Building Better Waste Landforms for Reactive Waste: A New Level of Waste Assessment and Construction

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ABSTRACT

Comprehensive waste characterisation and scheduling enables mines to design and construct waste landforms to manage acid and metalliferous drainage (AMD). Characterisation of wastes not only identifies problematic waste streams but also wastes with useful physical and geochemical properties that can be used to mitigate or neutralise AMD. However, optimising the placement of these beneficial materials whilst mirroring the mine schedule and avoiding double-handling requires planning from the outset.

Surface cover systems are often used in isolation at closure to manage water and oxygen ingress into waste rock storage facilities. Their effectiveness is generally limited by the type and availability of materials at that time, that is, there may be insufficient material, it may be degraded or otherwise lacking in its capacity to perform as wanted. Furthermore, the reliance on retro-active works may be complicated by competing demands for useful waste material and cost.

This paper outlines a holistic approach to designing and constructing mineral waste rock landforms based on a comprehensive understanding of the waste geochemical properties and schedule and integration with an appropriate landform design and cover system. The physical and geochemical properties of the waste, and interrelationships of key properties, including reactivity, hydraulic conductivity, moisture-holding capacity, erosion resistance is discussed. Consideration is given to construction and placement of wastes including tipping heights, selective placement of reactive waste, compacted intermediate low-permeability layers and surface water management.

The scope of this paper extends to the benefits of numerical modelling to provide a comprehensive understanding of materials placement and optimisation to reduce the reliance on only the final cover systems to manage net percolation and AMD generation. Specifically the ability to manage water seepage, oxygen ingress, acid generation rates and long-term surface erosion are fundamental.

Keywords: waste rock, geochemistry, landform, cover system, characterisation

INTRODUCTION

A continuing challenge to managing modern open-cast mining of deposits hosted in rocks that contain metal sulfides is the successful and "correct" disposal of reactive sulfidic and metalliferous waste rock within a landform that is geotechnical and geochemical stable, that is non-polluting and non-erodng. Waste rock containing metal sulfides when exposed to oxidising condtions will start to react and dissociate into more readily soluble and potentially deleteirous products (acidity, sulfate and metals) that may be released from their confining rock mass by meteoric waters, and are referred herein as reactive waste. Managing reactive waste rock during mining relies on a comprehensive understanding of the chemical and physical properties of the waste and an informed landform design. Only through better knowledge of materials characteristics and using this knowledge to effectively place mined waste in waste storage landform, considered in the context of the climate and environmental setting, can these objectives be reliably met. The presence of reactive waste necessitates a set of management procedures be developed to ensure effective waste rock landform design to minimise impacts of acid and metalliferous drainage (AMD). These procedures include those listed below and discussed in this paper:

- Construction of a geological model of the waste, based on the drillhole database;
- Waste chemical and physical properties characterisation using Static testing methods for waste rock, soil and subsoil;
- Block modelling of waste rock and merging with the ore resource model, to create the life of mine (LOM) waste mining schedule;
- Design and construction of waste landform for containment and management of reactive waste, including final batter design, and final cover system design, and erosion management;
- Design of water management for waste landform;
- Validating the waste model using in-pit geological mapping;
- Selective handling and placement of waste in designated areas of the waste rock landform;
- Validating placement of waste within the waste rock landform;
- Monitoring for success of placement using piezometers within the waste rock landform, and downstream of this facility;
- Regular technical reviews monthly (internal), three to six monthly (external);
- Implementing these procedures for Life of Mine.

MINE WASTE PROPERTIES

Geological model

The geological model of the potential waste associated the economic deposit is built from the exploration drillhole database of logged geological properties compiled during the exploration and resource evaluation phase. The drillhole database is the main source of geological information pertaining to the deposit and the potential waste, in the early stages of the project and will continue to be so through the life of the mine provided it is regularly updated with new data. A well-structured and comprehensive database makes it possible to define the range of waste rock types and their geological properties prior to undertaking the acid-base accounting testwork. The drill hole logging data that can be used to develop the sampling and to further classify waste include:

- Ore-waste boundaries;
- Lithology - major and minor (host rocks, cover rocks, construction material, soil, alluvium);
- Structural features - faults, shears, veins, fractures;
- Logged sulfide minerals quantity;
- Sulfide and carbonate mineralogy;
- Sulfide and carbonate texture and morphology;
- Spatial relationship of sulfides with acid consuming minerals in the host rocks;
- Depth of oxidation to include base of total oxidation (BOTO) and base of partial oxidation (BOPO);
- Depth of water table;
- Defining the transition waste areas to identify areas of partially oxidized PAF waste and flag these areas to be included in the waste model as reactive waste.

