Chapter 4
Tailings

4.1 Introduction

Mineral processing of hard rock metal ores (e.g. Au, Cu, Pb, Zn, U) and industrial mineral deposits (e.g. phosphate, bauxite) involves size reduction and separation of the individual minerals. In the first stage of mineral processing, blocks of hard rock ore up to a meter across are reduced to only a few millimeters or even microns in diameter. This is achieved by first crushing and then grinding and milling the ore (Fig. 1.3). Crushing is a dry process; grinding involves the abrasion of the particles that are generally suspended in water. The aim of the size reduction is to break down the ore so that the ore minerals are liberated from gangue phases. In the second stage of mineral processing, the ore minerals are separated from the gangue minerals. This stage may include several methods which use the different gravimetric, magnetic, electrical or surface properties of ore and gangue phases (Fig. 1.3). Coal differs from hard rock ore and industrial mineral deposits as it does not pass through a mill. Instead, the coal is washed, and coal washeries produce fine-grained slurries that are discarded as wastes in suitable repositories. Consequently, the end products of ore or industrial mineral processing and coal washing are the same: (a) a concentrate of the sought-after commodity; and (b) a quantity of residue wastes known as *tailings*. Tailings typically are produced in the form of a particulate suspension, that is, a fine-grained sediment-water slurry. The tailings dominantly consist of the ground-up gangue from which most of the valuable mineral(s) or coal has been removed. The solids are unwanted minerals such as silicates, oxides, hydroxides, carbonates, and sulfides. Recoveries of valuable minerals are never 100%, and tailings always contain small amounts of the valuable mineral or coal. Tailings impoundments may also receive very high concentrations of valuable minerals or coal during times of inadequate mineral processing or coal washing.

At nearly every metal mine site, some form of mineral processing occurs, and tailings are being produced. In metal mining, the extracted ore minerals represent only a small fraction of the whole ore mass; the vast majority of the mined material ends up as tailings. More than 99% of the original material mined may finally become tailings when low-grade metal ores are utilized. Tailings represent, therefore, the most voluminous waste at metal mine sites.

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This chapter documents the characteristics, disposal options, and environmental impacts of tailings. The main focus is on tailings from metal ores. Other aspects important to tailings such as sulfide oxidation and geochemical processes in AMD waters have already been presented (Chaps. 2 and 3). Sulfidic tailings and AMD waters of sulfidic tailings may be characterized and treated with the same type of approaches used to characterize and treat sulfidic waste rocks and AMD waters as discussed in the previous chapters.

4.2 Tailings Characteristics

Tailings vary considerably in their chemical and physical characteristics. These characteristics include: mineralogical and geochemical compositions; specific gravity of tailings particles; settling behaviour; permeability vs. density relationships; soil plasticity (i.e. Atterberg limits); consolidation behaviour; rheology/viscosity characteristics; strength characteristics; pore water chemistry; and leaching properties (Environment Australia 1995). Detailed procedures for tailings sampling, preparation and analysis are found in Ficklin and Mosier (1999). Laboratory methods for the mineralogical and geochemical analysis of tailings solids and waters are given by Jambor (1994), Crock et al. (1999), and Petruk (2000).

Tailings consist of solids and liquids. The solids are commonly discharged with spent process water into a tailings storage facility, most commonly a tailings dam. As a result, the waste repository contains liquids in the form of surface and pore waters. These tailings liquids tend to contain high concentrations of process chemicals. The following presentation of tailings is given in terms of process chemicals, tailings liquids, and tailings solids.

4.2.1 Process Chemicals

Many of the mineral beneficiation and hydrometallurgical operations process the crushed ore in water. Ground or surface water is exploited and used in the process circuits as so-called *process water*. The composition of process water is largely a function of the applied mineral processing and hydrometallurgical techniques. Hydrometallurgical processing requires specific chemicals for different ore characteristics and mineral behaviours. The chemicals can be classified as flotation reagents, modifiers, flocculants/coagulents, hydrometallurgical agents, and oxidants (Table 4.1). Flotation reagents are a group of chemicals used for froth flotation which is a common mineral processing technique to recover sulfides. Froth flotation works on the principle that water and a frothing agent are added to finely crushed mineral particles. The ore minerals cling to air bubbles and form a froth on top of the water. The froth is recovered and dried. The remaining water contains unwanted solids which are pumped to a tailings disposal facility.

Table 4.1 Examples of common flotation reagents, modifiers, flocculants, coagulants, hydrometallurgical reagents, and oxidants (after Allan 1995; Barbour and Shaw 2000; Ritcey 1989)

Class	Use	Reagent examples
Flotation reagents		
(a) Frothers	To act as flotation medium	Surface active organics such as pine oil, propylene glycol, aliphatic alcohols, cresylic acid
(b) Collectors	To selectively coat particles with a water repellent surface attractive to air bubbles	Water soluble, surface active organics such as amine, fatty acids, xanthates
Modifiers		
(a) pH regulators	To change pH to promote flotation	Lime, hydrated lime, calcite, soda ash, sodium hydroxide, ammonia, sulfuric acid, nitric acid, hydrochloric acid
(b) Activators and depressants	To selectively modify flotation response of minerals present	Surface active organics and various inorganics such as copper sulfate, zinc sulfate, sodium sulfide, lead nitrate, lime, sodium silicate
(c) Oils	To modify froth and act as collectors	Kerosene, fuel oils, coal-tar oils
Flocculants	To promote larger particle formation and settling efficiency by bridging smaller particles into larger particles	Clays, metal hydroxides, polysaccharides, starch derivatives
Coagulants	To promote larger particle formation and settling efficiency by reducing the net electrical repulsive forces at particle surfaces	Ferric and ferrous sulfate, aluminium sulfate, ferric chloride
Hydrometallurgical reagents	To selectively leach ore minerals	Sulfuric acid, sodium cyanide
Oxidants	To oxidize process water	Hydrogen peroxide, sodium hypochlorite, ferric chloride, potassium permanganate

Much of the process water accumulates in decant ponds of tailings dams. The tailings water can be decanted for reuse and pumped back to the plant. Recycling and reuse of process water and process chemicals makes economic sense and can reduce the load of contaminants contained in ponds and tailings dams. However, a proportion of the discharged process water remains in the tailings disposal facility. Various fractions of the chemical additives ultimately find their way into tailings, and tailings liquids often contain some levels of organic chemicals, cyanide, sulfuric acid, and other reagents used to achieve mineral recovery.

4.2.2 Tailings Liquids

Water present at the surface of tailings storage facilities and present within the pores of tailings solids is referred to as *tailings liquid* or *tailings water*. It has highly variable compositions depending on the processing technique, and its composition may change over time. Rainfall leads to the dilution of tailings water, and evaporative concentration causes secondary mineral precipitation at and below the tailings surface. In addition, the exploitation of fresh, brackish or saline water for mineral processing will influence the composition of tailings water. In arid regions, the use of saline ground water for the processing of ores can result in extreme saline process waters and tailings. Salt encrustations are common in the waste repositories. Also, tailings solids show poor consolidation behaviour, and the evaporation rate of tailings water is reduced due to the high salinity. Extreme salinities may also originate from chemical reactions in the tailings which are induced by the addition of process chemicals.

Process chemicals, used to extract ore minerals, may influence the behaviour of metals and other elements in tailings. For example, thiosalts ($S_2O_3^{2-}$, $S_3O_6^{2-}$, $S_4O_6^{2-}$) can oxidize to sulfate in waste repositories causing the acidification of waters, and organic chemicals may complex metals present in the tailings. As a consequence, the pore and surface waters of tailings dams may contain strongly elevated concentrations of various elements and compounds, including process chemicals. Some of the process reagents such as organics and cyanides may be destroyed with time by natural bacterial, chemical or photolytic degradation processes (Sect. 5.8). Other compounds may require naturally enhanced or engineered destruction; some elements have to be permanently isolated by the tailings impoundment (e.g. radionuclides, metals, metalloids).

The acidity of tailings waters is influenced by the applied processing technique. For instance, the digestion of bauxite ore and the dissolution of gold using cyanide solutions are conducted under alkaline conditions. In contrast, the hydrometallurgical extraction of copper, nickel, and uranium is based on the use of sulfuric acid under oxidizing conditions. This sulfuric acid or that generated by sulfide oxidation will leach the tailings minerals. For example, the acid leaching of the mineral fluorite (CaF_2) releases fluorine into waters (Petrunic and Al 2005). The fluorine in turn forms strong complexes with aluminium and enhances the dissolution of aluminosilicate minerals. As a result, strongly elevated Al contents can be present in tailings waters. In extreme cases, different processing techniques can create strongly acid or alkaline tailings waters with high concentrations of iron, manganese, aluminium, trace metals, metalloids, fluoride, chloride and sulfate (Bodénan et al. 2004).

4.2.3 Tailings Solids

At metal mines, the amount of the ore mineral (s) extracted from an ore is relatively small, and the vast majority of mined and processed ore ends up as tailings. At modern gold mines, more than 99.999% of the originally mined and processed ore may finally become tailings. The dry weight of tailings produced is nearly equal to the dry weight of the ore mined.

The grain size of tailings is relatively restricted and ranges from clay to sand (i.e. 2 μm to 2 mm). In some cases, the tailings solids have distinct grain sizes, and the solids are then referred to as *slimes* and *sands*. Dry tailings typically consist of 70–80 wt.% sand-sized particles and 20–30 wt.% finer clay-sized particles (Fig. 4.1). The grain size depends on the liberation characteristics of the ore and gangue minerals and the applied crushing and grinding process. The grain size influences the resistance of the tailings solids to wind and water erosion and the behaviour and settling characteristics of particles in tailings dams. The mineralogical and geochemical composition of tailings solids is site specific, and such variations provide different challenges. For example, sulfide-rich tailings are potential sources of AMD whereas uranium tailings have elevated levels of radiation.

