle is heavily influenced by *in situ* moisture conditions, air temperature within matrix of stored waste rock (as a result of exothermic reactions like sulfide oxidation), ambient air temperature, and material characteristics such as texture and structure (Ball and Schjønning 2002). Key conclusions from the airflow modelling work were

1) Advective airflow rates are substantially lower than diffusion rates as a result of the WRSF "wetting up". As long as the material maintains sufficient saturation advection will not be a significant source of oxygen for oxidation processes.

2) Oxygen ingress due to thermal convection cells is anticipated to be low, even with elevated internal WRSF temperature and low degree of saturation conditions (worst case scenario).

3) The placement of high grade sulfide sulfur near the outlying slopes of the landform should be minimised.

4) Oxygen ingress was shown to be substantially decreased by the presence of the sealing layers. Oxygen ingress varied greatly for the material depending on the texture of the material, its water retention characteristics (determined by k_{sat}, porosity, and air entry value) and the assumed in-place dry density.

5) With increased as placed waste density a decrease in oxygen ingress results. However, the result is not simply a result of increased density. Additional compactive effort produces increased density leading to decreased porosity, increased air entry value and water retention, and a decreased k_{sat}. All of these factors lead to an increase in the degree of saturation of the encapsulation system materials and decreased oxygen ingress rates.

Waste placement engineering design

Results from the numerical modelling program were used to inform waste material placement guidelines encompassing the range of potential waste and operational cover system materials for the interior of the WRSF. Material envelopes were developed based on particle size, and included the geotechnical specifications required for the as-constructed sealing layer to reach the specific targets for oxygen ingress (Table 1).

***Table 1** Sealing layer material placement guidelines.*

Specification Envelope	% Passing #4 Sieve	% Passing #200 Sieve	Minimum Placed Dry Density (kg/m³)	Maximum permissible k_{sat} (cm/s)
1	92%	65%	1,500	$1x10^{-4}$
2	82%	50%	1,675	$7x10^{-5}$
3	72%	38%	1,775	$3x10^{-5}$
4	55%	25%	1,800	$2x10^{-5}$
5	40%	12%	1,825	$1x10^{-5}$

WRSF Concept Validation

PT Agincourt initiated a program to validate the WRSF engineering design concept in 2015, with the objective of confirming that sulfide oxidation within the WRSF embankment is being reduced due to the implementation of the sealing layer concept. Validation work to date has consisted of OKC designing and installing monitoring systems (Figure 2) within the sealing layer profile at two locations (2015 and 2016 installations) to monitor temperature gradients, oxygen concentration, pore-water pressure, volumetric water content, and matric potential. Additional installations are planned for throughout the WRSF construction to capture spatial variability in material properties and evolution. In addition to the collection of *in situ* monitoring data, detailed material sampling and testing is completed during installation and as part of regular construction QA/QC procedures to develop an understanding of geotechnical characteristics across the facility, and ensure that construction specifications are being adhered to.

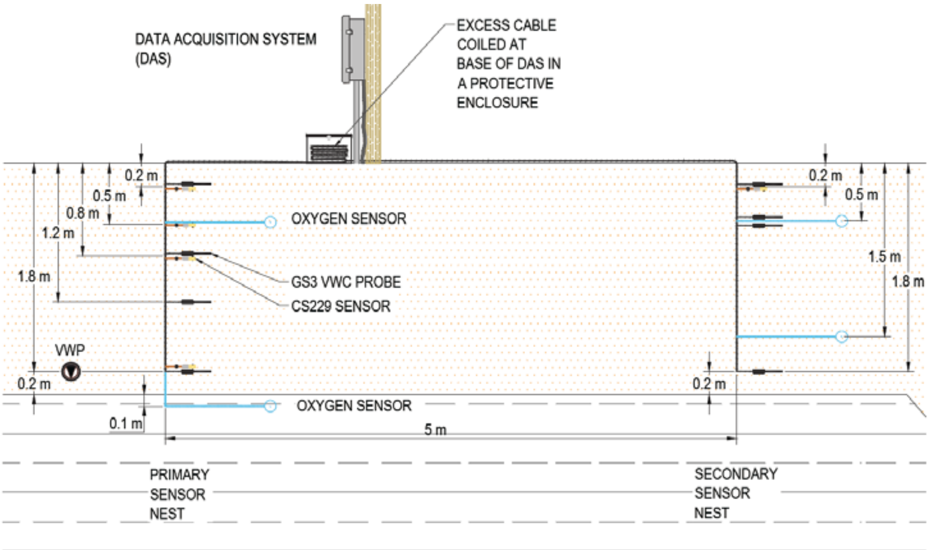

Figure 2 *Martabe WRSF sealing layer monitoring system.*

Preliminary monitoring data indicates that the the sealing layer is performing in line with the conceptual model and as per modelling predictions. Oxygen concentrations within and below the sealing layer are reduced to near zero, and VWC and suction data are indicative of material that is maintaining a high degree of saturation. Following the placement of additional lifts of material above the WRSF1 station, the observed performance is positive in that oxygen remains low, and moisture conditions are reflecting high water content.

Figure 3 shows the oxygen concentration within the WRSF sealing layer. Oxygen concentration remains at or near zero percent following initial spikes after installation at WRSF1. While oxygen at WRSF2 has slightly higher concentrations at shallow depths, below 0.5m concentrations are minimal. It is noted that material texture and geochemical composition has resulted in the different response between monitoring locations. In addition additional material was placed as a result of embankment raises over the WRSF1 location in September 2016, while WRSF2 has yet to have material placed above it.

Figure 4 shows the calculated degree saturation at the WRSF2 monitoring location. Saturation calculations are based on material geotechnical testing (porosity) and VWC from *in situ* monitoring. Calculated saturations are high in that they remain above approximately 80%.

