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Technical Article

Long-term Evaluation of a Composite Cover Overlaying a Sulfidic Tailings Facility

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Abstract. A high density polypropylene (HDPE) and bentonite composite cover, used to reduce oxygen ingress into a sulfidic tailings facility, was evaluated over a 7 year post-installation period between 1998 and 2005, and found to be a reliable long-term barrier to oxygen ingress and rainfall infiltration. The evaluation was based on multiple lines of evidence and included (i) changes in metal and inorganic concentrations in the regional ground water immediately underlying the tailings residue; (ii) oxygen concentrations from probes installed below the composite cover; (iii) changes in pore water levels within the tailings residue, and; (iv) changes in temperature of the vadose zone below the composite cover.

While no systematic reduction in metal and inorganic concentrations were observed, oxygen concentrations from most probes installed below the composite cover showed no measurable oxygen (< 0.01%) and indicated that oxygen ingress through the composite cover was slow, compared to oxygen consumption in the tailings residue. The decline and stabilization in pore water levels over time within the tailings residue provided evidence that the cover effectively reduced infiltration of rainfall-recharge through the tailings residue. Temperatures below the composite cover were offset and attenuated with depth, and showed a decrease in temperature (especially at the deepest location just above the tailings residue), suggesting that the exothermic sulfide oxidation reaction process was not maintained after the cover was installed.

Key Words: Composite cover; oxygen ingress; sulfidic; tailings; temperature

Introduction

Acid mine drainage (AMD) is a worldwide environmental problem, resulting from the exposure of sulfidic minerals to atmospheric oxygen. Oxidation of these sulfidic minerals leads to acid production in the tailings' pore water (Gleisner and Herbert 2002) and the potential release of heavy metals into surface and ground water, with a subsequent reduction in water quality (Moses et al. 1987). Techniques to reduce this AMD involve either (i) the use of pH-buffering materials within the tailings to neutralize acid production (Xenidis et al. 2002) or (ii) reducing the ingress of atmospheric oxygen into the tailings. Oxygen ingress can be reduced by the use of water covers, which maintain fully saturated conditions (Mitsch and Wise 1998), since oxygen has a low aqueous solubility and diffusion coefficient. However, water covers can increase infiltration into the tailings (Romano et al. 2003), especially if the tailings are located above the watertable. Alternatively, oxygen ingress can be reduced by the use of low oxygen-permeable synthetic covers overlaying the tailings (Kim and Benson 2004). These covers are designed to reduce the influx of oxygen into the tailings, thus minimizing the rate of sulfide oxidation. Also, they reduce the infiltration of water into the tailings, minimizing the potential for off site migration of acid and heavy metals.

Synthetic cover materials for sulfidic tailings have been used for a number of years, and while extensive modelling of the composite covers has been undertaken (Kim and Benson 2004), little long-term laboratory or field data are available to assess the effectiveness of these covers. This paper evaluates the effectiveness of a synthetic composite cover installed at a sulfidic tailings facility in Australia over a 7 year post-installation period between 1998 and 2005.

Site Description

A 20 ha tailings facility was constructed in 1970 near Perth, Western Australia, on the Swan Coastal Plain. The base of the tailings facility overlaid ≈ 20 m thick fine to medium dune sand layer with interbedded limestone and sandstone lenses. The regional water table was located ≈ 3 m below the base of the tailings facility. Regional ground water velocity was ≈ 45 m y^{-1} (Patterson et al. 2003). To protect the underlying ground water, a 2mm polythene base liner overlain with 0.5 m of clean sand was placed at the base of the tailings facility at the time of construction. Nickel tailings material deposited consisted of solid tailings [hematite (Fe_2O_3, ≈ 46%), pyrite (FeS, ≈10%), and pyrrhotite (FeS_{1-x} (x = 0 to 0.2), ≈10%)] and tailings liquor. In 1979, low-pH metal-contaminated ground water was detected below and down-gradient of the tailings facility, suggesting that the base liner had failed. Tailings disposal ceased, and a synthetic composite cover remediation strategy was implemented February – May 1998.

This remediation strategy consisted of dewatering the tailings facility to remove the tailings liquor and treatment of this liquor off-site, leaving tailings material termed "unoxidised residue". Towards the end of the dewatering process, tailings liquor with high suspended sediment content was temporarily stored in ponds up-gradient of the tailings facility to enable the fine solids to settle prior to off-site treatment of the liquor.

The second remediation step involved buffering the top 1 m of the tailings residue by mixing the tailings residue (40%) with limestone ($CaCO_3$, 20%) and clean quartz sand (SiO_2, 40%). This material was termed "mixed residue".

The third remediation step involved overlaying the mixed residue with a 2 – 4 m thick clean sand layer, followed by a synthetic composite cover. The cover consisted of a 7.2 mm thick woven textile membrane impregnated with sodium bentonite (Bentofix 2000X) overlaid with a 0.75 mm thick high density polypropylene (HDPE) membrane (Jaylon). To protect the composite cover, an additional 2 m thick clean sand layer was installed. A cross-section schematic of the tailings facility is shown in Figure 1.