The drillhole database containing logged geological information is used to construct the 3D geological model. Using the geological model drill sections are constructed at regular grid spacing (e.g. 50 m or less for smaller deposits) through the proposed pit area and are used to derive the sampling plan. Each section has the drillhole trace and geological units plotted as well as logged data such as presence of sulfides, oxidation depths, structural data (faults and shears), ore and waste boundaries etc.

Sampling plan

All waste holes should be analysed for total sulfur, ideally at 1 m or 2 m interval widths up to a maximum interval width of 5 m and analysed for total sulfur. Total sulfur should also be analysed for each sample, waste as well as ore, collected for the exploration and resource drilling programs to build up the sulfur database for constructing the waste model.

Additionally representative samples of all lithological units related to the mine development need analysing. The sampling should cover all the areas of the mine plan, at least for the proposed Pit "Shell". This approach should aim to identify the geological units likely to provide an AMD problem, are acid neutralising, non-polluting waste, metal and sulfate saline leachate generating waste, as well as timing, destination and placement of the waste rock. The number and type of samples to be tested and evaluated is site specific and should reflect the complexity of the geology and the problem being addressed. Sampling interval widths should be a minimum of 1–2 m.

Samples of potential waste rock and ore selected in the sampling plan should be analysed for following chemical properties:

- total sulfur (LECO and portable XRF(field)) as a minimum, and ideally sulfate sulfur, and sulfide sulfur (CRS) to estimate maximum potential acidity (MPA);
- the drill holes sampled for the full pit profile (from surface to footwall to the ore) should be analysed for total sulfur as a minimum; these samples will provide the basis for construction of the waste block model;
- acid neutralising capacity (ANC); where
- net acid generation (NAG), including NAG pH;
- rinse pH, and field peroxide oxidation test;
- total and leachable metal concentrations; and
- overburden of subsoil and topsoil tested for soil nutrients, exchangeable cations, sodicity, salinity, and acidity.

Samples are typically classified as PAF (potentially acid forming), NAF (non-acid forming) based on the ABA results (Sobek *et al.*, 1978; Coastech, 1989; INAP, 2009), NAG (Miller *et al.*, 1997) and ANC:MPA or net potential ratio (NPR).

The development and understanding of physical material properties to be used within a landform construction are equally critical to its success as its chemical properties. Key physical properties to be derived and fully understood include:

- Characterizing the texture of the material, easily completed through particle size distribution (PSDs).
- Atterberg limits: important to understand the activity of a clay (potential to shrink/swell) and organic content.
- If clays are to be compacted to form a low permeability layer (CCL) it is critical that an understanding of the compaction effort, optimum moisture content and density required, through compaction testing (e.g. Standard Proctor).
- Target sampling and drilling is important to understand variation in material properties for different material types
- Erosion tests (slake durability, Emerson crumb, rill and inter-rill development);
- Moisture Retention Curves (MRCs) used to predict the soil/rocky mulch water storage, water supply to the plants (field capacity) and material aggregate stability
- Field and lab-based permeability tests (falling head, gain K_{sat}).

Assessment of waste rock properties doesn't end at the pre-mining stage but continues through the life of the mine to closure and decommissioning of the waste rock landform. The geological model and the waste block model must be regularly reviewed, reconciled and updated by in-pit mapping, sampling and testing of the in situ waste rock throughout the life of the mine. In-pit validation of waste by Mine Geologist involves:

- Checking the boundaries of the waste rock domains against exposed geology in the pit floor on the current mining bench; the pit geologist should utilise the geological information in the pit walls as well as the pit floor.
- Undertaking/supervising the waste validation sampling plan
- Checking domain classification is correct.
- Correcting the boundaries and classification, before and after blasting;
- Supervising/undertaking field testing of waste using field oxidation pH and rinse pH tests (Ahern *et al.* 2004) and sulfur by portable XRF.