It is often assumed that tailings contain minerals similar to those of the ore, only in much smaller grain size. Nonetheless, tailings comprise a material which is significantly different to the mined ore in terms of grain size, mineralogy, and chemistry. By nature, mineral processing is designed to change the physical and chemical characteristics of the mined ore. The processing also promotes the dissolution and mobilization of elements present in the ore. The physical and chemical parameters (e.g. pH, Eh) change for individual elements and compounds from the ore deposit to the tailings repository. Consequently, tailings undergo chemical reactions after their deposition in the repository, and their composition changes over time. The tailings solids and the interstitial tailings liquids react and attempt to reach equilibrium. Tailings undergo forms of diagenesis. In addition, physical and biological processes occur such as compaction, cementation, recrystallisation as well as mineral dissolution and formation assisted by microorganisms (Praharaj and Fortin

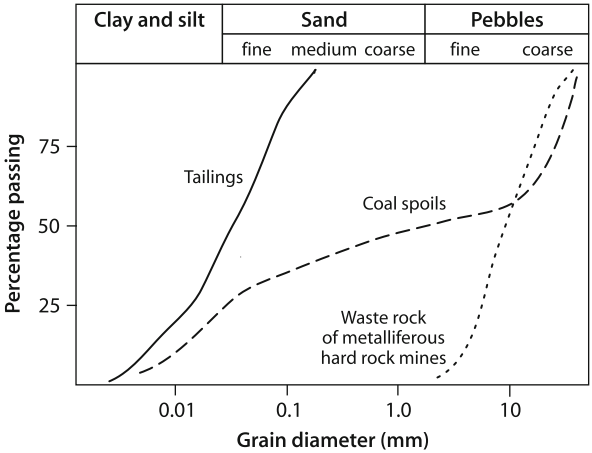


Fig. 4.1 Schematic particle size distribution curves for tailings, coal spoils, and waste rocks (after Robertson 1994; Younger et al. 2002)

2008). As a result, tailings contain elements as dissolved species and in potentially soluble and insoluble solid forms (Bobos et al. 2006; Craw 2003; Sidenko and Sherriff 2005).

The diagenetic processes highlight the fact that tailings solids can be the result of different origins. Tailings solids can be: (a) primary ore and gangue minerals; (b) secondary minerals formed during weathering; (c) chemical precipitates formed during and after mineral processing; and (d) chemical precipitates formed after disposal in the tailings storage facility. Minerals within tailings can be assigned to several events of mineral formation (Jambor 1994). Primary minerals are ore and gangue minerals of the original ore. Secondary minerals are those minerals which formed during weathering of ore and gangue phases. Chemical precipitates formed during and after mineral processing, including those minerals formed in tailings impoundments, may be labelled as tertiary or quaternary (Jambor 1994).

4.3 Tailings Dams

Most of the tailings mass produced worldwide is pumped into *tailings storage facilities*, including large surface impoundments so-called *tailings dams* (Fig. 4.2). The impoundments are best thought of as purpose-built sedimentation lagoons where fine-grained waste residues and spent process water are captured. There are at least 3500 tailings dams worldwide (Davies and Martin 2000). These dams may range from a few hectares to thousands of hectares in size. Because of their size, they leave the largest *footprint* of any mining activity on the landscape.

Tailings dams are cross valley (i.e. one or two dams constructed across a section of a valley), sidehill (i.e. one dam constructed perpendicular to the slope of a hill), or paddock impoundments (i.e. four sided impoundments constructed on flat land). In some cases, the tailings themselves – in particular the sand-sized fraction – are used to construct the embankments. If the tailings solids and other waste materials are used as a construction material for dam walls and banks, they need chemical and physical characterization prior to such use to ensure that they do not cause tailings

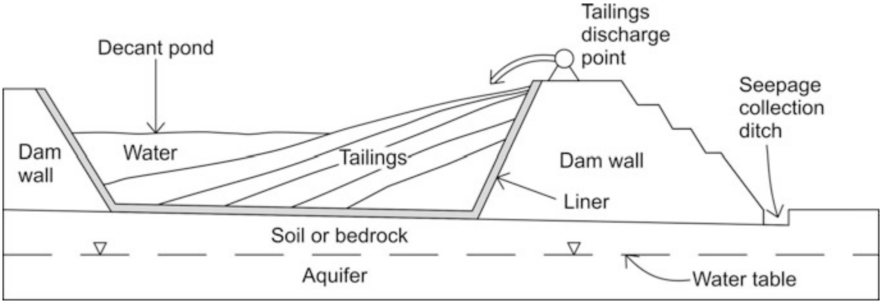


Fig. 4.2 Simplified cross-section of a tailings dam

dam failure or contaminant release. The storage areas also have to be engineered to optimize the amount of tailings stored and to eliminate any possible environmental impacts. Modern tailings dams and other engineered structures are designed to isolate the processing waste.

Tailings dams are constructed like, and built to standards applicable to, conventional water storage type dams. Generally, they are not constructed initially to completion. They are raised gradually or sequentially as the impoundment fills. The dams are thereby raised upstream towards the tailings, downstream away from the tailings, or in centreline (Davies and Martin 2000; Environment Australia 1995; Vick 1983) (Fig. 4.3). Each construction method has different advantages and disadvantages in terms of construction, use, economics, and seismic stability (Vick 1983). More than 50% of tailings dams worldwide are built using the upstream method although it is well recognized that this construction method produces a structure which is highly susceptible to erosion and failure. The failure rate of upstream tailings dams is quite high, and it appears that every 20th tailings dam fails (Davies and Martin 2000). Major and minor environmental concerns with tailings dams are:

- *The visual impact of the large engineered structure.*
- *The structural stability of the dam and the potential release of tailings into the environment through pipeline ruptures, dam spillages and failures* (cf. Sect. 4.3.3).

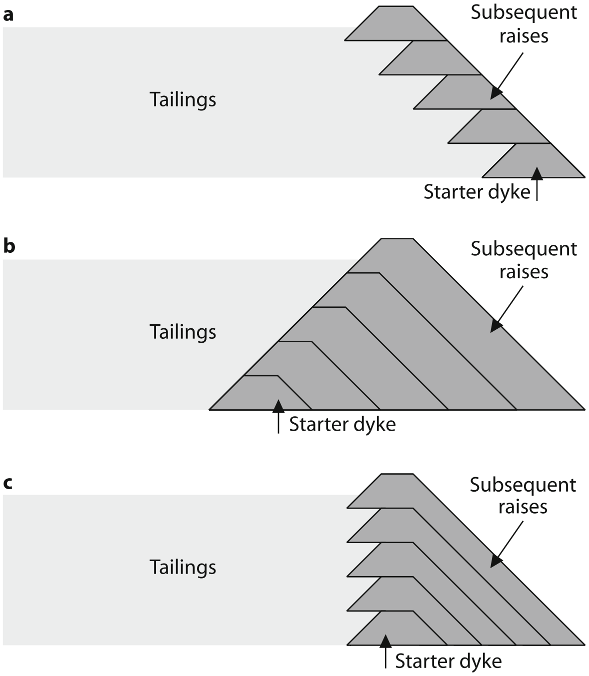


Fig. 4.3 Schematic cross-sections illustrating the construction of embankments for sequentially raised tailings dams; (**a**) upstream; (**b**) downstream; (**c**) centreline method (after Vick 1983)

- *Closure and associated capping and vegetation of the tailings dam* (cf. Sect. 4.3.5).
- *Release of radiation from tailings* (cf. Sect. 6.11).
- *Air and soil pollution through dust generation*. Unconsolidated tailings particles can be subjected to transport by wind and water erosion. Tailings dust particles including the inhalable size fraction (particulate matter <10μm; PM_{10}) may be dispersed around the repository, contaminating local topsoils and resulting in the direct exposure of humans and ecosystems to metals and metalloids (Chane Kon et al. 2007; Hayes et al. 2009; Kelm et al. 2009; Moreno et al. 2007). Dissolution and weathering of tailings dust, which has been deposited in local topsoils, can lead to the acidification of topsoils and the transfer of metals and metalloids into local plant species (Conesa et al. 2009).
- *Seepage from the tailings through the embankment and base into ground and surface waters*. Seepage from a tailings dam is a common environmental concern as seepage water may drain into local stream systems and contaminate surface water and sediment (Heikkinen et al. 2009; Talavera Mendoza et al. 2006). The chemistry of seepage waters is controlled by: (a*)* the mineralogy and chemistry of the tailings solids and the reactions taking place in the repository; (b) the seepage flow path; (c) process water input; and (d) local hydrological conditions. The amount of seepage is governed by the permeability of the tailings and the permeability of dam walls, liner or ground beneath the impoundment. There are various clay and synthetic liner systems applied to tailings dams so that they reduce leakage into ground water aquifers (Asher and Bell 1999; Environment Australia 1995; Hutchison and Ellison 1992). Plastic geotextiles and clay liners represent effective methods to reduce seepage from a tailings dam. A seepage collection system may need to be put into place, consisting of liners and filter drains placed at the base of the tailings. A toe drain, which will intercept emerging tailings waters, may need to be incorporated into the embankment. Capping tailings dams with dry covers will reduce seepages to even lower rates. On the other hand, acidic tailings solutions may react with a clay liner placed at the bottom of the tailings storage facility (Shaw and Hendry 2009). A breach of the clay liner may then be possible.

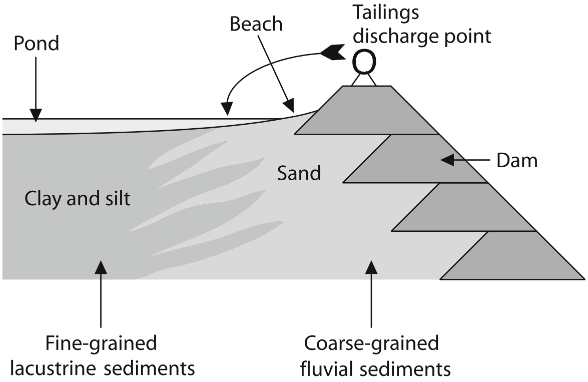
4.3.1 Tailings Hydrogeology

The slurry pumped into tailings dams commonly contains 20–40 wt.% solids (Robertson 1994). The tailings may be discharged via one or several so-called *spigotting points* and spread out over large areas (Fig. 4.4). This allows maximum drying and produces a uniform surface.