Site Monitoring

Assessment of the effectiveness of the composite cover to reduce sulfide oxidation within the residual tailings would be inconclusive based only on changes in ground water pH and heavy metal concentrations beneath and down-gradient of the tailings facility. Buffering of the tailings residue with limestone would substantially delay the release of acidity and heavy metals into the underlying ground water. Additionally, metal retardation (sorption/desorption) within the tailings and aquifer material, coupled with the size of the site and the relatively low regional ground water velocity of ≈ 45 m y^{-1} (Patterson et al. 2003) under the tailings facility would most likely result in substantial delays in observing improvements in ground water metal quality down-gradient of the facility. Interpretation of ground water chemistry could be further confounded due to responses to ground water pumping adjacent to the site that affects ground water flow direction and velocity under the tailings facility.

Accordingly, several additional lines of evidence were investigated, including use of literature oxygen diffusion coefficients for the composite cover to predict the reduction in oxygen ingress rates as a result of the installed cover, and validating this data by comparing it to oxygen ingress rates determined from measured vertical oxygen concentration profiles in the unsaturated zone below the composite layer, and soil porosity data.

Sulfide oxidation is exothermic and can lead to high temperatures within the tailings residue (Harries and Ritchie 1987); thus, the installation of a cover could reduce temperatures within the tailings residue as a result of reduced oxygen ingress. Therefore, changes in temperature of the unsaturated zone under the cover were monitored.

The effectiveness of the composite cover to reduce rainfall infiltration was also assessed by monitoring changes in pore water levels within the tailings residue. Lower pore water levels would likely indicate that the cover is reducing rainfall infiltration rates into the tailings.

Oxygen and Temperature Monitoring

Oxygen concentrations in the unsaturated zone were monitored using on-line oxygen probes (Patterson et al. 1995). Multilevel in situ oxygen probes and nylon gas sampling tubes (0.20 cm i.d.) with 3-way taps were installed above and below the composite cover in June 1998 (Oxy-01, Oxy-02, and Oxy-03) and April 1999 (Oxy-04, Oxy-05, and Oxy-06), and at the outer edge of the cover in April 1999 (Oxy-07) and March/April 2000 (Oxy-08 and Oxy-09). The depths for selected installations are shown in the cross-section schematic (Figure 1). Oxygen probes were monitored every two hours. Temperature thermistors were also installed in June 1998 in a vertical string at Oxy-01. The thermistors were located at 1.5, 2.5, 4.0, and 6.0 m below ground (0.5 m above, and 0.5, 2.0, and 4.0 m below the composite cover), and monitored every two hours. Oxygen probes and thermistors located below the composite cover were emplaced through pre-installed 100 mm diameter PVC casing sealed to the composite cover. A temporary 50 mm PVC bore was installed through the 100 mm PVC casing and the oxygen probes/thermistors were installed, with communication wires from the oxygen probes/thermistors exiting the top of the casing. During the installation, intact soil cores were collected to determine soil porosity and air-filled porosity for estimating an oxygen diffusion coefficient in the soil below the composite cover. The temporary 50 mm PVC bore was then withdrawn and backfilled with clean recovered sand. The top of the 100 mm PVC casing was then capped with a ≈ 50 cm thick bentonite layer. Approximately 3 months later, a 5 cm silicone layer was installed above the bentonite layer.

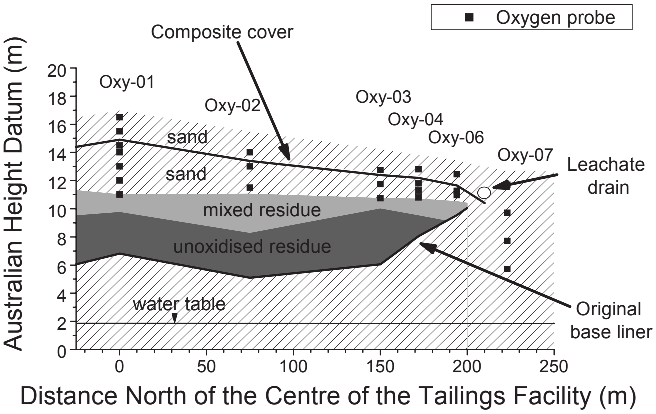

Figure 1. Cross-section schematic of the tailings facility showing the composite cover in relation to the underlying clean sand, mixed residue, unoxidized residue and original base liner; details of the composition of the mixed residue and unoxidized residue are given in the text.

A second separate hole was constructed 2 m north of each PVC casing for installation of oxygen probes and thermistors above the cover. Along with oxygen probes and thermistors, gas sampling ports were installed to enable either the collection of soil gas samples or the introduction of atmospheric oxygen to check oxygen probe calibrations.

