Some Mining Applications of Unsaturated Soil Mechanics

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ABSTRACT: Unsaturated soil mechanics continues to play poor relation to saturated soil mechanics, although an unsaturated soil at a given density is stronger, less compressible and less permeable (i.e. performs better) than the same soil in a saturated state. There are many examples of unsaturated conditions in the mining field, including the wetting-up and drain-down of initially dry surface waste rock dumps; the irrigation and drain-down of heap leach materials; the drain-down, desiccation and rewetting of mine tailings; the dewatering of mineral products such as coal; the shear strength and compressibility of stored mine wastes; and the performance of geo-covers placed on mine wastes on rehabilitation. This paper highlights the key unsaturated soil mechanics parameters, overviews the nature of mining and processing wastes, and some products, and discusses the issues involved. Some applications of unsaturated soil mechanics addressing the shear strength, compressibility and permeability of mine wastes, and mineral products, are presented, together with data to highlight them.

1. INTRODUCTION

The key parameters of interest in soil mechanics are: (i) the strength, or the capacity of a soil to support load; (ii) the compressibility, or the deformation of a soil under an applied load; and (iii) the permeability (hydraulic conductivity), or the rate at which a soil will drain and deform under an applied load. These apply to both (water) saturated and unsaturated conditions.

The shear strength of saturated soils is typically assessed by *in situ* vane shear strength testing of soft cohesive soils, or by laboratory direct shear or triaxial shear strength testing of intact stiffer soils. The compressibility of saturated cohesive soils is typically assessed by laboratory consolidation testing. The saturated hydraulic conductivity of soils is assessed in the laboratory by constant or falling head permeameter testing, or indirectly from the results of consolidometer testing, depending on the permeability of the soil.

Estimates of the shear strength and compressibility of unsaturated soils can be obtained by *in situ* vane shear strength testing of desiccated soft soil profiles, or by laboratory direct shear or triaxial testing of soils from their *in situ* unsaturated state. Estimates of the hydraulic conductivity of an unsaturated soil can be obtained by a combination of its soil water characteristic curve (SWCC) and its saturated hydraulic conductivity. The shape of the unsaturated hydraulic conductivity relationship with matric suction is a function of the shape of the soil's SWCC, and the saturated hydraulic conductivity sets the intercept at near-zero matric suction or near-saturated conditions.

Simplistically, the shear strength of unsaturated soils can be accounted for by adding a cohesion term for the additional shear strength provided by matric suction, which increases the effective stress. It can also be accounted for, simplistically, by laboratory testing of soils in their unsaturated state. The greater stiffness of unsaturated soils can simplistically be accounted for by testing the compressibility of soils in the laboratory in their unsaturated state.

There are also more sophisticated laboratory test apparatuses available that allow testing under constant matric suction, although these are not discussed in this paper. It could be argued that in reality the matric suction a soil experiences will change as it is loaded and compressed, as will its degree of saturation and hydraulic conductivity.

These simplistic approaches to determining the key unsaturated parameters for application to predicting the behaviour of unsaturated mining and mineral processing wastes, and mineral products, are the theme of this paper.

2. MINING AND MINERAL PROCESSING WASTES

2.1 Wastes Produced by Mining and Mineral Processing

The exploitation of mineral ore bodies involves either open pit or underground mining, followed by mineral processing. Open pit mining produces coarse-grained wastes including *overburden* or *waste rock*, while underground mining produces only limited coarse-grained wastes from the excavation of access ways and ventilation shafts.

Mineral processing of crushed and ground ores from open pit or underground mining operations produces fine-grained wastes known as *tailings*. The smelting of metalliferous concentrates typically produces coarse-grained *slag* or *scats*. The washing of run-of-mine coal produces both *coarse reject* and tailings.

Low grade ore bodies that do not warrant the high cost of grinding may be leached in a heap to recover the commodity. The *spent heap leach material* constitutes another form of coarse-grained waste, which will be contaminated with the process chemicals applied on leaching.

The mining and processing of mineral ores has the potential to generate contaminated water, which may impact the surrounding environment, transported by surface or ground waters, or by the wind.

2.2 Hard Rock Metalliferous Ore Body Wastes

Open pit mining of hard rock, disseminated, metalliferous ore bodies, such as copper, gold, nickel, and zinc, involves blasting of the rock to produce particles typically finer than about 1 m in size. The barren or unmineralised *waste rock,* which may comprise about half of the rock mined, is typically hauled to a surface *waste rock dump* where it is typically end-dumped from a tip-head to form angle of repose slopes (see Figure 1).

For open pit mining, the minimum economic copper ore grade is of the order of 1%, while the minimum economic gold ore grade is of the order of 1 part per million (1 ppm). The minimum economic grade of a metalliferous ore will also depend on the stripping ratio of waste to ore, and whether more than one metal is present in the ore, which could add value and make sub-economic primary ore bodies viable.

Underground mining of hard rock metalliferous ore bodies involves blasting of the accessed ore to produce particles typically finer than a few hundred mm in size. Given its greater cost, underground mining is typically only economic for relatively high grade ore bodies (say up to 10% for copper ore or up to 10 ppm for gold ore). For high grade ores found in veins, very selective extraction may be economic. Open stoping may be economic for medium grade ores, while block caving may be economic for more low grade ores, approaching the cut-off grades for open pit mining.

The blasted ore is crushed to a maximum particle size of the order of 15 mm, before being ground in a rod or ball mill to a maximum particle size of the order of 1 mm, to expose the commodity. The ground ore is then processed to yield the mineral commodity. Typically, mineral processing involves dissolution of the exposed commodity; e.g. using an acid for metalliferous ores, and cyanide in an alkaline bath (at a pH of about 12 to prevent the formation of cyanide gas) for gold. The presence of more than one metal in the ore can make the ore body more economic, but it can also complicate processing, potentially making the ore body less economic.

Figure 1 Typical surface waste rock dump at a hard rock open pit mine

The waste ground rock flour that remains after the extraction of the commodity (or *tailings*) are typically disposed as a slurry by pumping to a surface *tailings storage facility* (see Figure 2). For metalliferous ores, the bulk of the crushed and ground ore ends up as tailings. Since the tailings are discharged to the storage facility as a slurry, considerable water is also discharged, much greater than rainfall in a dry climate, resulting in inevitable seepage from the facility during its operation.

Figure 2 Typical surface tailings storage facility at a hard rock open pit mine

Depending on the geochemistry of the ore and the process water used, and the process chemicals used, the chemistry of the pore water within the tailings will vary, dictating the chemistry of any seepage reporting from the tailings storage facility to the environment. In the arid Kalgoorlie mining region of Western Australia, the shortage of fresh water supplies has forced the use of hypersaline groundwater for processing, leading to hypersaline tailings and seepage.

2.3 Soft Rock Bulk Ore Body Wastes

Soft rock bulk ore bodies include iron ore, steaming (brown or black coal for power generation) and black coking coal (for steel-making), and bauxite. The mining of these bulk commodities is typically by open pit methods, although as shallow coal deposits are exploited there is a move to underground highwall and longwall mining. The mining of bulk ore bodies generates soil and soft rock *spoil*, while the washing of these ores for beneficiation purposes generates soil-like *tailings*.

The washing of iron ore, when needed to meet market specifications, typically produces relatively small volumes of relatively coarse-grained *tailings* (see Figure 3).

Figure 3 Typical surface tailings storage facility at an iron ore mine

The washing of run-of-mine black coal, typically required to meet market specifications, produces up to about 25% washery wastes, comprising *coarse reject* (typically -50 mm) and *tailings* (typically -0.5 mm). Conventionally, the coarse reject is disposed of in *surface dumps* (see Figure 4), and the tailings in *surface tailings storage facilities* (see Figure 5), although many coal mines in Australia and Indonesia *co-dispose* of the washery wastes by combined pumping to a storage facility (Figure 6). As open pits become available and mining moves underground, the completed pits are often used to store coarse reject and tailings, or co-disposed washery wastes (Figure 7).

Figure 4 Typical surface coarse reject dump at a black coal mine

The washing of bauxite ore generates benign, soil-like *tailings* that typically comprise up to about 50% of the raw ore. The washed bauxite is processed under alkaline, high temperature and pressure conditions to produce alumina, generating alkaline *red mud* (see Figure 8). The red mud typically comprises up to about 50% of the process feed. In some cases, the alkaline red mud is neutralised using sea water prior to disposal.

Figure 5 Typical surface tailings storage facility at a black coal mine

Figure 6 Typical co-disposed washery waste storage at a black coal mine

Figure 7 Typical in-pit washery waste storage (tailings behind a coarse reject bund) at a black coal mine

2.4 Wastes from Some Other Ore Bodies

Other ore bodies include mineral sands and nickel laterites. The mining of mineral sands, of which Australia has about half the world's reserves, is generally carried out by dredging, and produces both *sand* and *slimes* tailings, with the commodity comprising up to 10% of the ore mined. The tailings are re-deposited into the lake formed by dredging the mineral sands (see Figure 9).

About two-thirds of the world's nickel reserves are in nickel laterites. However, to date the majority of the mined nickel is from hard rock ore bodies, which are generally nickel sulfides (being located below the groundwater table, and hence unoxidised). This is due to the fact that hard rock nickel ores are relatively straightforward, if energy-intensive, to mine, requiring blasting to fragment the rock, crushing and grinding to expose the disseminated commodity; and relatively straightforward to process; this simply requires a large amount of energy. Nickel laterites are a clayey silt-sized soil dominates by halocites, which are difficult to handle on mining, and require sophisticated processing under high temperature and pressure conditions, generating problematic fine-grained *tailings* in a high-density, magnesium-dominated liquor.

Figure 8 Typical surface red mud storage facility

Figure 9 Typical tailings disposal following sand mining by dredging

Other ore bodies extensively exploited include quarried rock, limestone for cement and lime manufacture, phosphate and potash for fertiliser production, pyrite for sulfuric acid production, plus a range of other metals; uranium, diamonds, and so on. These share some of the waste generation and disposal, and potential contamination, issues of the other ore bodies referred to above, to lesser or greater degrees.

2.5 Mine-Impacted Water

Even with the best efforts to divert clean surface and underground waters around impacted areas, the mining and processing of mineral ores inevitably generates mine-impacted water. In most jurisdictions, mine-impacted water cannot be released to the environment unless it can be shown to not impact water quality (pH, total dissolved salts, and turbidity). The consequent storage of mine-impacted water in surface storages leads to evaporation and the concentration of salts and other contaminants. These can potentially be released to the surrounding environment through seepage or overtopping during flooding.

The exposure on mining and mineral processing of sulfide-rich mine wastes to the atmosphere, previously unoxidised due to their being buried below the groundwater table in which dissolved oxygen levels are very low, leads to the generation of oxidation products. These, when combined with water, generate *acid and metalliferous drainage (AMD)*, which has the potential to reach and impact the surrounding environment through surface and ground water flows. A lowering of the pH leads to the dissolution of metals present in the wastes, leading to AMD of high acidity and high dissolved metal concentrations. Under certain circumstances, high dissolved metal concentrations can occur under near-neutral pH conditions.