A typical waste rock classification is summarised in Table 1.

WASTE BLOCK MODEL

Waste blocks commonly are larger in size (e.g. 20×20×5 m) external to the ore blocks, which may be 2.5×5.0×5.0 m in dimension. Block sizes used are governed by the geology of the ore and waste and the mining plan (Scott and Eastwood, 1998). The block model for waste is distinctively different from the sectional geological model used to identify waste types present and to design the sampling program. Block modelling for waste like ore resource modelling is used to calculate material volumes and hence tonnages. The block model calculates the volumes by defining and connecting adjacent cells with similar properties. The spatial properties of these cells are defined by x, y and z co-ordinates relative to a fixed reference point. Unlike the ore resource model, the amount of ana-

Table 1: Possible waste classes for sulfidic waste

Waste Type	Waste Class	Description
1	NAF	Non-reactive Waste comprising 100% NAF and negligible metals and is defined NAF non-metalliferous waste;
2	SD	Reactive Waste comprising rock material with excess acid neutralising capacity that will generate neutral to alkaline drainage with elevated sulfate and is defined as NAF sulfate saline (SD) waste;
3	MNAF	Reactive Waste comprising rock material with excess acid neutralising capacity and elevated metal concentration that will generate neutral to alkaline drainage with elevated sulfate and metals in leachate and is defined as mineralised NAF;
4	PAF	Reactive Waste that has limited acid neutralising capacity and elevated sulfide concentration and will generate acidic drainage with metals and sulfate and is classified as PAF waste.

lytical data concentration acquired from drilling for waste volume definition is commonly low. For some projects a large database for total sulfur has been compiled as part of the ore/waste definition and can be used to build the waste block model. For some project the deficiencies of analytical data in the waste database can be largely overcome through increasing the data density by integrating the acid base accounting (ABA) testwork with the drillhole database-derived geological model. This enables the testwork to be more effectively directed. It facilitates extrapolation of testwork data through association of test samples with like geology. It is advisable to keep the geological parameters simple, e.g. total pyrite, total carbonate, lithology, weathering, and fracture density etc. When interpolating static testwork data, it is important to use primary data such as ANC, MPA or sulfur values rather than ratios such as NPR or NAG.

Mine schedule

The waste schedule aims to identify waste units and their relative quantities to make use of their properties in different parts of the overall landform, including waste types suited for:

- NAF waste for basal layers and encapsulation of reactive waste, where exposure to oxygen, wind and water should be limited.
- Cover systems materials generally comprising inert material with properties that control the ingress of meteoric water into the landforms.
- The surface of landform embankments, comprising blockier units that resist erosion and or benign.
- Benign blocky material (rip-rap) waste for construction of drainage features, such as underdrainage, interflow drainage, drainage to intercept geological fracture flows (e.g. for in-pit or hillside landforms), diversion drains from upstream catchments, plateau catchment drains is required.
- Reduced permeability layers, typically comprising finer grained material, such as clays and oxide waste that can be suitably compacted.
- Use of natural alkalinity to neutralise acid salts: waste with excess ANC can be used in up gradient locations and in preferential flow areas to counter AMD.

- Growth medium to support vegetation, typically comprising stripped material from the landform (and pit) footprint, which generally is more suitable for revegetation.
- Layers forming capillary breaks, to limit the upward migration of salts.

WASTE LANDFORM CONSTRUCTION

Design and placement

The placement of PAF waste in the waste landform affects its reactivity by exposure to oxygen and seepage pathways. Consequently, the risk of gas production, AMD generation and the propensity for reactive material to self-heat and combust can be controlled via engineered placement.

