MINE TAILINGS RECLAMATION IN AUSTRALIA - AN OVERVIEW[1]

by

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Abstract. The paper briefly reviews legislative requirements for rehabilitation of mine tailings in Australia before consideration of case studies of rehabilitation in bauxite, base metal, gold and uranium mining operations. For particular mineral industries, comparisons are made of the limitations and approaches to tailings rehabilitation in markedly different geographic regions.

Introduction

Mining and mineral processing makes a major contribution to the Australian economy and, in 1987/88, exports of minerals and primary mineral products were valued at A$17,819 million representing 44% of the country's merchandise exports. Most of this production was derived from the 264 mines extracting metallic materials (primarily bauxite, gold, iron ore, copper, lead, zinc, nickel and uranium ores) and the 121 mines producing coal. The distribution of the major mining and mineral processing operations in Australia is shown in Fig. 1.

Most of the mines producing metallic minerals and their associated mineral processing plants produce tailings which must be contained to prevent on-site and off-site pollution during the mine life and which must be subsequently rehabilitated such that the disposal site has long term stability against the erosive forces of wind and water. Tailings dams are also a common feature of the coal mining industry. The fine particle size coal tailings have the potential to be retreated to produce a marketable product, and thus few dams have been rehabilitated with a vegetative cover to a condition where they could be abandoned.

The objective of this paper is to briefly review the rehabilitation of tailings resulting from mining and mineral processing in Australia. Some general comments about the legislative requirements for rehabilitation will be made prior to a discussion of some case examples for a number of the major mining industries where tailings rehabilitation is a major concern (bauxite, base metals, gold and uranium).

Legislative Requirements

Most of the specific legislation related to environmental matters including tailings containment and rehabilitation in Australia has been produced by the individual State Governments as a result of the division of powers under the Australian Constitution. The Commonwealth Government does have the opportunity to ensure that mining proposals are environmentally sound, however, through the Environment Protection (Impact of Proposals) Act of 1974 which requires that an environmental impact statement be prepared for projects proposed by or on behalf of the Commonwealth. Where export of minerals is involved, the Commonwealth Government has the power to prevent export where the environmental impact of the proposed operation is adverse. In addition to this non-specific power, the Commonwealth

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Government does have the power to legislate with respect to specific details of environmental control of mining for territories such as the Australian Capital Territory, the Australian Antartic Territory and, to a lesser extent, the Northern Territory (uranium) (Australian Environmental Council 1984).

At a State level, the legislative requirements with respect to air and water quality around tailings dam during filling, and to rehabilitation requirements once the dam is full, vary considerably from State to State. Even for a given State, the stringency of requirement may vary depending on the age of the mining operation; some old mines operate with requirements to protect the air and water quality of the mine surrounds but have no requirement for rehabilitation of tailings dams. Most new mines have legislative requirements covering rehabilitation and may involve specific reference to covering of the tailings with soil and establishment of a self-sustaining vegetative cover.

Bauxite Residue Tailings

In Australia, bauxite is mined in the northern tropics at Weipa (Comalco Aluminium Ltd.) and Gove (Nabalco Pty. Ltd.). In the temperate south-west, bauxite is mined at Jarrahdale, Huntly, Del Park and Willowdale (Alcoa of Australia Ltd.) and Mt. Saddleback (Worsley Alumina Pty. Ltd.). The bauxite mined at Weipa is beneficiated and then shipped to Gladstone on the central Queensland coast for refining (Fig. 1). There is a refinery at Gove, while in the south-west, Alcoa of Australia has refineries at Kwinana, Pinjarra and Wagerup, and Worsley Alumina has a refinery at Worsley near Collie. These six refineries produce 36% of the western world's alumina. Comalco Aluminium Ltd. operated a refinery at Bell Bay in Tasmania between 1956 and 1972.

All these refineries use the Bayer process and generate significant quantities of alkaline residue (2.7 mt/a of residue from the two northern refineries and around