The oxidation of sulfidic waste rock and coarse-grained processing wastes stored in surface dumps is largely unimpeded, due to the ready availability of air and rainfall infiltration. In fact, such dumps, which are typically constructed by end-dumping from a tip-head, are *oxidation reactors*, with air very readily supplied through convection via the coarse-grained base rubble zone formed due to the natural ravelling of coarser-grained particles to the base of the dump. The air then passes up the semi-continuous coarser-grained angle of repose layers, and from there diffuses into the adjacent finer-grained layers, which present a far higher surface area per unit volume available for oxidation. Infiltrating rainfall and bacteria catalyse the oxidation reactions, and water in excess of what can be held in storage within the dump emerges at the base of the dump as AMD. The base seepage will either percolate into the foundation or emerge from the toe of the dump from topographic low points.

3. SOME MINING-RELATED UNSATURATED SOILS ISSUES

Some mining-related unsaturated soils issues include: (i) the rainfall infiltration-induced wetting-up and drain-down of waste rock and coarse-grained processing waste dumps, and the irrigation and drain-down of heap leach materials, (ii) the drain-down, desiccation, and re-wetting by fresh tailings deposition and rainfall, of stored tailings, (iii) the dewatering and atmospheric drying and re-wetting of product coal, (iv) the bearing capacity and deformation of stored mine wastes, and (v) the performance of mine waste geo-covers.

3.1 Wetting-Up and Drain-down of Coarse-Grained Wastes

Coarse-grained waste rock, spoil, and processing wastes stored in surface dumps act as a "sponge" with respect to rainfall infiltration, due to their relatively porous and permeable surface (Williams, 2006). This is in contrast to natural hardpan surfaces which, in a dry climate, allow very little rainfall infiltration.

Rainfall infiltration into initially dry coarse-grained waste dumps goes largely into storage within the dump. Wetting-up occurs by progressive fingering (see Figure 10, which shows a 1/15th model of a 15 m high waste rock dump, with a finer-grained top layer to simulate a haul truck trafficked surface).

Eventually, the dump wets-up sufficiently, but without fully saturating, that its hydraulic conductivity equals the rate of rainfall infiltration, allowing seepage from the base at the same rate as rainfall infiltrates the top, or "continuum breakthrough". The time required to reach this point will be a function of the height (available storage) of the dump, the rainfall and intensity, and the physical and geochemical nature of the wastes. The higher the dump, the lower the rainfall and intensity, and the more well-graded the wastes, the longer it will take to reach continuum breakthrough.

Spreadsheet-based simulations of the wetting-up of waste rock dumps by Williams (2006) found that durable, fresh waste rock will only need to wet-up about 25% of its porosity to achieve continuum breakthrough, while well-graded, weathered waste rock will need to wet-up about 60% of its porosity to achieve this, both corresponding to a hydraulic conductivity of about 1.5×10^{-8} m/s. Once continuum breakthrough is reached, the dump will drain-down and desaturate until its hydraulic conductivity drops sufficiently that it again holds water in storage.

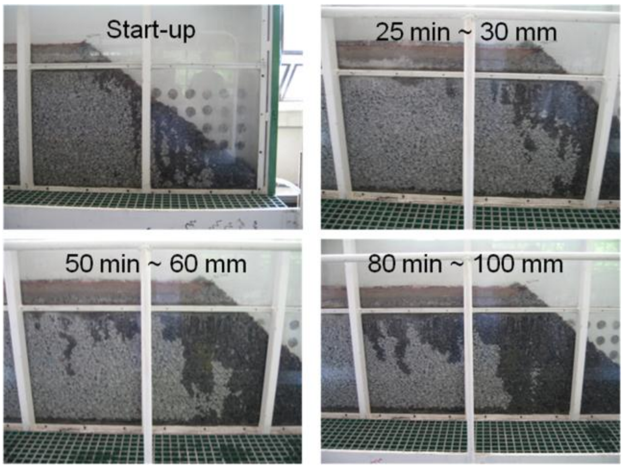

Figure 10 Progressive fingering observed in a 1/15th-scale model of a 15 m high waste rock dump

The heap leaching of a low grade metalliferous ore is typically somewhat of a trial-and-error approach. Heap leach material is irrigated with a leach solution to dissolve the commodity, which is collected as seepage at the base of the pad for further processing. As for the wetting-up of a waste dump by rainfall infiltration, the wetting-up of a heap leach pad due to irrigation will develop through fingering along preferred pathways. The presence of leach solution will tend to enlarge these preferred pathways, further concentrating the flow, and limiting the leaching of finer-grained materials which expose a far greater surface area of commodity per unit volume. Hence, heap leaching can be relatively inefficient, even ineffective, in maximising the metal yield.

3.2 Drain-down, Desiccation and Re-Wetting of Tailings

Tailings are typically disposed of as an aqueous slurry by centrifugal pumping. The slurry concentration will vary with the physical and chemical nature of the tailings, including the specific gravity of the solids. The pumpable solids concentration typically ranges from a low of about 25% solids (percentile mass of solids/mass of solids and water) for clay-rich coal mine tailings (low specific gravity), to a high of about 65% for ground hard rock tailings of high specific gravity (typically due to them being pyrite-rich). These % solids are equivalent to gravimetric moisture contents (percentile mass of water/mass of solids) of 300 to 54%, and total moisture contents (percentile mass of water/mass of solids and water, or 100 - % solids; which can be removed by a combination of mechanical dewatering and thermal drying) of 75 to 35%.

On disposal, the tailings undergo beaching, hydraulic sorting (according to particle size and specific gravity), sedimentation and consolidation (accompanied by drainage), and the released supernatant water forms a pond at the downstream end of the beach, while seepage will also likely be generated. The beaching processes can increase the % solids to between 50% and 70% (gravimetric moisture content to between 100% and 43%). The exposed beach then undergoes desiccation, and further consolidation, as the tailings develop matric suction, with the % solids increasing to perhaps between 60% and 80% (gravimetric moisture content to between 67% and 25%).

On the deposition of fresh tailings or incident heavy rainfall, the desiccated tailings will re-wet, possibly resaturating fully, with some minor decrease in the % solids. On closure, the stored tailings will again desiccate, and seepage potential will be much reduced.

3.3 Dewatering and Atmospheric Effects on Product Coal

Following beneficiation by washing, the various product coal size fractions are subjected to mechanical dewatering, typically by centrifuging and vacuum filtration, to meet the specified moisture content for sale (typically 10 or 11% total moisture content; Williams, 2009). The product coal size fractions are coarse (typically 5 to 50 mm), fine (typically 0.2 to 5 mm), and ultra-fine (typically up to 0.2 mm; see Figure 11).

(a) (b) (c)

Figure 11 Photographs of typical (a) coarse, (b) fine, and (c) ultra-fine product coal size fractions at their ex-plant moisture states

Conventional mechanical dewatering involves the application of different pressures to drive moisture from the capillaries of the different product coal size fractions, the pressure required being dependent on the type of coal, and its pore size distribution and connectivity. The smaller the pores, the higher the matric (capillary) suction that can develop as water retreats into them, and the higher the pressure required to remove the water.

Generally, the dewatered moisture content of each product coal size fraction correlates well with its particle size distribution, which relates to its pore size distribution; the dewatered moisture content increasing with decreasing particle size. Following mechanical dewatering, the coarse and fine product coal size fractions are unsaturated, while the ultra-fine product coal size fraction remains near-saturated to slightly unsaturated.

A coarse coal centrifuge applies a pressure of 40 to 50 kPa, depending on the coal properties, the centrifuge and its operating parameters, and the residence time of the coal within the centrifuge (typically only 1 to 2 s, which effects the bed depth and therefore the pressure differential across the bed). Despite the very short residence time, the relatively high hydraulic conductivity of the coarse product coal allows it to drain rapidly.

A fine coal centrifuge applies a pressure of 50 to 750 kPa, depending on similar factors to the coarse coal centrifuge over a residence time of 5 to 15 s. This short residence time is insufficient to allow much of the induced excess pore water pressure to dissipate. However, the fine product coal "remembers" the applied pressure and continues to drain in a dry atmosphere.

Conventional vacuum belt filtration of ultra-fine product coal applies a pressure of 60 to 80 kPa. Depending on the residence time on the belt (typically 1 to 2 min), which is a function of its length and speed, vacuum filtration drains about half of the moisture from the ultra-fine product coal. Pressure filtration of ultra-fine product coal applies a pressure of about 1,500 kPa. Briquetting may provide a maximum pressure of 50,000 kPa or higher, but for not more than 1 s, resulting in only about 1,500 kPa "felt" by the soil skeleton.

Table 1 indicates the typical composition and total moisture content of the various product coal size fractions.

Table 1 Typical composition and moisture of product coal size fractions

Parameter	Coarse Coal Centrifuges	Fine Coal Centrifuges	Vacuum Filtration of Ultra-Fine Coal
% of total dry mass	50 to 70	12 to 20	12 to 20
Total moisture content (%)	5 to 7	13 to 15	24 to 32
% of total moisture	35	20	45

The trend over time is for Australian product coals to become finer-grained due to improvements in the performance of ultra-fine coal recovery methods, the mining of poorer quality coal deposits, and increased rehandling the raw coal. Hence, the moisture content of the composite product coal will tend to increase.

Following mechanical dewatering, the re-combined composite product coal size fractions are stockpiled prior to use or transport to the port for export. On re-combination, the composite product coal is unsaturated. On the stockpile, the product coal undergoes drainage under gravity, cycles of atmospheric drying by the sun and wind action, and wetting by incident rainfall, plus wetting-up due to the spraying of water on the stockpile to suppress dust (Williams, 2010).

3.4 Bearing Capacity and Deformation of Stored Mine Wastes

Bearing capacity is assessed based on the shear strength of a soil. The shear strength of a saturated or desiccated tailings profile is best assessed by *in situ* vane shear strength testing, since tailings are virtually impossible to sample undisturbed for laboratory testing purposes.

The shear strength of spoil, waste rock and coarse-grained processing wastes is difficult to assess due to their coarse particle size distribution, and only scalped samples can be tested in the laboratory. Weathered spoil and waste rock, and fine-grained processing wastes, are more readily tested due to their finer particle size distribution, making scalped samples more representative. The scalped spoil, waste rock or coarse-grained processing wastes may be tested at their as-sampled moisture content, to provide an estimate of the unsaturated shear strength and bearing capacity, or saturated, to provide an estimate of their worst case shear strength and bearing capacity.

The deformation under load of tailings, spoil, waste rock or coarse-grained processing wastes may be assessed by consolidometer testing. Desiccated tailings could be tested at their as-sampled moisture content, or the tailings could be re-constituted and tested from a slurry.

To assess their deformation under loading, scalped samples of spoil, waste rock or coarse-grained processing wastes could be tested, preferably in a large-size consolidometer, initially prepared in a loose state. They could be tested at their as-sampled moisture content, in a water bath to assess their collapse on wetting-up and over time, and on wetting-up to assess weathering.

3.5 Performance of Mine Waste Geo-Covers

Cover systems have evolved from the desire to limit potential environmental impacts from stored mine wastes, including waste rock, coarse-grained mineral processing wastes, and fine-grained mineral processing wastes or tailings (Williams, 2011). The key means of limiting potential environmental impacts are to limit oxidation of the stored mine wastes, and/or to limit the transport of any oxidation products to the environment via water or air. The most effective means of limiting oxidation of mine wastes is to store them permanently below water; however, this is generally not possible in moisture-deficit climates such as exist at many mine sites in Australia and elsewhere in the world. In such climates, geo-covers comprising soil and/or rock are required, applied to relatively flat surfaces.