Pressure Difference and Gas Flow

The pressure difference above and below the composite cover was determined manually using a hand held manometer (TSI DP-Calc, model# 8705) connected to the open gas sampling tube located at Oxy-04. Gas flow through the open gas sampling tube was measured at a similar time using a hand held mass flowmeter (Alltech Digital Flow Check).

Pore Water/Ground Water Chemistry and Water Levels

Pore water and ground water samples collected from the site were analysed for pH, conductivity, Eh, dissolved oxygen, major ions (Na^+, Ca^{2+}, Cl^-, NO_3^-, NH_4^+, and SO_4^{2-}) using standard chemistry techniques and trace metals (As, Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, and Zn) using inductively coupled plasma mass spectrometry (ICP-MS). Laboratory analysis was conducted by the Chemistry Centre of Western Australia. Pore water and ground water levels were also monitored to assess the hydraulic changes within and beneath the tailings facility.

Pore water/ground water samples were collected from either narrow diameter "mini-piezometers" constructed of 12.5mm diameter PVC conduit with 20 μm sintered mesh stainless steel tips, or 50 mm diameter piezometers using class 9 PVC pipe with 1 mm slotted screens. For pore water samples, screens were located within the tailings residue; for ground water samples, screens were located in ground water beneath the tailings facility. Depth locations of the piezometers are given in Patterson et al. (2003).

The "mini-piezometers" were sampled using an air-lift technique using high-purity nitrogen gas to enable oxygen-free samples to be collected. Due to the long recovery times, only limited volumes of water (especially pore waters) could be collected from these mini-piezometers. The 50 mm diameter piezometers were sampled using a 12V submersible pump. Conductivity, pH, Eh, and dissolved oxygen were determined in-line prior to in-line filtration (using a 0.45 μm disposable filter) and collection. Samples were stored on ice prior to acidification and analysis.

Oxygen Diffusion Coefficient of the Composite Cover

To predict potential oxygen ingress through the composite cover, laboratory permeation experiments were conducted using the HDPE material and literature data for the bentonite-impregnated woven textile membrane. Details of these experiments and the procedures used to determine the oxygen diffusion coefficient are given in Trefry and Patterson (2001). Based on this data, an effective oxygen diffusion coefficient of 4.8×10^{-11} m^2 s^{-1} for a 7.95 mm thick composite cover at field moisture content was estimated.

Oxygen Flux Estimates Through the Composite Cover

Estimates of oxygen flux through the composite cover were determined via two independent methods. The vertical oxygen flux (q) through the composite cover can be estimated using the standard Fickian law (equation 1):

$$q = D_{eff} \frac{\partial C}{\partial z} \qquad (1)$$

where D_{eff} is the effective oxygen coefficient in the clean sand below the composite cover, or the effective oxygen diffusion coefficient through the composite cover. The gradient is based on either the field determined steady-state vertical oxygen concentration profile below the composite cover or based on the assumption of full atmospheric concentration (21% oxygen) immediately above the cover and zero oxygen below the cover to give a maximum gradient. These calculations assume oxygen consumption does not occur in the clean sand above the mixed tailings residue, but only in the tailings residue itself, and the advancement of this oxygen front through the mixed tailings residue is limited by the rate of diffusion of oxygen (Davis and Ritchie 1986).

The D_{eff} of oxygen through the clean sand below the composite cover was estimated via the Millington-Quirk (1961) equation (2), using measured data for porosity (n), air-filled porosity (θ_a), and the molecular diffusion coefficient for oxygen in air (D_{mol}) at 20ºC of 2.01 x 10^{-5} m^2 s^{-1} (Gliński and Stepniewski 1985).

$$D_{eff} = \frac{\theta_a^{10/3}}{n^2} D_{mol} \qquad (2)$$

Sulfuric Acid Production and Neutralization

The potential rate of sulfuric acid generation can be estimated stoichiometrically, based on the oxidation of pyrite (equation 3) and pyrrhotite (equation 4) and the oxygen flux through the composite cover.

$$FeS_2 + 3.75O_2 + 3.5H_2O \rightarrow Fe(OH)_3 + 2SO_4^{2-} + 4H^+ \qquad (3)$$

$$Fe_{0.95}S + 2.2O_2 + 2.4H_2O \rightarrow 0.95Fe(OH)_3 + SO_4^{2-} + 2H^+ \qquad (4)$$

The limestone in the mixed residue has the potential to neutralize a proportion of the sulphuric acid produced from oxygen ingress. The neutralization reaction can be described as:

$$SO_4^{2-} + 2H^+ + CaCO_3 \rightarrow Ca^{2+} + SO_4^{2-} + H_2O + CO_2 \qquad (5)$$

Results and Discussion

Effectiveness of the Composite Cover – Oxygen Flux through the Composite Cover

A plot of soil gas oxygen concentrations over a period of 7 years at location Oxy-01 is shown in Figure 2. Once oxygen probes were installed, oxygen concentrations below the composite cover decreased, but some initial fluctuations in oxygen concentrations were observed. Fluctuations over the first few months were probably a result of poor sealing of the bentonite layer to the inside of the 100 mm PVC casing. Improved sealing was achieved with the addition of 25 L of water within and around the bore casing to further swell the bentonite within the casing, followed by the installation of a silicone layer within the bore casing. After sealing with water and a silicone layer, oxygen concentrations below the composite cover remained < 0.01%.