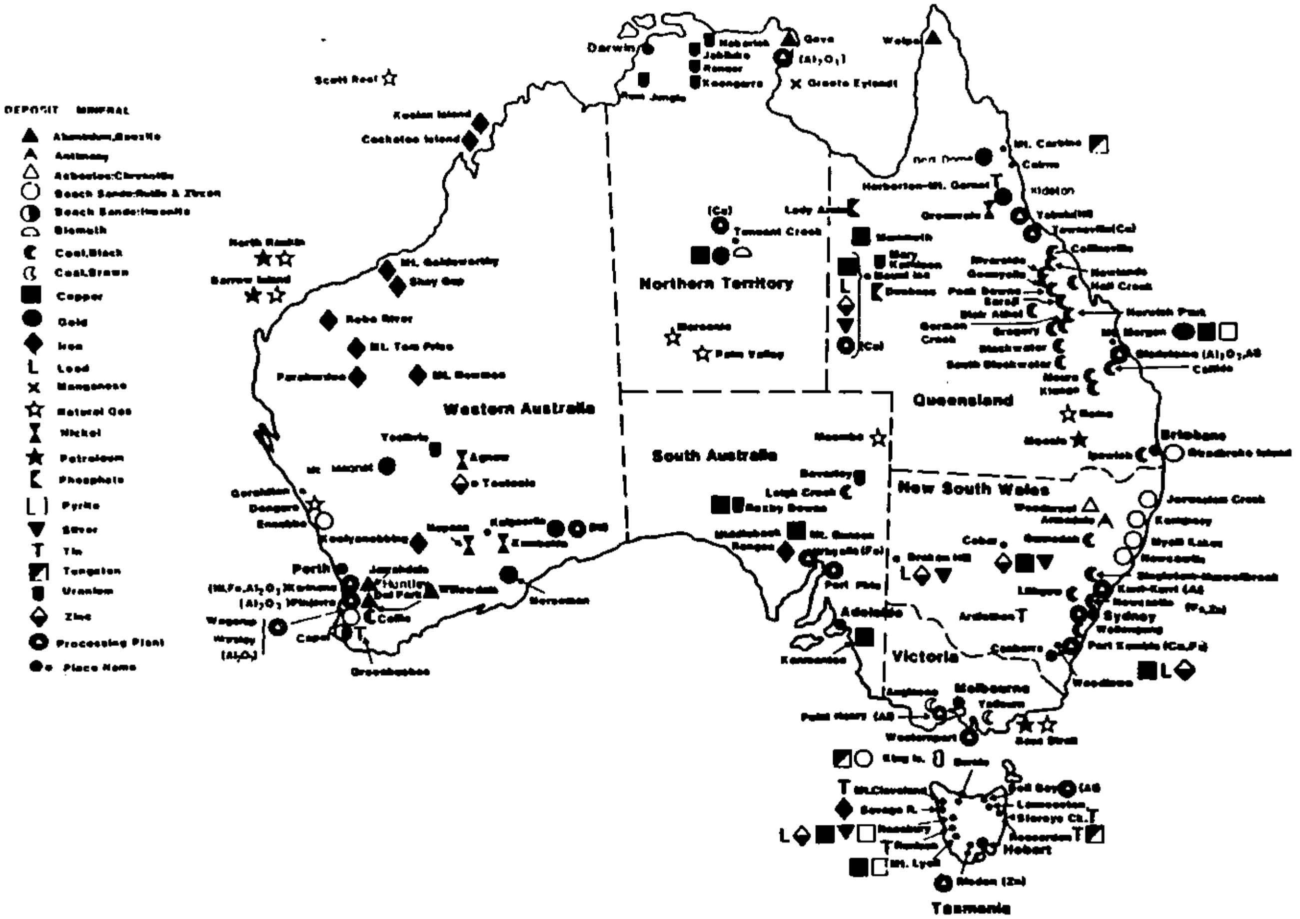

Fig. 1. Major mineral and mineral processing operations in Australia.

12 mt/a at the four south-western refineries). In the Bayer process, alumina is extracted from bauxite by digesting the crushed ore in sodium hydroxide at elevated temperature and pressure. The solid residue from the refining process is often separated into two size fractions during refining, viz. the coarse fraction known as residue sand (>150 µm) and a fine fraction known as red mud (<150 µm).

Properties of the Tailings

Red mud consists primarily of iron, aluminium and silica minerals, the dominant minerals being quartz, haematite and goethite. Alkaline substances such as sodium aluminium silicates (desilication product) are formed during the Bayer process and also form part of the red mud. Residue sand consists primarily of quartz with iron oxides such as haematite and goethite. The red mud fraction of the bauxite residues is dominated by silt and clay particles, whereas the residual sand contains little or none of these sized particles. The available water capacities of the mud and sand are moderately high and low respectively.

Most of the caustic soda associated with the residue is removed by washing, but a solution of sodium hydroxide, carbonate and aluminate remains entrained with the solids. At Gladstone, the bauxite residue is slurried in seawater after washing. At Gove, the residue is slurried with return liquor from the residue disposal areas, and at the other refineries fresh water is used. The tailings materials are all extremely alkaline, saline and sodic, and, when freshly produced, are incapable of supporting plant growth. In addition, both the red mud and sand are extremely deficient in nitrogen and phosphorus and, in many cases, the availability of manganese and zinc is also low.

Method of Tailings Disposal

Bauxite residue in Australia is usually disposed of by pumping it as a wet-slurry of 15-25% solids into natural depressions or lined or unlined artificial impoundments. 'Dry disposal' of residue has recently been introduced into a number of the refineries.

At Gladstone, red mud and residue sand are pumped to separate unlined ponds in a slurry of seawater. At Gove, a red mud/residue sand slurry is pumped to unlined containment ponds. At Bell Bay all the residue generated by the refinery between 1956 and 1972 is contained in an unlined 40 ha pond where it was depositied as a conventional wet slurry.

At Alcoa's refineries at Kwinana and Pinjarra, disposal was originally of a mixture of both red mud and residue sand. Since 1982, mud/sand separation plants have been operating at the disposal areas at these sites, and the two fractions can now be disposed of separately. At Wagerup, the two fractions have always been disposed of separately.

Alcoa's impoundments are up to 160 ha in area and around 20m deep with the total area of tailings at its three refineries now exceeding 720 ha. Leakage of caustic is prevented by a clay seal and, in one case, a synthetic membrane provides an additional seal. All impoundments built since 1983 have gravity underdrains to aid residue consolidation, improve caustic recovery and reduce the potential for leakage.