The solid tailings are transported and deposited in an aqueous environment similar to sediments (Fig. 4.5). Sedimentary textures are common and analogous to those of fluvial and lacustrine environments (Robertson 1994). Stratification, graded and cross bedding as well as lenticular and sinuous textures are typical. Extensive

Fig. 4.4 Discharge of tailings from a spigot pipe into a tailings storage facility, Cannington silver-lead-zinc mine, Australia

Fig. 4.5 Depositional environments of a tailings dam receiving tailings slurries (after Robertson 1994)



layering is uncommon in tailings. The position of the spigotting points – where tailings are discharged into the dam – usually changes many times. Therefore, depositional environments within the impoundment change over time, and each tailings pile represents a unique sedimentary heterogeneous mass.

Tailings particles have diverse mineralogical compositions and different specific gravities. This gravity difference controls how individual particles segregate and settle within tailings dams. Preferential accumulation and settling of different grain sizes and minerals may occur depending on the discharge rate, the density of the discharged slurry, the method of slurry entry into the impoundment, and whether the disposal surface has a distinct slope (Environment Australia 1995; Robertson 1994). In general, larger, heavier and sand-sized particles settle near the slurry outlet; smaller, lighter and finer-grained particles are located well away from the outlet. If sulfides occur within a particular grain size, this may result in the formation of sulfide-rich tailings sediment. Prolonged surface exposure of these tailings to atmospheric oxygen or subsurface exposure to dissolved oxygen in the vadose zone of tailings may lead to localized AMD generation (Sherriff et al. 2007).

The hydraulic sorting of tailings solids results in coarse-grained size fractions near discharge points and smaller grain size fractions towards the decant pond. This grain size distribution also results in an increased hydraulic conductivity of the coarser grained tailings mass. The coarser tailings drain quicker than the finer material, and there will be a lower ground water level near the dam wall (Environment Australia 1995; Younger et al. 2002).

Ground water storage and flow conditions in tailings dams are site specific and controlled by the grain size and hydraulic conductivity of the tailings, the prevailing climatic conditions as well as the impoundment geometry and thickness (Robertson 1994; Younger et al. 2002). If the tailings have been placed on a permeable base, regional ground water may migrate into the tailings, or tailings seepage may enter the aquifer underlying the tailings dam (Fig. 4.6). Hence, tailings impoundments may represent ground water recharge or discharge areas, depending on whether the water table elevation in the tailings is lower or higher than in the surrounding terrain. Active tailings impoundments have higher water table elevations than inactive ones. Inactive tailings impoundments have unsaturated and saturated zones separated by a ground water table (Fig. 3.18). Such hydrological characteristics are similar to waste rock dumps (Sect. 3.9.1).

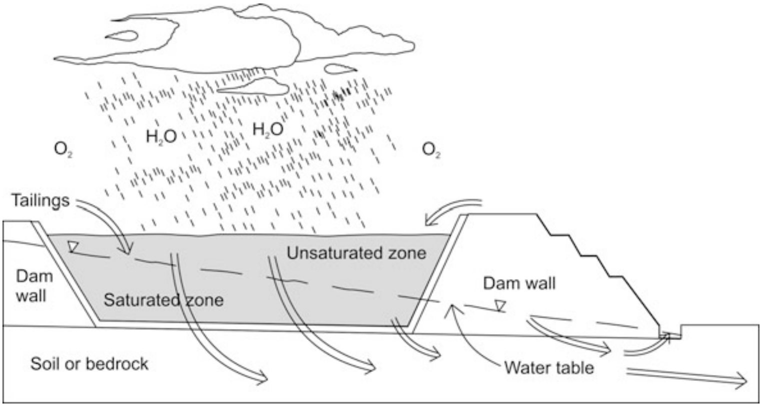


Fig. 4.6 Simplified cross-section of a tailings dam, showing downward flow of infiltrating water into the tailings and the underlying aquifer (after Blowes et al. 2003)

4.3.2 AMD Generation

Tailings may have a high sulfide content in the form of rejected pyrite and other sulfide minerals. Sulfidic tailings are a potential source of AMD (Blowes et al. 1998; Jambor 1994; Johnson et al. 2000; Lei and Watkins 2005; Petrunic and Al 2005).

If sulfidic tailings are exposed to atmospheric oxygen or to dissolved oxygen in the vadose zone of tailings, the oxygen infiltrating the waste may cause sulfide oxidation and trigger AMD. Acid producing and acid buffering reactions and secondary mineral formation will occur, and low pH pore waters with high concentrations of dissolved constituents will be generated (Coggans et al. 1999; Johnson et al. 2000; Romero et al. 2007). Indicators for sulfide oxidation – such as abundant iron oxyhydroxide and hydroxide precipitates or acid, sulfate and metal-rich tailings liquids – are generally observed in the upper part and vadose zone of tailings impoundments (Al et al. 2000; Heikkinen and Räisänen 2008; Jambor 1994; Schippers et al. 2007). Acid, saline tailings liquids may also accumulate in ponds at the surface of the tailings repository (Fig. 4.7).

If sulfidic tailings are present in the unsaturated zone and are exposed to atmospheric oxygen, sulfide oxidation will commence in the upper level of the unsaturated zone. The oxidation front in the tailings will then gradually move downward towards the ground water table where the oxidation of sulfides will almost completely stop. Compared to surface water and pore water in the vadose zone, the ground water in the saturated zone of sulfidic tailings impoundments usually has higher pH and lower Eh values and lower concentrations of dissolved constituents (Fig. 3.18) (Al et al. 2000; Blowes and Ptacek 1994; Coggans et al. 1999). Sulfidic tailings below the ground water table remain protected from oxidation. Unoxidized sulfidic tailings may underlie oxidized sulfidic materials. These unoxidized tailings within the saturated zone have the potential to oxidize as soon as the water table within the impoundment falls to lower levels.

In oxidizing sulfidic tailings, pore waters may exhibit a distinct chemical stratification. For example, oxidation of exposed tailings and subsequent burial of the material by renewed tailings disposal may lead to sulfate-, metal-rich pore waters at deeper levels and saturated zones (Jambor 1994). Also, repeated wetting and drying cycles may result in fluctuating water tables and variable oxidation fronts causing extensive sulfide oxidation, secondary mineral formation and dissolution, and AMD development (Boulet and Larocque 1998; McGregor et al. 1998).

Fig. 4.7 Ponding of acid, saline water on an abandoned sulfidic tailings dam, Croydon gold mine, Australia

The oxidation and weathering reactions will release metals, metalloids, acid, and salts to tailings pore waters. The released contaminants may: (a) be retained within the tailings impoundment; (b) reach surface and ground water systems; or (c) be precipitated at a particular level of the tailings impoundment. Copper may be precipitated, for instance, as covellite below the zone of sulfide oxidation to form a zone of copper enrichment, akin to the formation of supergene copper ores (Holmström et al. 1999; Ljungberg and Öhlander 2001). Massive precipitation of secondary minerals including oxides (e.g. goethite, ferrihydrite, lepidocrocite, schwertmannite), sulfates (e.g. jarosite, gypsum, melanterite), and sulfides (e.g. covellite) may occur at particular levels within the tailings impoundment (Dold and Fontboté 2001; McGregor et al. 1998). In tailings dams, secondary minerals typically precipitate in the zone of oxidation and at the interface between oxic and anoxic layers (Fig. 2.11). Here, released metals, metalloids and sulfate can be adsorbed and coprecipitated with mineral precipitates (Heikkinen and Räisänen 2008). Adsorption and coprecipitation of dissolved metals and metalloids on iron precipitates is particularly common. Mineral precipitation can cement sulfidic tailings at or near the depth of sulfide oxidation. Prolonged precipitation causes the formation of a hardpan layer which acts as a diffusion barrier to oxygen and limits the downward migration of low pH, saline pore waters (Blowes et al. 1991; Coggans et al. 1999; Gunsinger et al. 2006b; Romero et al. 2007) (Sect. 2.6.4).

If sulfidic tailings are exposed to the atmosphere for extended periods, evaporation of tailings water commonly leads to the formation of sulfate-bearing mineral salts such as gypsum or jarosite (Dold and Fontbote 2001; Johnson et al. 2000). These secondary mineral blooms occur on or immediately below the impoundment surface, and surficial tailings materials may form a cohesive, rigidly cemented material (Fig. 4.8). Soluble secondary minerals may redissolve upon rainfall events or due to increased water levels within the tailings dam.

Fig. 4.8 Drying of sulfidic tailings has resulted in the formation of white metal sulfate efflorescences and desiccation cracks, Cannington silver-lead-zinc mine, Australia

While the oxidation of sulfidic tailings is possible, most tailings deposits generally remain water saturated during the operating life. This limits the transfer of air into the tailings and the supply of oxygen to sulfide minerals (Blowes and Ptacek 1994). Moreover, if unoxidized sulfidic tailings are flooded, deposition of organic material may occur, and layers rich in iron and manganese oxyhydroxides may develop at the water-tailings interface. These layers can prevent the release of metals into the overlying water column through adsorption and coprecipitation processes (Holmström and Öhlander 1999, 2001).

Tailings are much finer grained and have a much higher specific surface area (i.e. $m^2\ g^{-1}$) available for oxidation and leaching reactions than waste rocks. Thus, the onset of AMD development in tailings can be more rapid than in waste rocks of the same deposit, yet crushing and milling of sulfidic ores do not necessarily increase the oxidation rate of pyrite in tailings dams. The rate of AMD generation in tailings is reduced by:

- *Uniform and fine grain size.* Tailings possess a uniform and fine particle size which leads to a much lower permeability than that in waste rock piles. Compared to coarse-grained waste rocks, tailings exhibit: (a) less and slower water and oxygen movement into the waste; (b) reduced contact of sulfides with oxygen due to slower oxygen transport into the waste; (c) slower water movement and slower replenishment of consumed oxygen; and (d) very slow seepage of an AMD plume to outlets of the waste impoundment because the generally low hydraulic conductivity of tailings will delay movement of the AMD plume (Ljungberg and Öhlander 2001). The behaviours of oxygen and water influence the depth and rate of AMD generation. Consequently, tailings permit a smaller depth of active acid generation than coarse-grained wastes, and sulfidic tailings often generate AMD more slowly than coarser, more permeable waste rock from the same deposit (Mitchell 2000).
- *Addition of alkaline process chemicals.* Some tailings have a high pH due to the addition of alkaline materials during mineral processing (Craw et al. 1999). Any acid generated may immediately be neutralized by residual alkaline processing agents. Tailings may also be stabilized through the addition of neutralizing materials such as lime, crushed limestone or fly ash (Stouraiti et al. 2002). This may prevent highly reactive sulfidic tailings from developing AMD waters.