Oxygen concentrations in the unsaturated zone above the composite cover remained relatively high, between 15 and 20%, indicating limited oxygen use in this zone compared to oxygen ingress from the atmosphere. However, on a few occasions, oxygen concentrations were observed to decrease in the winter and rebound in summer (e.g. Figure 2). This was most likely due to heavy winter rainfall saturating the soil profile and reducing oxygen ingress.

Oxygen data for above and below the composite cover suggest that oxygen was retarded in its movement through the composite cover and that the rate of oxygen ingress is lower than the rate of oxygen consumption (likely due to sulfide oxidation).

To quantify the effectiveness of the composite cover, the oxygen flux through the composite cover was estimated, using an oxygen gradient based on the vertical oxygen profile below the cover or assuming full atmospheric concentration (21% O_2) immediately above the cover and 0% O_2 below the cover. An average steady-state vertical oxygen concentration profile above and below the composite cover at Oxy-01 between Jan. 2002 and Dec. 2003 (n = 8760) is shown in Figure 3. Average oxygen concentrations below the composite cover were ≈ 0.02 % and close to the detection limit of the oxygen probes (< 0.01 %). The shallow vertical oxygen concentration gradient (31 μg L^{-1} m^{-1}) profile below the composite cover suggested that oxygen ingress was low; the estimated oxygen flux was only 9.1 mg m^{-2} day^{-1} (0.66 t $year^{-1}$) (Table 1).

Based on the estimated oxygen diffusion coefficient through the composite cover of 4.8 x 10^{-11} m^2 s^{-1} (Trefry and Patterson 2001), a composite cover thickness of

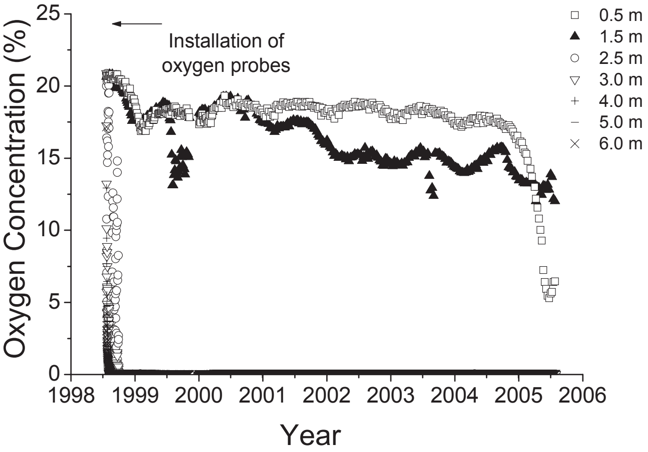

Figure 2. Oxygen concentrations for depths below ground at Oxy-01; the composite cover was located 2.0 m below ground.

7.95 cm, and assuming a maximum oxygen gradient (21% O_2 immediately above the cover and 0% O_2 immediately below the cover), an oxygen flux of 150 mg m^{-2} day^{-1} (11 t $year^{-1}$) was estimated (Table 1).

Estimated oxygen fluxes through the composite cover for the two independent methods gave values that were different by approximately an order of magnitude. For the field gradient method, this variation may be due to the extremely low oxygen concentrations observed below the cover, reducing the reliability of the estimated oxygen concentration gradient. Also, the oxygen flux estimated using the laboratory derived D_{eff} may be overestimated since a maximum gradient was used for this calculation.

A transport limited oxygen flux estimate without a composite cover installed was also calculated by assuming 21% O_2 at the ground surface and 0% O_2 at a depth of 6 m (the approximate depth of the tailings residue).

Both oxygen flux estimates through the composite cover were 2 – 3 orders of magnitude lower than an estimated oxygen flux assuming no composite cover was installed (Table 1). This indicated that the composite cover was effective at substantially reducing oxygen flux into the tailings residue.

The potential rate of acid generation based on the stoichiometric oxidation of pyrite and pyrrhotite (equations 3 and 4) and oxygen flux is given in Table 1. Based on equation (5), and a potential buffering capacity of the limestone (110,000 t of $CaCO_3$) in the mixed residue, the net increase in acidity (from vertical downward oxygen ingress) may be delayed for a period between 6,600 (using a laboratory-derived D_{eff}) and 110,000 years (using a field-derived D_{eff}). These estimates do not take into account the heterogeneity of the tailing material and assume that reaction rates were not kinetically controlled.

