

Evaluation of a Single-Layer Desulfurised Tailings Cover

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ABSTRACT

A desulfurised tailings cover was installed at the Detour Lake Mine in Ontario, Canada, to reduce oxygen penetration into the underlying sulfidic tailings. The cover ranges from one to 1.5 m in thickness and was intended to maintain high water saturation to reduce oxygen diffusion and consume oxygen by oxidation of the residual sulfide minerals.

The tailings impoundment was instrumented to measure climatic parameters, water levels and water content profiles within the tailings and single-layer cover. One year of monitoring data was collected. Additional tailings samples were obtained for geotechnical and geochemical characterisation. The average grain size of the cover material was found to be coarser than the underlying tailings. Monitoring also indicated that air entry values of the cover material were lower than the tailings.

Numerical modelling was conducted on the cover to predict water content profiles under varying climate conditions together with the depth of oxygen penetration and diffusive oxygen fluxes. Estimates of the diffusion coefficient and kinetic oxidation rates from field data compared well with values obtained by laboratory measurements. Numerical simulations indicate water saturations of less than 85 per cent can be expected under varying climate conditions. Predicted oxygen flux rates through the desulfurised cover over tailings with high acid potential indicate low flux rates reaching these tailings due to either consumption of oxygen by residual sulfur within the cover or saturation of the underlying tailings.

INTRODUCTION

Acid rock drainage (ARD) from mining waste rock is one of the most important environmental issues facing the mining industry (MEND, 2001). ARD can be reduced by preventing primary oxidation through limiting the availability of oxygen or preventing transport to the environment by limiting water availability. These aims can be accomplished with the use of engineered covers. The cover may include placement of a layer of fine granular materials over coarse grained materials to create a capillary barrier that limits oxygen entry by maintaining a layer at high saturation (Nicholson *et al.*, 1989; Barbour *et al.*, 1993; Yanful *et al.*, 1993; Aachib *et al.*, 1994). Oxygen diffusion coefficients have been found to decrease significantly at degrees of saturation greater than 85 per cent (O'Kane *et al.*, 1995). Engineered covers often require large volumes of materials with specific hydraulic properties. These must be brought onto site if local materials do not meet the required properties.

The use of treated tailings as a cover system has been investigated in the present study. A secondary flotation process was used to decrease the sulfide content of reactive tailings. The flotation process produced a material with a lower sulfur content and low potential to generate acidity. These tailings are referred to as desulfurised or depyritised tailings. Laboratory column testing and pilot-scale models have demonstrated the potential of desulfurised tailings as a cover material (Reardon and Moddle,

1985; Aachib *et al.*, 1994; Bussière *et al.*, 1997a and b; Benzaazoua and Bussière, 1998; Elliot *et al.*, 1997). However, there has been limited investigation completed on field-scale desulfurised tailings covers.

This study investigated a single layer desulfurised cover installed between 1998 and 1999 at the Detour Lake gold mine near Timmins, Ontario, Canada. The cover was designed to:

1. maintain 85 per cent saturation to limit oxygen diffusion; and
2. utilise the residual sulfur content within the cover to consume oxygen.

Together, these processes would limit oxygen ingress to the underlying reactive tailings. The aim of this study was to assess the effectiveness of the cover at meeting these two criteria. A field program was undertaken to characterise both the as built desulfurised cover and the underlying untreated tailings. Instrumentation was installed to permit long term monitoring of site conditions. Laboratory testing determined the geotechnical and geochemical properties of the cover and tailings. Data obtained from the characterisation studies and field monitoring was used to undertake a numerical study of the cover performance. Changes in water saturation were simulated using the SoilCover model (SoilCover, 1997). A new numerical technique was developed that couples atmospheric forcing conditions with predicted water saturation profiles and kinetic data to predict oxygen diffusion and consumption rates in the desulfurised tailings cover along with the resulting oxygen flux to the underlying sulfidic tailings.

THEORY

Two principle factors affect the rate of oxygen diffusion through a desulfurised cover:

1. the degree of water saturation; and
2. the rate of consumption of oxygen through oxidation of the remaining sulfide minerals.

The processes of diffusion and oxidation are described individually in the following.

Oxygen diffusion

One-dimensional oxygen diffusion through tailings can be described using Fick's First Law:

$$q_v = -n_e D^* \frac{\partial C}{\partial x} \quad (1)$$

where:

q_v = diffusive mass flux of oxygen (kg/m²/s)

n_e = effective porosity

D^* = bulk diffusion coefficient (m²/s)

C = oxygen concentration (kg/m³)

x = dimension in the direction of diffusion (m)

The effective porosity in Equation 1 defines the proportion of the voids available for diffusion. Aubertin *et al.* (2000) proposed that effective porosity in Equation 1 can be represented by an equivalent porosity:

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$$n_{eq} = n_a + Hn_w \quad (2)$$

where:

- n_{eq} = equivalent porosity (m³/m³),
- n_a = air-filled porosity (m³/m³),
- n_w = water-filled porosity (m³/m³), and
- H = Henry's Law coefficient (approximated as 0.03 for O₂ in air and water at 20°C).