Approximately 50% of the red mud at Kwinana and Pinjarra is currently being disposed of by dry disposal which involves separating the mud and sand fractions using cyclones. The red mud is then dewatered to about 50% solids then pumped into an impoundment and solar-dried to around 70%-75% solids, at which time it has a strength similar to naturally occurring soils. The sand fraction of the residue is used to build dykes and to top-off filled disposal areas before they are reclaimed. The impoundments originally designed for wet-slurry disposal are being converted to dry disposal after appropriate drainage. Worsley Alumina Ltd. uses a dry disposal technique which involves dewatering. A combined red mud/red sand mixture is dewatered to about 55%-65% solids and then pumped into clay-sealed and underdrained storage areas developed in natural valleys adjacent to the refinery, where it is solar-dried.

Rehabilitation of Tailings

Plants are grown on or around residue disposal areas to control dust on operating areas, to prevent wind and water erosion on filled areas, to blend the areas in with their surroundings, to reclaim filled areas to a productive use and to stabilise the batters of the dykes surrounding the impoundments. Red mud, which contains the majority of the caustic solids such as the desilication product, is more alkaline, saline and sodic than residue sand. Red muds and residue sands slurried in seawater are more saline than those that are slurried with fresh water. Both materials are deficient in many of the nutrients essential for plant growth.

Before satisfactory plant growth can occur in both red mud and residue sand, their alkalinity, salinity and sodicity must be reduced. Meecham and Bell (1977), working with Gladstone refinery wastes, showed that the excess salts in residue sand could be quickly leached. Experience at Alcoa's refineries has shown that well-drained residue sand, which has a high hydraulic conductivity, can support plant growth after only a few weeks leaching by winter rainfall or irrigation, provided adequate plant nutrients are supplied. The red mud has a very low hydraulic conductivity, is not readily leached and remains very difficult to vegetate.

Tropical and sub-tropical sites. At Gove (12°S) much of the annual rainfall of 1800 mm falls between December and March, and there is a distinct dry winter season. The ability to survive this severe dry season is a major factor in determining a species suitability for growing on residue areas. Temperatures are high all year round, the average maximum ranging from 25°C in July to more than 30°C in December.

Ninety eight hectares of residue ponds have been rehabilitated at Gove. A further 85 ha of ponds have been filled, and there is currently one 170 ha pond being filled. These ponds are unlined but are built on a relatively impermeable material.

The main aim of rehabilitation is to establish a vegetation cover which stabilises the surface of the storage areas and eventually blends in with the surrounding flora. Salt - and alkali-tolerant grasses including Chloris gayana and Cynodon dactylon, legumes such as Stylosanthes humilis and Dolichos lablab, and tree and shrub species such as Eucalyptus alba, Acacia leptocarpa and Acacia holosericea have been established after covering the surface of impoundments with 10 cm of topsoil (Hinz and Doettling 1979). Growth and root penetration of plants has been greater on areas of sandy residue than on areas with finer residue (Hinz 1982).

At Gladstone (24°S), where Weipa bauxite is refined, the average annual rainfall is 972 mm, 60% of which falls from December to March. August and September are relatively dry, but the dry winter season is less severe than at Gove. The average daily maximum temperature ranges from 22°C in June to 30°C in January.

The main aim of vegetating the red mud and sand residue storage areas at Gladstone is to stabilise the surface to reduce wind and water erosion. Following extensive experimentation on the red mud tailings, Bell and Meecham (1978) concluded that, in the short-term, there was no prospect of vegetating red mud areas without using a minimum of 200 mm of soil to cover the surface. Growth limiting factors of the mud were identified as excessive salinity, alkalinity and sodicity as well as severe deficiencies of nitrogen, phosphorus, manganese and possibly zinc. A major factor identified for successful rehabilitation was the provision of drainage to prevent upward movement of salt.

The current rehabilitation technique involves building bunds around the area to be rehabilitated, allowing the red mud to drain and then covering the mud with 200 mm of topsoil. Superphosphate, ammonium sulphate and zinc sulphate fertilizers are applied and the area sown with Chloris gayana, Cynodon dactylon and Macroptilium atropurpureum. Acacias native to the area have colonised the rehabilitated areas within three years.

The residue sand at Gladstone is disposed separately from the red mud in bunded low lying areas. Bell and Meecham (1977) showed that establishment of vegetation on this material could be achieved by leaching of excess salt and addition of fertilizer; incorporation of fly ash from the refinery's power station significantly improved the sand's ability to support plant growth through the increase in available water of the mixture.

Mediterranean sites in south-west Australia. The south-west corner of Western Australia has a mediterranean climate with a wet mild winter and a hot dry summer. The average annual rainfall ranges from 858 mm at Kwinana to 1050 mm at Wagerup (Fig. 1). This rainfall is reliable but seasonal, with about 80% falling between May and September. Annual gross evaporation is high generally being in excess of 2000 mm. The mean maximum daily temperature in July is around 17°C and the minimum 9°C. In January the mean maximum daily temperature is around 30°C and the minimum around 18°C.