In the waste rock landform and reactive waste and NAF are dumped separately, with the reactive waste encapsulated by the NAF waste. NAF waste is paddock dumped and then worked with a dozer to form the flattened and compacted base layer of the landform. Reactive Waste is placed in the middle each lift of the landform by paddock dumping and flattening with a dozer to reduce preferential pathways for air entry and net percolation. Finally, an outer NAF layer is constructed on each dump lift to complete the encapsulation. Compaction of materials occurs as dumping progresses, minimising infiltration of water into the dump. The tops of each lift are compacted and graded to slope away from the crest to manage runoff.

The key processes affecting pyrite oxidation are water seepage through the dump, thermal conductive heat transport and airflow through the dump mass. Numerical modelling and assessment at various mine sites has found that waste material texture and placement methodology is highly influential for both seepage rates and air flow rates (O'Kane *et al.*, 2012).

Most slopes in nature are characterized by a variety of shapes including convex and concave forms interspersed with ridges (spur ends) and swales (hollows), Carson and Kirkby (1972). Waste rock landform batter slopes should ensure geotechnical and erosional stability, aided by the coarse-texture and minimum length of slopes left at the angle of repose. Hence, low height slopes should be left at the angle of repose, and high slopes should retain the angle of repose for the upper part, retain intermediate benches or fill them, with the lower bench only pushed out to half the angle of repose (18° or 1 in 3). Reprofiled waste rock slopes should mimic natural concave slopes, which are stable geotechnically and erosionally (Ayres, 2006).

Erosion

Landform stability is related to erosion potential, and its assessment is a vital component of the landform design process. The greatest risk of failure of final rehabilitated mined landscapes is associated with gully erosion and failure of the re-established surface water drainage courses to adequately convey surface water flows McKenna and Dawson (1997). Erodibility and infiltration parameters are used to assess erosion potential for various batter slope options and overall landform shapes. Factors that should be considered include:

- selecting the least erodible materials for use in high erosion risk areas;
- modifying the erodibility of highly erodible materials, often through addition of rock or tree debris;
- batter gradient, slope length, and shape (linear, concave);
- additional inputs or design changes if required to manage risk of tunnel erosion;

- impact of increasing surface contact cover (rock, standing vegetation, tree debris etc.) and whether additional resources will be needed to stabilize batter slopes;
- impact of allowing flow from the landform top to discharge onto batters;
- impacts of concentrating flows (berms, rock drains); and
- Water infiltration and gas influx into the reactive mine wastes.

The Watershed Erosion Prevention Project (WEPP) modelling can be used to develop the indicative geometry of the variable concave landform at specific locations along the width of the landform and compares erosion along a series of transects that represent different longitudinal profiles (perpendicular to embankment contours) of a designed landform. In WEPP numerous slope configurations can be modelled and compared to develop a set of profiles that erode quite consistently along the modelled profile length. The slope configurations can then combined to form a 3D surface and modelled in SIBERIA to provide a quantitative assessment of erosion. The site survey can be interrogated using AutoCAD Civil 3D and together used to validate model predictions. The modelling is used to inform the engineering design.

Cover systems

The mine's primary strategy to manage reactive waste is to reduce the deep percolation of surface water through the waste material and thereby prevent AMD. This includes cover systems that limit advective gas transport into the waste pile and limit the flow of water (Cash *et al.*, 2014; Wilson *et al.*, 2014). Increasingly store and release covers are being provided to waste rock landforms as part of the closure design with the purpose of controlling percolation of rainfall runoff through these facilities. The focus in successful design is on the specification of the cover with respect to percolation performance and erosional stability facilitated by understanding cover material properties.

Construction of a cover system over reactive waste rock is a technique used at numerous mine sites around the world to control AMD over the long term. A cover for a waste landform located in a semi-humid or humid climate would typically include a reduced permeability layer of compacted fine-textured material (RPL) to reduce the ingress of atmospheric oxygen and net percolation of meteoric waters to the underlying waste material. A cover system with a RPL also requires an overlying layer to protect the integrity of the barrier layer and provide a medium for the growth of vegetation. This layer, referred to as the growth medium layer, also helps to reduce the percolation of meteoric waters to the underlying waste through storage and subsequent release of moisture to the atmosphere as a result of evapotranspiration. Where the site is subject to intense rain events there may be a need to install a drainage layer above the RPL and below the cover system to remove excess infiltration of meteoric water via interflow processes (O'Kane, 2012).