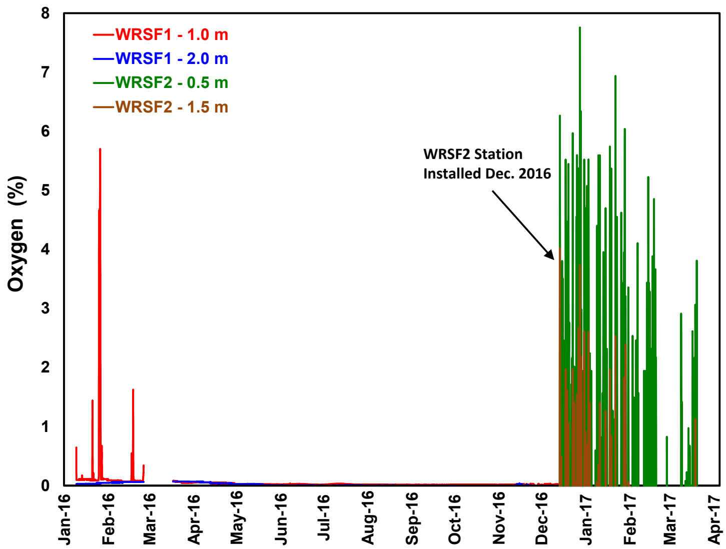

Figure 3 *Oxygen concentration within the WRSF sealing layer.*

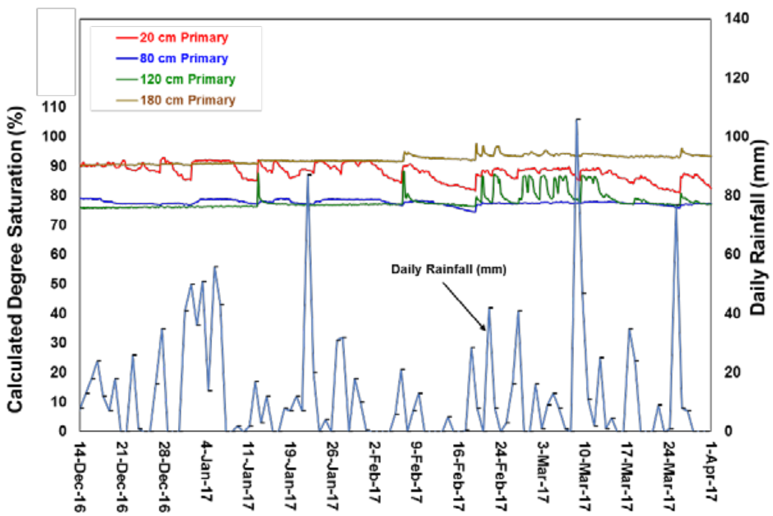

Figure 4 *Calculated degree saturation at the WRSF2 monitoring location.*

Material characteristics and monitoring data collected during the 2016 monitoring period, were utilised to develop estimates of a range of air permeability (k_{air}) for the field for the various material envelopes at the Martabe site under a range of dry density values (Fig. 5), which is an important facet in understanding the potential air permeability.

In situ dry density significantly affects the achieved field k_{air}, as illustrated in Figure 5. The estimates in k_{air} shows that material can have up to an order of magnitude decrease with increases in compaction effort.

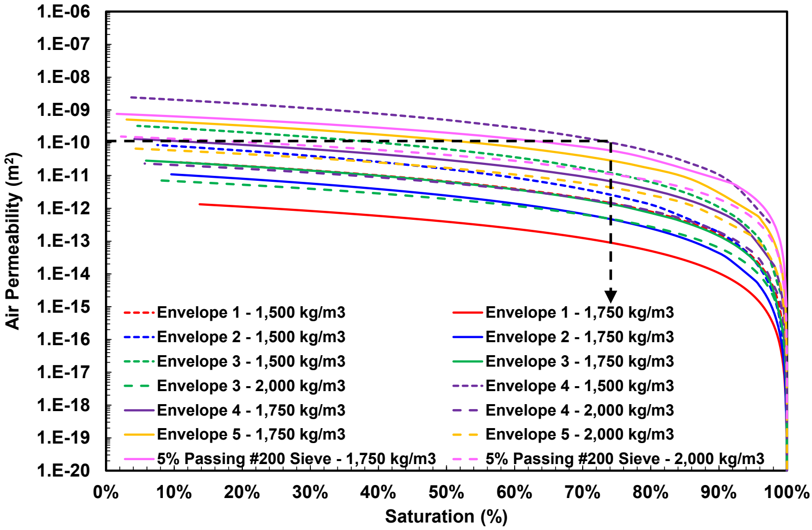

Figure 6 *Air permeability of Martabe material under various levels of compaction.*

In general, the data shows that if saturation levels are maintained above 75% this would ensure that the air permeability is lower than $1x10^{-10}$ m² (limiting the dominant oxygen ingress mechanism to diffusion) irrespective of the Envelope that the material falls into. These calculations indicate there is some inherent flexibility in the construction of the WRSF sealing layers given that if sufficient fine grained material is not available, oxygen ingress targets can still be achieved through application of increased compaction effort.

Discussion and Conclusion

The placing of sealing layers as part of a progressive closure strategy to mitigate AMD risk has been successfully implemented at the Martabe Gold Mine to date. Conditions supporting this outcome include the site's climate and, the nature of the waste rock from the pit. However successful implementation of this strategy has required detailed waste characterisation studies, complex numerical modelling to identify effective seal specifications and detailed mine planning, and control of construction to defined standards. It is notable that to date the strategy has proven to be compatible with the mine plan, logistically feasible and cost effective. The strategy has been validated to date by detailed *in situ* monitoring studies, with close alignment between modelled and measured performance.

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