Equivalent porosity and the bulk diffusion coefficient (D^*) can be combined into an effective diffusion coefficient, D_e :

$$D_e = n_{eq} D^* \quad (3)$$

The method chosen to predict the diffusion coefficient for the present study is that described by Mbonimpa *et al* (2001) and Aachib *et al* (2002). The effects of tortuosity of the pore space and dead end pore spaces are included in the equation:

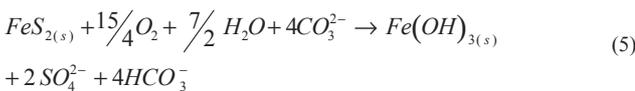
$$D_e = \frac{1}{n^2} [D_a^0 n_a^{3.5} + HD_w^0 n_w^{3.5}] \quad (4)$$

where:

- n = total porosity
- D_a^0 = diffusion coefficient of gas through air (m²/s)
- D_w^0 = diffusion coefficient of gas through water (m²/s)

Pyrite oxidation

Pyrite is the dominant mineral in the Detour Lake mine tailings and its kinetic properties can be used to describe all sulfide oxidation occurring within the desulfurised cover and tailings. The tailings within the Detour Lake mine tailings facility have a relatively high buffering capacity and the tailings were found to remain near neutral pH at the time of investigation (Ferguson, 2003). The effects of both ferric ion and bacterial oxidation are insignificant at near neutral pH and the major factors that affect the rate of pyrite oxidation are surface area, oxygen concentration, temperature and degree of saturation (Nicholson *et al*, 1988). The overall oxidation reaction for solutions with sufficient carbonate to buffer all of the acid and maintain near-neutral pH can be defined by (Nicholson *et al*, 1988):



The stoichiometry of pyrite oxidation in Equation 5 can be used to express the rate of pyrite oxidation as a function of oxygen consumption for a given surface area and temperature. The reaction rate can be approximated as first-order for low concentrations of oxygen (Nicholson *et al*, 1988):

$$\frac{\partial C}{\partial t} = -k_r^* C \quad (6)$$

where:

- C = oxygen concentration in the pore space (kg/m³)
- k_r^* = kinetic oxidation coefficient (1/s)
- t = time (s)

The effects of particle size and pyrite concentration can be included (Collin, 1998):

$$k_r = k' \frac{6}{D_h} (1-n) C_p \quad (7)$$

where:

- k_r = the reaction rate constant
- k' = constant of reactivity (approximated as 15.8×10^{-3} m³ O₂/m² pyrite/year)
- D_h = equivalent particle diameter (m)
- n = total porosity
- C_p = pyrite concentration (kg/kg dry tailings)

Equation 7 includes the reaction rate coefficient, k_r , which differs from the kinetic oxidation coefficient, k_r^* , given in Equation 6. These are related by the equivalent porosity (Mbonimpa *et al*, 2001):

$$k_r = n_{eq} k_r^* \quad (8)$$

The equivalent particle diameter (D_h) is used to derive a single representative grain size from the range of grain sizes found in the material. It can be estimated from grain size analysis data using (Aubertin *et al*, 1998):

$$D_h = [1 + 1.17 \log(C_u)] D_{10} \quad (9)$$

where:

- D_{10} = grain diameter corresponding to ten per cent passing (m)
- C_u = uniformity coefficient, ($= D_{60}/D_{10}$)
- D_{60} = grain diameter corresponding to 60 per cent passing (m)

Decreasing equivalent particle diameter increases the reactive surface area and the oxidation rate.

The relationships describing oxygen diffusion in Equations 1 to 4 and pyrite oxidation in Equations 6 to 9 can be combined assuming constant D_e with depth and constant n_{eq} with time. One-dimensional transient oxygen diffusion and consumption can be described using:

$$D_e \frac{\partial^2 C}{\partial x^2} - k_r C = n_{eq} \frac{\partial C}{\partial t} \quad (10)$$

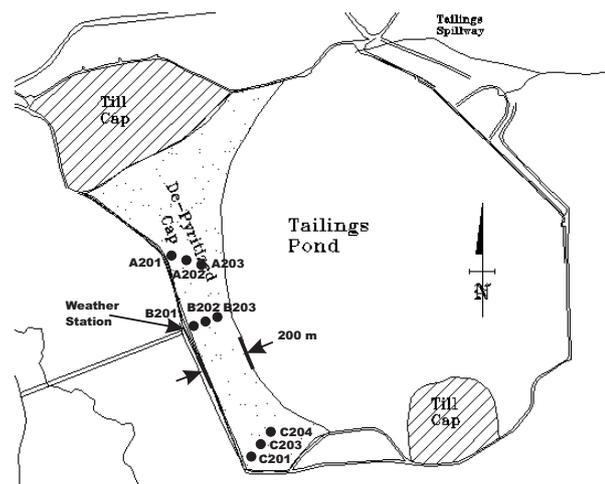


FIG 1 - Schematic of the Detour Lake Mine tailings facility illustrating the desulfurised (depyritised) cover and the location and designation of the instrumentation (not to scale). Reproduced with permission from Placer Dome Inc.

SITE DESCRIPTION

Placer Dome Inc. operated the Detour Lake Gold Mine from 1983 until operations ceased in 1999. The mine site is located 290 km northeast of Timmins, Ontario. Tailings were deposited by end-pipe discharge into a dam impoundment that contains approximately 15 million tonnes of sulfidic tailings and covers an area of approximately 300 ha. Existing tailings have a sulfide sulfur content ranging from one to 2.5 per cent by mass and a net neutralisation potential (NNP) ranging from -5 to -75 (kg CaCO₃ equivalent per ton material) (Ferguson, 2003). An assessment conducted prior to mine closure indicated the tailings have potential for producing acid rock drainage. The remediation strategy adopted was to cover the majority of the tailings with a water cover and to install an engineered cover over the remaining tailings.

An engineered cover was designed using desulfurised tailings produced by a pilot desulfurisation plant. The initial cover design was based on a capillary barrier effect when placed above the sulfidic tailings. The desulfurisation process was designed to reduce the sulfide sulfur content of the cover material to between 0.5 and one per cent. Design cover thickness ranged from greater than 1 m at the dam to 0.5 m at the pond. The single layer desulfurised cover system was installed on the tailings facility by end-pipe discharge beginning in 1998 and continuing until mine production ceased in 1999. Figure 1 shows the Detour Lake mine tailings area illustrating the portion covered with the desulfurised tailings cover.