Of the three Alcoa refineries, that at Kwinana has 298 ha of tailings of which 93 ha have been rehabilitated, that at Pinjarra has 381 ha of which 10 ha has been vegetated, and the Wagerup refinery has 42 ha all of which is still being used for disposal. The Worsley Alumina Ltd. refinery has not yet filled any of its disposal areas.

At Alcoa's refineries, it has been found that the most important requirement for successfully establishing vegetation on residue disposal areas is to ensure that the surface is covered by a well-drained layer of residue sand; it is extremely difficult to grow plants on areas of exposed red mud. Areas filled prior to 1973 at Kwinana, the oldest refinery, presented problems for rehabilitation as the edge-of-empoundment disposal resulted in a separation of the sand and red mud leaving the central areas of the ponds difficult to vegetate. Subsequently sand areas were pushed from the fringes to the centre of the ponds and/or sandy topsoil applied to the central areas. These procedures, plus the installation of surface drains, allowed vegetation to be established successfully. In impoundments built since 1973, dumping points have been rotated so that large-scale separation of red mud and residue sand does not occur. Also, the mud/sand separation facilities at the disposal areas enables hydraulic placement of a layer of sand (1 m) over mud areas following some surface strength development by drainage and drying.

Alkaline groundwater in the filled impoundments at Kwinana is removed using pumps, and the alkali recovered is re-used in the refinery. Controlling the perched groundwater by combination of pumping and surface drains prevents capillary rise of salts which can be a major factor restricting successful rehabilitation. Bottom drains, included in impoundments built since 1983, will increase the recovery of caustic and reduce the level of groundwater in the impoundments when they are filled.

Rehabilitation of the Alcoa refinery wastes has always concentrated on agricultural use of the areas as they are surrounded by predominantly farming areas. The current rehabilitation procedure is to establish a vegetative cover in the first instance to control dust. On filled impoundments, this initial cover may be replaced in subsequent years with a range of possible crops. Ideally, rehabilitation is timed so that autumn rainfall can leach the sand of entrained alkali before sowing. After surface preparation, which includes incorporation of 120 m^3/ha of organic matter, the areas are seeded to S. cereale and L. rigidum. Legumes such as Medicago polymorpha and Medicago sativa may also be sown. In summer, a layer of rock mulch is laid down after sowing to control dust before the plants become established. Finally superphosphate with copper and zinc and ammonium nitrate are applied. Potassium, magnesium, manganese and boron have also been applied to some areas.

The pasture species which have shown the most promise for grazing and hay production in the years following the initial reclamation with S. cereale and L. rigidum are the Medicago polymorpha varieties Serena and Circle Valley, Trifolium balansae and Trifolium fragiferum var. Palestine. A wide range of vegetables have been grown successfully on filled impoundments.

A number of species of native trees and shrubs have been planted on or have invaded the filled areas at Kwinana. The most successful species are Eucalyptus camaldulensis, E. platypus, Casuarina obesa and Melaleuca armillaris. Other species which are surviving and growing include Jacksonia sp., Acacia saligna, A. cyclops, Eucalyptus gomphocephala, E. coolibah, E. botryoides, E. rudis, E. cladocalyx, Melaleuca lanceolata and Casuarina glauca. However, excavation of the root systems of some of these trees has shown that root development is restricted to areas of residue sand or imported sandy topsoil.

The control of dust is important in the efficient management of operating disposal areas and bitumen or paper mulches, rock mulching, irrigation, establishment of a vegetation cover and the use of mesh windbreaks have all been used. Irrigation and growing a cover of vegetation have proved the most successful dust control methods.

Another solution to the problems of managing bauxite residue areas is to find uses for the material. Incorporation of gypsum-treated red mud into coarse sandy soils on the Swan Coastal Plain has been shown to increase pasture yields by up to

100% on well-drained sites due primarily to an increase in their water-holding capacity (Ward 1986). Amending these sandy soils with red mud has the additional benefit of reducing the amount of phosphorus fertilizer leached from them into adjacent coastal water-bodies. However, at the present time the costs associated with these alternative uses makes them uneconomic.

Conclusion

The management of bauxite residues in Australia has progressed considerably since the industry commenced in the 1950s. Some of the improvements which have been made in storage technology include the advent of 'dry' disposal, red mud/residue sand separation and under-drained storage areas. Improved dust control and a better understanding of how to grow plants on filled disposal areas have also been significant factors in improving the management of bauxite residues.

Base Metal Mine Tailings

In this paper, base metals are considered to include copper, zinc and lead which commonly occur as sulphide ores. Typically base metal operations involve extraction of the ore from the ground, grinding of the ore and separation of the metal sulphides from the remainder (80 to 99%) of the finely ground material which is disposed of in surface storages as tailings.

In Australia, base metals are mined at a number of locations (Fig. 1), but the two major mining areas for these metals are situated in semi-arid to arid areas around Mt. Isa in Queensland and Broken Hill in New South Wales. This section of the paper will review the rehabilitation of tailings at these two locations. Additionally, a brief discussion of the rehabilitation of tailings at a former base metal mine at Captains Flat, near Canberra in a sub-humid climate will be given as a comparison with the mines situated in a drier environment.