At other monitoring locations below the composite cover (Oxy-03, Oxy-04, Oxy-05, and Oxy-06), similar oxygen data were also observed, providing good evidence that the composite cover provided a long-term reliable barrier to the ingress of oxygen. However, at Oxy-02, rapid fluctuations in oxygen concentrations were observed below the composite cover during the summer months of each year, and the addition of the silicone layer sealant to the top of the bore casing (to seal a suspected leak), did not reduce oxygen ingress (Figure 4).

Additional experiments were conducted at Oxy-02 to help explain the occasional rapid fluctuations in oxygen concentrations observed below the composite

Table 1. Estimated oxygen flux based on field oxygen gradient and laboratory-derived composite cover diffusion coefficient, with and without the composite cover installed

Method	D_{eff} (m^2 s^{-1})	Gradient (mg L^{-1} m^{-1})	O_2 flux q (mg L^{-1} m day^{-1})	Total O_2 flux for site (t y^{-1})	Rate of H_2SO_4 acid production (t y^{-1})
Field gradient	3.4×10^{-6}	0.031	9.1	0.7	1.0
Laboratory-derived D_{eff}	4.8×10^{-11}[a]	35000	150	11	16
No composite cover	3.4×10^{-6}	47	14000	1000	1500

[a] Trefry and Patterson (2001)

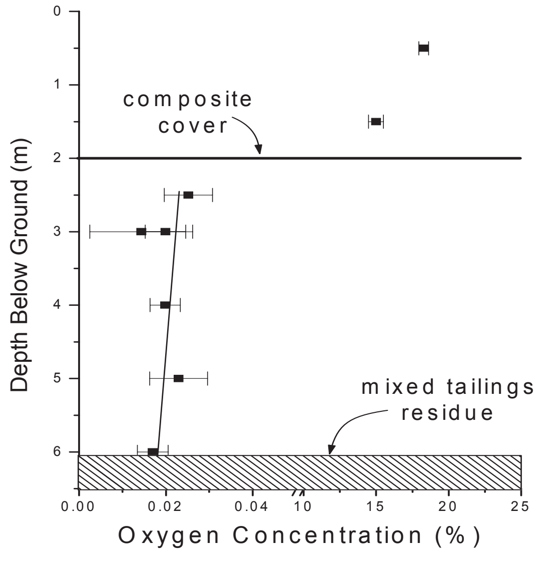

Figure 3. Average vertical oxygen profile at Oxy-01 between January 2002 and December 2003 (n = 8760)

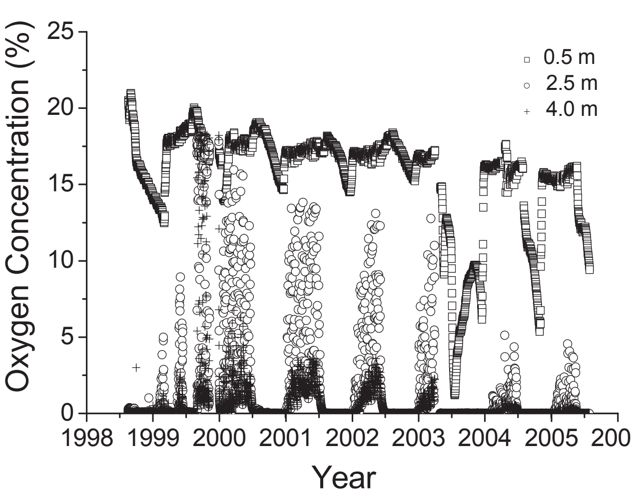

Figure 4. Oxygen concentrations for depths below ground at Oxy-02. The composite cover was located 2.0 m below ground

(0.5 and 2.0 m below the cover) were left open between July 20 and October 8 1999 to provide a small air passage below the cover. Oxygen concentrations below the cover were compared to changes in barometric pressure (Figure 5). Oxygen concentration fluctuations showed a similar pattern to fluctuations observed previously during the summer months. A strong correlation was observed between increases in O_2 concentrations below the cover and increases in barometric pressure. Further experiments (Figure 6) using the gas sampling tube to 1.5 m below the composite cover at Oxy-04 showed a strong correlation (r^2 = 0.975; n =13) between pressure differences (above and below the composite cover) and gas flow rates through the gas sampling tube determined on 13 occasions over a 6 month period. This data indicated that oxygen ingress at Oxy-02 between July and October 1999 was the result of barometric pumping. Oxygen fluctuations observed prior to and after this experiment were also likely to be the result of barometric pumping coupled with drying of the soil profile over summer. Oxygen ingress due to barometric pumping appeared to be a localized problem and an artefact of the installation of the oxygen probes at the Oxy-02 location. However, this data suggests that barometric pumping can contribute substantially to oxygen ingress if covers are punctured or ruptured.

