

CLOSURE AND REHABILITATION – MINIMIZING THE LEGACY

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Mining, and in particular mine residue deposits (MRD's), have an unfavorable legacy of polluting the environment and are sources of potential public danger, primarily due to the absence of appropriate closure and rehabilitation management. Notwithstanding, the great strides that have been made in MRD closure over the past 20 to 30 years there still remains a need to elevate MRD closure to a higher level of awareness. The paper provides a brief insight into the enormity of MRD's that have already been produced and clean up / liability costs associated with poor mine and MRD closure. Key issues surrounding MRD closure, which are required to minimize past and potentially future legacies, are presented, namely the understanding and definition of closure objectives, adherence to the "life cycle" mine (and hence MRD) closure process, and finally aspects that need to be addressed in MRD closure design with particular emphasis on structural integrity and water ingress.

1 Introduction

A legacy of abandoned (or orphaned) mine sites around the world has harmed both the environment and the mining industry, and continue to be sources of potential public danger. One of the areas of mine closure risk, if not the largest contributor to environmental damage over the long term, are mine residue deposits (MRD's), namely tailings storage facilities, waste rock dumps, spent ore heap leach piles, and slag dumps. Typical factors that have contributed to environmental damage (and social discontent) leading to an unsavory legacy for current and future generations to confront, include poor mine closure planning, inappropriate or sub standard closure design techniques, substandard implementation, insufficient post closure monitoring, poor stakeholder consultation, inadequate funding, premature mine closure and in some cases mine owners irresponsible stance on mine closure.

The paper briefly provides insight into the staggering magnitude of MRD's that have already been produced internationally and clean up / liability costs associated with poor mine and MRD closure. Two primary issues surrounding MRD closure are presented which are required to minimize past and potentially future legacies, namely, a) the overarching principles of i) defining closure objectives and ii) adherence to the "life cycle" mine (and hence MRD) closure process and b) aspects that need to be addressed in MRD closure, with particular emphasis on structural integrity and water ingress.

2 What is the Legacy of MRD's

Given their adverse environmental and social impacts, there is surprisingly limited information or databases on the magnitude, characterisation, and resultant negative impacts of abandoned MRD's and current operational MRD's, both in South Africa and worldwide. From a few of the sources available, some points are presented which illustrate the staggering magnitude of mine residue that has and continues to be produced, and the severity (measured in liability / clean up costs) associated with poor mine and MRD closure.

- Van Zyl et al (2002) reports that it has been estimated that there are "millions" of abandoned mines around the world and that in the USA alone, it has been estimated that 50 billion tons from 557 650 abandoned sites requires appropriate closure and rehabilitation. Van Zyl et al (2002) provides data from Gardner and Sampat (1998) which indicates that on a world wide scale, the iron, copper, gold, lead and aluminum industry generated some 35 billion tons of waste rock and tailings in 1995 alone. The COM (2006) reports that in South Africa the gold industry produced some 0,74 billion tons of gold tailings from 1997 to 2006. Given these statistics, and if one considers that MRDs are

associated with nearly all mining operations, it is not unreasonable to assume that 100's of billions of tons of mine waste around the world are considered untreated and un-reclaimed (this includes both abandoned and currently operational MRD's).

- Sutton et al (2006) states that, according to Chevral (2003), MRD's footprints in South Africa covered an area of 400 km² to 500 km² which consist of some 6 billion tons of tailings containing 430 000 tons of raw low grade uranium (Winde-2004) (radon emissions) and 30 million tons of sulphur (Witkowski, 1998) (Acid Drainage (AD) issues). The questions arise; were these MRD's designed for closure, what environmental damage have they been responsible for to date, and how well have these MRD's been closed to prevent further negative long term impacts?
- Van Zyl et al (2002) provide the following cost estimates of liabilities for orphaned mines: C\$2-5 billion in Canada, US\$20 billion in the USA, DM13 billion for uranium mines in former East Germany (mainly Acid Drainage (AD) issues), US\$300 million in Sweden, and A\$ 60 million annually in Australia. Most of these liability costs are likely to be attributed directly to MRD's, as illustrated by Lersow (2006) who quotes a closure / rehabilitation cost of €6,2 billion for the Wismut uranium tailings, waste rock dumps and open pit which is to be rehabilitated over a number of years. This reinforces the fact that mining is as much about waste disposal as it is of resource extraction.

The above indicates that mining generates massive volumes of various mine residues which require appropriate closure and rehabilitation management to minimize, or preferably eliminate, long term impacts. As discussed in the following sections, this can be achieved by ensuring that appropriate and internationally adopted mine and MRD closure objectives and processes are adhered to for current operational and new MRD's, and all aspects of designing MRD's for closure are considered.