4.3.3 Tailings Dam Failures

Tailings dams should be constructed to contain waste materials indefinitely. The impoundment should be designed to achieve negligible seepage of tailings liquids into ground and surface waters and to prevent failures of tailings dam structures. Therefore, the dams should be engineered for: (a) long-term stability against erosion and mass movement; (b) prevention of environmental contamination of ground and surface waters; and (c) return of the area for future land use. The overall design objective of tailings dams should be to achieve a safe, stable post-operational tailings impoundment (Davies and Martin 2000; Environment Australia 1995).

The stability of tailings dams is controlled by the embankment height and slope as well as the degree of compaction, nature, and strength of foundation and embankment materials (Environment Australia 1995). Conventional tailings dams can exceed 100 m in height and have to hold back a significant pool of water and up to several hundred million cubic metres of water saturated tailings. The easiest way to maintain dam stability during operation is to keep the decant pond as small as possible and as far as possible from the containing embankment as practical (Environment Australia 1995). This ensures that the phreatic surface remains at low levels. Nonetheless, the mechanical stability of tailings is very poor due to the small grain size and the usually high water content. The level of the water table in the impoundment and embankment falls as tailings discharge ceases. This results in the increased stability of the embankment and tailings mass. Any further accumulation of water on the dam is prevented by capping the impoundment.

In the past 70 years, numerous incidents involving operating tailings dams have occurred (e.g. Wagener et al. 1998). There have been about 100 documented significant upstream tailings dam failures (Davies and Martin 2000) (Table 4.2). The causes for tailings dam failures include:

- *Liquefaction.* Earthquakes are associated with the release of seismic waves which cause increased shear stresses on the embankment and increased pore pressures in saturated tailings. Tailings and the dam may liquefy during seismic events (e.g. Veta de Agua, Chile; 03.03.1985). Liquefaction may also be caused by mine blasting or nearby motion and vibrations of heavy equipment.
- *Rapid increase in dam wall height.* If an upstream dam is raised too quickly, very high internal pore pressures are produced within the tailings. High pore pressures decrease the dam stability and may lead to dam failure (e.g. Tyrone, USA; 13.10.1980).
- *Foundation failure.* If the base below the dam is too weak to support the dam, movement along a failure plane will occur (e.g. Los Frailes, Spain; 25.04.1998).
- *Excessive water levels.* Dam failure can occur if the phreatic surface raises to a critical level; that is, the beach width between the decant pond and the dam crest becomes too small (Fig. 4.5). Flood inflow, high rainfall, rapid melting of snow, and improper water management of the mill operator may cause excessive water levels within the impoundment, which then may lead to overtopping and collapse of the embankment (e.g. Baia Mare, Romania; 30.01.2000; Case Study 5.1). If overtopping of the dam crest occurs, breaching, erosion, and complete failure of the impoundment are possible.
- *Excessive seepage.* Seepage within or beneath the dam causes erosion along the seepage flow path. Excessive seepage may result in failure of the embankment (e.g. Zlevoto, Yugoslavia; 01.03.1976).

Table 4.2 Chronology of tailings dam failures since the 1920s (Genevois and Tecca 1993; Lindahl 1998; Morin and Hutt 1997; Wagener et al. 1998; WISE Uranium Project 2009). (Most of it has been reprinted from *www.wise-uranium.org*, with permission from P. Diehl)

Date	Location	Incident	Release	Environmental impact and fatalities
29.08.2009	Karamken, Russia	Tailings dam failure	?	1 person killed, destruction of houses
14.05.2009	Huayuan country, China	Tailings dam failure	?	3 people killed
22.12.2008	Kingston, USA	Failure of retention wall	4.1 million m^3 of ash slurry	160 ha covered with ash slurry
08.09.2008	Taoshi, China	Collapse of waste repository	?	At least 254 people killed, destruction of buildings
06.11.2006	Nchanga, Zambia	Failure of tailings slurry pipe	?	Contamination of local river
30.04.2006	Miliang, China	Tailings dam failure during raise	?	17 people missing; cyanide release to local river
30.11.2004	Pinchi Lake, Canada	Tailings dam collapse	6000–8000 m^3 of rock and waste water	Spill into lake
20.03.2004	Malvesi, France	Tailings dam failure after heavy rain	30,000 m^3 of liquid and slurry	Nitrate contamination of local creek
03.10.2004	Cerro Negro, Chile	Tailings dam failure	50,000 t of tailings	Contamination of local stream
27.08.2002	San Marcelino, Phillippines	Overflow spillway failure after heavy rain	?	Villages flooded with waste; contamination of lake and stream system
22.06.2001	Sebastiao das Aguas Claras, Brazil	Tailings dam failure	?	At least 2 mine workers killed
18.10.2000	Nandan, China	Tailings dam failure	?	At least 15 people killed, 100 missing; more than 100 houses destroyed
11.10.2000	Inez, USA	Tailings dam failure	950,000 m^3 of coal waste slurry released into local streams	Contamination of 120 km of rivers and streams; fish kills

Table 4.2 (continued)

Date	Location	Incident	Release	Environmental impact and fatalities
09.09.2000	Aitik, Sweden	Tailings dam failure	1 million m^3 of water from the settling pond	?
04.05.2000	Grasberg, Irian Jaya	Waste rock dump failure after heavy rain	Unknown quantity of heavy metal bearing wastes	4 people perished; contamination of streams
10.03.2000	Borsa, Romania	Tailings dam failure after heavy rain	22,000 t of heavy metal bearing tailings	Contamination of streams
30.01.2000	Baia Mare, Romania	Tailings dam crest failure after heavy rain and snow melt	100,000 m^3 of cyanide-bearing contaminated liquid and tailings	Contamination of streams; massive fish kills and contamination of water supplies of >2 million people
26.04.1999	Surigao del Norte, Philippines	Tailings spillage from pipe	0.7 Mt of cyanide-bearing tailings	17 homes buried; 51 ha covered with tailings
31.12.1998	Huelva, Spain	Dam failure during storm	50,000 m^3 of phospho gypsum tailings with pH 1.5	Spillage into local river
25.04.1998	Los Frailes, Aznacollar, Spain	Collapse of dam due to foundation failure	4.5 million m^3 of acid, pyrite-rich tailings	2616 ha of farmland and river basins flooded with tailings; 40 km of stream contaminated with acid, metals and metalloids
22.10.1997	Pinto Valley, USA	Tailings dam slope failure	230,000 m^3 of tailings and waste rock	16 ha covered with tailings
29.08.1996	El Porco, Bolivia	Dam failure	0.4 Mt	300 km of stream contaminated
March 1996	Marinduque Island, Philippines	Loss of tailings through drainage tunnel	1.5 million t	Siltation of water courses
December 1995	Golden Cross, New Zealand	Dam movement	Nil	Nil

Table 4.2 (continued)

Date	Location	Incident	Release	Environmental impact and fatalities
02.12.1995	Suriago del Norte, Philippines	Dam foundation failure after earthquake	50,000 m^3	12 people killed; coastal pollution
19.08.1995	Omai, Guyana	Tailings dam failure	4.2 million m^3 of cyanide-bearing tailings	80 km of local river declared environmental disaster zone
22.02.1994	Merriespruit, South Africa	Dam wall breach after heavy rain	600,000 m^3	17 people killed; extensive damage to town
14.02.1994	Olympic Dam, South Australia	Leakage of uranium tailings dam into aquifer	5 million m^3	?
1993	Marsa, Peru	Tailings dam failure from overtopping	?	6 people killed
January 1992	Luzon, Philippines	Collapse of dam due to foundation failure	80 Mt	?
1989	Ok Tedi, Papua New Guinea	Collapse of waste rock dump and tailings dam	170 Mt waste rock and 4 Mt tailings	Flow into local river
30.04.1988	Jinduicheng, China	Breach of dam wall	700,000 m^3	20 people killed
19.01.1988	Grays Creek, USA	Dam failure due to internal erosion	250,000 m^3	?
May 1986	Itabirito, Brazil	Dam wall burst	100,000 m^3	Tailings flow 12 km downstream
1986	Huangmeishan, China	Dam failure from seepage/instability	?	19 people killed
19.07.1985	Stava, Italy	Failure of fluorite tailings dam due to inadequate decant construction	200,000 m^3	269 people killed; two villages buried/wiped out
03.03.1985	Veta de Agua, Chile	Dam wall failure due to liquefaction during earthquake	280,000 m^3	Tailings flow 5 km downstream
03.03.1985	Cerro Negro, Chile	Dam wall failure due to liquefaction during earthquake	500,000 m^3	Tailings flow 8 km downstream

Table 4.2 (continued)

Date	Location	Incident	Release	Environmental impact and fatalities
08.11.1982	Sipalay, Philippines	Collapse of dam due to foundation failure	28 Mt	Widespread inundation of agricultural land
18.12.1981	Ages, USA	Dam failure after heavy rain	96,000 m^3 of coal refuse slurry	Slurry flow downstream; 1 person killed; fish kill; homes destroyed
13.10.1980	Tyrone, USA	Dam wall breach due to rapid increase in dam wall height	2 million m^3	Tailings flow 8 km downstream
16.07.1979	Church Rock, USA	Dam wall breach	360,000 m^3 of radioactive tailings water; 1000 t of tailings	Contamination of river sediments up to 110 km downstream
1978	Lincoln, Montana	Dam wall breached by flood water following a small landslide	153,000 m^3 of tailings	Tailings flow into local river
31.01.1978	Arcturus, Zimbabwe	Slurry overflow after heavy rain	30,000 t	1 person killed; extensive siltation
14.01.1978	Mochikoshi, Japan	Wall failure of gold-silver tailings dam due to liquefaction during earthquake	80,000 m^3	1 person killed; tailings flow 7–8 km downstream
01.02.1977	Milan, USA	Dam failure	30,000 m^3	Nil
01.03.1976	Zlevoto, Yugoslavia	Dam failure due to excessive water levels and seepage	300,000 m^3	Tailings flow into river
1975	Mike Horse, USA	Dam failure after heavy rain	150,000 m^3	?
11.11.1974	Bafokeng, Impala, South Africa	Embankment failure of platinum tailings dam due to excessive seepage	3 million m^3	15 people killed; tailings flow 45 km downstream
01.06.1974	Deneen Mica, USA	Dam failure after heavy rain	38,000 m^3	Tailings flow into river
26.02.1972	Buffalo Creek, USA	Failure of coal refuse dam after heavy rain	500,000 m^3	150 people killed; 1500 homes destroyed