Broken Hill and Mt. Isa Mines

Broken Hill has been the site of mining and milling activity by a number of companies since the 1880s, the city developing around the mine operation and tailings disposal areas. This case study will discuss work carried out at The Zinc Corporation Limited and New Broken Hill Consolidated Limited (ZC/NBHC) which mine lead, zinc and silver from sulphide ores. At Mt. Isa, where copper, lead, zinc and silver sulphide ores occur, Mount Isa Mines Limited (MIM) began mining, milling and smelting operations in 1931. Tailings disposal areas lie to the west of the mine workings and the city.

Methods of tailings disposal and tailings properties. At both Broken Hill and Mt. Isa, tailings are hydrocycloned to separate the sand fraction (which is used as underground fill) from the silt and clay size fines. The fine tailings are thickened to 45 to 50% solids and pumped or gravitated to tailings dams.

The tailings dams at Broken Hill are constructed by the ring embankment containment method. Mullock forms the base of the first embankment which incorporates a road base and the starter bank with a coarse sand filter forming a drainage blanket. The dam is completed with a series of 10 m lifts of free standing walls built of tailings sand using the upstream method. The fine tailings are confined within these walls (Kelly and Lean 1983; Chilman and Johns 1978). Thus, on completion of the dam, there are two distinct areas for treatment; the unstabilised portion of the sloping embankment made up of coarse tailings and the horizontal top surface of the dam composed of the fine slime fraction. Harris and Leigh (1976) characterise the properties of each area as follows. Wall material has a high permeability to water and air and is easily penetrated by plant roots; metal sulphide and soluble salt content is comparatively low, although soluble salts can concentrate at the base of the wall from seepage and evaporation. Material on top of the dam has low permeability making plant root penetration difficult. Metal sulphide and soluble salt content are comparatively high with salts often migrating to the area from more permeable material. Lean et al. (1983) note that tailings are neutral to slightly alkaline as a result of the lack of active sulphide minerals and the use of alkaline conditions in the treatment of plants.

The valley containment method at Mount Isa currently uses a zoned earth and rockfill wall about 31 m high constructed across a narrow valley to enclose a catchment area of over 20 km^2. The final projected capacity of this dam (No.8) in 20 years is about 100 x 10^6 m^3 of tailings covering about 1400 ha (a number of smaller dams totalling 115 ha are no longer in use).

Tailings are discharged into the dam at a point furtherest from the embankment forming a gently sloping beach with gradients ranging from about 1 in 75 to 1 in 850. No provision is made for stormwater diversion from the valley catchment; however, the high evaporation rate and some re-use control the water level. A small quantity of seepage from the embankment is returned to the pond.

As the Mount Isa embankment acts as a water holding dam, unassisted drying of the tailings mass is slow. High evaporation rates result in the net upward movement of moisture and dissolved salts producing a substantial salt crust on the tailings surface. As the dam catchment extends beyond the tailings surface, rainfall runoff is concentrated onto the tailings.

The properties of the Mt. Isa tailings relevant to the rehabilitation have been reviewed by Bell and Jones (1987). Approximately 90% of the solids discharged to the storage area are less than 37 mm in diameter. The material lacks aggregation and forms a massive structure with high bulk density and surface crust strength. Infiltration of water is very low, but available water is reasonable.

The dominant minerals in the tailings are quartz and dolomite with smaller amounts of muscovite, orthoclose, albite, limonite, gypsum, pyrite and traces of the metal-containing minerals chalcopyrite, galena and sphalerite. Generation of acid from oxidation of pyrite is neutralized by the dolomite, and the pH is kept approximately neutral. The level of soluble salts is extremely high, and the material is very deficient in nitrogen and phosphorus.

<u>Rehabilitation of Broken Hill tailings</u>. The major objectives of rehabilitation of the tailings are to control wind erosion and to improve the visual impact because of the dams' proximity to residential and commercial areas. Thus vegetation is the preferred stabilizing agent, but the major constraint to its establishment however, is the arid climate. The annual evaporation of 2000 mm far exceeds the very low annul rainfall of 224 mm, most of which falls in winter. Mean maximum temperature in December, the hottest month, is 31°C, whereas the mean minimum temperature in July, the coldest month, is 5°C.

Some work was initiated in the mid 1950s to counteract problems of wind-blown dust from the sides and tops of the elevated tailings dams (Harris and Leigh 1976; Lean <u>et al</u>. 1983). However, it was not until the 1970s that the availability of the trickle irrigation technique and a supply of sewage effluent water from the Broken Hill treatment system allowed large scale rehabilitation tests using vegetation on the sides of the dams (Thorne and Hore-Lacy 1979; Lean <u>et al</u>. 1983). The sewage water has a relatively high salt content, but contains sufficient nitrogen, phosphorus and potassium to supply the needs of the wide range of native species used in the rehabilitation program.

Of the 30 species planted as seedlings in autumn, <u>Eucalyptus camaldulensis</u>, <u>E. largiflorens</u>, <u>Acacia salicina</u>, <u>Tamarix parviflora</u>, <u>Atriplex nummularia</u> and <u>Pinus halepensis</u> are the most important. The plants are watered by a combination of drip then sprinkler irrigation for approximately 3 years in order to ensure their survival (Lean <u>et al</u>. 1983).