3 Mine and MRD Closure Objectives and Process

Two overarching principles promoting successful mine closure, and MRD's in particular, are the need to a) define and adhere to the aims and objectives of mine (and MRD) closure and b) implement the so called "life cycle" mine closure process.

3.1 Mine and MRD Closure Objectives

The five key objectives for mine closure planning and completion are (DITR 2006, OM 1992, INAC 2006, Robertson & Shaw 2007):

- **Health and Safety:** Protect public health and safety in the immediate and long term.
- **Environment:** Alleviate, or preferably eliminate, environmental damage (due to physical and chemical deterioration) once the mine ceases operation.
- **Land Use:** In order of preference, either a) achieve a productive use of the land (giving a greater overall community benefit) or b) return it to its original or pre-mining condition/ land use or c) an acceptable alternative, which must be beneficial and sustainable in the long term.
- **Socio economic:** Maximise socio-economic benefits as far as possible.
- **Sustainability:** To the extent achievable, provide for the sustainability of social and economic benefits resulting from mine development and operations.

Other related, and more specific closure objectives obtained from the sources mentioned above typically include the following; reduce the need for long term monitoring and maintenance; produce self sustaining ecosystems following closure; meet all local and international legal requirements for mine closure; secure release of closure bonds; there must

be no liability to the state; meet corporate objectives and criteria on mine closure; and enhance corporate image.

Most of the above objectives for mine closure are of direct or indirect application and relevance to MRD's, and can be translated into the following indicators for MRD's:

- **Physical Integrity:** Assurance of long term physical stability and erosional stability from water and wind by means of a stabilized surface cover with little need for ongoing maintenance, thereby preventing the release of mine residues to the environment and protecting public health and safety.
- **Geochemical stability:** Potential contaminants must not migrate into the receiving environment at harmful concentrations i.e. short and long term impacts on surface and groundwater quality must be minimized and contained at acceptable levels. .
- **Land Use:** The final land use / function of the surface of the MRD must be rehabilitated to pre-mining conditions, or conditions that are compatible with the surrounding environment, or other acceptable agreed land use. The MRD must blend into the surrounding environment in terms of post closure aesthetics.
- **Biological stability:** A self sustaining ecosystem is required to the MRD surface.
- **Sustainable development:** The long term burden on future generations must be eliminated, while post closure social and economic benefits arising from MRD closure, and possibly for succeeding custodians, should be maintained.

3.2 Mine and MRD Closure Process

The underpinning concepts for successful MRD (and mine) closure and completion are “Life Cycle Mine Closure Planning” and “Designing for Closure“. This is illustrated in Figure 1 (after Robertson and Shaw (2007)). Designing for closure means that the design of any MRD should be based on the closure objectives and criteria established amongst the various stakeholders before any development occurs.

As shown in Figure 1, closure planning should start well before mining commences at the conceptual / pre-feasibility stage. There is currently a call for more intensive and detailed mine closure plans to be included in all mine feasibility studies. This results in long lead times for studies which are often in conflict with the demand for rapid mine development. Figure 1 indicates that the process of mine closure (and likewise MRD closure) is a cyclical process that needs continual assessment and updating as a mine moves from concept study level through to final mine closure and post closure, which therefore takes account of the ever moving “goal posts” e.g. technology improvements, ore reserve re-assessments, updated results from ongoing field closure trials, legal updates, changes in stakeholder expectations, etc). For a more detailed description of the cyclic development of closure plans and designs at various stages of a mine's life reference should be made to Robertson and Shaw (2007). It is reported by Robertson and Shaw (1999) that mining operators are expected to expand the “Designing for Closure” philosophy and also prepare “Post Mining Sustainable Use Plans”, all with a view to not only minimizing future MRD closure legacies, but attempting to turn them into long term assets to the environment and communities.

Mine and MRD closure objectives and the process have been presented above. The next section addresses specific closure design aspects associated with MRD's that require consideration.