Table 4.2 (continued)

Date	Location	Incident	Release	Environmental impact and fatalities
1971	Florida, USA	Tailings dam failure caused by excessive seepage	0.8 Mt	Peace River polluted over a distance of 120 km
1970	Mufulira, Zambia	Tailings move into underground workings	1 Mt	89 miners killed
1967 and 1968	Blackpool and Cholwich, Great Britain	Failure of kaolinite tailings dams	?	?
1966	East Texas	Flow of liquefied tailings from impoundment caused by excessive seepage	80,000–130,000 m^3 of gypsum	?
21.10.1966	Aberfan, Great Britain	Liquefaction of coal refuse dam after heavy rain	?	144 people killed
1965	El Cobre, Chile	Liquefaction of eleven tailings dams during earthquake	2 Mt	250 people killed
25.02.1963	Louisville, USA	Failure of calcium carbide tailings dam due to freezing of down stream slope	?	?
1944	Aberfan, Great Britain	Failure of coal refuse dam	?	?
December 1939	Abercyan, Great Britain	Liquefaction of coal refuse dam	?	?
1939	Cilfyndd Common, Great Britain	Failure of coal refuse dam	0.18 Mt	Flow into local river
15.12.1928	Barahona, Chile	Liquefaction of copper tailings dam during earthquake	4 Mt	54 people killed

If failure occurs, tailings may enter underground workings or more commonly, the wastes spill into waterways and travel downstream. Depending on the dam's location, failures of tailings dams can have catastrophic consequences. Streams can be polluted for a considerable distance downstream, large surface areas can become covered with thick metal-rich mud, the region's sediment and water quality can be reduced, and contaminants may enter ecosystems (e.g. Aguilar et al. 2007; Benito et al. 2001; Cabrera et al. 2008; Hinojosa et al. 2008; Hita et al. 2008; Hudson-Edwards et al. 2003; Macklin et al. 2003; Martín et al. 2007, 2008; Ordóñez Fernandez et al. 2007; Simón et al. 2008, 2009; Vanderlinden et al. 2006; Villarroel et al. 2006). Tailings dam failures in numerous countries have caused the loss of human life and major economic and environmental costs (Table 4.2) (Mining Journal Research Services 1996).

The prevention of tailings dam failures requires: (a) an effective geotechnical characterization of the tailings site; and (b) a detailed understanding of the risk of local natural hazards such as earthquakes, landslides, and catastrophic meteorological events. It is important to design tailings dams to such a standard that they can cope with extreme geological and climatic events.

Most tailings dam failures have been in humid, temperate regions. In contrast, there have been very few tailings dam failures in semi-arid and arid regions. However, tailings dams in semi-arid climates suffer from other chronic difficulties including seepage problems, supernatant ponds with high levels of process chemicals, dust generation, and surface crusting. Crusting prevents drying out of tailings, and rehabilitation may not be undertaken for many years after tailings deposition has ceased.

4.3.4 Monitoring

Monitoring of tailings dam structures is essential in order to prevent environmental pollution and tailings dam failures and spillages. Site specific conditions require tailored monitoring programs. The monitoring program should address the following aspects:

- *Dam performance.* Performance monitoring of tailings dams includes measurements of the filling rate, consolidation, grain size distribution, water balance, and process chemical concentrations such as cyanide.
- *Impoundment stability.* Impoundment stability monitoring establishes the phreatic surface in the embankment and tailings as well as the slope stability and pore pressure within the tailings.
- *Environmental aspects.* Environmental monitoring includes: meteorological observations; measurements of radioactivity levels; investigations of the tailings chemistry and mineralogy; performance of geochemical static and kinetic tests for AMD generation potential; and chemical analyses of ground, surface and seepage waters, downstream stream sediments, and dust particles. Ground water monitoring is an integral part of tailings monitoring and allows an evaluation of

tailings seepage into aquifers (Environment Australia 1995; Robertson 1994). Piezometers are essential to monitor water pressure and water level in the impoundment. Piezometers and boreholes also need to be established at background points and along the ground water flowpath that is expected to be affected by tailings leachates. Suitable computational tools (e.g. MODFLOW) are available to model ground water flow and to illustrate potential impacts of leachates on ground water aquifers.

4.3.5 Wet and Dry Covers

Tailings disposal areas can occupy large areas of land and render them useless for future land use unless the tailings repositories are covered upon mine closure. Also, uncovered tailings are susceptible to severe water and wind erosion because of their fine grain size. There are numerous examples where wind-blown particles from uncovered tailings have polluted air, streams and soils and created health problems for local communities (Hossner and Hons 1992). Hence, the objectives of tailings covers are twofold: (a) to prevent ingress of water and oxygen into the processing waste; and (b) to prevent wind and water erosion.

During operation tailings dams are mostly covered with water, and these wet covers prevent wind erosion. Wet covers over sulfidic tailings also prevent sulfide oxidation and acid production (Sect. 2.10.1). Upon closure and rehabilitation, flooding of reactive tailings and establishment of a shallow water cover on top of tailings will curtail sulfide oxidation (Romano et al. 2003). Amending water-saturated tailings with organic carbon may also result in an abundance of sulfate reducing bacteria (SRB), a reduction in dissolved sulfate and metal contents, the formation of secondary mineral precipitates, and an improvement in water quality of tailings ponds (Lindsay et al. 2009b). The placement of tailings into an aqueous environment can only be used in regions where climatic conditions will sustain a permanent water cover. The implementation of water covers over oxidized tailings is inappropriate because metals dissolve into the water cover or are present as water-soluble salts. Such flooded tailings impoundments require a protective layer such as peat at the tailings/water interface to inhibit metal transport (Simms et al. 2001).

A common rehabilitation strategy of tailings involves dry capping. This technique is applied to tailings deposited in tailings dams or backfilled into mined-out open pits. Before dry capping can proceed, the tailings need to settle and consolidate (i.e. *to thicken*). Thickening is the process by which water is removed from the tailings and the volume of the waste is reduced. In some cases, appropriate civil engineering techniques such as wicks, drains or filter beds have to be put into place to ensure consolidation and drying out of tailings in tailings dams and open pits. After drying out and consolidation of the tailings, dry covers are constructed from locally available solid materials. Dry cover designs for tailings are numerous and site specific (Fig. 4.9). They include single layer and multi-layered designs and are largely identical to the dry cover techniques for sulfidic waste rock dumps (Sect. 2.10.2). Dry covers range from the direct establishment of native vegetation

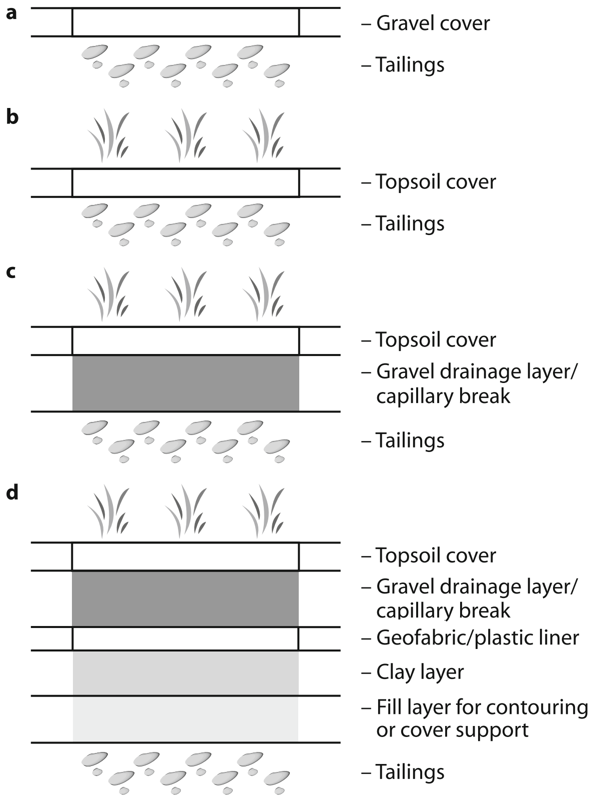


Fig. 4.9 Schematic cross-sections illustrating the principal dry cover designs for tailings storage areas (after Environment Australia 1995; Hutchison and Ellison 1992); (**a**) gravel layer; (**b**) single soil cover and revegetation; (**c**) multilayered soil cover and revegetation; (**d**) surface recontouring plus a multi-layered cover incorporating an infiltration barrier

on the waste to complex, composite covers (Hutchison and Ellison 1992; Patterson et al. 2006). The latter type has a number of layers, some compacted to reduce their permeability and others uncompacted to support vegetation. Materials used for dry covers include geotextiles, low sulfide waste rocks, oxide wastes, organic wastes, clay, soils, and clay-rich subsoils. A top surface cover of soil on all external surfaces provides a substrate for a self-sustaining plant cover. Suitable drainage installed prevents erosion of the dam. Additional earthworks may be necessary such as diverting creeks, reprofiling of the slopes of the side walls, and rock armouring of the side walls in order to prevent erosion and slumping of the walls.

4.4 Thickened Discharge and Paste Technologies

The thickened tailings discharge and paste technologies remove a significant proportion of water from the tailings to produce a high-density slurry or paste (Brzezinski 2001; Environment Australia 1995; Williams and Seddon 1999). The water is removed from the tailings at or prior to the point of tailings discharge, and it is possible to create a self-supporting stack or hill of tailings. Consequently, the waste

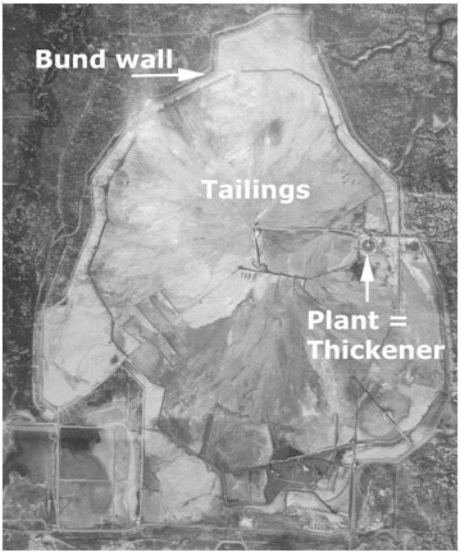


Fig. 4.10 Aerial photograph of the tailings disposal facility at the Kidd Creek base metal mine, Canada. Over 100 million tonnes of tailings have been spread out as a cone with a 2.4 km diameter using thickened tailings disposal

impoundment does not contain large amounts of water. In an arid to semi-arid environment, solar drying of the tailings completes rapid consolidation.