<u>Rehabilitation of Mt. Isa tailings</u>. Research into rehabilitation of tailings dams began at Mount Isa in the 1960s. The objective was to develop and trial suitable techniques on small completed dams to control wind blown dust and improve their appearance, and apply successful approaches to the current operating No. 8 dam on its completion. Most of the research, which has been reviewed by Bell and Jones (1987), was carried out on the No. 3 dam of which about 30 ha has been rehabilitated.

As in the case of Broken Hill, climate is a major limitation to the establishment of a stabilizing vegetative cover at Mt. Isa (chemical methods of stabilization proved unsuccesaful). The area has a semi-arid climate with an annual rainfall of 429 mm and annual evaporation of 3117 mm; evaporation exceeds rainfall in each month of the year. Summer temperatures are high with the mean maximum temperatures exceeding 36°C in each of November, December and January. In winter, frosts are rare, and the lowest mean monthly minimum temperature of 12°C occurs in July.

Early research showed that the major limitations to plant growth on the Mt. Isa tailings were excessive salinity, low levels of nitrogen and phosphorus and high bulk density, combined with the arid climate (Hunter and Whiteman 1975). Glasshouse and field trials showed that leaching of salts with irrigation and application of nitrogen and phosphorus fertilizer would enable growth of some pasture species to be achieved. Mixing of fly ash, a waste product from the local power station, with the tailings in 1:1 ratio to a depth of 20 cm greatly improved plant growth through an improvement in physical properties. Leaching of salts was increased by the improved infiltration; the available water capacity was also improved. The ash had no major detrimental chemical properties and had the additional advantage of having moderate levels of available phosphorus.

Of the grass species tried, those giving the best growth were Rhodes (Chloris gayana), buffel grass (Cenchrus ciliaris) and couch (Cynodon dactylon). Although these results were encouraging, the maintenance of nutrient levels and the water requirements were demanding, and this approach was not seen as a long term solution to revegetation of the dams. Subsequently trials were established to assess the suitability of using crushed rock as part or all of the root zone in the tailings rehabilitation. A siltstone is mined and used to fill underground voids, and this operation produces a large amount of <50 mm waste which was available for use on the tailings dams. The material is dominated by quartz, dolomite, muscovite, albite and orthoclose. Apart from its deficiency in nitrogen and phosphorus, it has few chemical limitations to plant growth, although its available water capacity is low.

Initially the siltstone was applied as a 70 mm layer on the tailings and either left undisturbed or incorporated into the tailings. Application of fertilizer and irrigation produced good growth of Rhodes grass particularly in the surface-applied treatment. The major advantages of the surface-applied stone mulch were (1) the stones provided protection to the emerging seedlings by reducing wind erosion and sand blasting, (2) the salinity of the tailings immediately below the rock decreased due to better water infiltration and (3) evaporation and upward movement of salt was also reduced.

In spite of the fact that a relatively thin layer of siltstone mulch resulted in reasonable establishment and persistence of introduced species such as Rhodes grass, additional trials by MIM staff showed that it was necessary to apply up to 1 m of siltstone on the tailings surface to support the heavy equipment used to dump and spread the material. An advantage of such a thick layer of relatively coarse material is that it acts to reduce upward migration of salt by capillary rise. The most recent rehabilitation has involved the incorporation of 100 mm of fly ash into the top 1 m of siltstone to improve water holding capacity.

In the initial rehabilitation trials, emphasis was placed on the use of grasses which would build up organic matter in the tailings surface to produce a more favourable environment for subsequent plantings or invasion of native species. In 1980/81, approximately 30 ha of an old tailings dam, which had been treated with an 0.3 to 1.0 m rock layer and a surface incorporation of 100 mm of fly ash, was planted to introduced grasses (Rhodes and buffel) and a large number of native shrub and tree seedlings which are now dominated by Aerva javanica, Acacia hemsleyi, A. holosericea, Atalaya hemiglauca and Eucalyptus argillacea. The vegetation was supplied with trickle irrigation for 2 years to ensure the survival of the majority of the seedlings. Monitoring of this area will provide valuable information on the long term stability of the system which can then be used in the rehabilitation of the remaining tailings areas (> 1500 ha) when they become available in approximately 20 years.

Captains Flat Mine

Captains Flat is a former zinc, lead, copper, gold and pyrite mining area about 50 km upstream from the national capital, Canberra, on the Molongolo River (Fig. 1). Mining, which started in 1874 and continued periodically until 1962, involved extraction of the minerals by froth flotation and subsequent disposal of the tailings. Hydrocycloning was used to separate the tailings into a fine fraction which was pumped to earth dam storage areas, and a coarse fraction which was piled high to form large dumps. At the cessation of mining, the total area covered by fine and coarse tailings was 15 ha (Craze 1979).

The tailings dumps were unsightly and a major source of air and water pollution. The dumps of fine and coarse material lacked stability along their outer faces and, in 1939 and 1945, two dumps collapsed into the Molongolo River, and the material covered alluvial flats, 15 km downstream, with polluted material. In spite of efforts in 1961 and 1962 to prevent further collapse of the dumps by application of slag or tar to the dam walls, the treatments were unsuccessful, and considerable pollution of the Molongolo River continued. A joint State and Federal Government committee was formed in 1974 (Anon 1974) to enquire into the problem of pollution from Captains Flat and to recommend procedures which would lead to a permanent abatement of pollution of the Molongolo River.