Soil around the Oxy-02 location was excavated and the concrete liner and protective concrete ring (just above the base of the cover) was removed in April 2003. This revealed a tear in the HDPE near where it was attached to the bore casing used to install the oxygen probes (Figure 7). It appears that a protective concrete ring installed around the base of the PVC pipe may have torn the HDPE during the initial installation. Repairs to this tear have reduced, but not eliminated, oxygen ingress below the composite cover (Figure 4). Further investigation has identified additional tears associated with the excavation of soil in April 2003.

Temperature Fluctuations below the Composite Cover

Temperatures in pyritic waste rock dumps can exceed 50ºC (Harries and Ritchie 1987); however, at this site, temperatures immediately above the tailings residue ranged between 17 and 24ºC and were close to the average ambient temperatures determined at the surface of the tailings facility. The temperature at Oxy-01 below the composite cover for the period July 1998 to July 2005 is shown in Figure 8. Temperatures were offset and attenuated with depth; thus, interpretation of pyritic oxidation/temperature generation was difficult to assess. In fact, if temperature would have been monitored only once a year, the results might have been highly misleading

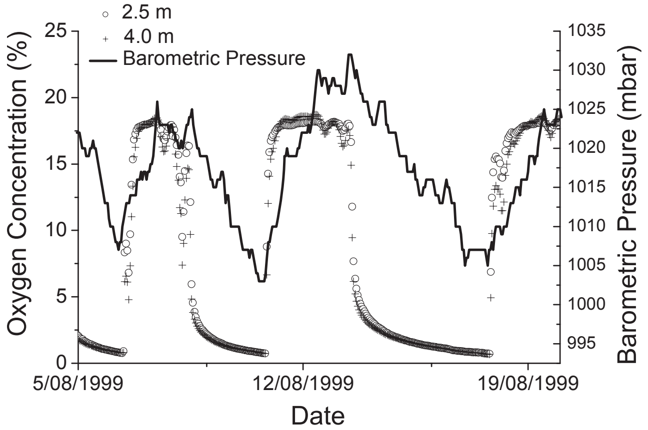

Figure 5. Barometric pressure and oxygen concentrations for depths below ground at Oxy-02; the composite cover was located 2.0 m below ground

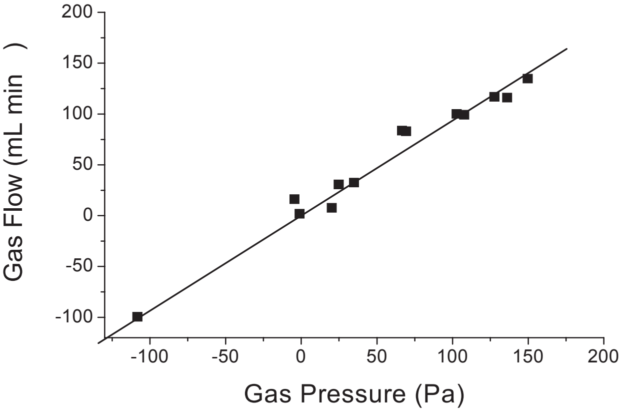

Figure 6. Comparison of pressure differences (above and below the composite cover) to gas flow rates through the gas sampling tube to 1.5 m below the composite cover at Oxy-04 on 13 occasions over a 6 month period. Also shown is a linear fit (r^2 = 0.975; n = 13) of the experimental data.

Figure 7. Bore casing at Oxy-02 (used to install oxygen probes below the composite cover), showing the tear in the composite cover near where it was attached to the bore casing.

depending on the time of year the temperature was monitored. For example, if the temperature data were only collected in the winter months (June, July, and Aug.), the strong increasing temperature gradient with depth would suggest that the tailings residue was exothermic, possibly due to pyrite oxidation and inferred oxygen ingress. However, in the summer months (Dec., Jan., and Feb.), the gradient would be negative, suggesting that the tailings residue was endothermic.

To better interpret this data, the 12-month average temperatures (from Aug. to the following July) at each depth below the cover was compared to 12-month average ambient temperatures (Figure 8b). For the year 2000, not all the data were available to provide an average temperature, so year 2000 data were excluded.

The average temperature at 6.0 m below ground (immediately above the tailings residue) was ≈ 3ºC above the ambient temperature in 1999. Since this time, the average temperature at 6.0 m has decreased by ≈ 7 to ≈ 4ºC below the average ambient temperature, over the 7 years post-installation period. The reduction in temperature has been relatively consistent between 1999 and 2004, but appears to be stabilizing in 2005. At the other locations below the composite cover (2.5 and 4.0 m), the average temperatures were ≈ 2ºC above the average ambient temperature in 1999, and have decreased by ≈ 3 to ≈ 1ºC below the average ambient temperature between 1999 and 2003, and appear to have stabilized between 2003 and 2005.