The thickened tailings discharge method is used to construct storage dumps whereby tailings are thickened in a large settler and discharged onto a sloped bed (Fig. 4.10). This technique results in a steep cone of dried tailings. Alternatively, thickened tailings may also be spread out in gently sloped layers for drying. The disposal facility is then constructed progressively as each waste layer is progressively stacked on top of each other. Such stacking of thickened tailings is, for example, carried out at alumina processing plants for the disposal of fine tailings (i.e. red mud) from bauxite refining.

The thickened discharge and paste technologies have numerous advantages. Thickened tailings disposal sites do not cover large tracts of lands as conventional tailings dams do. The technologies also reduce water consumption, the risk of water shortage at the mine, and hydraulic sorting of tailings particles (Brzezinski 2001; Environment Australia 1995; Williams and Seddon 1999). Compared to tailings dams, the methods have economic advantages to the operator and reduce the risks of tailings dam failure, water run-off, and leaching. However, thickened tailings operations may also be subject to dust generation or even to failure due to liquefaction of the waste (McMahon et al. 1996).

4.5 Backfilling

Tailings may be pumped into underground workings and mined-out open pits (i.e. in-pit disposal). Such a disposal practice has been used in the mining industry for over 100 years. Tailings are placed directly into the voids from which the ore was

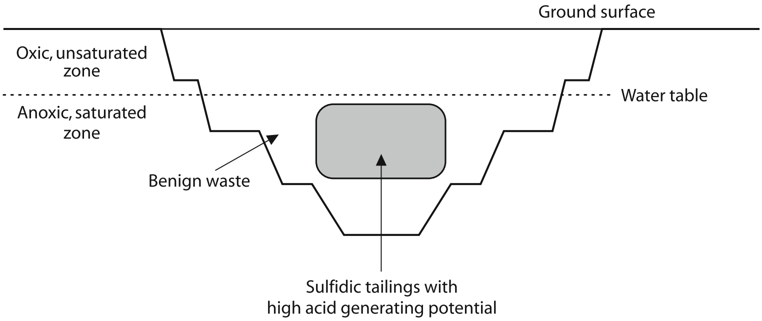


Fig. 4.11 Backfilled open pit showing return of pre-mining ground water table and different hydrological zones (after Abdelouas et al. 1999)

won. Backfilling of open pit mines eliminates the formation of an open pit lake. Once backfilling has occurred, ground water will eventually return, approximating the pre-mining ground water table (Fig. 4.11). Within a backfilled open pit, several zones can be identified in terms of oxygen abundance. The saturated anoxic zone is located below the ground water table. Mine waste with the highest acid generating capacity is to be placed into this zone in order to prevent contact of sulfide minerals with oxygen. Wastes with very high acid-generating capacities may require the addition of neutralizing agents prior to or during backfilling.

The advantages of in-pit disposal compared to other tailings disposal methods include:

- The placement of tailings below the ground water table, ensuring limited interaction with the hydrosphere and biosphere;
- No spillages, failures or erosion of tailings dams;
- The backfilling of a large open void with mine waste to such an extent that landscaping and revegetation of the area is possible; and
- A greater depth of cover, ensuring suppression of oxidation of sulfidic wastes or radiological safety of uranium tailings.

While backfilling may appear at first sight a suitable technique to fill and remediate unwanted mine workings, it can, nevertheless, bear several problems:

- The placement of tailings liquids and solids into open pits does not mean that the tailings are as secure chemically and physically as the original mined ore. Chemical and mineralogical changes occur within the processed ore during and after mineral processing. Tailings are not fine-grained ores. They contain very fine-grained, modified and in many cases, reactive ore particles with a large surface area. In addition, tailings contain interstitial pore waters with reactive process chemicals and other dissolved elements and compounds.

- Most pits are deep with a relatively small surface area. In such cases, the evaporation rate of water is slow, and the consolidation of tailings takes considerable time (Environment Australia 1995).
- Any backfill material placed below the water table will become part of the aquifer (Lewis-Russ 1997; Siegel 1997). In particular, if the open pit is not lined with clay or other impermeable liners and if the tailings are disposed of below the post-mining ground water table, the tailings will become part of the local aquifer. Water-rock reactions may lead to the mobilization of contaminants into ground waters. The impact depends on the mineralogical and geochemical characteristics of the tailings and their permeability. The permeability of backfilled material can be very low if significant compaction has occurred. However, if the water is flowing through reactive, permeable and soluble materials, the increased surface area of the waste coupled with its reactivity will result in ground waters enriched in various components. For example, if oxidized sulfidic waste is disposed of in an open pit or a flooded pit, soluble secondary minerals may dissolve in the pore water. This may lead to the release of metals, metalloids, and salts to the ground water or to the overlying water column. Surface or ground water may need to be treated to prevent environmental contamination.

Sulfidic tailings should be disposed of into open pits or underground workings below the post-mining water table once mining ceases. Placement of sulfidic tailings below the post-mining ground water table will preclude any ready access of atmospheric oxygen to sulfidic tailings. The backfill of tailings into underground workings as tailings-cement paste mixtures is also possible. The paste backfill is produced in a paste plant using thickened tailings, sand or crushed rock, and cement. Such a technique is primarily used to provide ground support during underground mining (Bertrand et al. 2000). The disposal technique also provides limited acid buffering capacity to the waste as cement contains minerals that are able to neutralize acid generated by the oxidation of sulfides.

4.6 Riverine and Lacustrine Disposal

Tailings may also be disposed into rivers and lakes. Once discharged into the streams, the solids and liquids of tailings may be transported considerable distance downstream. In historic mining areas, the riverine and lacustrine disposal practice was commonly applied (Figs. 4.12 and 4.13) (Bäckström et al. 2006; Bhattacharya et al. 2006; Black et al. 2004; Jambor et al. 2009; Palumbo-Roe et al. 2009; Toevs et al. 2006; Willscher et al. 2007). Unconstrained erosion and associated leaching of tailings may also occur from abandoned waste repositories (Gómez-Alvarez et al. 2009; Owor et al. 2007). At these locations, the transport of waste particles and leachate may impact on regional stream and water quality, even years after the

Fig. 4.12 Cobalt Lake, Cobalt, Canada. Historic silver mines and processing plants placed their tailings into local lakes. Leaching from these wastes continues and consequently, lakes and streams around Cobalt are laden with arsenic

Fig. 4.13 Sulfidic tailings layer in ephemeral creek bed downstream from the derelict lead-zinc Webbs Consols mine, Australia. The tailings contain wt.% levels of arsenic, lead and zinc

mines closed. Riparian plant species may grow on tailings contaminated substrates, leading to metal uptake by plants and possible metal transfer into wildlife and domestic livestock (Bourret et al. 2009; Boyter et al. 2009). Sulfidic tailings may be exposed on the banks of impacted waterways and represent potential AMD sources.

Rehabilitation of streams and lakes contaminated with tailings may involve dredging, removal, and disposal of the tailings in suitable impoundments, or revegetation of the banks with suitable metal-tolerant local plant species. If the deposited tailings are sulfidic, oxidation of sulfides is possible during dredging, draining or erosion. Therefore, precautions must be taken to prevent any change to these potentially reactive, acid materials. While sulfide minerals in discharged mine tailings generally oxidize in oxygenated waters, sulfide grains can be transported considerable distances downstream from their source zone without weathering (Leblanc et al. 2000).

Today, riverine disposal of tailings and erodible waste dumps are used at copper mine sites in Indonesia (Grasberg-Ertsberg) and Papua New Guinea (Porgera, Ok Tedi, Bougainville) (Apte et al. 1996; Hettler et al. 1997; Jeffrey et al. 1988; Salomons and Eagle 1990; Trisasongko et al. 2006) (Fig. 4.14). Tailings are discharged directly into the streams or after neutralization. In these earthquake- and landslide-prone, rugged, high rainfall areas, the construction of tailings dams has been proven to be geotechnically impossible, so riverine disposal of tailings is preferred. In these environments, natural erosion rates are very high, and landslides are common. As a result, high natural sediment loads occur in local streams and rivers which can dilute tailings discharges. This disposal practice comes at a price. It causes increased sedimentation of the river system, increased turbidity, associated flooding of lowlands, and contamination of stream and floodplain sediments with metals (Case Study 4.1). Diebacks of rainforests and mangrove swamps occur while the impact of elevated copper concentrations in sediments and waters on aquatic ecosystems will become clearer in the long term.

Fig. 4.14 Earthworks in the Ajkwa River, Irian Jaya, Indonesia. Tailings are discharged (~8.7 Mt per year) from the giant Grasberg-Ertsberg mine into the Ajkwa River, causing severe aggradation and flooding of vegetated lowland downstream of the mine. Areas inundated with tailings are to be turned into productive and sustainable agricultural land

Case Study 4.1. Riverine Tailings Disposal at Ok Tedi, Papua New Guinea

The Ok Tedi Mine

The Ok Tedi mine is one of the largest copper mines in the world. The mine is also a major contributor to the economy of Papua New Guinea (PNG), accounting for much of PNG's total annual export income (Murray et al. 2000a). Ok Tedi is located in highly mountainous terrane at an altitude of approximately 1600 m. Annual rainfall is at 8–10 m per year, and the mine is located in an earthquake- and landslide-prone area. The construction of a tailings dam was attempted; however, the waste repository could not be completed due to landslides. Since 1984, the large-scale open cut operation produces a copper–gold–silver concentrate as well as significant quantities of mining and processing wastes.