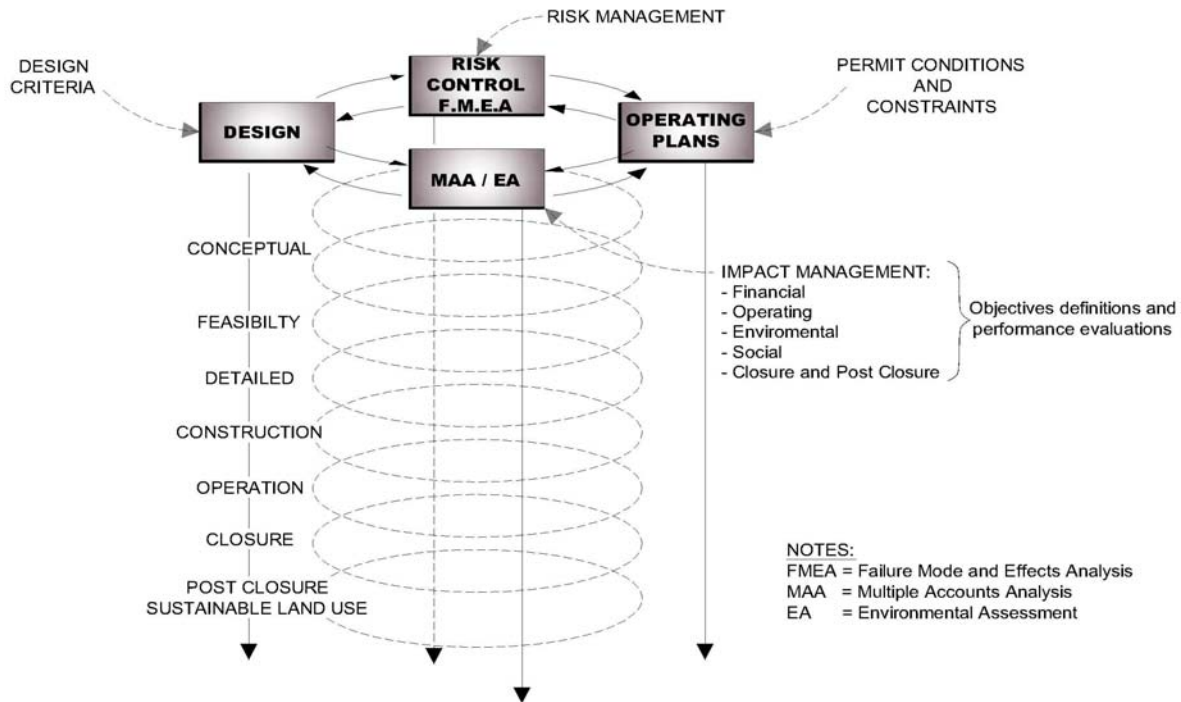


Figure 1: Cyclic Development of Closure Plans and Designs at Various Stages of a Mine's Life Cycle (Robertson and Shaw 2007)

4 Closure Design Aspects of MRD's

4.1 General Closure Design Aspects of MRD's

Designing for closure and extending this principal to developing sustainable land use plans (i.e. designing with the end in mind) requires a holistic understanding of all the aspects associated with the functional “systems” of an MRD. The various “systems” and their associated aspects that need to be considered in designing an MRD for closure, is presented in Table 1 which has been developed based on a similar approach by Caldwell (1993).

Table 1 defines the various MRD aspects that need to be considered for a) the hydrological system, b) the geotechnical / geomorphological system, c) the air–gas phase system, d) the ecological system, and finally e) the stakeholder system. It is highly likely that the design of any one or all of the various components of an MRD (e.g. cover, layout, shape, basal liner, under drains, etc) requires the interaction and consideration of a number of these aspects i.e. a holistic view has to be adopted. For example, the design of a cover may be required to limit water infiltration into the waste, prevent ingress of oxygen (typically for AD generating wastes), ensure cover side slope and erosional stability, while at the same time meeting the stakeholders expected end use e.g. a forested area or grassland.

Cross cutting issues that have an influence on some or all of the five systems are reflected at the base of the Table 1. For example, site selection revolves around preference for the site showing the lowest risk of contaminating the groundwater, yet it must be suitable from a stability perspective, minimizing the impact on neighboring communities, and must blend in with the surrounding topography from an ecological perspective. Caldwell (1993), Jabkubick (2003), and many other practitioners are of the opinion that appropriate MRD site selection is one of, if not the single most important issue regarding the minimization of long term post closure impacts, specifically to surface and groundwater regimes.