In dry or seasonally dry climates, the geo-cover system should prevent exposure of the stored mine wastes to air-borne mobilisation, and is best aimed at limiting net percolation of rainfall into the waste to limit the transport of any oxidation products. In wet climates, the aim of the geo-cover system should be to either shed rainfall runoff or, where acid neutralising materials are available, to place a thick alkaline cover over the wastes and rely on the alkalinity produced to neutralise any acidity generated by the underlying mine wastes.

Geo-covers need to be understood in the context of the recharge of natural ground systems. The impact of tailings slurry deposition and waste rock (or coarse-grained processing waste) dumps as they wet-up due to rainfall are then superimposed on the net percolation of a natural dry climate system. A range of geo-cover systems is available, of variable effectiveness in limiting net percolation into the underlying mine wastes.

Being located on the surface and of limited thickness, geo-covers are in the active moisture zone, and exist mainly in an unsaturated state. They undergo seasonal drying and wetting cycles.

Data on the recharge of natural systems in Southern Africa (Beekman *et al.*, 1996; reproduced as Figure 12) show that in arid climates, with an average annual rainfall of up to 250 mm, average annual recharge is in the range from about 1 to 10 mm (0.4 to 4% of 250 mm). Natural systems in semi-arid climates, with an average annual rainfall of up to 500 mm, experience an average annual recharge of about 0.5 to 50 mm (0.1 to 10% of 500 mm). For average annual rainfalls above 500 mm, there is a tapering off of average annual recharge at a maximum of about 100 mm, implying that an increasing proportion of rainfall reports as runoff for increasingly wet climates.

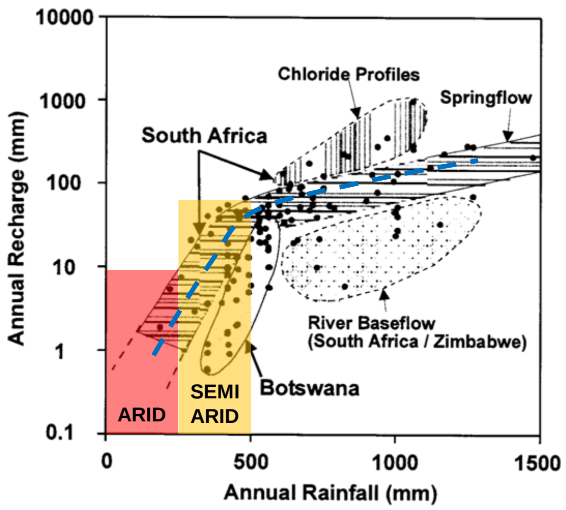

Figure 12 Data on the recharge of natural systems in Southern Africa (after Beekman *et al.*, 1996)

The Australian Bureau of Meteorology website (http://www.bom.gov.au/) report data on average annual rainfall and estimated actual average annual evapotranspiration across Australia. Figure 13 is based on these data, in which the average annual rainfall normalised by the estimated actual average annual evapotranspiration is plotted against the average annual rainfall. For dry climates the estimated actual average annual evapotranspiration approaches the average annual rainfall, while for wet climates there is a substantial excess of rainfall over actual evapotranspiration (or a net positive water balance).

Figure 13 allows the net positive water balance (or wet) climates to be identified. Also marked in Figure 13 is the average annual rainfall for Kalgoorlie in Western Australia of about 250 mm, which delineates net evapotranspirative from net infiltrative climatic conditions.

4. SOME MINING APPLICATIONS OF UNSATURATED SOILS MECHANICS

In the following sections, selected applications of unsaturated soil mechanics to mining and mineral processing wastes, and to mineral products, are described. These include (i) the wetting-up and drain-down of initially dry surface waste rock dumps, (ii) the deposition, desiccation, rewetting and loading of mine tailings, (iii) the dewatering of product coal, (iv) the shear strength and compressibility of clay-rich coal mine spoil, and (v) the performance of a store and release cover placed on the top of waste rock dumps by way of rehabilitation.

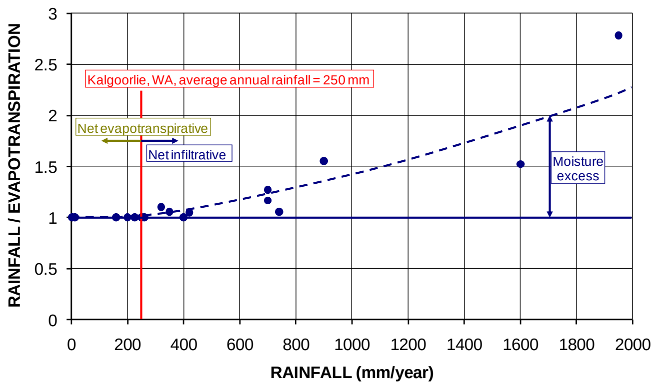

Figure 13 Identification of net positive water balance (or wet) climates

4.1 Wetting-Up of and Seepage from Waste Rock Dumps

Rainfall infiltration into a bare, loosely-dumped waste rock dump is commonly assumed to be approximately 50% of average annual rainfall, depending on the climate, and the physical and chemical characteristics of the rock. However, there is a lack of field data to confirm this. Taking Kalgoorlie in Figure 13 as a basis, the potential impact of the wetting-up of a waste rock dump in that climate to the point of continuum breakthrough (of half the annual rainfall) is shown in Figure 14. Wetter climates would be expected to result in correspondingly greater volumes of continuum breakthrough, and this would occur more rapidly the higher the average annual rainfall.

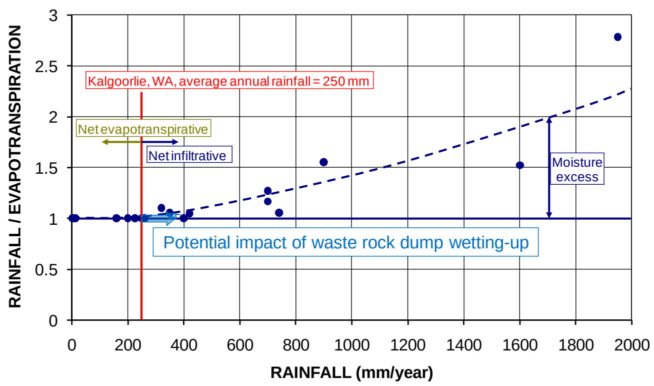

Figure 14 Potential impact of waste rock dump wetting-up in Kalgoorlie's climate

In 2006, a 15 m high trial waste rock dump covering 0.7 ha was constructed at Cadia Hill Gold Mine in New South Wales, Australia. It was instrumented with two lysimeters at the perimeter-bunded (for the safety of plant, and also to limit runoff over the dump sides) surface of the dump and 24 lysimeters at the base of the dump, to monitor rainfall infiltration through the top and base seepage beneath the top surface and the side slopes of the dump, respectively. The lysimeters have been monitored for 4 years, providing information of surface infiltration, storage within the dump, and seepage from the base of the dump.

Heavy rainfall occurred during the construction of the trial dump, resulting in a high average volumetric moisture content for the placed waste rock of about 0.11 (gravimetric moisture content of 6.2%, for a measured specific gravity of 2.65), saturating about a third of the porosity of about 0.33 (corresponding to an initial dry density of 1.78 t/m^3).

Over the 4 years of monitoring to 29 January 2010, the single largest rainfall event occurred on 18 October 2006, with 73.8 mm recorded in 24 hours. The annual rainfall totals recorded on Cadia's trial waste rock dump have been 606 mm, 927 mm, 1,553 mm, and 1,609 mm, for 2006/2007, 2007/2008, 2008/2009 and 2009/2010, respectively. The first two years of the monitoring period had up to the average annual rainfall for the site of about 900 mm, while the final two years of monitoring had substantially above the average annual rainfall.

Surface infiltration into the flat top of the trial waste rock dump has been monitored from 1 June 2006, following the construction of the dump and the installation of the two lysimeters on its traffic-compacted top surface. The lysimeters responded within 24 hours of the first rainfall, building up to an average peak infiltration of 86% of cumulative rainfall in mid-August 2006, followed by a gradual decline since, with little further infiltration recorded after 1 December 2006, as seen in Figure 15 (Rohde *et al.*, 2011). The average measured surface infiltration over the first 12 months of the monitoring period was about 50% of cumulative rainfall, dropping to an average 22% of cumulative rainfall over 4 years.

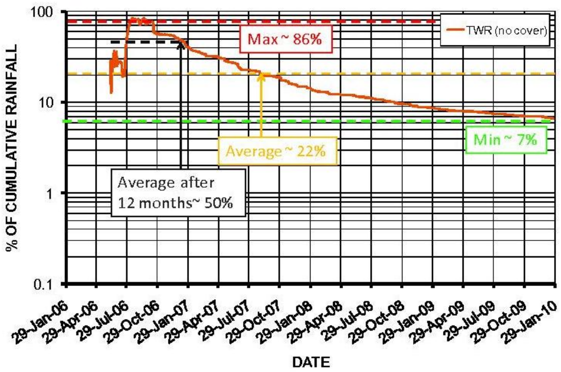

Figure 15 Surface infiltration into Cadia's trial waste rock dump, expressed as a % of cumulative rainfall with time

Differential settlement and hard-panning of the surface of the dump (see Figure 16), and the concentration of rainfall runoff in ponds and at sinkholes not intersected by the surface lysimeters, are the main factors behind the lack of recorded infiltration after 1 December 2006. The patterns of infiltration vary markedly across the dump and with variations in rainfall over time, as would evaporation. Hence, the average recorded infiltration over 4 years of 22% of cumulative rainfall represents a lower bound. The actual average infiltration may be of the order of 50% of cumulative rainfall.

Figure 17 shows the average cumulative base seepage (expressed as a % of cumulative rainfall) recorded by lysimeters beneath the flat top and the angle of repose (AOR) slopes of Cadia's trial waste rock dump. The base seepages responded broadly to rainfall, increasing over time as the dump wet-up. Over the 4-year monitoring period, the average base seepage beneath the flat top of the trial waste rock dump was about 2.7% of cumulative rainfall, while that beneath the AOR slopes was about 6.6%. This latter value is higher, as might be expected given the lower average height of the AOR slopes and their more open-textured surface. Both values are very much smaller than the average surface infiltration over the same 4-year time period of 22% of cumulative rainfall or higher, implying that the majority of rainfall infiltration went into storage within the dump.

Figure 16 Differential settlement and hard-panning of surface of Cadia's trial waste rock dump over time, causing internal runoff and concentrated ponding

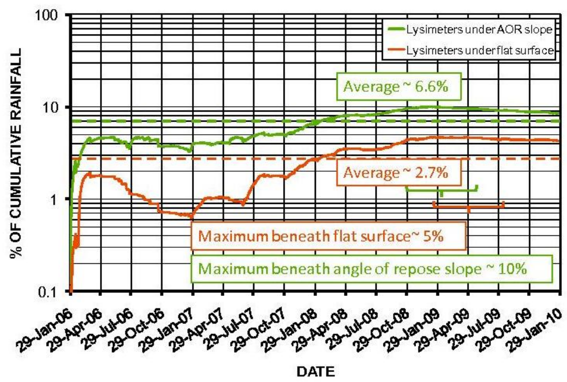

Figure 17 Average base seepage beneath flat top surface and angle of repose side slopes of Cadia's trial waste rock dump, expressed as a % of cumulative rainfall

Maximum cumulative base seepage of about 5% of cumulative rainfall beneath the flat top and about 10% beneath the AOR slopes of Cadia's trial waste rock dump occurred in early 2009, which appears to be a consequence of heavy rainfall events in the months prior to this.

