ACID MINE DRAINAGE AND MINESITE SALINITY

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1. INTRODUCTION

Acid mine drainage (AMD) and minesite salinity are, arguably, the most serious threats posed to the environment by open cut mining and mineral processing (Australian Mining Industry Council Environmental Workshop, 1992). AMD arises when sulphur, usually in the form of iron sulphide (pyrite), contained in the ore and/or waste materials, is exposed to oxidation and the oxidation products are subsequently leached out by water as acid. As the pH of the system drops, bacteria begin to catalyse the chemical reactions. Any metals present go into solution and accompany the AMD. Open cut mining and mineral processing activities also lead to the storage of water on the surface, where evaporation raises the salinity of the water.

Acid mine drainage and salinity, along with open cut mining, waste rock dumps, and tailings dams, won't go away. The treatment of the AMD and salinity issues will, however, become part of the mainstream of open cut mining and mineral processing. AMD has been the subject of much study over recent years. This paper reviews some of this work, suggests engineered solutions to mitigate the problem, and shares some local experiences of AMD and minesite salinity.

2. ACID BASE ACCOUNTING TESTS

Acid base accounting (ABA) tests are the most common and widespread approach used for assessing the AMD potential of the wastes produced in open cut mining and mineral processing. ABA tests are static, providing an estimate of the total acid-generating potential of a material, but giving no information about the lag period before which acid would be produced, nor about the time rate of acid production. Minesite AMD prediction based on ABA is considered overly conservative (Murray, et al., 1995; in Grundon and Bell, 1995). This is because it represents a worst case. The material is usually crushed before testing, presenting fresh, unoxidised faces, and producing a higher surface area per unit volume. The tests are conducted under conditions conducive to oxidation, and, because all of the oxidation products are flushed, acid generation is maximised. In a minesite waste rock dump or tailings dam, the availability of both oxygen and water are limited to varying degrees, and the generation of AMD is reduced and/or delayed.

Various ABA procedures are in use. In North America, the neutralisation potential/acidification potential (NP/AP) procedure is most commonly used (Wildeman, et al., 1994). In Australia, the two common approaches are the net acid producing potential (NAPP) procedure (Murray, et al.; in Grundon and Bell, 1995; similar to the North American NP/AP procedure), and the net acid generation (NAG) procedure (Miller and Jeffrey, 1995; in Grundon and Bell, 1995).

2.1 NA/AP PROCEDURE AND INTERPRETATION

The NP is the balance between the rate of acid production from iron sulphide and the rate of acid consumption by the dissolution of any calcium carbonate present. It is determined by titration to a known pH, and is expressed as kg of CaCO₃ needed to neutralise a t of material. The reaction of iron sulphide (pyrite) with oxygen and water releases 1 mole of sulphate and 2 moles of acid. The AP, based on sulphur fractionation and pyrite oxidation stoichiometry, is given by

\[ AP = \text{total sulphur} \times 31.25 \]

expressed as kg of CaCO₃ per t of material. This determination of AP assumes that all forms of sulphur present in the material will oxidise (not all will), and that all ferrous ions will oxidise to ferric ions. The result therefore overestimates the potential of the material to generate acid, even under favourable acid-generating conditions. The NP/AP is interpreted as follows:
NP/AP - 1 implies that acid generation is likely. NP/AP = 1 to 2 implies that acid generation is possible (particularly in high rainfall areas). NP/AP > 2 or 3 implies that the material is non-acid-generating (there is some argument about whether 2 or 3 should be the limiting value).

2.2 NAPP Procedure and Interpretation

The net acid producing potential (NAPP) is given by:

\[ \text{NAPP} = \text{MPA} - \text{ANC} \quad (2) \]

expressed as kg of CaCO₃ per t of material. The maximum potential acidity (MPA) is given by:

\[ \text{MPA} = \text{total sulphur} \times 30.6 \quad (3) \]

The acid neutralisation capacity (ANC) is determined by titration with NaOH to a pH of 7.