SYSTEM	HYDROLOGICAL SYSTEM		GEOTECHNICAL & GEOMORPHOLOGIC SYSTEM	AIR /GAS PHASE SYSTEM	ECOLOGICAL SYSTEM	STAKEHOLDER SYSTEM
	<i>Infiltration</i>	<i>Surface Flow</i>				
PERFORMANCE ISSUE	Flow of water into, through & out of, MRD with potential contaminants entering the receiving water body - through base and sides <i>Infiltration</i>	Flow of water off and around MRD <i>Runoff</i>	Foundation, waste/residue material, the cover, the liner (Soils, rock, geomembranes, asphalt, geopolymers, shotcrete etc.)	Transfer of air and / or other gases into or out of the MRD	Near surface top and side slope ecological system (interaction of plant, insects, microbes, soils, people, etc. on the MRD)	Sustainable post closure - benefits to the environment and stakeholders
ASPECTS	COVER (Tops,sides) WASTE / RESIDUE BASAL DRAINS LINER FOUNDATION / VADOSE ZONE GROUNDWATER REGIME	COVER (Tops, sides) SURROUNDING CATCHMENTS DIVERSIONS SURFACE WATER	STABILITY DEFORMATION CRACKING DESSICCATION CRACKING EROSION (Water, Wind) DRAINS (Covers & Basal layers) SURFACE ACCESS FOR REHABILITATION PLACEMENT TECHNIQUE	OXYGEN INFILTRATION (AD PREVENTION) RADON EMISSION GAS RELEASE HEAT GENERATION	VEGETATION- (Ecologically functional) BIO INTRUSION- PLANTS, ANIMALS, PEOPLE WATER BALANCE- EVAPOTRANSPIRATION BACTERIAL ATTACK (LINERS) LAND USE ROCK (ecologically dysfunctional) LONG TERM MAINTENANCE	STAKEHOLDER EXPECTATIONS SOCIO ECONOMIC BENEFITS CHANGE OF PROPERTY OWNERSHIP POST CLOSURE PREMATURE CLOSURE MOVING GOAL POSTS CORPORATE POLICY TRADE OFF'S
CROSS CUTTING CONTROLS AND ACTIVITIES	PLANNING AND MANAGEMENT SITE SELECTION GEOMETRIC DESIGN DISPOSAL TECHNOLOGY ADOPTED DESIGN STANDARDS/ INTERNATIONAL PRACTICE/ BATNEC / ALARA DESIGN LIFE / SERVICE LIFE of MRD COMPONENTS / EXTREME EVENTS RISK ASSESSMENT / SENSITIVITY ANALYSES LEGAL CONTROLS / REGULATIONS COSTS IMPLEMENTATION- CONSTRUCTION MODELING to FIELD TESTING / TRIALS to OPERATIONAL AND POST CLOSURE MEASUREMENTS POST CLOSURE MAINTENANCE PERIOD / MONITORING / ASSURANCE / MEETING OBJECTIVES					

Table 1: Systems and Associated Aspects for consideration in MRD Closure Design

The “system” view of an MRD is useful in that specific closure objectives can be defined for each system e.g. under the hydrological system the quality and load of contaminants leaving the groundwater compliance point(s); in the geotechnical system the acceptable factor of safety or probability of failure for a side slope and the degree of erosion and the erosional design life for a slope; in the ecological system the objectives associated with successful rehabilitation (vegetation type, cover density, number and type of invertebrates, reptiles etc.); in the stakeholder system targets for socio – economic projects.

Addressed below are a number of key principals and objectives associated with MRD stability and water ingress management both of which are key elements in achieving the goal of minimizing future legacies.

4.2 Design Life and Service Life for MRD Closure Design

In assessing long term closure (physical and chemical stability, and final land use) to minimize long term degradation, fundamental criteria need to be defined, namely the post mining /operational **design life** of the MRD and the expected **service life** of the various components (basal liners, covers, etc) in the MRD. The issue of how long the residues / wastes continue to be chemically unstable has not been considered herein.

Typical closure design life periods for MRD’s are described as follows:

- Long term stability means until the next ice age, which can be taken as any thing between 200 years and 2000 years (EC 2004)
- Long term cover performance integrity must be assured for 1000 years (MEND 5.4.2d 2001)
- Physical stability and integrity must be assured for 200 years (Robertson & Shaw 2007)
- Caldwell (1993), reporting on Uranium Mill Tailings Remedial Action (UMTRA) requirements, quotes a design life of 500 years for low level radioactive wastes, and for high level radioactive uranium tailings piles it is 1000 years to the extent reasonably achievable, and at any rate 200 years.

It can be summarized therefore that for low level in-noxious residues a design life of 100 to 200 years is not unreasonable (for structural integrity of a MRD and its cover) while the more high risk / high hazard residues (typically associated with uranium and AD residues) should be up to 1000 years as far as possible, with a guarantee period of 200 years. This may be reasonable and attainable for typical mass instability but the effects of long term perpetual forces leading to erosion pose a serious threat especially for the covers and basal liners. Alternatively, MRD closure design life span could be viewed as the “contaminating lifespan” defined as the period of time during which the MRD will produce contaminates at levels that could have unacceptable impacts if they were discharged to the environment.

In considering these long post mining MRD design life periods, the service life of the various components need review as these may not match the design life. Service lives of various MRD components are described as follows:

- Compacted Clay Liners (CCL’s) typically found in basal liners and top covers, should provide the desired design hydraulic conductivity for thousands of years provided they are designed and constructed correctly, and attention has been paid to clay leachate compatibility(ISSGE 2005).
- Geomembranes (GM’s)/ polymeric liners service lives depends on the type of membrane (PE, uPVC, etc). HDPE geomembranes are predominantly utilized and

as a primary geomembrane with leachate against it, the service life of HDPE is typically 200 years at 15°C or less, while at elevated temperatures a drop in service life can be expected e.g. at 33°C it is 70 years. For secondary or lower GM liners a service life of 400 years at temps 7°C to 10°C can be expected (ISSGE 2005, Caldwell 1993).