The average temperature data suggests that the exothermic sulfidic oxidation of pyrite tailings has decreased since the composite cover was installed and provides additional evidence to suggest that the composite cover has reduced oxygen ingress into the tailings residue. However, another possible reason for the higher initial temperature of the tailings could be thermal build-up from solar radiation exposure prior to covering of the tailings. The relatively stable, but lower than average ambient temperature at 6.0 m may indicate endothermic processes were occurring in the tailings; however, this requires further investigation.

Pore Water Levels within the Tailings Residue

The occurrence of pore water within the tailings residue is most likely due to entrapment of residual tailings water, as a result of the presence of the original base liner located below the tailings, and the low permeability of the tailings residue material (Turner et al. 2001). After the composite cover remediation strategy was implemented, pore water levels initially increased between Feb. and May 1998 due to probable overburden pressure from the sand cover (Turner et al. 2001). Since that time, pore water levels within the tailings residue have shown a consistent exponential decline (Figure 9). The decline in pore water levels within the tailings residue may suggest some leakage of pore water through the original base liner; however, the decline in average water levels between July 2002 and July 2005 was small, suggesting pore water levels may be stabilizing. Assuming consistent hydraulic conductivity of the bottom liner and no further consolidation of the tailings residue, the data for the last two years of monitoring (2004 to 2005) suggests either that leakage to the underlying regional ground water was minor or that leakage rates were being matched by infiltration rates. The decline in pore water levels provides evidence that the cover has

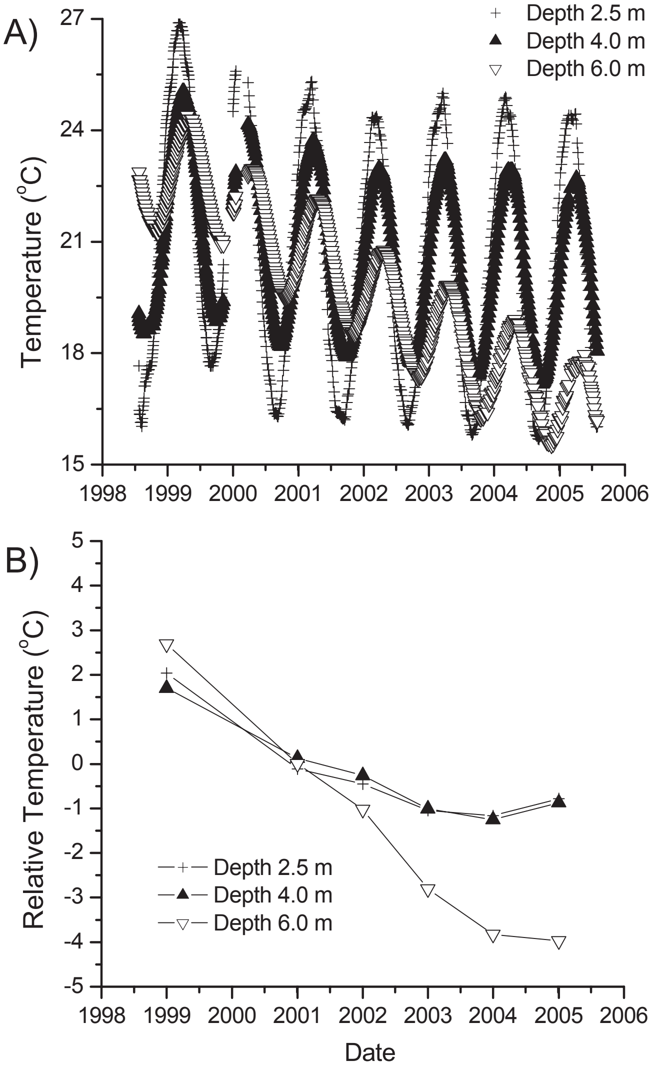

Figure 8. A) Temperature changes over time at various depths below ground at Oxy-01; B) 12-month average temperatures relative to average ambient temperatures for various depths below ground. The composite cover was located 2.0 m below ground.

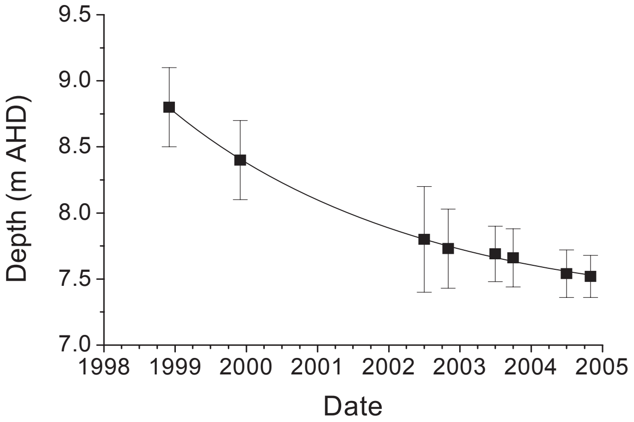

Figure 9. Average pore water level data within the tailings residue (errors bars are standard deviation)

effectively reduced infiltration of rainfall-recharge through the tailings residue.