The NAPP is suitable as a screening test for AMD (Miller and Jeffrey, 1995; in Grundon and Bell, 1995, and is interpreted as follows:

NAPP ≥ 0, i.e. NAPP positive, implies that there is a potential for AMD,
NAPP ≤ 0 i.e. NAPP negative, implies that AMD is unlikely.

2.3 NAG Procedure and Interpretation

The net acid generation (NAG) test involves oxidation of the material with hydrogen peroxide, the acidic conditions also releasing any CaCO₃ present. Hydrogen peroxide is a very strong oxidant, so the NAG test is extreme. It is capable of releasing organic acids from coal wastes, which are not be released under field conditions (Clarke and Jenkin, 1995), and is therefore more of a worst case for these materials than the NAPP approach. The NAG test is interpreted as follows.

NAG pH ≥ 4 implies that the material is non-acid-generating.
NAG pH < 4 implies that the material is acid-generating; with either low (treatable) or high capacity, depending on the amount of acid produced.
The NAG test has the potential to provide indicative lag periods for the commencement of acid generation (Miller and Jeffrey, 1995; in Grundon and Bell, 1995).

3. Kinetic Tests

Kinetic tests, of which column leachate tests are the most common, are an attempt to simulate the oxidation and flushing of potentially acid-generating wastes from open cut mining and mineral processing (Wildeman, et al., 1994). Their aim is to estimate the lag period before which acid would be produced, and the time rate of acid production. However, the test apparatus and procedure are not standardised, and the procedure used often bears little resemblance to field conditions. Kinetic tests have not yet been satisfactorily related to field observations, and cannot yet be applied to the field with any reliability.

4. Waste Rock Dumps and AMD

Waste rock dumps, formed from the overburden removed during open cut mining, are essentially free-draining, typically having a gravimetric moisture content in the range 5 to 10% (Ritchie, 1995; in Grundon and Bell, 1995). They are formed by loose dumping over a slope, at the angle of repose of the waste rock (35 to 40 degrees to the horizontal). The ravelling of waste rock down the slope leads to the formation of alternating angle of repose layers of fine and coarse particles (Wilson, 1995; in Grundon and Bell, 1995), with layers typically 0.3 to 0.6 m thick. The waste rock on the slope surface is not representative of the dump as a whole, being typically coarser grained. Subsequent erosion of the surface will
remove fines, retaining the coarse-grained appearance of the surface. The coarse layers provide pathways for oxygen ingress into the dump, and oxidation fronts move into potentially acid-generating fine layers on either side of a coarse layer. The fine layers make available for oxidation a far larger specific surface. Under dry conditions, water is stored in the fine layers. Under wet conditions, oxidation products will be flushed from the waste rock dump, leading to AMD.

To inhibit the formation of AMD from a potentially acid-generating waste rock dump, a cover is required to minimise the entry of oxygen and infiltration of rainfall into the dump. Oxygen entry can occur by diffusion from the top of the dump or by convection through the sides of the dump, and can be minimised by one or more of the following means:

- A low diffusivity (air permeability) cover, which should be fine grained and maintained in a saturated state.
- A geomembrane cover. However, this may be prohibitively expensive, and is of doubtful longevity.
- Flooding. Since most waste rock dumps are necessarily above ground, flooding is usually not an option. However, it may be an option where waste rock is dumped into a dis-used open cut.

The infiltration of rainfall into the dump can be minimised by one or more of the following means.

- A low (water) permeability cover, which should be fine grained and compacted, but not necessarily saturated.
- A geomembrane cover.
- Selective placement of the waste rock, to encapsulate the material having an acid-generating potential with non-acid-generating material.

Common features emerge from a comparison of the means by which oxygen entry and rainfall infiltration can be minimised. The waste rock should be selectively placed in the dump to encapsulate any acid-generating material. If this can be done effectively, the side slopes of the waste rock dump may not require a cover. Durable, non-acid-generating waste rock on the side slopes of the dump could be left at the angle of repose. A fine grained, compacted layer is recommended to seal the top of the dump to minimise oxygen and water entry. To maintain the seal in a saturated state and guard against erosion, it should be protected by a loose mulch layer on top. However, this will increase infiltration. A coarse grained capillary break layer below the seal may also be desirable, to prevent any capillary rise of AMD. Covers currently being used in Australia (Grundon and Bell, 1995) typically comprise 0.3 to 2.0 m of compacted clay or weathered (oxide) rock, overlain by a loose mulch layer/growing medium 0.3 to 1.5 m thick. The top surface is generally grassed, since tree roots may penetrate the seal (although roots tend to spread laterally). However, in the longer term, there is nothing to stop trees from propagating naturally.