- Geosynthetic Clay Liners (GCL's) are affected by solution chemistry, construction installation, wet dry cycles, frost, freeze / thaw cycles and hence no specific service life can be provided. The service life should therefore be based on the limiting element of concern in the GCL i.e. if shear resistance due to the polymeric filaments is the major design characteristic then the service life should be based on polymer filament life, while if it is the filler (normally bentonite) then a service life would be similar to soils.
- Drains. The natural materials used in drains will have long service lives typical of soils while the geomembrane components are likely to have service lives as described above for GM's. However the actual service life is ultimately controlled by the propensity for micro biological clogging (ISSMGE 2005).
- Concrete has a service life of 200 to 500 years.
- Rock remains durable and soils do not change their properties for 1000 years.
- The service life of the biological system associated with surface soils / eco systems is difficult to define. Rather several seasons are required to prove sustainability, and in some cases the need to demonstrate survival through a number of droughts, excessively wet seasons, and fires is now being called for.

The above indicates the necessity to model and design a MRD and its various components (liner, cover, side slopes, etc) in a manner that although the service life of a particular component is shorter than the design life, the MRD as whole unit needs to comply with the design life and associated objectives. Typically, whereas a base liner may fail after 100 years the cover preventing infiltration into, through, and out of the base of the MRD, must last for the prescribed design life, taking into consideration the concentration and rate of flow of contaminants at the compliance point. According to Caldwell (1993) the cover is considered to be the most important component to limit long term (in excess of 200 years) seepage and structural integrity, especially for high hazard residues.

4.3 Stability and precipitation design events for MRD closure

Extreme events: Given the long closure periods for MRD's, recommended design limits and criteria need to be adopted as follows:

Stability

- Static stability: EC(2004) calls for a factor of safety (FOS) for MRD's and heaps of 1.3 during operations and 1.5 at closure.
- Dynamic (seismic) stability: For long term closure where consequences would be catastrophic use should be made of the 1:10 000 year seismic event (i.e. the Maximum Credible Earthquake (MCE). (Mylona et al 2004, Robertson and Shaw 2007) and a FOS of 1.1 adopted.
- In considering slope failure in terms of a Probability of Failure, various levels of acceptable risk are provided by Cole (1993) and ANCOLD (2000) who relate risk levels to the potential consequences of a failure impacting on people, property and the environment.

Precipitation:-

- For non critical structures the 1:100 year flood event should be adopted (Mylona et al 2004).

- For structures that could cause large, but not catastrophic impacts, the 1:1000 year flood event should be used (Mylona et al 2004).
- For those structures for which failure would result in casualties / death or cause catastrophic environmental impacts, then the probable maximum flood (PMF) should be adopted (Robertson and Shaw 2007).

Perpetual Forces

Over the long post closure design periods consideration has to be given to not only short duration sudden events (flood and seismic events) as eluded to above, but also the perpetual forces over the closure period i.e. water erosion, wind erosion, rainfall infiltration, wet/dry cycles, frost, freeze / thaw. In addition cognizance should be taken of the uncertainty in extreme precipitation and seismic events, the cumulative damage due to a series of extreme events, climate change (global warming) and geologic hazards.

Two important issues from Table 1 that are considered key in any MRD closure design is that of structural integrity and the management of water ingress into the MRD post closure.

4.4 MRD Structural Integrity

The various facets associated with the structural integrity of an MRD, as shown in Table 1, include:

Stability: Stability issues include:

- a) Side slope instability covering i) the normal mass side slope instability failure mechanisms due to gravity and seismicity, and ii) shallow or surficial sliding (low interface shear strengths typically between soils and GM's are of concern). These failure modes over a closure period will result in water ingress, gully formation, and resultant exposure of the residue and transportation into the environment.
- b) Top cover instability for sloping top covers, typically formed over high hazard wastes requiring water shedding, where a soil and/or rock layer slides (due to seismicity) on top of a geomembrane / bentonite cover. The resultant crevice acts as a conduit for gully erosion.
- c) Frost protection: Repeated freeze and thaw alters soil structure and hence a low permeability barrier such as a clay layer needs to be protected with a deep protective overlying soil cover to suit the depth of frost penetration e.g. typically 1m or more.

Deformation Cracking: Deformation cracking arises due to the effects of consolidation of the foundation and the residue. Cracks from deformation can be considered as a result of a) sharp differential settlements (shear cracks); b) concave settlements in the large settlement areas (e.g. fines area of tailings facility) resulting in tensile cracks on the underside of a clay liner (as used in multilayered covers for high hazard wastes); c) convex cracks at the outer crest areas where the residue and cover settle more than the outer earth wall as evidenced in outer perimeter earth dike / containment walls encapsulating the residue. Deformation cracking is of a major concern for covers on high hazard residues as the cracks allow increased infiltration, promote gully erosion, and increase radon emissions etc. For low hazard residues, deformation cracking still remains an issue as water ingress promotes rapid gully erosion with subsequent release of undesirable residue from the MRD with time, especially on side slopes. Finite element models are required to characterize cracking due to deformation.