When base seepage has been recorded, lysimeters beneath the flat top of Cadia's trial waste rock dump have flowed for about twice as long (40 to 120 days, implying an average hydraulic conductivity during drain-down of 4.3 x 10^{-6} to 1.4 x 10^{-6} m/s) as those beneath the angle of repose slopes (20 to 60 days, implying an average hydraulic conductivity during drain-down of 8.7 x 10^{-6} to 2.9 x 10^{-6} m/s), due to the greater height of waste rock involved.

Over the 4-year monitoring period, as wetting-up fingers penetrated Cadia's trial waste rock dump (as shown in the laboratory; see Figure 10), the rainfall amount required to trigger some base seepage reduced from about 30 mm initially to less than 2 mm, and the lag time (delay) before the emergence of base seepage reduced from about 15 days to less than 2 days (see Figure 18; Williams and Rohde, 2009).

Table 2 presents the average initial and 4-year moisture states of Cadia's trial waste rock dump. After 4 years, the degree of saturation is starting to approach 60%, at which continuum breakthrough would be expected for well-graded waste rock.

The time for a waste rock dump to reach continuum breakthrough may be estimated using the continuum approach described by Williams (2006). A continuum approach is required, since preferred flow pathways are unknown. As a result, no base seepage is calculated until continuum breakthrough is reached. While in reality some base seepage via preferred pathway flow does occur prior to continuum breakthrough, the amount is limited and short-lived following significant rainfall events.

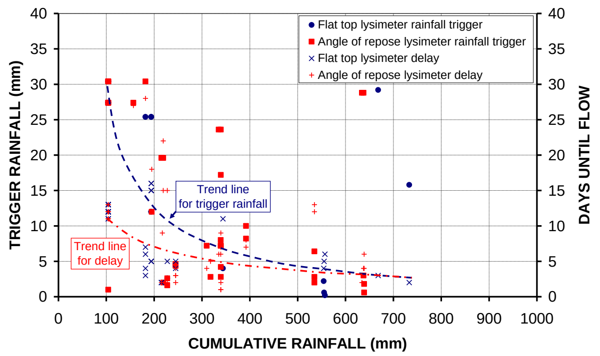

Figure 18 Trigger rainfall and delay for some base seepage following a rainfall event on Cadia's trial waste rock dump

Table 2 Average initial and 4-year moisture states of Cadia's trial waste rock dump

Parameter	Initial	Final Beneath	
		Flat Top	Slopes
Volumetric water content	0.11	0.13	0.17
Gravimetric moisture content (%)	6.2	7.3	9.5
Degree of saturation (%)	36	43	56

Over the time required to reach continuum breakthrough, even initially fresh waste rock is likely to weather, hence well-graded weathered waste rock may be assumed. An estimate of its SWCC may be obtained from its particle size distribution, dry density and specific gravity of the soil, using Fredlund *et al.* (1997) and the library of data contained within the SoilVision software (www.soilvision.com).

From the SWCC and measured saturated hydraulic conductivity of the soil, the unsaturated hydraulic conductivity function of the soil may be calculated using the method of Fredlund *et al.* (1994). Using the unsaturated hydraulic conductivity function expressed in terms of volumetric water content, simulations of the wetting-up of weathered mine waste rock by rainfall infiltration may be obtained by iteration in a spreadsheet calculation. Spreadsheet calculations are preferred over numerical methods, which would incur convergence problems due to the high suction gradients within the waste rock as it wet-up.

For the purposes of the spreadsheet simulation, Cadia's 15 m high trial waste rock dump was divided into 10 equal 1.5 m sub-layers. It was conservatively assumed for the purposes of the simulation that 50% of the average annual rainfall of 900 mm infiltrated the dump over the average 123 days/year of rainfall, with the remainder lost to evaporation. The rainfall infiltration was applied to the top sub-layer, causing it to wet-up. This raised its hydraulic conductivity, and when it rose sufficiently to allow breakthrough of the top sub-layer this breakthrough was then applied to the second sub-layer, and so on through successive sub-layers. Continuum breakthrough was estimated to commence after about 5 years, and to become fully developed after about 7 years, as shown by the solid line in Figure 19.

Also shown in Figure 19 is the possible average seasonal variation in base seepage with time, and the point reached by January 2010 after 4 years. Applying the spreadsheet simulation to a range of waste rock dump heights and average annual rainfall totals, Figure 20 is obtained (Williams, 2008).

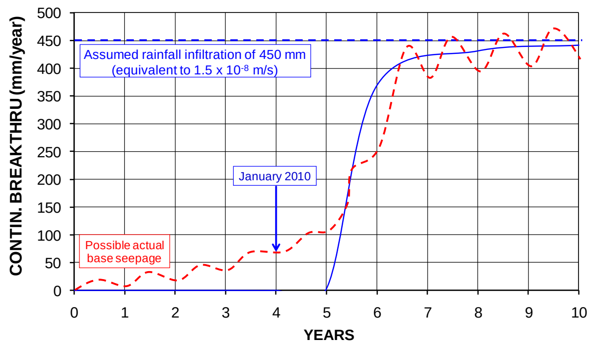

Figure 19 Estimated wetting-up and continuum breakthrough of Cadia's trial waste rock dump

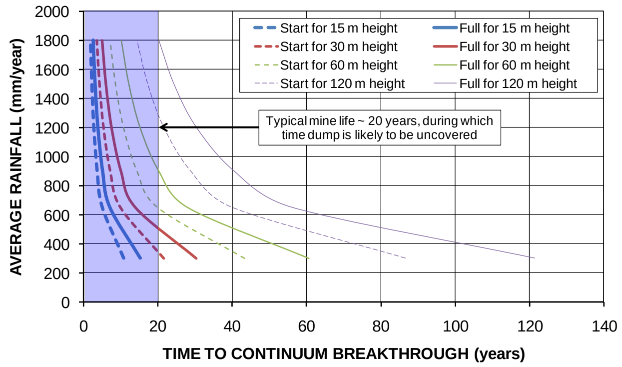

Figure 20 Estimated wetting-up and continuum breakthrough of waste rock dumps of different height subjected to a range of average annual rainfall totals

4.2 Deposition, Desiccation, Re-Wetting and Loading of Mine Tailings

Taking Kalgoorlie in Figure 13 as a basis, the dramatic impact of the volume of water typically discharged with tailings slurry is shown in Figure 21.

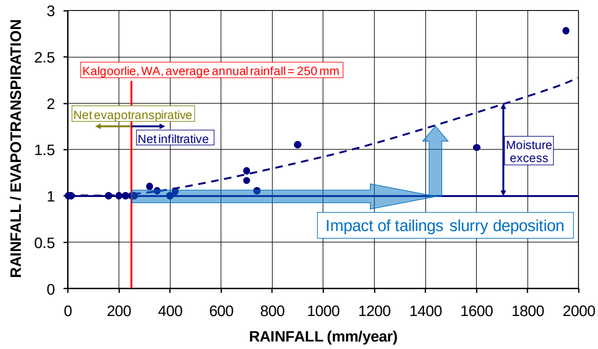

Figure 21 Potential impact of tailings disposal in Kalgoorlie's climate

Understanding the unsaturated flow behaviour of mine tailings is described in Figure 22, which highlights the need to measure not only the phreatic surface but also the matric suction profile with depth. Matric suctions lower than the "no-flow" hydrostatic case imply net infiltration, while matric suctions higher than the no-flow case imply net evaporation.

As tailings desiccate on exposure, a surface crust forms, beneath which the tailings remain slurry-like (as shown in Figure 23 for coal mine tailings). The reduced hydraulic conductivity of the desiccated crust limits the depth of desiccation and maintains the underlying tailings wet and soft.

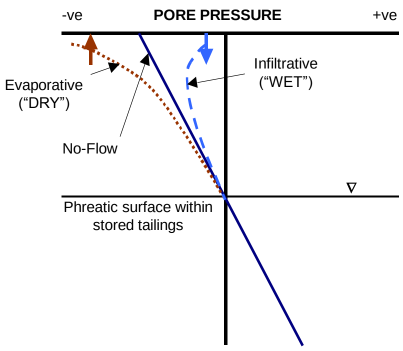

Figure 22 Flow conditions for deposited tailings

Figure 23 Surficial desiccated crust over fluid coal mine tailings

Stolberg and Williams (2006) described the results of a laboratory tailings column experiment conducted on fresh hypersaline, Western Australian, hypersaline, Mt Keith nickel sulfide tailings in a Perspex column 2 m high by 300 mm in diameter (see Figure 24). The column was instrumented along its height with 10 sets of sensors to measure volumetric water content and matric suction. Pan evaporation was measured adjacent to the column and seepage from the column was measured directly. The water balance for the column allowed the actual evaporation to be calculated.

Figure 24 Instrumentation of tailings column experiment

The tailings were placed to a height of 1.5 m at 50% solids by mass, allowed to drain-down (draining to the top and the base, accounting for about 60% of the tailings water) and desiccate, and were then flooded and re-dried (see Figure 25).

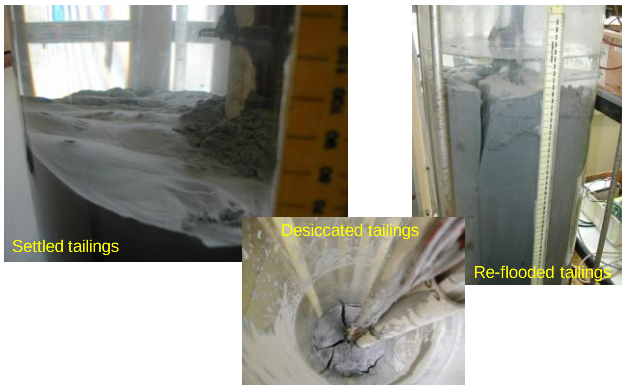

Figure 25 Settled, desiccated and re-flooded Mt Keith tailings in column experiment

Figure 26 shows SWCC data collected directly from cemented and structured Mt Keith tailings in the field, from re-slurried tailings tested in a Tempe cell in the laboratory, and from the laboratory column test, both on initial drying from a slurry and on re-drying following flooding.