The climate at the Detour Lake mine site is defined as a moist continental mid-latitude climate with an annual precipitation of approximately 920 mm with one third occurring as snowfall. Total potential evaporation is approximately 800 mm (Barbour *et al.*, 1993). Air temperature fluctuates between a maximum of 37°C in the summer and a minimum of -47°C in the winter (Minister of Public Works and Government Services Canada, 2001).

METHODS

Instrumentation was installed in the Detour Lake mine tailings facility in July 2000 to obtain detailed meteorological data, water content profiles and water levels. Piezometers and neutron probe access tubes were installed at nine locations in the desulfurised tailings cover along three profiles named A, B and C. The instrumentation is shown in Figure 1. Location C202 was not used for the study as the instrumentation was too shallow. An additional location, C204, was installed as a replacement. Piezometers were constructed using 64 mm OD PVC pipe with 850 mm of slotted (ten slot) PVC screen. Neutron probe access tubes were constructed using 64 mm OD aluminium tubing with welded end caps. Water levels and water content profiles were measured monthly from July 2000 to July 2001.

A Campbell Pacific Nuclear 503DR neutron probe was used to measure the water content profiles in the nine neutron probe access tubes. A calibration curve was obtained from two separate data sets obtained in 1999 for the tailings at the Detour Lake mine and at the nearby mine site of Dona Lake (Sjoberg Dobchuk, 2002). The water contents of the tailings were measured from samples taken at various depths and corresponding neutron probe readings were obtained to produce the calibration curve. An automated weather station was installed adjacent to the B201 instrument location (Figure 1) to measure wind speed, wind direction, relative humidity, temperature, net radiation and rainfall precipitation on an hourly basis.

A total of 41 samples of desulfurised tailings cover and underlying tailings material were collected during installation of nine piezometers. Geotechnical characterisation of the tailing samples was completed at the University of Saskatchewan, Saskatoon. Grain size analyses were performed on 22 samples representing one metre intervals for each bore hole. Six samples were then chosen to represent a fine, mid-range and coarse

grain-size sample of both the desulfurised and sulfidic tailings. These six samples were also selected for further geotechnical testing. Specific gravities were measured using ASTM method D854-92. Saturated hydraulic conductivity was measured using a modified consolidation/falling-head permeameter (Barbour, 1986) with compressive loads incrementally increased up to 1000 kPa. The soil-water characteristic curves were measured using a standard pressure plate apparatus and air. It has been found that oxidation occurs within the cell when air is used for testing reactive materials. More recent tests have used nitrogen instead of air to avoid any errors introduced to the soil-water characteristic curves by oxidation. The error introduced by oxidation may have increased the air entry value of the reactive materials.

Static acid base accounting tests were conducted by Placer Dome Inc on a total of 38 tailings samples representing both the desulfurised cover and sulfidic tailings using the methods of Lawrence and Scheske (1997). This included measurement of net neutralisation potential, net acid generation potential (NAG) pH values and total sulfide sulfur. Additional geochemical characterisation was carried out at École Polytechnique (Montréal, QC). Samples for both the desulfurised cover and the sulfidic tailings were analysed using X-ray diffraction analysis and petrography to determine mineralogy (Bernier, 2001). A diffusion/kinetic cell test apparatus was used to measure the diffusion and kinetic oxidation coefficients (Mbonimpa *et al.*, 2001; Aubertin *et al.*, 2000) on a sample of desulfurised tailings obtained near bore hole B201.

A two stage numerical modelling strategy was developed to use Equation 10 to quantify oxygen diffusion. SoilCover was used to predict transient saturation profiles through the cover. SoilCover is a one-dimensional finite element model that predicts the exchange of water and energy between the atmosphere and the soil surface (SoilCover 1997). Daily saturation profiles output by SoilCover were used as input to a finite difference diffusion and reaction model. The diffusion and reaction model used the program MatLab to solve Equation 10 (MathWorks, 1997). The model was verified by comparison to a closed form solution (Mbonimpa *et al.*, 2001), a finite difference diffusion only model, POLLUTE (Rowe *et al.*, 1994), and to results measured from a column experiment (Yanful *et al.*, 1993). The diffusion and reaction model calculated a new diffusion coefficient for each node as the degree of saturation varied from day to day. A reaction rate constant (k_r) was assigned to each node and used to calculate the oxygen consumed due to sulfide mineral oxidation.

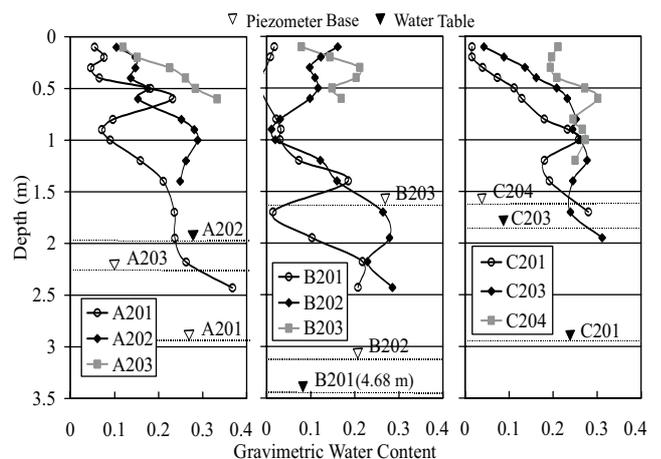


FIG 2 - Water content profiles measured in July, 2002. Water tables measured in July, 2002 are indicated. If the water table was below the base of the piezometer, the depth to the base of the piezometer is indicated.