Desiccation Cracking: Desiccation cracking arises in fine grained high PI soils that are subject to direct evaporation and evapotranspiration due to root penetration, both leading to water being driven out of the soil leading to high capillary suction forces with a resultant reduction in soil volume and development of shrinkage cracks. Desiccation crack depths for

exposed clays can reach up to 0,5m or more. Desiccation cracking is a major problem with CCL's which can be overcome by placing the clay barrier at depth well below the effects of evaporation and evapotranspiration and / or with the inclusion of an overlying GM. Severe droughts are a problem even with CCL's buried under a surface soil layer. It has been shown that infiltration through a cracked clay liner is increased by orders of magnitude, even after re-wetting and hence careful attention has to be paid to this issue when a specialized low infiltration clay layer is required over high hazard residues. Soil characterisation and climate extremes, in association with analytical techniques, give an indication to desiccation crack development (ISSMGE 2005).

Water Erosion: The top cover of a MRD is usually very flat and therefore there is less influence by water erosion. Sheet erosion is therefore the predominate force for near horizontal surfaces. Side slopes however, which can make up 50% of an MRD plan area (including the outer retaining or starter walls) are eroded by a) sheet erosion in the form of parallel and mass balance slope flattening processes, and b) gully erosion. Sheet or surficial erosion is determined using programs like RUSLE, CREAMS, WEPP (Willgoose 1995). However these do not model the more damaging gully erosion associated with water flowing down slopes. The use of SIBERIA (Willgoose 1995) allows gully erosion to be evaluated over long time frames e.g. 200 to 1000 years. McPhail (2006) indicates that longer and flatter concave slopes are more erosion resistant than short steep slopes, the issue being the velocity of the water flowing off a gentle slope is far less, and hence less erosive, than that from a steep short slope, notwithstanding the fact that more water flows down a shallower slope. This applies to both sheet and gully erosion. In addition flatter slopes are far easier to cover and therefore have a greater chance of success especially when closure design lives of 100 years or more are now being considered the norm for MRD's. Another area of interest is that step backs at height intervals along the side slope should be avoided, rather long flat concave slopes adopted. The motivation is that step backs will, over long periods of time (typically 50 years to 200 years), eventually silt up followed by overtopping leading to gully erosion. If step backs are required, then these need to be made very wide. McPhail (2006) reports on the need for 20m step backs with 2m high and 3m wide erosion resistant edge bunds for an erodable mine waste rock pile.

Wind Erosion: Blight (2007) reports that, in the semi arid area of the Witwatersrand; wind erosion from top surfaces of tailings dams is small in comparison to the side slopes; up to half of the annual erosion of an exposed tailings dam can be attributed to wind (which originates predominantly from side slopes); and that side slopes of 25° (1:2,1) to 30° (1:1,73) typical of most old tailings facilities in South Africa provide the highest wind erosion. There is a need therefore to flatten MRD side slopes to minimize wind erosion and /or appropriately cover a tailings side slope from start up and as part of operations as a tailings facility (or MRD) rises with time, and cover crest walls/edges immediately. The flatter slopes to reduce wind erosion i.e. less than 25° (1:2.1), are supported by the need to form flatter concave shallow slopes to minimize water erosion as eluded to above. Gartner Lee (1991) calls for side slope angles of 14° (1:4) as the "optimum maximum slope" for vegetation, while Caldwell (1993) quotes an optimal side slope angle for the outer encapsulating earth walls to hazardous uranium tailings residue of 11,3° (1:5).

Erosion control requirements conflict with the requirements to limit water ingress i.e. whereas rock and gravel surfaces are good at limiting the effects of erosion they not only allow more rapid water ingress to the MRD but because they are poor areas for vegetation development they do not allow water loss through evapotranspiration via a thick vegetation cover. In addition rock generally promotes deep rooted species which can penetrate and impair the lower clay barriers if a surface protection layer above the CCL is not present.

4.5 MRD Infiltration

As shown in Table 1, the hydrological system for closure design describes the flow of water into, through and out of the MRD, passing through the vadose layer and entering the groundwater regime. Infiltration prevention via the cover is considered to be of more importance than the basal liners and drains in terms of the long term closure design life (200-1000 years) of a MRD, as indicated previously. Accordingly, surface infiltration in association with various types of cover design is addressed in more detail below.