A cover incorporating a compacted clay seal reduces both oxygen entry and rainfall infiltration typically by 10- to 100-fold. The rate of seepage from the waste rock dump will be reduced by a similar multiple, while the concentration of contaminants in the seepage will be little changed. Waste rock dump covers cost from about $10,000 to $55,000/ha; the lower end of the range applies where covering is integrated into the dumping operation, making use of available waste materials, and the upper end of the range applies to retro-fitting of a cover.

5. Tailings and AMD

Fine grained wastes, or tailings, are produced in the processing of most ores. They are produced as a very aqueous slurry, which is thickened prior to disposal in a tailings storage. Tailings are typically silt-sized (mostly in the size range 0.002 to 0.06 mm). As a result, they have low permeability and drain very slowly. Thickened tailings are conventionally pumped to a surface containment or dis-used open cut, where they are usually depos-
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It is sub-aerially. On deposition, they undergo beaching, particle sorting, sedimentation, self-weight consolidation, and desiccation crusting. The tailings remain essentially saturated, apart from 200 to 400 mm below the surface (Williams, et al., 1989), in which oxidation and leaching may take place. However, most tailings are initially highly alkaline due to the presence of process chemicals, which helps to neutralise any acid generated, and their low permeability limits the potential for seepage of any AMD to the ground. The main AMD risk from tailings may be through the contamination of surface runoff.

Where a tailings cover is required for AMD control, it should comprise a capillary break, a compacted clay seal, and a protective mulch layer/growing medium. Such a cover costs in the range from $40,000 to $80,000/ha, depending on the strength of the tailings and the availability of suitable cover materials. Alternatively, it may be possible (and possibly far cheaper), depending on the elevation of the tailings deposit and the climatic conditions, to permanently flood the tailings to control AMD. This is practised in Ontario and Quebec, Canada. At Louvicourt Metal Mine in Quebec, the tailings are disposed of below water in a man-made water storage which will be maintained flooded. In Australia, permanent flooding may be possible only in the wet tropics and the temperate southeast, but is yet to be adopted.

6. TREATMENT OF AMD

The well-established steps involved in treating acidic mine drainage laden with dissolved metals are as follows:

1. Add lime (or, in extreme cases, caustic soda) to the water to raise its pH to a level sufficiently high (in the range from 8 to 11) to precipitate any dissolved metals present.

2. Provide sufficient residence time in a pond to allow the metal precipitates and unspent lime to settle.

3. Add carbon dioxide, if necessary, to lower the pH to a level acceptable for release to the environment (about 6 to 9).

There are a number of problems with lime treatment. Lime becomes coated, and is, at best, only 10% efficient, due to it becoming coated (Jones, 1995; in Grundon and Bell, 1995). The unspent lime and precipitates form enormous quantities of sludge, which remains at only a few % solids creating disposal problems. A high density thickener can be used to recycle the sludge (and added chemicals), discharging the overflow to a settling pond for release. The underflow is discharged only when the % solids exceeds about 20%. The residual flocculants in the thickened sludge lead to further settling.

Wetlands can be successful in raising the pH of mildly acidic mine drainage (pH > 4), and in precipitating sufficient amounts of metals from water with moderate total dissolved salt (TDS) levels, up to several thousand ppm (Jones, 1995; in Grundon and Bell, 1995). However, wetlands are not simple systems, and are not yet fully understood. It should be noted that plants do not remove metals from the water, but may take up metal precipitates from the soil in the wetland. Wetlands can also be used for polishing water after conventional lime treatment.