In contrast to Mt. Isa, Captains Flat has a temperate climate and a moderate rainfall of 740 mm/a which is distributed relatively evenly throughout the year. In summer, pastures and crops experience periods of moisture stress. Mean monthly temperatures range from 20°C in summer to 6°C in winter when frosts are frequent; the growing season is constrained by the fact that there are only 85 frost-free days per year.

The tailings at Captains Flat contained a range of sulphides which, on oxidation, resulted in pH values less than 3. High salinity and high concentrations of zinc, lead and copper prevented any plant growth on the tailings, and the acidity, salinity and metal load in the mine drainage escaping to the Molongolo River effectively sterilized it for many kilometers downstream.

Research by Craze (1977) showed that plant growth on tailings limed to an acceptable pH with 40-50 t/ha and fertilized with nitrogen and phosphorus was still poor as a result of other limiting factors such as salinity. There was also no guarantee that the pH would stay in a favourable range because of the large amount of sulphate on the tailings. In order to achieve the objectives of stabilizing the tailings against erosion and leaching, therefore, it was apparent that the tailings would have to be recontoured and covered with a medium which was capable of supporting plant growth. The tailings were reshaped to produce terraced slopes with grades not greater than 33% and not less than 5%. These slopes were chosen to reduce erosion, to facilitate revegetation and to provide adequate surface and internal drainage. The terraced slopes were then covered with approximately 220 mm of compacted clay to seal the tailings from air and moisture to reduce oxidation of the sulphides. On top of the clay seal was placed 450 mm of shale rock to inhibit capillary rise of any toxic water which might move through the clay from the tailings and to provide a lateral drainage layer. Finally, a 300 mm layer of the surface of a nearby soil was placed on the rock fill to enable establishment of a vegetative cover.

Considerable laboratory, glasshouse and field testing of the final procedure used was undertaken by the Soil Conservation Service of New South Wales (Craze 1979). A grass-legume pasture was established on the fertilized and limed soil by sowing a mixture of _Agrostis tenuis_, _Festuca arundinacea_, _Cynodon dactylon_, _Vicia dasycarpa_, _Trifolium pratense_ and _T. repens_. _Secale cereale_ was also included in the mixture as a quick growing cover crop. After planting, the surface was covered with a straw mulch and bitumen and watered by sprinkler irrigation. The pasture is maintained by the periodic application of fertilizer and the slashing of the pasture.

Only time will tell if the rehabilitation program, which cost approximately A$3.5 million, will be successful in the long term. Craze (1979) indicated, however, that, in 1979, the revegetated areas appeared to be stable to significant storm events and that the pollution in the Molongolo River was dropping; the pH of the river water had risen from 4.1 to 6.5, the metal content had declined dramatically, and algae had begun to reappear.

The pollution problem arising from mining at Captains Flat developed at a time when there were few environmental controls on mining. Current legislation should preclude such examples as Captains Flat ever occurring again in Australia.

Gold Mine Tailings

Gold has been mined in Australia since the 1850s when the country produced almost 40% of the world's production. Production of the metal has fluctuated markedly since that era with the industry currently undergoing a major resurgence, particularly in Western Australia and Queensland. In Western Australia, the largest producer, the major goldfield is centred on Kalgoorlie-Boulder (Fig. 1) where the metal has been mined for about 90 years. In Queensland the resource is more dispersed, and a large number of small mines operate down the eastern portion of the state. Many of these mines are new with little rehabilitation of tailings being undertaken, and thus this paper will concentrate on the goldfields of Western Australia.

Gold mining in the arid Kalgoorlie-Boulder area has resulted in the production of approximately 500 ha of tailings dumps which flank the twin towns. The dumps are particularly vulnerable to wind erosion and have been identified as the major source of dust in the area. The tailings have been contained by a ring embankment system using coarse tailings to raise the life of the embankment. Such an approach has produced solid tailings structures with outside face slopes up to 70° and heights of 40 m (Kurzeme 1986).

The particle size of the tailings varies with the age of the dump, the older deposits having a coarser texture. However, all deposits are dominated by the fine sand fraction (53 to 74%), which is particularly prone to movement by saltation and effective in sand blasting of seedlings (Nunn 1981). The available water capacity of the tailings is moderate, but little water is held in the air dry state and cohesion between particles of the dry tailings is poor. Chemical analyses indicate the tailings are alkaline (8.3 to 8.7) and that salinity in the top 150 mm can range from moderate to high with a tendency for the salt concentration to be highest in the surface 20 mm.

The climate is a major limitation to vegetative stabilization of the tailings dam with a mean annual rainfall of 238 mm which is winter dominant. The evaporation is 2436 mm per annum and exceeds rainfall in each month of the year. The mean maximum monthly temperatures range from 16.5°C in July to 33.6°C in January, whereas mean minimum monthly values range from 4.8°C in July to 25.9°C in January.