The objectives of any cover system (Mylona et al 2004, EC 2004, Rykaart & Caldwell 2006) are summarized as follows:

- Remain physically stable (in line with general mine closure objectives)
- Resist erosion (by wind and rainfall runoff) to prevent exposure of the residue and limit dust.
- Limit water infiltration (promote runoff and evaporation / evapotranspiration) and /or air entry, typically for high hazard wastes (AD, coal, uranium wastes) to a) render the waste chemically stable and b) control the release of contaminants from the base of the MRD.
- Provide a growth media for establishment of vegetation and support a biotic regime (ants, termites etc.)
- Endure for a defined period of time (MRD closure design life).

Covers can range from single layer covers to complex multilayered covers, but they can be categorized into three general cover types as follows: (Mylona et al 2004):

- **After use cover** (typically a one layer cover) is used to improve the surface appearance of a MRD, prevent erosion, limit contact between the tailings and surface runoff, and to provide a growth media for sustainable vegetation. This type of cover is used for inert / non toxic or non-contaminating residues, and is typical of most RSA mine residue deposits regardless of their geochemical nature.
- **Low water flux cover** is required to impede infiltration into the residue. There are three types; a) *low permeability* cover (water shedding), b) *capillary barrier* cover, and c) *evapotranspiration (ET)* cover (also referred to as *store release* cover, *water balance* cover, *soil plant* cover, and *alternative earthen final* cover (EPA 2003)).
- **Oxygen barrier cover** has the objective of impeding the transport of oxygen into the residue by either a) acting as a barrier against oxygen diffusion (water or wet cover) or b) by consumption of the oxygen at surface (organic covers). Oxygen barrier covers are typically considered for coal and AD residues.

Cover design is site specific depending on the physical and chemical characteristics of the residue, climatic conditions, material availability for cover construction, and sensitivity of the receiving environment. Most MRD's in South Africa appear to have "after use" covers, however due to the medium to high hazard potential of some mine residues e.g. pyretic bearing gold tailings, they should be designed as low water flux covers. The above three cover types can be considered as either wet covers or dry covers.

Dry covers ("after use" cover and "low water flux" covers) entail one or all of the following components from top down: a) the *surface layer* to support vegetation and provide surface erosion resistance, b) *protection layer* to prevent bio intrusion by plants, animals and humans into the underlying low permeability layers and /or acting as a moisture retention layer c) *drainage layer*, d) *hydraulic barrier layer* to limit water and or oxygen infiltration e) *reinforcing / foundation layer*. One or two, and possibly all of these layers could be present in a dry cover depending on the residue properties and the site specific conditions. It must be

recognized that differences in cover design is required between the top and side slopes of a MRD due to the stability and structural integrity issues (erosion, cracking etc) as presented previously. In addition, different slopes may need to be treated differently, as is the case with ET covers for high latitude MRD's where the evaporation and evapotranspiration is considerably different between north and south facing slopes (Weeks and Wilson 2006). This effect on the ecological system can be seen on partially vegetated slopes on some MRD's in South Africa as well. The dry covers are discussed as follows:-

- *Covers with a low permeability hydraulic layer* can be a single or composite of materials / soils, and could include geosynthetics (GCL's, GM's) as well. Historically the low permeability hydraulic layer has been a CCL but it suffers from desiccation cracking as discussed previously. CCL's normally require a hydraulic conductivity of 10^{-7} cm/sec which can increase 10 to 1000 fold due to desiccation cracking in adverse climatic conditions. This is over come by thickening the superficial layer above the CCL to typically 1m or more to protect it from drying. CCL's have been shown to be effective for thicknesses of 0,6m to 0,9m above which there is little benefit in terms of improving infiltration. Since high PI clays are highly susceptible to desiccation drying better results are achieved by using clayey silts and clayey sands (due to the lower PI). Settlements of anything between 5% to 30% (for low density saturated fine silt tailings) are possible on mine residues which can cause cracking due to differential settlement as previously discussed. For CCL's differential settlements resulting in distortion of up to 7% to 9% can be tolerated thereafter cracking can be expected (ISSMGE 2005). Geogrids or woven geotextiles under CCL's can be used to reduce the effects differential settlement.

GM's (mainly HDPE) and asphaltic liners are used in some cover designs due to their low hydraulic permeability typically 10^{-10} cm/sec. However their aging and durability (service life) requires consideration. HDPE GM's are resistant to freeze/thaw and wet/dry cycles, have superior chemical resistance to most leachates, and prevent root intrusion to an underlying low permeability barrier. However they exhibit lower diffusion characteristics (in comparison to GCL's and CCL's) due to their thinness, are prone to puncturing due to mechanical accidents, and offer low inter face shear strengths. Accordingly it has been found that composite covers of a GM overlying a CCL and/ or a GCL's provides the best results for limiting infiltration. However composite covers are very expensive and stability problems at liner - clay interfaces on slopes is a major issue.