RESULTS AND DISCUSSION

Field monitoring

Heterogeneity of the tailings was observed during installation of the instrumentation. Both desulfurised and untreated tailings were composed of interbedded layers varying between silt and clay-size particles to fine sand-size particles. The layering is attributed to segregation of the tailings during deposition. Variations in flow rates and the discharge pattern account for the variation in grain-size at any given location. The transition between desulfurised and untreated tailings was not distinguishable in the field based on observational data.

Figure 2 presents the results of neutron probe measurements for water content at all locations along with the depth to the water table depth, measured in July, 2001. Fluctuations in water content with depth represent heterogeneity of particle size with depth. Water contents in the upper 2 m range from 0.2 per cent to 40 per cent. Figure 2 illustrates that each bore hole generally contains at least one layer of tailings at high water content in the upper 2 m. This occurs regardless of the water table depth. The surface tailings (approximately 0.2 m) for all bore holes show low water contents. Depth to water table generally increases with distance from the pond. The greatest depth to the water table, 4 to 5 m, was measured in piezometer B201.

The 2000/2001 year of Detour Lake mine weather data were compared to the climate normals for Timmins, Ontario. Average air temperature values compared well with the climate normals but the Detour Lake mine 2000/2001 rainfall precipitation (April to October) was 341 mm compared to the normals value for the same period of 591 mm. The 2000/2001 year was concluded to be a dry year based on the rainfall measurements.

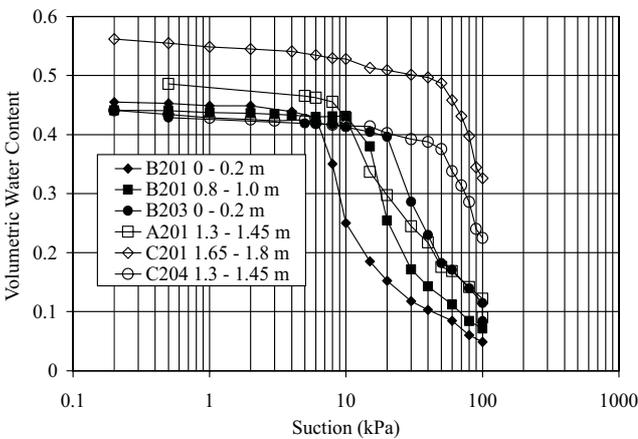


FIG 3 - Soil-water characteristic curves for the tailings samples (solid symbols – desulfurised, hollow symbols – sulfidic).

Laboratory results

Results from the sulfide sulfur analysis were used to delineate the boundary between desulfurised and sulfidic tailings in each borehole. Previous analyses indicated existing tailings ranged from one per cent to 2.5 per cent sulfide sulfur (Ferguson, 2003). Sulfide sulfur values for this study tended to fall into two categories: less than one per cent, and greater than one per cent. A value of one per cent was used to distinguish between the desulfurised cover and the sulfidic tailings. The final cover thickness was estimated in each borehole and found to range in thickness from 1 to 1.5 m.

Based on the grain size analyses, the desulfurised cover material was found to be coarser than the underlying tailings. This result can also be seen in the soil-water characteristic curves for the desulfurised and sulfidic tailings samples presented in Figure 3. The air-entry values for the desulfurised tailings vary between six and 20 kPa. The air entry values for the sulfidic tailings were found to range between eight and 50 kPa. The grain size of the desulfurised cover material was found to be generally coarser than the underlying tailings and the associated air entry values were lower. Engineering requirements for scaling up of the pilot desulfurisation plant may have led to changes in the grain size distribution of the production desulfurised material over the pilot plant material (Ferguson, 2003).

The measured saturated hydraulic conductivity (k_{sat}) values for both types of tailings were similar and fell in the range of 2×10^{-6} to 1×10^{-7} m/s with increasing consolidation pressure, except for sample C204 1.3 - 1.45 m, which varied between 1×10^{-5} and 1×10^{-6} m/s. The data for this sample is not considered reliable as some difficulties were encountered during testing. Specific gravity of the tailings was measured to be 2.87 and 2.91 for the desulfurised and sulfidic tailings, respectively.

The oxygen diffusion measurements were carried out at École Polytechnique for the sample obtained from bore hole B201 at a depth of 0.5 m. The diffusion coefficient (D_e) was measured to be 1.9×10^{-8} m²/s and the reaction rate constant (k_r) to be 10/yr at a degree of saturation of 82.4 per cent ($n = 0.443$; $n_{eq} = 0.089$). Details of this type of analysis are presented in Mbonimpa *et al* (2001) and Aubertin *et al* (2000). Equations 4 and 8 were also used to estimate the effective diffusion coefficient (D_e) and the reaction rate constant (k_r) from field data. Values of grain size (D_{10} , D_{60}) were taken from the grain-size distribution of sample B201 0 - 0.2 m obtained adjacent to the sample used for the diffusion and kinetic cell testing. The calculated value for the kinetic oxidation coefficient was 7.1/yr. The calculated diffusion coefficient was 1.2×10^{-8} m²/s. These results indicate good agreement between the estimated and measured values of kinetic oxidation coefficient and diffusion coefficient. In summary, empirical estimations based on Equations 4 and 8 are considered to provide a reasonable estimation for the diffusion coefficient and kinetic oxidation coefficient for the Detour Lake mine tailings.