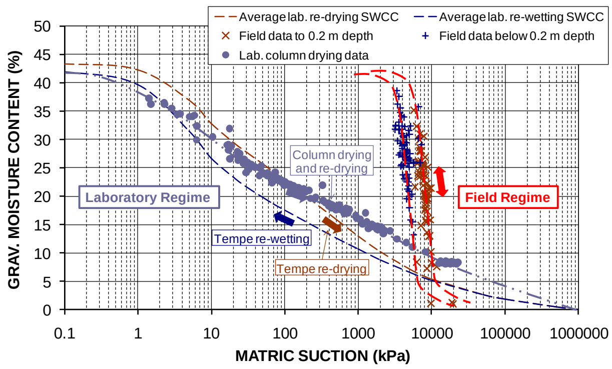

Figure 26 Field and laboratory SWCC data for Mt Keith tailings

Figure 26 shows that tailings exhibit "stiffer" behaviour, shown by the estimated SWCCs, if they cement and development structure in the field, which is largely destroyed on laboratory preparation for testing. The laboratory regime corresponds to drying after initial deposition or flooding, while the field regime corresponds to dry conditions and those at depth unaffected by surface flooding.

Figure 27 shows the unsaturated hydraulic conductivity functions derived using the method of Fredlund *et al.* (1994) from the laboratory and field SWCC data for Mt Keith tailings shown in Figure 26. Under a hydraulic gradient of unity, these tailings under field conditions would pass water at a rate of about 10^{-10} m/s (6 to 60 mm/year), not 10^{-16} m/s as is implied by the laboratory-derived SWCC data.

Chapman *et al.* (2008) described a field trial involving saline, Cosmos nickel sulfide tailings in Western Australia. In order to track the water cycle of the tailings deposition and desiccation cycles, towers fabricated from 25 mm box section were installed in advance of tailings deposition, on which piezometers, and series of 16 pairs of matric suction and Time Domain Reflectometry (TDR) volumetric water content sensors were fixed at 300 mm centres (Figures 28 and 29).

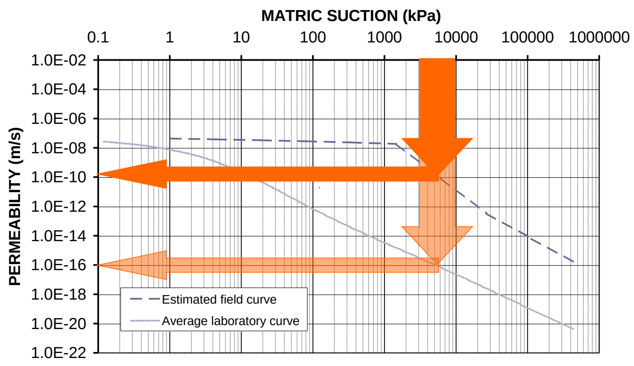

Figure 27 Field and laboratory hydraulic conductivity functions for Mt Keith tailings

Figure 28 Piezometer, and matric and moisture sensors

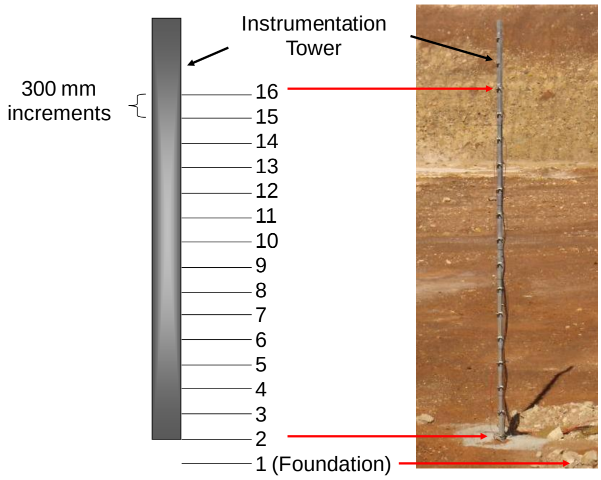

Figure 29 Sensor locations on tower and in foundation

Figure 30 shows the Cosmos tailings deposition and desiccation stages over a number of months, to a total height of about 4 m.

Figure 31 shows the response of the matric suction sensors as they were progressively inundated by tailings, which were allowed to desiccate between deposition cycles.

The matric suction data shown in Figure 31 suggest that desiccation following a cycle of tailings deposition is rapid (shown by the rapid rise in matric suction), wetting-up by fresh tailings deposition is also rapid (shown by a rapid drop to zero matric suction), and both desiccation and wetting-up extend into the foundation. The majority of the supernatant tailings water was removed by evaporation.

Figure 30 Cosmos tailings deposition and desiccation cycles

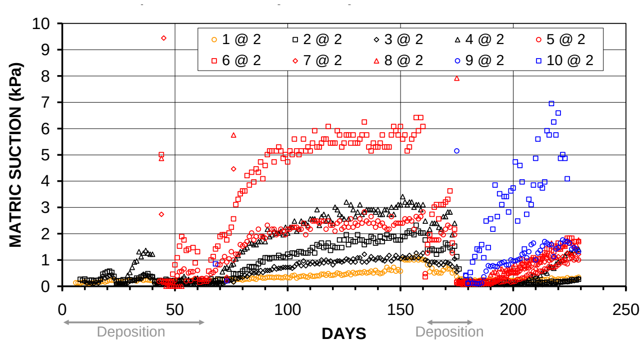

Figure 31 Matric suction data with time during deposition and desiccation cycles

Figure 32 demonstrates that seepage from freshly-deposited tailings, or as a result of rainfall, will readily infiltrate through the full depth of near-saturated tailings and into the foundation (as evidenced by the lack of matric suction in response to 19.6 mm of rainfall on 12 December 2007). However, desiccation between deposition cycles drastically reduces the hydraulic conductivity of the full depth of the tailings, holding up rainfall within the upper 0.5 m depth of tailings, from which it can readily be removed by evaporation (as evidenced by the shallow wetting-up of the desiccated tailings in response to rainfall on 28 July and 29 September 2007).

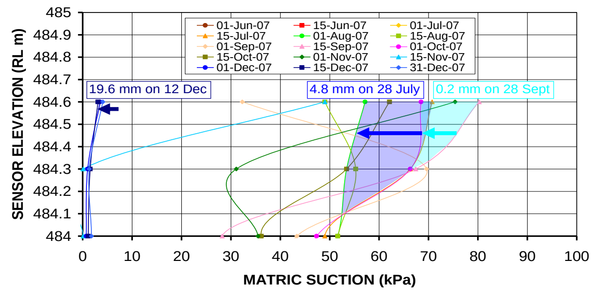

Figure 32 Wetting-up of desiccated tailings by rainfall

Tailings are typically allowed to desiccate and crust prior to a geo-cover being placed by way of rehabilitation. The shear strength of the crust is required to provide sufficient bearing capacity to safely support the equipment used to place the cover and to support the loading imposed by the thickness of cover material. The typical use of large mining equipment leads to the rapid placement of an excessive thickness of cover material over thinly-crusted tailings, running the risk of inducing a “bow-wave” failure in the tailings.

This occurs if the pressure imposed by the thickness of cover material extends to the softer tailings underlying the crust, and causes the tailings to undergo remoulding, soften, and cause bow-wave failure. Figure 33 shows about 5 m of cover material placed on thinly-crusted coal mine tailings at Ulan Mine in New South Wales, Australia, which caused a bow-wave failure extending about 15 m from the toe of the cover.

Figure 33 Bow-wave failure of crusted coal mine tailings due to rapid placement of an excessive thickness of cover material

Vane shear strength testing was carried out at the location depicted in Figure 33 to arrive at the vane shear strength profiles with depth shown in Figure 34 (Williams and Morris, 1987). Figure 34 shows the "underwater" shear strength profile that would result if the tailings had always been kept below water, and is the result of the self-weight of the tailings, determined by its specific gravity. The specific gravity of coal tailings is of the order of 1.8 to 2.2, resulting in an underwater shear strength increase of about 0.8 kPa/m depth. In fact, the Ulan tailings were allowed to desiccate periodically.

The "desiccated" and "remoulded" shear strength profiles were measured away from the influence of the cover loading, the former being the peak vane shear value, and the latter the value obtained on remoulding the tailings by rotating the shear vane a full three revolutions. The "loaded-initially" shear strength profile was measured through the bow-wave failure, immediately after cover placement. The "loaded-drained" shear strength profile was measured through the bow-wave two weeks after cover placement, when the excess pore water pressures induced by loading had fully dissipated.

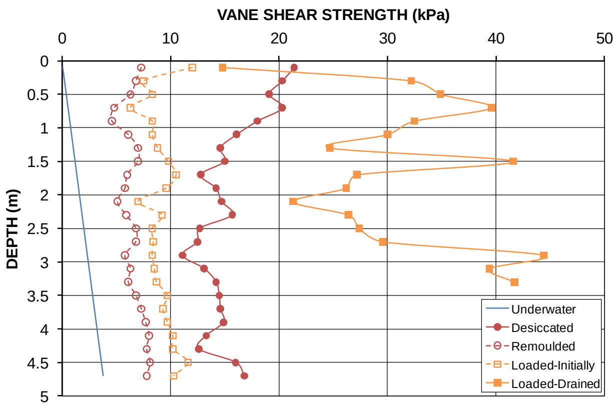

Figure 34 Vane shear strength profiles for Ulan coal mine tailings

The effect on shear strength of the development of matric suctions on desiccation is clearly evident, as is the effect of remoulding of the desiccated tailings. The initial effect of cover placement was to remould and soften the tailings, causing a bow-wave failure to develop. The tailings softened towards their remoulded strength. Over time, drainage of the excess pore water pressures induced by cover placement caused the tailings to generally strengthen, particularly at depth. Towards the surface, the low unsaturated hydraulic conductivity of the desiccated crust resulted in only a small increase in shear strength from the initial value on loading, as it wet-up due to drainage from the more permeable tailings below.

The average shear strengths ranged from 2 kPa for the underwater case, 15 kPa for the desiccated case and 7 kPa for the remoulded case, 9 kPa immediately after cover placement (causing bow-wave failure), and over 30 kPa after drainage.

4.3 Characterising Dewatering and Atmospheric Effects on Product Coal

The application of pressure to a product coal size fraction induces drainage and a transfer of the applied stress from excess pore water pressure to an effective stress. On the removal of the applied pressure, any transferred effective stress is "felt' by the product coal as matric suction, hence the two stresses are equivalent, and the SWCC may be used to provide an estimate of the effectiveness of dewatering under a given pressure.

Figure 35 shows the particle size distributions of typical composite product coal and size fractions (Williams, 2009). The composite product coal particle size distribution is close to that of the dominant coarse size fraction, while the more minor fine and ultra-fine size fractions are largely sand-sized and silt and clay-sized, respectively.

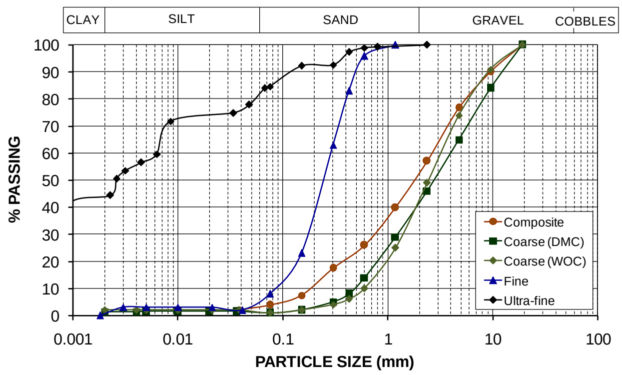

Figure 35 Particle size distributions of typical composite product coal and size fractions (DMC = dense medium cyclone, WOC = dense medium bath + water)

Figure 35 shows the measured SWCC drying and re-wetting data and drying curves, fitted using the method of Fredlund *et al.* (1994) and the SoilVision software, for typical composite product coal and size fractions. The order of the SWCCs shown in Figure 36 is what would be expected, given the particle size distributions of the materials. The coarse size fraction is most readily dewatered, followed by the composite, then the fine size fraction, and lastly the ultra-fine size fraction.