GCL's (typically 10^{-8} cm/sec hydraulic permeability) are not affected by frost based on short term field testing, however their long term performance is still questionable in cold regions. GCL's are likely to fail in the long term unless cation exchange can be prevented. This means GCL's should not be used in covers unless they are placed directly under a geomembrane (ISSMGE 2005). GCL's are used to prevent air ingress and gas egress (via advection and diffusion) provided they are moisture conditioned correctly and when subjected to confinement. GCL self shear strength and interface friction angle with soils and other GM's are very low and requires careful appraisal with appropriate laboratory testing.

A low permeability hydraulic barrier is acceptable for relatively small MRD's, but become very expensive for large MRD's. Other solutions like ET covers, use of depyritised tailings, granulated slag, paper mill sludge's and fly ash are possible alternatives that have been considered.

- *Capillary barrier* cover comprises a layer of coarse grained material (gravel) located between the underlying residue and an overlying fine grained material. At most water contents (except saturation), the upper fine grained soil has a higher matrix suction than the coarse grained soil due to their different Soil Water Characteristic Curves (SWCC). This results in the hydraulic gradient at the fine grained soil / coarse grained soil interface normally being upward (except at saturation). In addition infiltration water into the fine grained soil is stored in the fine grained soil until the matrix suction becomes low enough to allow water entry in the coarse grained layer. The coarse grained soil also acts as a capillary break and prevents water rising from the waste due to the low capillary force (suction) in the coarse material. Water infiltration into the fine material is limited by either diverting it away horizontally in a drainage layer (humid sites) or removed by evapotranspiration (semi arid to arid sites). The addition of another coarse layer above the fine layer prevents water rising from the fine grained soil by capillarity and hence maintains a high degree of saturation in the fine grained layer as required in some cover designs.
- *The Evapotranspiration (ET) cover*, as an alternative to the CCL cover, is normally used where the annual precipitation is less than 300mm and the evaporation is high (700mm/year or more). ET cover designs are based on the water balance components at a site, namely water storage capacity of the soil, precipitation, surface runoff, evapotranspiration, and infiltration. In essence the ET cover stores infiltrating water in the root zone long enough to allow removal by evapotranspiration. It is a soil cover with an engineered vegetative cover.

Empirical and analytical methods are not suitable for the determination of infiltration into and through cover systems, rather numerical methods are required. However care is required in adopting numerical methods (e.g. HELP, UNSAT-H, Soilcover, etc) as a) the climatic conditions have to be accurately determined and applied to any model as this can make a large difference to the results and b) numerical modeling does not have the ability to handle “macro pore” structure and heterogeneous soil structure which can lead to preferential flow paths in an otherwise assumed homogeneous low permeability soil. It is therefore important to accurately characterize the soils and their behavior. For example, laboratory permeability testing results on small samples can not be given a high level of credence, rather permeability results from field pilot trials is more appropriate for modeling purposes, and even then it has been reported that full scale covers do not perform as per the field pilot trials and associated numerical modeling i.e. full scale cover infiltration is always higher than the model predictions (Wilson (2006), ISSMGE (2005), Campbell (2004)). It is considered that the integrity of soil covers due to stability issues (cracking due to deformation and desiccation, erosion etc) are the causes of increased percolation rates compared to results from numerical modeling. This highlights the need to consider any cover holistically as described in Table 1, and more specifically relate or adjust inputs into models based on potential changes in the structural integrity of the cover. As an example, Wilson (2006) has identified that there is a need to extend the moisture - suction and hydraulic conductivity - suction curves to incorporate the effects of expected cracking, fissures and macro pores for soils for modeling purposes i.e. the curves need to be extended to define increased hydraulic conductivity for very low suctions below the air entry value (AEV).

5 Conclusion

Abandoned and probably current operational MRD's, comprising 100's of billions of tons of varying types of mine residues, require appropriate closure and rehabilitation management to limit their adverse impacts on the environment and to protect public safety. The overarching

principles of “designing for closure” from the start, “life cycle mine closure planning” and meeting defined closure objectives, are some prerequisites to promote responsible MRD closure. MRD closure design requires consideration of the various aspects associated with each of the following “systems”; the hydrological system, geotechnical / geomorphological system, air/gas phase system, ecological system, and stakeholder system. A holistic approach is required to assess the interaction of the various system aspects in relation to the MRD components (cover, drains, shape etc.). Specific issues relating to MRD long term structural integrity and infiltration are one such interaction, and it has been demonstrated that these two issues can sometimes oppose one another, highlighting the need for a suitably engineered and ecologically acceptable solution, that embraces all aspects satisfactorily in the long post mining MRD design life of typically 100 years or more. It could be argued that mine residue closure in South Africa and third world countries needs to be raised to a new level in line with international approaches and standards as briefly presented herein.

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