Static geochemical testing was used to assess the potential for the cover and tailings to produce ARD. All data is presented in Figure 4, which presents net neutralisation potential (NNP), net acid generation (NAG) pH values and sulfide sulfur (per cent mass). NNP describes the neutralising capacity of the system

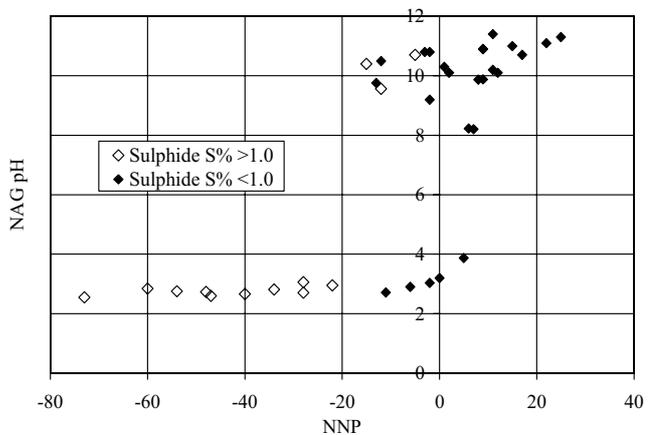


FIG 4 - NAG pH versus NNP for the desulfurised tailings (Sulfide S per cent <1.0) and the sulfidic tailings (Sulfide S per cent >1.0).

above that required to neutralise all the acid the system could potentially produce. A positive NNP is representative of material that has sufficient buffering capacity to neutralise all the acid that may be produced. NAG pH is an empirical measure of stored acidity. A comparison of the NNP with the NAG pH is a more useful indication of whether or not ARD will occur. It can be seen in Figure 4 that some samples have a NNP greater than zero but have an acidic NAG pH. Conversely, some samples have values for NNP less than zero but alkaline NAG pH. The tailings were divided into three groups based on Figure 4. The criteria adopted was as follows: tailings with a NNP between approximately -15 and 5 (kg CaCO₃ equivalent per ton material) may or may not produce acidic pH, tailings with a NNP greater

than five do not produce acidic pH, and tailings with a NNP less than -15 produce acidic pH. Figure 5 visually summarises the NNP, NAG pH and sulfide sulfur content (per cent by mass) results with depth in each bore hole. The sulfide sulfur (per cent) increases with depth as expected since the tailings change from desulfurised to sulfidic. There is a noticeable change in each bore hole with respect to the sign of the NNP values from positive near the surface to negative. Each bore hole was classified as three layers based on the criteria explained above. Static acid base accounting testing indicated the desulfurisation process was successful in converting reactive tailings material to a suitable cover material with the potential to consume oxygen, but with insufficient capacity to generate ARD.

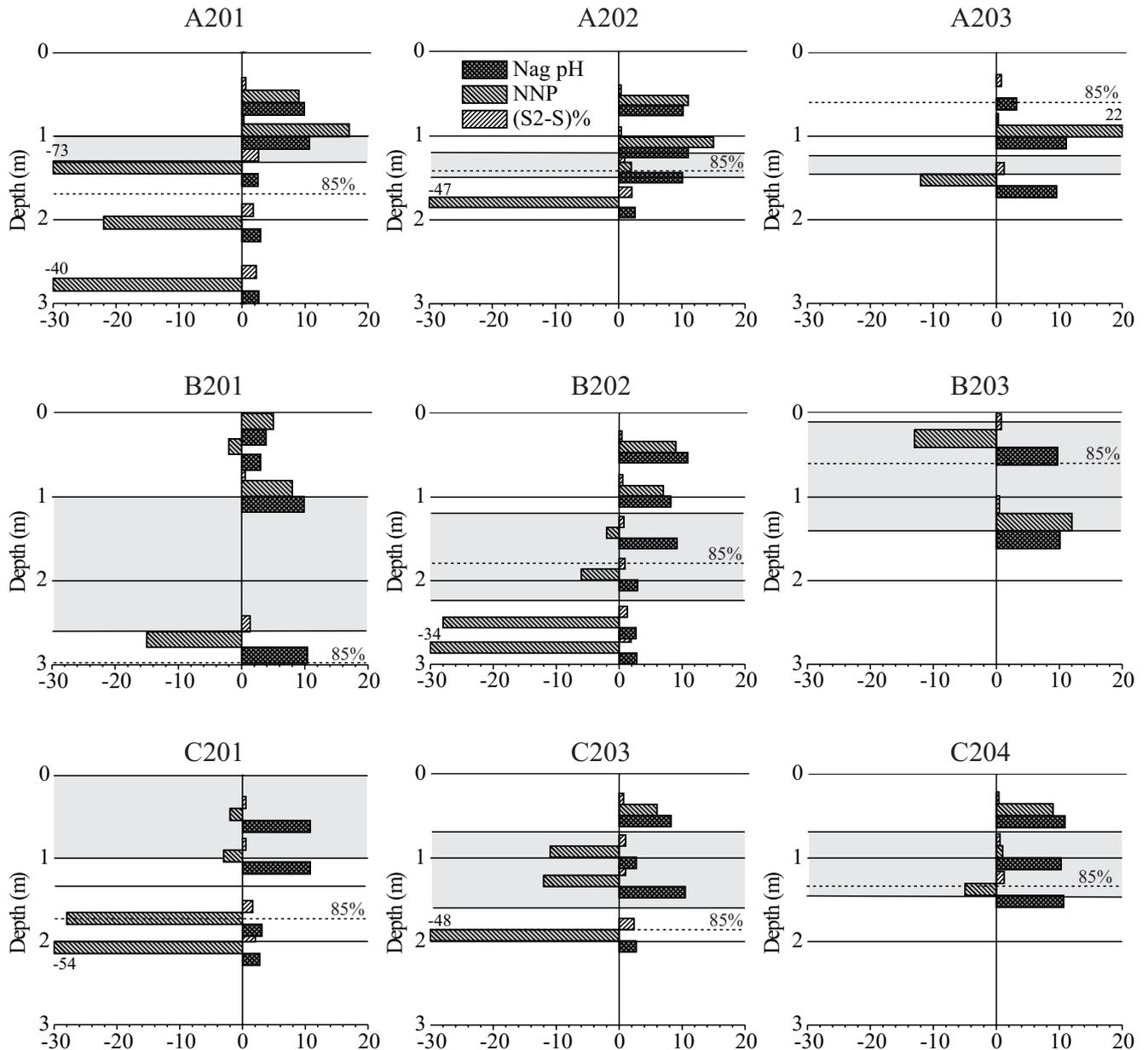


FIG 5 - Summary of geochemical data with depth for all boreholes. The shaded portion represents the uncertain layer. The material above and below this layer represents the non-acid and acid layers, respectively. The dashed line indicates the depth to 85 per cent saturation.