Discharge of Waste into Ok Tedi River

Since 1986, tailings have been discharged and waste rock dumps have been left to erode into the headwaters of the Ok Tedi and Fly River system. The discharge rate amounts to about 160,000 t of waste per day. Mine-derived wastes are transported from the mine site into the Ok Tedi River which flows into the Fly River, 200 km downstream of the mine site. The Fly River joins the even larger Strickland River. The combined river system flows via a large estuary and discharges about 120 Mt of sediment a year into the Gulf of Papua. The massive input of tailings and waste rock at the Ok Tedi mine has distinct hydrological, sedimentological and geochemical impacts on the Fly River system throughout the entire length of the river, a distance of over 1000 km (Hettler and Lehman 1995; Hettler et al. 1997; Salomons and Eagle 1990):

- *Increased turbidity.* The small grain size (<100 µm in diameter) and large quantity of wastes add to the suspended sediment load of the Ok Tedi River system. As a consequence, the suspended matter content in the Middle Fly River is 5–10 times higher than the natural background. The increase in suspended sediment load possibly impacts on aquatic organisms.
- *Increased sedimentation.* The tailings and mine waste solids are transported significant distances downstream from the mine. The wastes are then deposited as sediments on the floodplains of the Middle and Lower Fly River, in the delta of the Fly River, and in the Gulf of Papua. Very high

deposition rates of mine-derived sediment are found in floodplain environments. Floodplain lakes, creeks, channels, and cut-off meanders receive the greatest quantities of mine-derived sediment. The increased sedimentation on flood plains has buried large areas of tropical lowland rainforests and mangroves with a thin veneer of waste and has caused dieback of the vegetation on a large scale.

- *Metal contamination of sediments.* The near surface sediments – deposited along river channels, in lakes and swamps, and on floodplains – are enriched in copper and gold. Mobilization of copper occurs from the contaminated sediments into surface waters. Chronic copper toxicity to aquatic communities in the affected streams and floodplains are expected, and negative ecological impacts on the fish population may occur in the long term.

From 1984 to 2007, there would have been a release of 1400 Mt of waste into the tropical river system. Riverine disposal is allowed under and occurs in compliance with PNG laws and regulations. Increasing concern over environmental impacts has led to dredging trials in the lower Ok Tedi (Murray et al. 2000a). Sand and gravel particles are being dredged from the river bed and stored on the river bank. The dredging efforts may create suitable sediment traps which prevent the burial of lowland rainforests and mangroves with a thin veneer of mine waste.

4.7 Marine Disposal

Tailings may also be disposed of into the ocean. The marine disposal of tailings is a preferred option for handling tailings in coastal settings (Berkun 2005; Hesse and Ellis 1995; Jones and Ellis 1995; Rankin et al. 1997) (Case Study 4.2, Fig. 4.15).

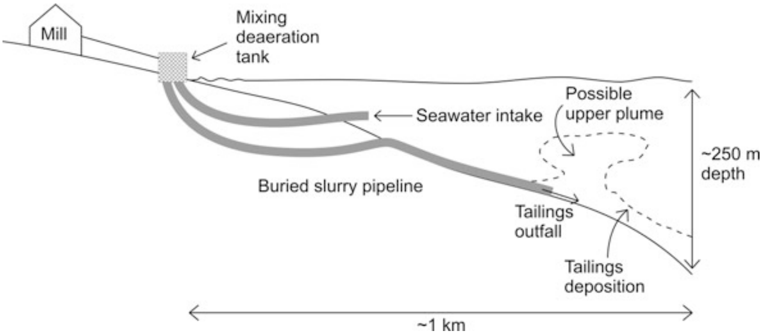


Fig. 4.15 Schematic cross-section of deep sea tailings placement (DSTP) (after Spitz and Trudinger 2009; Rankin et al. 1997)

Ideally, the aims of this disposal method are: (a) to place the tailings into a deep marine environment which has minimal oxygen concentrations; and (b) to prevent tailings from entering the shallow, biologically productive, oxygenated zone. Prior to their discharge, tailings are mixed with seawater to increase the density of the slurry. Upon their discharge from the outfall at usually more than 100 m below the surface, the tailings are transported down the seafloor to their ultimate resting place. The disposal technique achieves a permanent water cover and inhibition of sulfide oxidation, yet the physical dispersion of tailings must be assessed, and the extent of metal uptake from the tailings solids by fish and bottom dwelling organisms has to be evaluated (Blanchette et al. 2001; Johnson et al. 1998; Powell and Powell 2001; Rankin et al. 1997). Some tailings may contain bioavailable contaminants in the form of soluble metal hydroxides and sulfates. In addition, the mobility and bioavailability of metals and metalloids may increase once the tailings have been injected into the sea (Blanchette et al. 2001). Therefore, the submarine tailings discharge method requires waste characterization as well as modeling and monitoring of the disposal site.

Case Study 4.2. Submarine Tailings Disposal at the Black Angel Mine, Greenland.

The Black Angel Lead-Zinc Mine

The Black Angel lead-zinc mine site is located at 71 degrees north on the west coast of Greenland, some 500 km north of the Arctic Circle. The mine site is situated in an alpine landscape, where the 4 km long Affarlikassaa Fjord joins the 8 km long Qaamarujuk Fjord. The name Black Angel derives from the angelic appearance of an exposed contorted band of pelite, clearly visible on the face of the 700 m cliff face that overlooks the Affarlikassaa Fjord (Fig. 4.16). The orebodies were mined from 1973 to 1990 using underground methods, with a total production of 11 million tonnes of ore grading 4.1% Pb, 12.5% Zn and 30 ppm Ag (Asmund et al. 1994). The mineralisation consists of pyrite, sphalerite and galena and the sulfide orebodies are enclosed by thick marble units and clastic metasediments.

Tailings Discharge

The entrance to the mine was 600 m up the cliff facing Affarlikassaa Fjord. The mined ore was transported by an aerial cable car across the Fjord to an industrial area for processing. Mineral recovery was by conventional selective flotation and the tailings were discharged into the Affarlikassaa Fjord.

Fig. 4.16 View of the 700 m cliff face that overlooks the Affarlikassaa Fjord at the Black Angel mine, central West Greenland. Over 8 million tonnes of tailings and a large shoreline waste rock pile of 0.4 million tonnes were dumped into the Affarlikassaa Fjord. The two small black spots beneath the left wing of the angel-like figure are the cable car entrances to the mine. The ship MS Disko II is 50 m long

The total amount of discharged tailings was about 8 million tonnes, containing elevated arsenic, cadmium, copper, lead and zinc values (Poling and Ellis 1995).

Environmental monitoring of the fjord system prior to mining showed elevated metal concentrations in local seaweed and mussels (Poling and Ellis 1995). These metal distributions were due to the natural exposure of the sulfide orebodies to weathering and erosion. Within a year from starting the submarine tailings disposal, distinctly elevated lead and zinc values were found in waters and biota of the entire fjord system. This led to extensive investigations into the origin and dispersal mechanisms of metal contaminants. Prior to marine discharge, it was assumed that all residual metals would be present in the tailings only as insoluble sulfides. Yet, the tailings contained lead and zinc phases that were soluble in seawater. In addition, oceanographic investigations contradicted an earlier assumption that the discharged tailings are permanently protected by stagnant bottom waters of the Affarlikassaa Fjord. The studies demonstrated that the disposal site did not have a permanently stratified water column and that complete mixing of the water took place during winter (Poling and Ellis 1995).

Consequently, several changes were made to the mineral processing and tailings discharge which significantly reduced the levels of metal release to the environment. Firstly, improvements in mineral processing led to tailings with lower lead values released to the ocean (1973, 0.4% Pb; 1989, 0.18% Pb). Also, the tailings were treated with chemicals, deaerated prior to discharge and mixed with seawater. These initiatives led to the coagulation and flocculation of small tailings solids, prevented the dispersion of metal-rich particles via mineral-laden air bubbles, and increased the tailings density which led to the deposition of tailings in bottom waters. As a result, the lead and zinc concentrations in water and biota of the Affarlikassaa Fjord decreased (Asmund et al. 1994).

Transfer of Metals into the Fjord

Despite the improvements to the submarine tailings disposal system, metal contamination of the area could not be prevented. The tailings discharge resulted in the metal enrichment of water, suspended particulate matter, sediment and biota in the Affarlikassaa and Qaamarujuk Fjords up to 70 km away from the tailings outfall (Elberling et al. 2002; Loring and Asmund 1989). During mining, analyses of seals and fish species largely revealed no metal contamination, while deep sea prawns and capelins as well as the livers of certain fish species and seabirds contained lead concentrations above the safe consumption limit (Asmund et al. 1994). Mussels and seaweed obtained increasingly elevated cadmium, lead and zinc concentrations, depending on their location relative to the tailings outfall.

Since mine closure, metal concentrations have declined in fjord waters as well as animal and plant life (Asmund et al. 1994). Yet, dispersion and release of metals from the tailings continues (Elberling et al. 2002). In hindsight, detailed mineralogical, geochemical and oceanographic studies prior to tailings discharge would have allowed an informed decision on whether submarine tailings disposal was appropriate at this particular site (Poling and Ellis 1995).

Improper disposal of tailings from industrial operations and unregulated dumping of tailings from artisanal mining into shallow marine environments, bays, lagoons, estuaries and shorelines come at a price. Such practices can cause increases in metal and metalloid concentrations of ocean waters, sediments, seaweeds and molluscs, and may impact on shallow and deep water habitats including fish communities (Andrade et al. 2006; Blackwood and Edinger 2007; Dambacher et al. 2007; Dold 2006; Edinger et al. 2007; Martínez-Sánchez et al. 2008; María-Cervantes et al. 2009). There is a risk to human health if the local marine life is consumed by the local population.

4.8 Recycling and Reuse

An alternative to the disposal of tailings is to put the waste to good use. For example, manganese tailings may be used in agro-forestry and as coatings, resin cast products, glass, ceramics, glazes as well as building and construction materials (Verlaan and Wiltshire 2000). In future, base metal tailings and low grade metal ores may be planted with suitable plant species which extract the metals from the substrate (Scientific Issue 4.1). Phytomining may not only recover metals from wastes, but the technique may also turn hazardous materials into benign wastes with much lower metal concentrations.