Early attempts to stabilize the tailings dumps by vegetation were not successful, and thus non-vegetative measures were tried (Marshall et al. 1978). Trials showed that 40 mm screened rock fragments at a rate of 40 t/ha significantly reduced wind speed at the surface and particle movement by 80 to 90%. Unfortunately the effectiveness of the treatment declined rapidly after 2 years. Additional research showed that a rate of 124 t/ha of rock fragments was necessary for long term effects but that this rate was uneconomic. Subsequently heavy black granular waste (iron silicate) from the Kalgoorlie nickel smelter was applied as a 9 mm thick blanket (200 t/ha) over the tailings following wind tunnel experiments which showed it would have long-term effectiveness in stabilizing the tailings. This material, which is provided free of charge by the smelter, is now an integral part of the rehabilitation program involving vegetative stabilization.

In the early 1980s, renewed emphasis was placed on trying to use vegetation to stabilize the tailings dumps at Kalgoorlie, and considerable success has now been achieved following trials which identified appropriate native species and documented the need for phosphorus and micronutrients (Burnside et al. 1986). The recommended procedure now involves (1) establishing low contour banks (200 mm high and 3 to 5 m apart) to reduce wind velocity and increase water availability to the plants, (2) direct seeding of saltbush species such as *Atriplex nummularia*, *A. undulata* and *A. amnicola*, (3) application of phosphorus, copper, zinc and molybdenum fertilizer and (4) addition of at least 200 t/ha of nickel smelter slag as a surface mulch (approximately 10 mm). Only a small proportion of the 500 ha of dumps have been treated in this manner. There is the possibility that some of the older tailings dumps will be reworked for gold, but it appears that techniques are now available to achieve rehabilitation on those not destined for disturbance in the near future.

Uranium Mine Tailings

Australia has large reserves of uranium with significant deposits in the Northern Territory, South Australia and Western Australia, but most mining to date has been confined to the Northern Territory (Fig. 1). In the 1950s and 1960s, a number of uranium mines in the Northern Territory operated by mining companies on behalf of the Commonwealth Government. Most of these initial mines had ceased operation by the early 1970s and, as no legislation requiring rehabilitation of the mines existed at the time, the mining works, mill facilities and tailings dumps were abandoned at the end of operations (Bastias 1987). Relatively new mines were established at Narbarlek in 1979 and Jabiru in 1980, under strict Commonwealth Government environmental legislation, but the stage of operation of these mines has not yet allowed rehabilitation of tailings.

The climate of area containing uranium mines in the Northern Territory is monsoonal with a mean annual rainfall of 1500 mm, most of which falls in the period from November to March. Much of the rain falls during storms and intensities are high creating the potential for excessive erosion on unprotected areas. The long dry season coupled with a high evaporation leads to water stress, and this influences the choice of plant species in rehabilitation programs.

The abandonment of uranium mines initially developed in the 1950s and 1960s in the Northern Territory resulted in several examples of major environmental insult (Bastias 1987; Ryan 1987). At Rockhole and Moline, tailings (2 ha and 18 ha respectively) were contained by bunds which later failed resulting in erosion and transport of tailings downstream. Analysis of the area affected by the tailings showed high levels of metals and an unacceptable level of radioactivity. The tailings have been found to contain economic concentrations of gold and, since 1985, a company has been given the authority to extract gold from this material at Rockhole and Moline. Environmental requirements of this new operation include the building of new tailings storage structures and the retrieval of tailings and contaminated soil downstream from the original tailings dams (Bastias 1987).

Another abandoned uranium mine, that at Rum Jungle in the Northern Territory (Fig. 1), was responsible for costliest rehabilitation program ever undertaken on an Australian mine (approximately A$20 m). Uranium and copper ore concentrates were produced between 1954 and 1971 from five open-cuts in close proximity. After mine closure, no rehabilitation was required or undertaken (Ryan 1987). The mining and processing operations resulted in the pollution of the nearby East Finniss River with acid mine drainage resulting from oxidation of pyrite in the mine waste and overburden and causing elevated levels of aluminium, iron, copper, zinc, cobalt and manganese.

Between 1982 and 1986, the overburden heaps and tailings dam were rehabilitated, and the 4 million m^3 of acid water in pits treated. Tailings had been disposed onto 33 ha of bunded low lying land, and some of this material had been eroded into the adjacent East Finness River. The pollution resulting from the tailings was removed by excavating the material (approximately 330,000 m^3) and dumping into one of the existing open-cuts. The floor of the original tailings dam was treated with 8 t/ha of hydrated lime, covered with 300 mm of topsoil, fertilized and seeded to a mixture of tropical grasses (*Chloris gayana*, *Cynodon dactylon*, *Brachiaria decumbens*, *Urochloa mozambicensis* and *Paspalum notatum*), legumes (*Stylosanthes hamata* and *S. guianensis*) and native shrub and tree species (Acacias and Eucalypts). The former tailings area and rehabilitated overburden heaps are maintained by annual mowing and by application of fertilizers every second year (Ryan 1987).

The environmental planning and legislation which are associated with the new uranium mines in Australia should result in the avoidance of the pollution problems and high cost of after-thought rehabilitation which have been unfortunate features of the Rum Jungle mine.

Conclusions

This paper has briefly reviewed tailings rehabilitation for some of the major mining industries in Australia. It has not been possible to cover all mining operations in the country which have to dispose of tailings, but the examples given provide an insight into the range of limitations affecting rehabilitation and the approaches used to overcome them.

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