The water content profiles shown in Figure 2 together with the geochemical data can be used to make a qualitative assessment of the ability of the cover to reduce oxygen diffusion. The approximate thickness of each layer was estimated and compared to the location where the tailings become greater than 85 per cent saturated as shown on Figure 5. The entire depth of the uncertain layer is saturated and therefore unlikely to produce acidity at borehole A203. Bore holes A202, B202, B203 and C204 are greater than 85 per cent saturated in the acid producing tailings layer but some of the uncertain layer tailings can be seen to be less than 85 per cent saturated. This indicates a potential for oxygen to reach the uncertain layer. The saturation profiles for bore holes A201, B201, C201 and C203 are less than 85 per cent saturated at the top of the potentially acid producing tailings layer. This indicates a potential for oxygen diffusion to reach the potentially acid generating tailings. In summary, the field and laboratory data show that greater than 85 per cent water saturation in the reactive tailings was achieved at five bore hole locations. The remaining four bore hole locations indicate the potential for oxygen to penetrate the potentially reactive tailings based on protection provided by high water saturation alone (ie no oxygen consumption in the desulfurised cover). Therefore, a numerical modelling program was carried out to determine oxygen fluxes based on diffusion and consumption.

Numerical modelling

Several simplifications of the field cover configuration were necessary to permit numerical simulation of the oxygen diffusion process. The thickness of the desulfurised cover was assigned a single value of 1.8 m representing the average combined thickness of the non acid generating and the uncertain layers described in Figure 5. The tailings for each layer were specified as either coarse or fine. The samples chosen to represent the fine and coarse layers were: C204 1.3 - 1.45 m and B201 0 - 0.2 m and have air entry values of 50 kPa and 6 kPa, respectively. Four profiles were defined to represent the variations in the cover and tailings profiles at Detour Lake mine. Profiles I and II are composed of a desulfurised cover and tailings with a uniform fine and coarse grain size, respectively. Profile III and IV represent variation of grain size between the cover layer (1.8 m) and the material below; fine over coarse and coarse over fine. The water table was considered at a two different depths, 1 m and 4 m, to represent the range of values observed in the field.

SoilCover modelling

Three representative weather years were developed to evaluate cover saturation under varying precipitation conditions: a wet year, a dry year and the mean year of precipitation. The wet and dry years represent the one in 50 year occurrence of high and low precipitation. Precipitation data measured at Detour Lake mine in 2000 was used to represent the one in 50 dry year. The one in 50 wet year and the mean year were determined from 50 years of Environment Canada precipitation data for Timmins, Ontario. The hourly average measurements of wind speed, relative humidity, temperature and net radiation from Detour Lake mine in 2000 were used for all three representative weather years. A vegetative cover was included in the SoilCover simulation to represent the vegetation that is to be established on the Detour Lake mine cover. The SoilCover results discussed in the following section are those determined for the dry model year predicting the worst case with respect to the development of unsaturated conditions.

The profile consisting of a fine grain size cover over fine grain sized tailings (Profile I) was found to remain at 100 per cent saturation regardless of water table depth and thus little oxidation would occur. The 50 kPa air entry value prevents desaturation of the tailings and further calculations were not performed for this case. The results for Profile II with a 4 m water table showed approximately 0.75 m of the tailings above the water table remained above 85 per cent saturation with the remaining upper 3 m varying between 20 per cent and 40 per cent. The results for Profile III with a 4 m water table showed that the fine tailings layer retained more moisture than the underlying coarse layer but remained slightly below 85 per cent saturation throughout the year.

The results for Profile IV with a 4 m water table showed the coarse cover layer desaturated to approximately 30 per cent for most of the year while the fine tailings remained fully saturated. A comparison between the wet, dry and mean weather data for this profile determined that the average saturation of the coarse material varied by approximately 15 per cent between the dry and wet years. In summary, both the simulated saturation profiles and the measured saturation profiles at bore holes A201, B201, C201 and C203 indicated saturation within the cover is less than 85 per cent. Air filled porosity will exist for oxygen diffusion under these conditions.