Chemistry of the Tailings Pore Water

Over the 7 years of monitoring, there were no systematic trends at the pore water sampling locations (n = 14) to indicate that trace metals adsorbed to the oxidised components of the tailings residue were being released into the tailings pore water. For example, the average copper concentrations ranged between 0.41 ± 0.3 and 1.9 ± 2.9 mg L^{-1}, and average nickel concentrations ranged between 3.0 ± 3.4 and 9 ± 19 mg L^{-1}. Average pore water pH ranged between 8.3 ± 0.7 and 8.6 ± 0.6, suggesting the consistent elevated pH of the pore water was preventing substantial desorption of trace metals from the oxidised components of the tailings residue. These observations would be consistent with Welp and Brümmer (1999), who identified pH as the dominant factor controlling the partitioning between the solid (soil) and liquid phase for a range of metals.

Ammonium concentrations ranged from 3800 ± 1700 to 6800 ± 1800 mg L^{-1} NH_4^+-N, and sulphate concentrations ranged from 17000 ± 4000 to 22000 ± 4000 mg L^{-1} SO_4^{2-} during the 7 year monitoring period, again without any systematic trends. However, average pore water nitrate concentrations have substantially decreased from 68 ± 162 in 1998 to 4.2 ± 4.6 mg L^{-1} NO_3^--N in Nov. 2002. After this time, nitrate concentrations have remained relatively stable. The reduction in nitrate may be due to the development of anaerobic denitrifying conditions as a result of the installation of the composite cover.

Ground Water Chemistry below the Tailings Facility

As pore water metal concentrations were relatively consistent within the tailings residue over time, and assuming a consistent ground water flow rate and direction, changes in ground water quality in bores located immediately under the tailings residue may reflect changes in pore water infiltration rates from the tailings residue above.

The shallow ground water monitoring locations (n = 3) immediately underlying the tailings residue showed that the average metal concentrations decreased about 70% over the first 3 years of monitoring, but concentrations have remained reasonably stable since then. Average copper concentrations decreased from 1.4 ± 1.4 mg L^{-1} in December 1998 (Turner et al. 2001) to 0.38 ± 0.42 mg L^{-1} in October 2003. Average nickel concentrations decreased from 1.7 mg L^{-1} in December 1998 to 0.35 ± 0.20 mg L^{-1} in October 2003. The metal data may indicate the effectiveness of the composite cover to reduce infiltration of pore water into the underlying ground water. However, these pore water metal concentrations are strongly controlled by pH and sorption /desorption processes within the tailings and underlying aquifer material, making detailed interpretation of the effectiveness of the cover difficult with respect to metals mobility.

No systematic trend of decreasing ammonium and sulphate concentrations were observed over the 7 year period. Any improvement in ammonium and sulphate ground water concentration beneath the tailing's residue as a result of reduced pore water leakage was possibly masked by ground water movement due to the ground water recovery that was occurring around the site.

Even with a reduction in pore water leakage, substantial improvements in ground water quality directly under the tailings facility may take many years. This is based on the time up-gradient contaminated water would take to move under the tailings facility (assuming ground water pumping around the site was not affecting ground water flow direction or velocity) and be replaced with uncontaminated ground water further up-gradient (not accounting for potential retardation of contaminants).

Conclusions

The assessment of the long-term effectiveness of the composite cover to reduce oxygen ingress, based on metal concentrations in the regional ground water quality immediately underlying the tailings residue was problematic. While selective bores monitoring regional ground water quality immediately underlying the tailings residue showed improvements in ground water metal concentrations between 1998 and 2005, no systematic reduction in ammonium and sulphate concentrations were observed. Additionally, reduced pore water metal concentrations over time were not evident. Therefore, a comprehensive assessment of the effectiveness of the composite cover could not be made based only on ground water chemistry.

However, multiple lines of evidence from 7 years of post-installation monitoring have indicated that the composite cover continues to provide a reliable barrier to oxygen ingress and rainfall infiltration.

Oxygen concentrations from most probes installed below the composite cover showed no measurable oxygen (<0.01%). Estimated oxygen flux through the composite cover, based on an independently-derived composite cover diffusion coefficient, was also consistent with oxygen flux estimates determined from vertical oxygen gradients observed at the site. A reduction in average temperature within the tailings of up to 7°C suggests that the exothermic sulphidic oxidation of pyrite tailings has decreased since the composite cover was installed and provides additional evidence to suggest that the composite cover has reduced oxygen ingress into the tailings residue.

Additionally, the decline and stabilization of pore water levels within the tailings residue provides evidence that the cover is effectively reducing infiltration of rainfall-recharge. The stabilization of average pore water levels at lower levels over the last few years suggested leakage to the underlying regional ground water was minor, due to reduced head pressures (lower vertical downward head gradients), and that a new balance of lower leakage and infiltration rates had become established.

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