The SWCC data shown in Figure 36 are the equilibrium values, achieved after sufficient time is allowed at each level of matric suction for the minimum total moisture content to be established. These values will not be achieved on dewatering if the residence time is limited.

Figures 37 and 38 show the effect of residence time on the dewatering of fine and ultra-fine product coal, respectively.

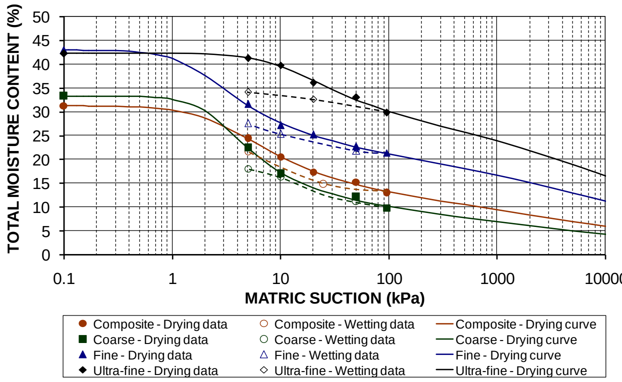

Figure 36 SWCCs for typical composite product coal and size fractions

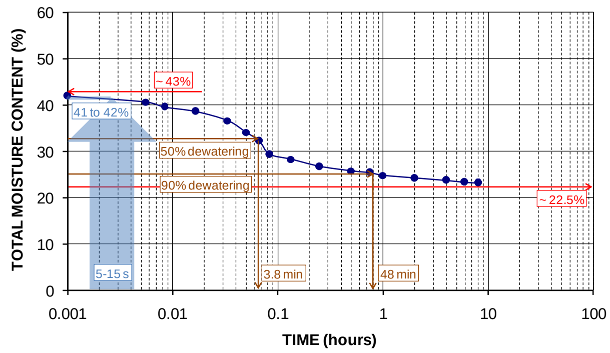

Figure 37 Drying typical fine product coal under a suction of 55 kPa, simulating dewatering using a fine coal centrifuge

From Figure 37, the 5 to 15 s residence time of fine product coal in a fine coal centrifuge will be relatively ineffective in dewatering the material, achieving only 5 to 10% of the dewatering potential under the pressure applied. To achieve 50% and 90% of the dewatering potential would require residence times of 3.8 min and 48 min, respectively.

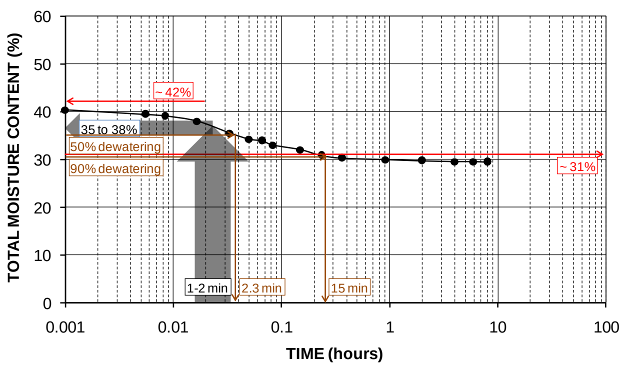

Figure 38 Drying typical ultra-fine product coal under a suction of 85 kPa, simulating dewatering using vacuum filtration

From Figure 38, the 1 to 2 min residence time of ultra-fine product coal on a vacuum belt will achieve 20 to 50% of the dewatering potential under the pressure applied. To achieve 90% of the dewatering potential would require a residence time of 15 min.

Figure 39 compares the SWCCs and data for filtered and briquetted typical ultra-fine product coal. While vacuum filtration would achieve at best a final total moisture content of about 35%, the very much higher pressure applied by briquetting was found to initially achieve a total moisture content of about 16%. The nominal 5,000 kPa pressure exerted by the rollers between which the material is squeezed on briquetting is applied for not more than 1 s. The briquette emerges from the rollers having an effective stress of about 1,500 kPa (the stress that has transferred to the material skeleton, as indicated by the measured matric suction shown in Figure 39) and an excess pore water pressure of about 3,500 kPa (the stress that is still carried by the pore water).

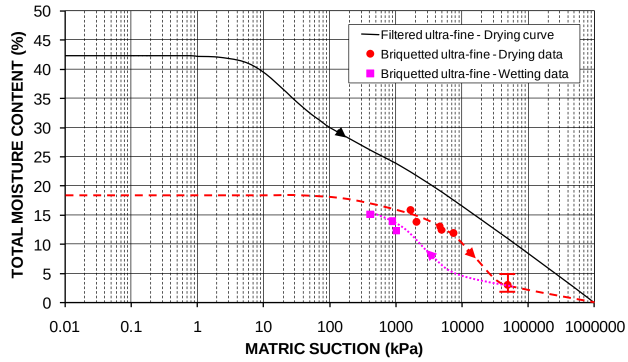

Figure 39 SWCCs and data for filtered and briquetted typical ultrafine product coal

Under the action of the excess pore water pressure, the briquette will continue to dry in the air, provided it is less humid than the pore space (which is likely), eventually achieving a total moisture content of 2 to 5% (about 10 times lower than that achievable on vacuum filtration), as the suction rises to the nominal pressure of 5,000 kPa originally applied, inducing structure. If the briquette is re-wet, its total moisture content will return to about 15%, since it will retain its compressed structure, while the vacuum filtered material could re-wet to its original total moisture content of 42% in the absence of an induced structure.

A 11.5 m high composite product coal stockpile at its angle of repose of 38° was placed at an ex-plant total moisture content of about 9.5%. After 8 days of drying under hot (maximum daytime temperatures of the order of 35°C), dry weather, the measured total moisture contents and inferred 5%, 7.5% and 10% contours were as shown in Figure 40 (Williams, 2010). The high total moisture contents towards the crest are due to the "hanging-up" of moisture-retaining fines, while those at the base are due to gravity drainage. The lowest total moisture contents are along the face of the stockpile, due to solar drying and the predominance of coarse particles on the surface.

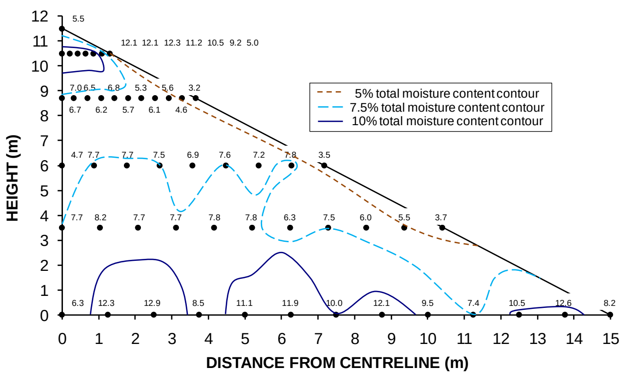

Figure 40 Total moisture contents and approximate contours within composite product coal stockpile after 8 days of drying

In the absence of natural rainfall, the same material was subjected to simulated rainfall in a laboratory tank 2.4 m long, by 750 mm high by 300 mm wide. Two simulations were performed: (i) rainfall at 24 mm/hour for 5 hours, immediately followed by sampling for total moisture content and, (ii) rainfall at 24 mm/hour for 4 hours, followed by drain-down, then sampling. The total moisture contents of the composite product coal from the field and laboratory tests are given in Table 3, which highlights the dramatic effects that climatic conditions can have on stockpiled product coal.

Table 3 Total moisture contents of composite product coal from field stockpile and laboratory simulations

Test	**Final Total Moisture Content (%)**
Field – After8 days of drying	6.8 (0.6 to 12.9)
Lab (i) – 5 hours rain, immediate sampling	11.8 (8.5 to 16.2)
Lab (ii) – 4 hours rain, after draw down	9.5 (5.4 to 13.3)

4.4 Characterising Shear Strength and Compressibility of Clay-Rich Coal Mine Spoil

The shear strength of clay-rich coal mine spoil from Jeebropilly Coal Mine in the Ipswich Coalfields of South East Queensland, Australia, is substantially affected by whether the material is tested at its relatively dry as-sampled gravimetric moisture content of 14.8% (corresponding to a matric suction of about 4,300 kPa), or in a water bath (corresponding to near-saturation and near-zero matric suction on wetting-up by rainfall infiltration and/or groundwater recharge; Williams *et al.*, 2011).

Figures 41 and 42 show the shear stress versus shear strain plots from single-stage, 60 mm size, direct shear strength tests carried out on weathered rock spoil specimens, scalped to pass 2.36 mm, placed initially loose, and tested at the as-sampled moisture state and in a water bath, respectively. The applied normal stress was limited to a maximum of 500 kPa for the specimens tested at the as-sampled moisture content, and to a maximum of 150 kPa for the specimens tested in a water bath, the latter normal stress being limited by the large compression of the sample due to wetting-up and loading. Under 100 kPa normal stress, the specimen placed loose at the as-sampled moisture content compressed rapidly by about 17%, while the specimen placed loose in a water bath settled more slowly and by 29% (almost twice the compression). Shearing was at a shear strain rate of 0.1 mm/min, which resulted in drained behaviour.

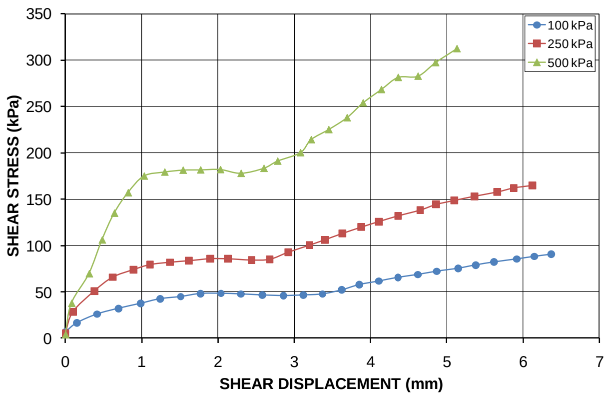

Figure 41 Shear stress versus shear displacement plots for Jeebropilly weathered rock spoil placed initially loose and tested at the as-sampled gravimetric moisture content of 14.8%

The corresponding normal displacement versus shear displacement plots during shearing are shown in Figures 43 and 44, for shearing at the as-sampled moisture content and in a water bath, respectively.