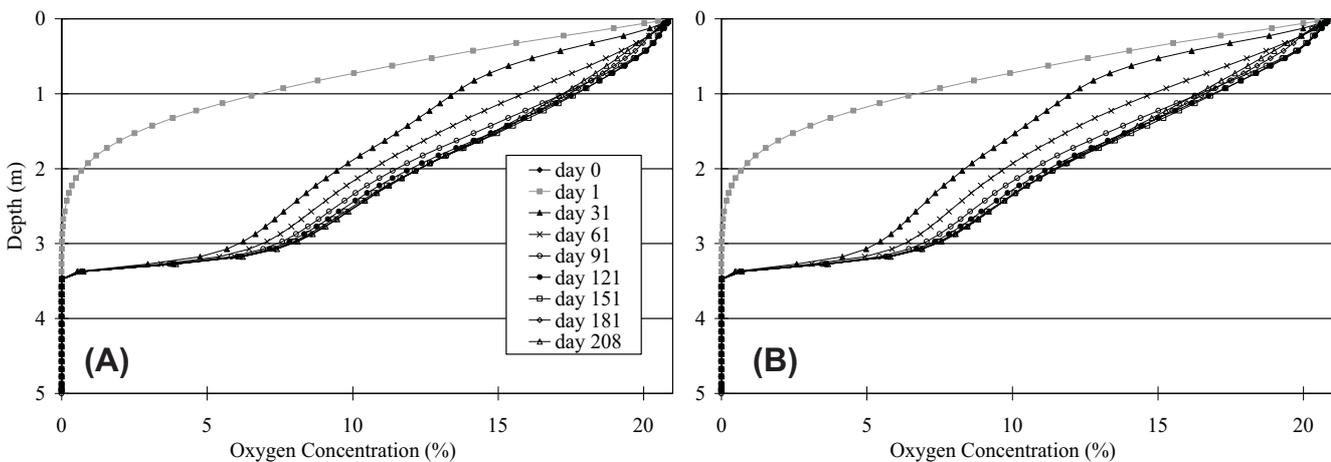


FIG 6 - Oxygen concentration profiles for homogeneous coarse profile, 4 m depth to water table and dry weather data: (a) $k_r = 0$ (top 1.8 m), $k_r = 14.88/\text{yr}$ (bottom 3.2 m), (b) $k_r = 3.42/\text{yr}$ (top 1.8 m), $k_r = 14.88/\text{yr}$ (bottom 3.2 m).

Oxygen diffusion and consumption modelling

Reaction rate constants were chosen for the oxygen diffusion and consumption modelling to represent reasonable values for the fine and coarse tailings with respect to low (0.46 per cent) and high (two per cent) sulfide mineral contents. Values of k_r were calculated using Equation 7 for each of the coarse (C204 1.3 - 1.45 m) and fine tailings samples (B201 0 - 0.2 m). The reaction rate constants for the desulfurised tailings were calculated to be 3.42/yr for the coarse tailings and 44/yr for the fine tailings. The reaction rate constants for the sulfidic tailings were calculated to be 14.88/yr for the coarse tailings and 191/yr for the fine tailings. The reaction rate constants are higher for the fine tailings samples due to the increased surface area exposed to oxygen and water.

Oxygen diffusion and consumption modelling was performed for eight different profile/water table/weather cases. Each case was evaluated with and without kinetic oxidation in the cover material to illustrate the effect of sulfide mineral oxidation on the oxygen concentration profile and oxygen flux through the cover. The results of the modelling are presented in Figures 6 - 8. Figure 6 (a and b) presents the oxygen concentration profiles for the homogeneous coarse tailings profile with a 4 m water table. Regardless of the kinetic oxidation potential in the cover material, a similar steady state oxygen concentration profile is produced through the tailings after approximately 100 days.

Figure 7 (a and b) illustrates the effect of a capillary break. It can be seen in Figure 7a that a small concentration of oxygen (one per cent) penetrates through the fine tailings since the cover layer is less than 85 per cent saturated. In contrast, kinetic oxidation in the fine cover layer consumes sufficient oxygen to prevent oxygen from reaching the interface between the coarse and fine tailings and oxygen does not penetrate into the coarse tailings (Figure 7b).

Figure 8 illustrates the oxygen penetration into the coarse over fine tailings profile with a 4 m water table. The profiles with and without oxidation in the cover were very similar and therefore only the profiles with oxidation were illustrated. The oxygen concentration at the base of the coarse tailings was attenuated to a steady-state value of 15 per cent when kinetic oxidation was not included in the cover (not shown) and 14 per cent when kinetic oxidation was included (Figure 8).

The Fickian flux of oxygen through the surface can be used to approximate the rate at which oxygen is consumed by sulfide mineral oxidation through the tailings profile (Elberling and Nicholson, 1996). The oxygen diffusion/consumption model

described above was used to calculate the diffusive flux and the oxidative flux at each node for the last run 'day' (day 208). The last day was assumed to represent quasi steady-state conditions. The diffusive flux between the top two nodes was also assumed to approximate the surface flux.

The surface flux and the flux at the interface between the desulfurised cover and sulfidic tailings for each of the simulations are summarised in Table 1. Fourteen different simulation cases are presented that represent three profile types, three precipitation years, two water table configurations and simulations with or without kinetic oxidation.

Comparison of the computed oxygen fluxes for cases with and without kinetic oxidation indicate the surface oxygen flux is higher when kinetic oxidation within the cover (ie upper 1.8 m of desulfurised tailings) is considered. Oxygen consumption within the desulfurised cover reduces the interface flux to approximately zero when the water table is located at 1 m depth. Surface oxygen fluxes are higher when the water table is positioned at a depth of 4 m due to the decreased saturation and increased air-filled porosity for oxygen diffusion. A significant interface flux can be seen when unsaturated coarse material with open pore space extends to the base of the profile (Case 4).

The numerical simulations indicate that a fine cover over fine

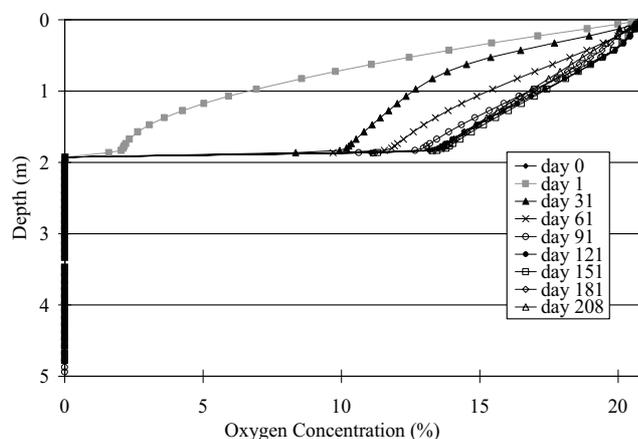


FIG 8 - Oxygen concentration profiles for a 1.8 m thick layer of coarse tailings over fine tailings, 4 m depth to water table and dry weather data: coarse tailings: $k_r = 3.2/\text{yr}$, fine tailings: $k_r = 191/\text{yr}$.