Scientific Issue 4.1. Phytoremediation and Phytomining of Metalliferous Wastes

Introduction

Plants and microorganisms (fungi, yeast cells, algae, bacteria) can influence the behaviour of metals and metalloids in surface environments. While some organisms tolerate elevated concentrations of dissolved precious and heavy metals and metalloids, others can dissolve, contain or immobilize such elements. Organisms – which contain or immobilize metals and metalloids – extract the dissolved elements by adsorption, intracellular uptake, and chemical transformations. The metals and metalloids, accumulated by these living plants and microorganisms or their dead biomass, may amount up to several weight percent of the cell dry weight.

Phytoremediation

The ability of particular plants and microorganisms to influence the cycling of metals may be used in the clean-up of metal contaminated soils, sediments, waters, and wastes. Plants have been used for some time to remove or immobilize environmental contaminants, a process which is commonly referred to as *phytoremediation* (Brooks 1998). Phytoremediation was initially applied in the 19th century when authorities began to treat municipal wastewaters in constructed wetlands and spray irrigation systems. Today, phytoremediation is an emerging technology for the rehabilitation of contaminated sites (Johansson et al. 2005). The techniques of phytoremediation can be grouped into the following strategies:

- *Phytostabilization.* Plants transform toxic forms of metals into non-toxic forms. This technique uses metal-tolerant plants to immobilize heavy metals in the root zone. Metals are absorbed into and accumulated by roots, adsorbed onto roots, or precipitated in the root zone. The processes reduce mobility and bioavailability of the metals (Grandlic et al. 2008; King et al. 2008; Mendez et al. 2007; Santibáñez et al. 2008). Plants that tolerate elevated metal concentrations in the substrate and do not transport them into the above-ground biomass may have direct applications in the remediation of mined land (cf. Sect. 2.9.2).

- *Rhizofiltration.* Dissolved heavy metals – surrounding the root zone – are adsorbed or precipitated onto plant roots, or the metals are absorbed into the roots. The technique may be applied to decontaminate ground water rather than soils and wastes.
- *Phytoextraction.* This strategy involves the uptake of precious and heavy metals by roots into the above ground portions of plants (i.e. metal accumulators). A phytoextraction operation could entail planting a hyperaccumulator crop over the contaminated site. This would be followed by harvesting and incineration of the biomass to produce a metal concentrate for subsequent disposal. The ideal plant to use for phytoextraction has a large biomass, grows well in metal-rich environments, and accumulates metals to high concentrations. Plants that accumulate large concentrations of metals in their dry biomass are termed *hyperaccumulators* (Brooks 1998). There are natural hyperaccumulators for a range of metals and metalloids (As, Cd, Co, Cu, Mn, Ni, Pb, Se, Tl, U, Zn). However, many hyperaccumulators tend to grow slowly and produce little biomass. An alternative approach is to genetically engineer fast-growing species to improve their metal tolerance and metal accumulating capacity (Pilon-Smits et al. 2000). The key limitation to metal uptake by any plant species is the solubility of the metal in the root zone since metals must be dissolved in the soil solution for uptake to occur. The natural solubility of metals can be artificially induced by adding suitable chemicals to the substrate in which the plants grow. The complexing agents dissolve additional metals which become bioavailable and are subsequently taken up by the plants. Induced phytoextraction can increase the natural uptake of metals by plants (Anderson et al. 1998).

Phytomining

An alternative strategy to phytoremediation is phytomining (Anderson et al. 1999; Robinson et al. 1997). In this emerging technology, hyperaccumulators are not only used to remove metals from substrates, they are also used to yield a metal-rich biological ore for smelting. Phytomining would be conducted as follows: Hyperaccumulators would be planted on wastes and ores. The plants accumulate metals in their harvestable tissue, followed by the removal of plant tissue from the site, ashing of the plants, and extraction of the metals. In most cases, a phytomining operation would be conducted on low grade ores or wastes such as tailings, containing metal concentrations too low for conventional extraction. Phytomining represents an emerging technology and may *clean* ores and wastes to shallow depths. Phytomining has many advantages and unique features which could make it part of future metal mining operations.

The capture and storage of atmospheric carbon dioxide in tailings represents a potential carbon dioxide sequestration technology. Stabilizing atmospheric greenhouse gas concentrations by mid-century is one of the world's great challenges. The scale of the possible problems caused by increased atmospheric carbon dioxide has promoted research and development of various sequestration efforts including geological storage, ocean storage, biological and terrestrial approaches, and mineral carbonation.

Mineral carbonation is a scheme to sequester carbon dioxide by inducing the fixation of carbon dioxide as carbonate minerals. It involves the reaction of atmospheric carbon dioxide with either mafic/ultramafic rocks, alkaline solid wastes (e.g. slags, ashes), relatively unstable silicates (e.g. olivine, wollastonite, serpentine, anorthite), or glass to bring about the formation of carbonates. Both in nature and during induced mineral carbonation reactions, the metal-bearing mineral or glass dissolves, releasing metal cations (e.g. Fe^{2+}, Mg^{2+}, Mn^{2+}, Ca^{2+}). Then, through a series of reactions, atmospheric carbon dioxide reacts with the liberated divalent cations and metal carbonates such as calcite, dolomite, magnesite, ankerite and siderite precipitate. These carbonates are thermodynamically stable products and safe, environmentally benign minerals. Ultramafic mine tailings typically have large surface areas and high mass fractions of reactive calcium, iron and/or magnesium-bearing minerals, making them an attractive source material for mineral carbonation. Consequently, the abundance of fine-grained alkaline tailings and their large surface area could make them very suitable for carbonation reactions. Published studies of mineral carbonation related to mine wastes have been restricted in the past to: (a) serpentine-rich tailings (Wilson et al. 2006, 2009a, b); and (b) laboratory experiments on bauxite red mud (Bonenfant et al. 2008). Yet, despite the knowledge that atmospheric carbon dioxide can be captured in mine wastes, mineral carbonation of alkaline tailings has enjoyed very limited scrutiny, and our knowledge of mineral carbonation and its possible application as carbon dioxide sequestration technology are still incomplete.

4.9 Summary

Mineral processing methods of metalliferous hard rock deposits involve crushing, grinding and milling the ore, and concentrating the ore minerals. Chemical additives are often employed to help separate or leach the ore minerals from the gangue phases. The additives include flotation reagents, modifiers, flocculants/coagulents, oxidants, and hydrometallurgical agents. The desired fraction containing the ore minerals is recovered, and other materials are disposed of as wastes. Such wastes are referred to as tailings. Tailings consist of solids and liquids. The liquids contain process chemicals which influence the chemical behaviour and mobility of elements within the waste repository.

The pH of tailings waters is influenced by the applied processing technique. Any sulfuric acid added as process chemical or generated by sulfide oxidation will leach ore and gangue minerals. In extreme cases, the applied processing techniques may create highly acid or alkaline tailings with high concentrations of dissolved and soluble salts, metals and metalloids.

Tailings contain minerals similar to those of waste rocks from the same deposit, only in much smaller grain size. Primary minerals are the ore and gangue minerals of the original ore. Secondary minerals crystallize during weathering of the ore. Tertiary and quaternary minerals form before, during, and after the deposition of the tailings in their impoundment as a result of chemical reactions. Evaporation of tailings water commonly leads to the formation of mineral salts such as gypsum at and below the tailings surface.

The accumulation of sulfide-rich tailings sediments may occur in an impoundment, and subsequent sulfide oxidation and AMD generation may be possible. In particular, if sulfidic tailings are present within the unsaturated zone of an inactive impoundment, sulfide oxidation will occur. However, tailings remain water saturated during operation and are deposited as fine-grained sediments that have a relatively low permeability. Consequently, tailings often generate AMD more slowly than coarser, yet more permeable waste rocks from the same deposit.

Disposal of tailings commonly occurs into engineered tailings dams. Tailings dams are constructed like conventional water storage type dams whereby the tailings are pumped as a water-rich slurry into the impoundment. The safety record of tailings dams is poor. On average, there has been one major tailings dam failure or spillage every year in the last 30 years. Tailings dam failures are due to liquefaction, rapid rise in dam wall height, foundation failure, excessive water levels, or excessive seepage. Tailings dam failures and spillages have caused environmental impacts on ecosystems, loss of life, and damage to property. Other concerns with tailings dams include air pollution through dust generation, release of radiation from tailings, and seepage from the tailings through the embankment into ground and surface waters. Monitoring of tailings dams is essential and includes investigations on dam performance, impoundment stability, and environmental impacts. Dry capping techniques of tailings are highly variable and site-specific, and consist of single layer and multi-layered designs using compacted and uncompacted materials.

Tailings disposal, using the thickened discharge or paste technology, results in a cone or stack of dried tailings. The methods are based on the discharge of dewatered tailings into the impoundment. Containment of tailings in open pits and underground workings is also possible; nonetheless, consolidation of the wastes may take considerable periods of time. If the tailings are placed below the post-mining ground water table, the restricted access of atmospheric oxygen will restrict any sulfide

Table 4.3 Web sites covering aspects of tailings

Organization	Web address and description
Tailings.Info	*http://www.tailings.info/* Detailed information on tailings
InfoMine	*http://technology.infomine.com/tailingsmine/* News and reports on tailings
World Information Service on Energy (WISE) – Uranium Project	*http://www.wise-uranium.org* Case studies, information, and record on tailings dam safety and failures

oxidation. An interaction of the tailings with ground water occurs if permeable, reactive, soluble tailings materials are present.

In historic mining areas, tailings were commonly discharged into nearby rivers. Today, such a disposal is applied in earthquake- and landslide-prone, rugged, high rainfall areas where the construction of engineered tailings disposal facilities has proven to be impossible. This disposal practice comes at a price. It can result in considerable metal contamination and increased sedimentation downstream. Similarly, submarine tailings disposal is applied in areas where high rainfall, increased seismicity, and limited land make the construction of tailings dams impossible. Tailings are released into the ocean at significant water depth well below wave base and commercial fishing grounds. While the oxidation of sulfides in deep sea environments is insignificant, the long term uptake of metals and metalloids from the tailings by bottom dwelling organisms remains to be investigated.

The ever increasing volume of tailings has stimulated research into their recycling potential. The alternative uses of tailings are dependent on the chemical and mineralogical characteristics of the wastes. Phytoremediation is one emerging technology whereby plants remove or immobilize metals in tailings. The technique has the potential to convert metal-bearing wastes and ores into benign wastes.

Further information on tailings can be obtained from web sites shown in Table 4.3.