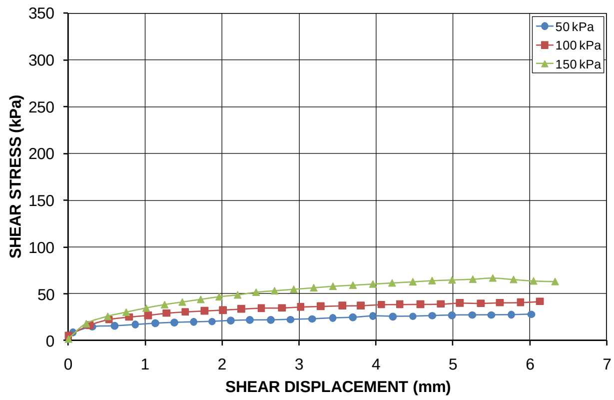

Figure 42 Shear stress versus shear displacement plots for Jeebropilly weathered rock spoil placed initially loose and tested in a water bath

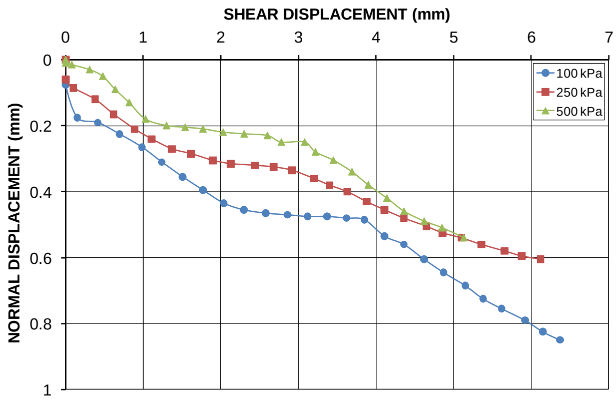

Figure 43 Normal displacement versus shear displacement plots for Jeebropilly weathered rock spoil placed initially loose and tested at the as-sampled gravimetric moisture content of 14.8%

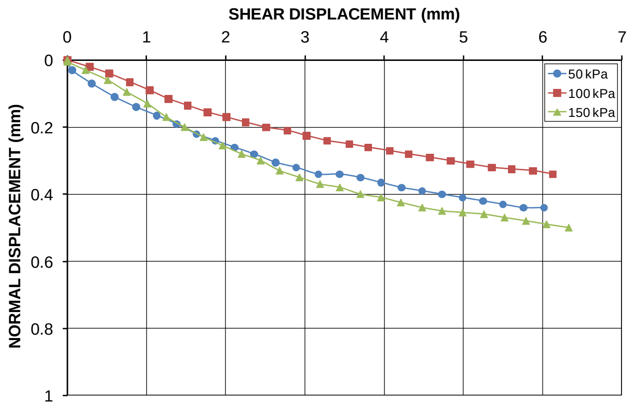

Figure 44 Normal displacement versus shear displacement plots for Jeebropilly weathered rock spoil placed initially loose and tested in a water bath

The shear stress vs. shear displacement behaviour for the two cases was reasonably similar at low shear displacement (Figures 41 and 42). However, there was a consistent step in the stress-strain behaviour of the specimens tested at the as-sampled moisture content, at about 3 mm shear displacement (5% shear strain), corresponding to a consistent step in the normal displacement.

It is considered that the stress-strain behaviour up to about 5% shear strain was dominated by the applied normal stress, accompanied by relatively little further settlement. Beyond about

5% shear strain, the significant decrease in pore sizes associated with the step in normal displacement is considered to have led to increased matric suction and hence effective stress, causing an increase in the measured shear stress required to further shear the specimens. This effect was not observed for the specimens in a water bath since they were essentially water-saturated, hence matric suction would have been close to zero.

Figure 45 compares the direct shear strength envelopes derived from the stress-strain plots in Figures 41 and 42. The plateaux in the plots for the specimens tested at the as-sampled moisture content and the peaks for the specimens tested in a water bath gave similar drained shear strength parameters, with an effective stress cohesion intercept of about 13 kPa and an effective stress friction angle of about 17.9°. The final points of the plots for the specimens tested at the as-sampled moisture content gave an effective stress cohesion intercept of about 33 kPa and an effective stress friction angle of about 27.3°.

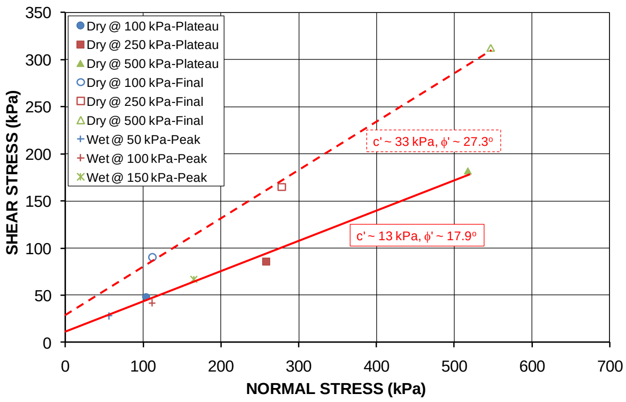

Figure 45 Direct shear drained strengths of Jeebropilly weathered rock spoil tested dry (as-sampled moisture content) and wet (in a water bath)

The compressibility of the same Jeebropilly weathered rock spoil is also substantially affected by whether the material is tested dry or wet, as shown in Figures 46 and 47. These data were obtained by 75 mm diameter oedometer testing of -2.36 mm-scalped, initially loose-placed specimens, at the as-sampled moisture content and in a water bath, respectively.

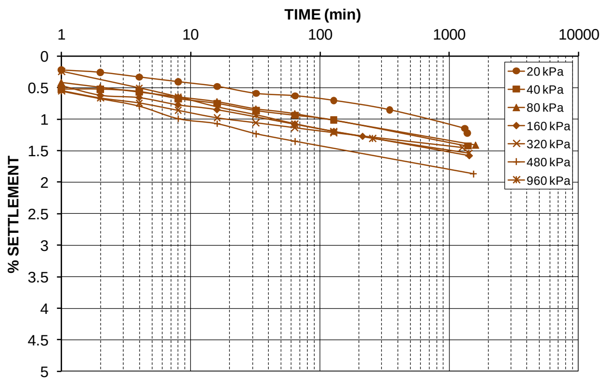

Figure 46 Settlement versus time plots for Jeebropilly weathered rock spoil placed initially loose and tested at the as-sampled gravimetric moisture content of 14.8%

Figures 46 and 47 show that testing at the as-sampled moisture content resulted in about half the relative settlement compared with testing in a water bath, the difference considered to be due to flooding-induced "collapse" settlement and weathering of the material.

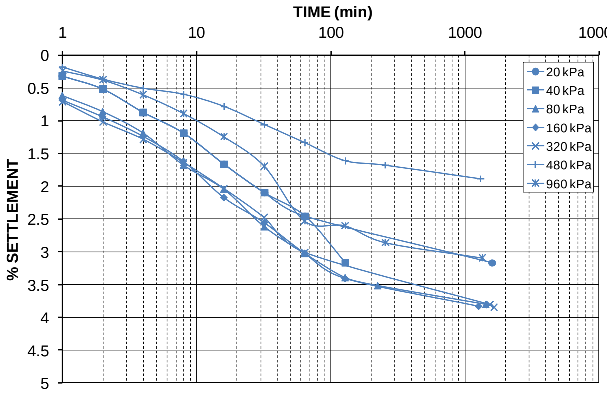

Figure 47 Settlement versus time plots for Jeebropilly weathered rock spoil placed initially loose and tested in a water bath

Figure 48 shows the consolidation plots from the end-points of the plots shown in Figures 46 and 47. Also indicted in Figure 48 are the increase in dry density from 1.020 to 1.121 t/m^3 (from 61 to 67% of Maximum Dry Density, MDD, of 1.68 t/m^3) with increasing applied stress when tested at the as-sampled moisture content, increasing to 1.204 t/m^3 (72% of MDD) on flooding in a water bath, and increasing further to 1.469 t/m^3 (87% of MDD) on loading in a water bath.

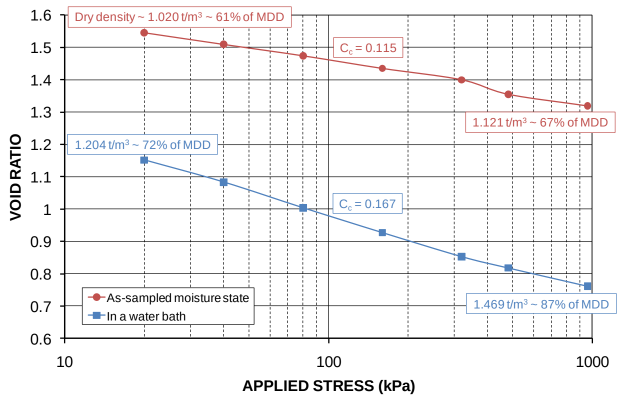

Figure 48 Consolidation plots for Jeebropilly weathered rock spoil placed initially loose and tested at the as-sampled moisture content or in a water bath

The plots obtained for the "dry" and "wet" cases are both essentially linear, and as the material is loosely-placed represent normally consolidated conditions. The values of Compression Index C_c calculated for testing at the as-sampled moisture content and in a water bath are shown in Figure 48 as 0.115 and 0.167, respectively, confirming that the material tested in a water bath is almost twice as compressible as the material tested at the as-sampled moisture content.

To assess the relative magnitude of weathering-induced settlement of the same Jeebropilly weathered rock spoil, loosely-placed, -19 mm scalped material, placed at the as-sampled moisture content, was exposed to the weather for a period of 35 days, during which 112.6 mm of rainfall fell on 20 of the 35 days (ranging from 0.2 to 19.4 mm/day, with an average of 5.6 mm/rain day and 3.2 mm/day overall).

Figure 49 shows that the median particle size D_{50} generally decreases with cumulative rainfall, although there is some reversal, considered to be due to re-agglomeration on wetting and drying cycles. Figure 50 shows the substantial % settlement of up to 25% that the spoil undergoes on weathering, with some reversal apparent on re-agglomeration.

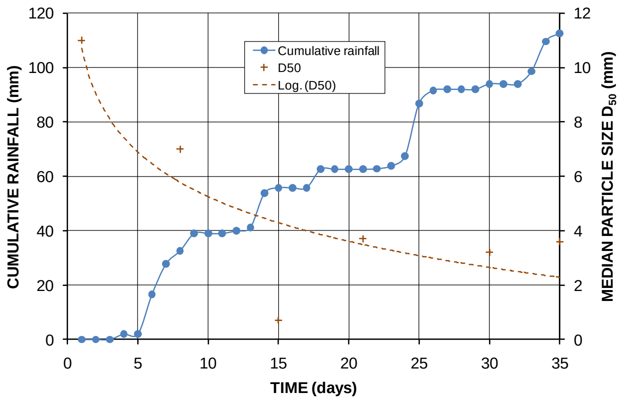

Figure 49 Variation of median particle size D_{50} with cumulative rainfall and time for Jeebropilly weathered rock spoil placed initially loose and exposed to weathering

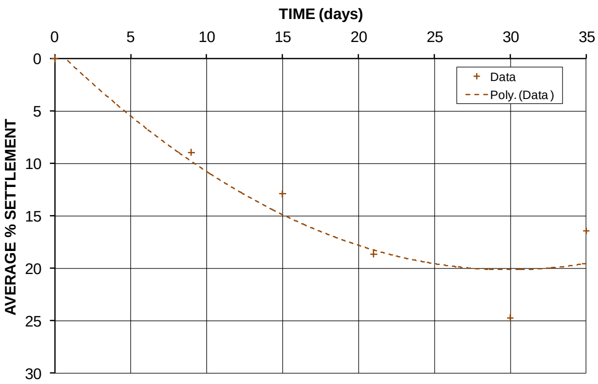

Figure 50 Settlement versus time for Jeebropilly weathered rock spoil placed initially loose and exposed to weathering

4.5 Characterising Performance of a Store and Release Cover

The store and release cover system was developed specifically for mine sites located in dry or seasonally dry climates (Williams *et al.*, 1997), with the intention of developing a cover system more robust than the more conventional rainfall-shedding cover; a cover system that does not rely on rainfall-shedding and the consequent risk of failure of the cover.