7. SALINITY AND pH

The salinity limit for drinking water for humans is generally taken to be about 1,000 mg/l. TDS levels above 2,000 mg/l begin to affect salt-sensitive plants, and cattle can tolerate TDS levels of at least 5,000 mg/l. Sea water has a TDS level of about 35,000 mg/l, and groundwater in Kalgoorlie, Australia, has a natural TDS level of between 200,000 mg/l and 300,000 mg/l.

Some pH and TDS ranges measured by the author during September 1994 (towards the end of the dry season) in the Bowen Basin Coalfields, in Central Queensland, Australia, are given in Table 1. The TDS ranges reflect
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Table 1: Some pH and TDS ranges for Bowen Basin Coalfields

<table>
<thead>
<tr>
<th>LOCATION</th>
<th>pH RANGE</th>
<th>TDS RANGE (mg/l)</th>
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<tbody>
<tr>
<td>Pit water</td>
<td>4.2 to 8.5</td>
<td>2,700 to 5,800</td>
</tr>
<tr>
<td>Evaporation pond water</td>
<td>2.5 to 8.7</td>
<td>2,100 to 16,200</td>
</tr>
<tr>
<td>Environmental pond water</td>
<td>8.0 to 8.6</td>
<td>1,800 to 4,100</td>
</tr>
<tr>
<td>Spoil seepage</td>
<td>3.9 to 6.9</td>
<td>4,800 to 8,000</td>
</tr>
<tr>
<td>Coarse reject seepage</td>
<td>2.4 to 8.7</td>
<td>1,900 to 10,300</td>
</tr>
<tr>
<td>Tailings pond water</td>
<td>6.9 to 8.6</td>
<td>1,200 to 4,400</td>
</tr>
<tr>
<td>Tailings seepage</td>
<td>2.4 to 8.6</td>
<td>1,900 to 7,000</td>
</tr>
</tbody>
</table>

The lower pH limits and higher TDS limits given in Table 1 tend to occur together at particular mines in the Bowen Basin Coalfields which generate some AMD. These mines have materials relatively high in sulphur (>0.5%) and/or low in calcium carbonate. Relatively high sulphur contents are associated with the deposition of coal-forming peat in a marine environment. Other mines in the Bowen Basin Coalfields display neutral or alkaline pH levels and relatively low TDS levels. These mines do not generate AMD, because the materials present have a low sulphur content (<0.5%) and/or a high calcium carbonate content.

There is a common misconception that open cut mining and mineral processing produces salinity. However, waste disposal from open cut mining initially inverts the natural profile, burying the higher salinity surficial soils. Over time, rainfall infiltration, capillary rise, and surface evaporation lead to a rise in the salinity of the new surficial soils of the post-mining profile. Investigations at Jeebropilly Colliery in the Ipswich Coalfields in southeastern Queensland, compared the near-surface profiles of undisturbed ground, 1 year old spoil, 5 year old spoil and 10 year old spoil (Lodge and Williams, 1993). The 1 year old spoil was found to be much drier than the undisturbed ground and older spoil. The pH of the undisturbed ground (at about neutral) was lower than that of the spoil, particularly near the surface, but the spoil pH reduced slowly with age. It is estimated that it would take about 20 years for the spoil pH to fully recover to the undisturbed value. The undisturbed profile showed a salt bulge at 1.5 m depth. The 10 year old spoil showed a salt bulge developing at 2 m depth and similar salinity to the undisturbed ground, but the younger spoil had about half this level of salinity.

Minesite salinity results from the evaporation of surface water or moisture, and TDS levels measured in surface water will reflect the rainfall/evaporation balance at the time. To minimise minesite salinity the following steps should be taken:

1. Minimise the surface (evaporative) area of stored water.
2. Discharge surplus water (such as during storm events), if possible. Discharge quality requirements are often more stringent than ambient conditions and, if so, should be challenged.
3. Vegetate where possible.
8. CONCLUDING COMMENTS

Acid mine drainage and salinity are now sufficiently well understood issues for them to be incorporated into mine feasibility and operational planning. There are engineering techniques available to reduce AMD and salinity to manageable levels, reducing potential long-term liabilities.

9. REFERENCES