Over compaction of the growth medium layer, particularly in the root zone, should be avoided during construction. Soil compaction restricts root growth and reduces the available water holding capacity of the growth medium. Daniels & Amos (1981) found compaction was the major soil factor limiting long-term revegetation success at a re-claimed mine site in Virginia. Compaction between 80% and 85% of the standard Proctor maximum dry density provides many of the stabilizing benefits of soil compaction without jeopardizing the viability of vegetation development and growth (Gray, 2002).

WATER MANAGEMENT

The waste rock landforms must be able to provide drainage of surface water without significant erosion, limit net percolation of meteoric water to contained reactive waste rock and must retain sufficient moisture to support vegetation within the cover system. Options available in the landform design for managing meteoric water entering the landform catchment to minimise erosion and interaction with placed reactive waste rock include:

- Diverting clean water around the waste rock landform; limit run-on from external catchment to the landform;
- Diverting mine-affected water to holding dams for treatment prior to release or completed pits;
- Avoid shedding runoff from waste rock landform tops over slope crests which will result in erosion of the slopes; slope final and intermediate landform plateaus away from the slope crest and install crest bunding;
- Wherever possible divert runoff from waste rock landform tops to intercept natural gullies;
- Construct a cover system to handle incidental rainfall through increased storage capacity (e.g. store and release system);
- Construct cover system to handle excess water through providing drainage beneath the cover system (interflow) to reduce velocity and remove water excess to cover system capacity;
- Where reactive waste needs to be contained and managed the cover system must be designed to limit net percolation through the entire waste landform and may require a low permeability layer beneath the cover to assist in limiting net percolation;
- Avoid where possible contour banks and downslope drains as long term water management structures as they are prone to overtopping and piping; install these structures as temporary measures only (Williams *et al.*, 2012);
- Where possible avoid placement of reactive waste beneath final batter slope unless it can be adequately sealed to minimise interaction of reactive waste rock with meteoric water and discharge to receiving environment;
- Limit exposure of reactive waste to meteoric water during and post waste rock landform construction;
- Utilize compaction of intermediate waste rock landform surfaces to limit rainfall infiltration during landform construction; and
- Use cross-bunding and paddock dumping as part of the final cover system on the waste rock landform top surfaces to compartmentalise the landform catchment and contain incident rainfall, to encourage infiltration and reduce surface runoff.

MONITORING

The landform performance monitoring herein is referred to as initial (over a period of 1 – 2 years) and short-term (variable time frame) performance observation, investigation, and recording. The components of performance monitoring include erosion stability, vegetation establishment, weed and grazing control, and contaminant seepage rate from the wastes. The initial performance monitoring will provide inputs to the early remedial actions if the deficiency is identified in design and construction processes. During the short-term performance monitoring, the vegetation community develops and a range of soil processes continue to establish. As a result, landform stability should improve in response to the rehabilitated site evolution, and the contaminant leaching rate becomes stable and acceptable to the receiving environment. At the end of the short-term performance monitoring, the landform should complete the transition from "newly rehabilitated land" to "established rehabilitated land".

Monitor key processes such as:

- Net percolation
- Heat transfer
- Vadose zone gas composition
- Oxygen migration
- Salt uptake
- Soil water characteristic curves

Cover system performance monitoring involving instrumentation includes:

- Meteorology
- Actual evapotranspiration (eddy covariance)
- Surface runoff
- Net percolation (lysimeter)
- Interflow or lateral sub-surface drainage
- Soil moisture
- Temperature
- Gas flux

CONCLUSION

The understanding of unsaturated zone hydrology and geochemistry is of key importance when considering the design of landforms containing mineral waste(s). Limited knowledge of waste material properties can lead to poorly designed and constructed landforms have the potential to cause unwanted environmental impacts, such as AMD, saline drainage, erosion, along with the inability to meet closure objectives and the desired final land use(s). Good environmental outcomes over long time scales is more likely with a thorough understanding of the waste materials properties, combined with early planning and design informed by in-situ data collection.

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