Store and release covers comprise a compacted sealing layer overlain by a gently-hummocked, loosely-placed rocky soil mulch layer, which is vegetated with a mix of shrubs, trees and grasses appropriate to the climatic setting (see Figure 51). The intention of the compacted sealing layer is to "hold-up" and store wet season rainfall infiltration in the loose rocky soil mulch growth medium, which is sized to store significant wet season rainfall infiltration, while not being so thick that the roots of the vegetation are unable to access it. A typical thickness of loose rocky soil mulch is 1.5 to 2 m. The stored infiltration is then released during the dry season through evapotranspiration. The rocky soil mulch is placed by paddock dumping and the surface is smoothed using a low bearing pressure dozer to smear the preferred flow pathways between truck-dumps, leaving a gently-hummocked surface with catchments sufficiently small that erosion will be negligible. Typically, the smoothed surface is first planted with native shrubs and trees, excluding grasses since these tend to out-compete shrubs and trees. Grasses are then planted the following wet season. Aerial seeding is preferred since it allows planting immediately following rainfall. The resulting store and release cover system is relatively straight-forward to construct and is robust.

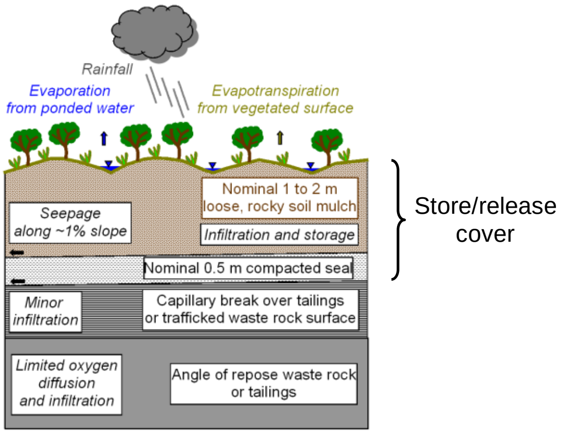

Figure 51 Schematic of a typical store and release cover over mine wastes

The first application of the store and release cover system was on the tops of mineralised waste rock dumps at Kidston Gold Mine in north Queensland, Australia (Williams *et al.*, 1997). The store and release cover was instrumented with matric suction and volumetric moisture content sensors through its thickness, and a weather station was installed on the cover. Data collected from the cover are shown in Figure 52 (Williams *et al.*, 2006), which demonstrates the seasonal wetting-up and drying of the cover, returning to similar wet-up and dry states each wet and dry season.

The field SWCC data obtained from the Kidston instrumented store and release cover are shown in Figure 53, which shows the initial seasonal fingering of the data, with "equilibrium" curves developing over time at each elevation in the cover.

The response of lysimeters beneath the Kidston store and release cover has shown that net percolation has been limited to about 1% of annual rainfall. The limited store and release cover performance data available worldwide (shown in Figure 54; Williams, 2011) suggest that, provided appropriate materials and construction methods are employed, they can be effective in limiting net percolation to between 1% and 2% of cumulative rainfall, for at least 10 years.

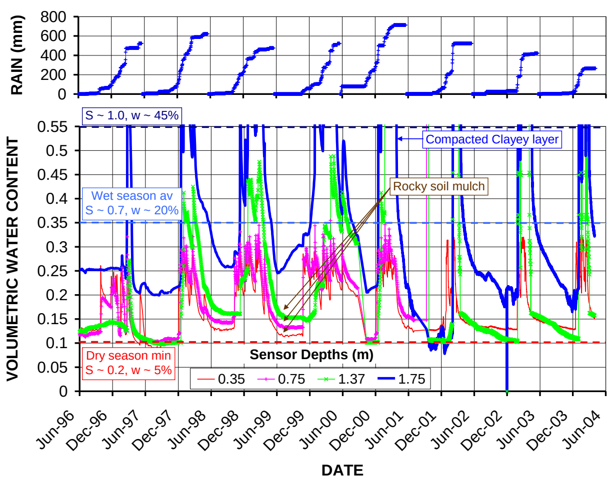

Figure 52 Rainfall and volumetric water content data collected from Kidston's store and release cover

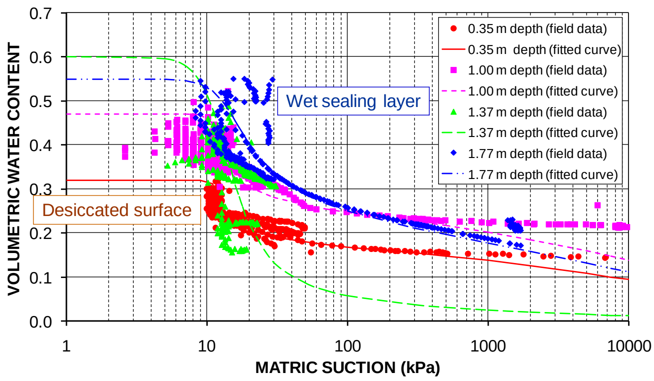

Figure 53 SWCC data collected from Kidston's store and release cover

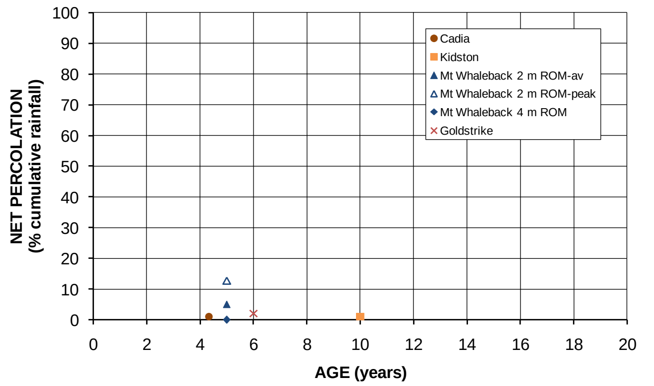

Figure 54 Performance data on store and release covers on the tops of waste rock dumps worldwide

5. CONCLUSIONS

There are many applications of unsaturated soil in the mining field. These include the wetting-up and drain-down of initially dry surface waste rock dumps; the irrigation and drain-down of heap leach materials; the drain-down, desiccation and rewetting of mine tailings; the dewatering of mineral products such as coal; the shear strength and compressibility of stored mine wastes; and the performance of geo-covers placed on mine wastes by way of rehabilitation. This paper highlights the key unsaturated soil mechanics parameters involved, overviews the nature of mining and mineral processing wastes, and some mineral products, and discusses a number of the issues involved. Some applications of unsaturated soil mechanics addressing the strength, compressibility and permeability of mining and mineral processing wastes, and mineral products, are presented, together with data to highlight them.

6. ACKNOWLEDGEMENTS

This paper is based on many years of research on the application of unsaturated soil mechanics principles to mine waste management and mined landform design, which has involved numerous past research students and research funding primarily from the Australian Research Council Linkage Program, the Australian Coal Association Research Program, and from industry.

7. REFERENCES

Beekman, H. E., Gieske, A. and Selaolo, E. T. (1996) "GRES: Groundwater recharge studies in Botswana 1987-1996". Botswana Journal of Earth Sciences, III, pp1-17.

Chapman, P. J., Williams, D. J., Rohde, T. K. and Ennor, S. J. (2008) "Understanding the water balance of potentially acid forming tailings deposited in a dry climate". Proceedings of 3rd Int. Seminar on Mine Closure, 14-17 October 2008, Johannesburg, South Africa, pp400-509.

Fredlund, M. D., Fredlund, D. G. and Wilson, G. W. (1997) "Prediction of the soil water characteristic curve from grain size distribution and volume mass properties". Proceedings of Third Brazilian Symp. on Unsaturated Soils, Rio de Janeiro, Brazil, 22-25 April 1997, 12 p.

Fredlund, D. G., Xing, A. and Huang, S. (1994) "Predicting the permeability function for unsaturated soils using the soil water characteristic curve". Canadian Geotechnical Journal, 31, pp533-546.

Rohde, T. K., Williams, D. J. and Burton, J. (2011) "Waste rock dump rainfall infiltration and base seepage". Proceedings of 7th Australian Workshop on Acid and Metalliferous Drainage, Darwin, Australia, 21-24 June 2011. 17 p.

Stolberg, D. J. and Williams, D. J. (2006) "Large-scale column testing of hypersaline tailings". Proceedings of 5th Int. Congress on Environmental Geotechnics, Cardiff, Wales, 26-30 June 2006, II, pp976-983.

Williams, D. J. (2006) "Mine closure as a driver for waste rock dump construction". Proceedings of 1st Int. Seminar on Mine Closure, Perth, Australia, 13-15 September 2006, pp697-706.

Williams, D. J. (2008) "The influence of climate on seepage from mine waste storages during deposition and post-closure". Proceedings of 3rd Int. Seminar on Mine Closure, 14-17 October 2008, Johannesburg, South Africa, pp461-473.

Williams, D. J. (2009) "Use of SWCCs to describe the dewatering of product coal". Proceedings of 4th Asia Pacific Conf. on Unsaturated Soils, Newcastle, Australia, 23-25 November 2009, pp233-238.

Williams, D. J. (2010) "Atmospheric drying and laboratory wetting of stockpiled product coal". Proceedings of 5th Int. Conf. on Unsaturated Soils, Barcelona, Spain, 6-8 September 2010, 1, pp513-518.

Williams, D. J. (2011) "Keynote address: appropriate geo-cover systems for different climates". Proceedings of 7th Australian Workshop on Acid and Metalliferous Drainage, Darwin, Australia, 21-24 June 2011, 17 p.

Williams, D. J. and Morris, P. H. (1987) "Bearing capacity and deformation characteristics of ponded fine-grained coal mine tailings". Proceedings of Nat. Conf. on Mining and Environment - A Professional Approach, Brisbane, Australia, July 1987, pp139-144.

Williams, D. J. and Rohde, T. K. (2009) "Reliability of using laboratory-determined soil water characteristic data for mine waste cover design". Proceedings of Mine Closure 2009, Perth, Australia, 9-11 September 2009, pp493-504.

Williams, D. J., Stolberg, D. J. and Currey, N. A. (2006) "Long-term performance of Kidston's 'store/release' cover system over potentially acid forming waste rock dumps". Proceedings of 7th Int. Conf. on Acid Rock Drainage, St Louis, Missouri, USA, 26-30 March 2006, pp2385-2396.

Williams, D. J., Wilson, G. W. and Currey, N. A. (1997) "A cover system for a potentially acid forming waste rock dump in a dry climate". Proceedings of 4th Int. Conf. on Tailings and Mine Waste '97, Fort Collins, Colorado, 13-17 January 1997, pp231-235.

Williams, D. J., Kho, A. and Daley, A. (2011) "Settlement and strength of clay-rich coal mine spoil". Proceedings of Tailings and Mine Waste 2011, Vancouver, Canada, 6-9 November 2011, 12 p.