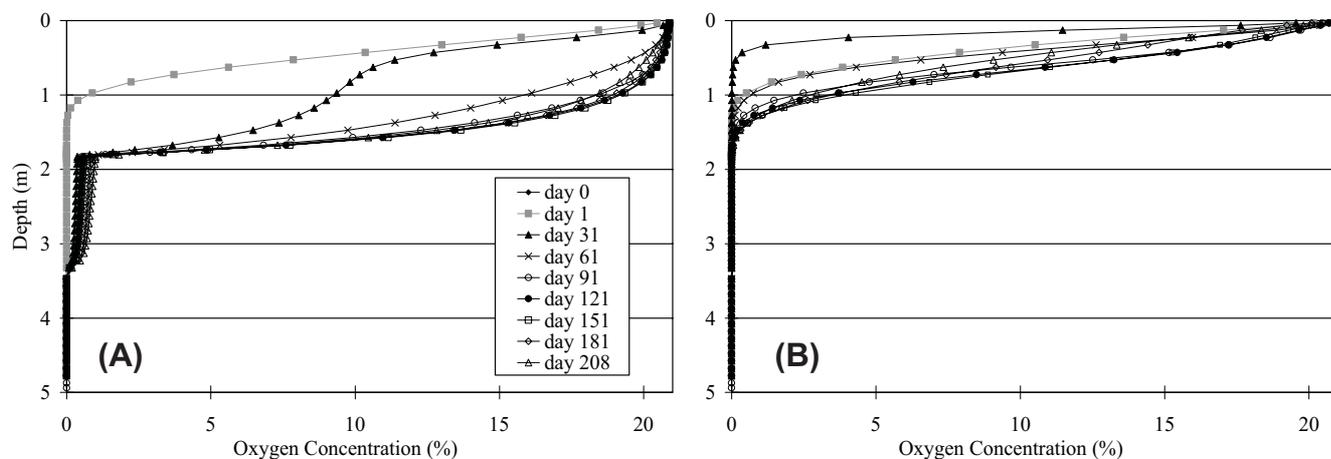


FIG 7 - Oxygen concentration profiles for a 1.8 m thick layer of fine tailings over coarse tailings, 4 m depth to water table and dry weather data: (a) fine tailings: $k_r = 0$, coarse tailings: $k_r = 14.88/\text{yr}$, (b) fine tailings: $k_r = 44/\text{yr}$, coarse tailings: $k_r = 14.88/\text{yr}$.

TABLE 1

Oxygen flux rates calculated for each of the oxygen concentration profiles on the last simulation day (day 208).

Case #	Profile [†]	Weather	Water table (m)	k_r [‡]	Surface flux (kg/m ² /yr)	Interface flux (kg/m ² /yr)
1	C	Dry	1	N	4.96E-4	1.76E-9
2	C	Dry	1	Y	0.322	~0
3	C	Dry	4	N	3.27	3.27
4	C	Dry	4	Y	4.53	3.11
5	F/C	Dry	1	N	6.88E-4	~0
6	F/C	Dry	1	Y	6.65E-3	~0
7	F/C	Dry	4	N	0.259	0.262
8	F/C	Dry	4	Y	6.92	1.85E-3
9	C/F	Dry	1	N	6.07E-5	1.86E-8
10	C/F	Dry	1	Y	0.496	~0
11	C/F	Dry	4	N	2.86	1.64E-6
12	C/F	Dry	4	Y	4.19	1.52E-6
13	C/F	Mean	4	Y	3.64	1.33E-6
14	C/F	Wet	4	Y	2.92	8.94E-7

† Profile indicates the tailings type: C = coarse, F = fine. The layered profiles are indicated by top layer/bottom layer.

‡ N = kinetic oxidation not included in cover layer, Y = kinetic oxidation included in cover layer.

or coarse tailings both reduce oxygen influx to the tailings. It can be seen that the oxygen flux at the base of the desulfurised cover is less than 2 mole/m²/yr (ie 6.4×10^{-2} kg/m²/yr) in all the cases except the homogeneous coarse (Cases 3 and 4) and the fine over coarse (Case 7) with no oxidation in the cover. Two mole/m²/yr corresponds approximately to the expected rate of oxygen flux through a 0.5 - 1 m deep stagnant water cover. Case 4 indicates that a coarse grained desulfurised cover may not contain sufficient oxygen consumptive capacity to reduce oxygen fluxes below 2 mole/m²/yr at the interface when saturation levels are low. Case 7 indicates that even with a capillary barrier effect, oxygen may still reach the reactive tailings in dry years. Case 4 and Case 7, however, are not the most representative profiles of the desulfurised cover system actually constructed at Detour Lake mine. Case 12 is considered to be most typical. The computed oxygen flux into the sulfidic tailings for this case was 1.64×10^{-6} kg/m²/yr for the dry year. The numerical simulations conducted in this study did not consider variations in grain size observed in the cover and tailings. Thin layers with higher saturation were observed in all the bore holes that indicate capillary breaks similar to Case 8 should occur. The actual rates of oxygen flux should be confirmed using direct field measurements of oxygen consumption (Elberling *et al*, 1996).

SUMMARY

The thickness of the Detour Lake mine cover was determined using geochemical data to be between one and 1.5 m deep. The static acid base accounting testing indicated that the cover materials were reduced in sulfur, retained an oxygen consumption potential, but were unlikely to produce acidity. The field monitoring data, laboratory testing and SoilCover modelling indicated that the cover does not retain 85 per cent saturation throughout all of the cover. Some potential exists for oxygen ingress into the cover. Numerical simulations of the rates of oxygen consumption by the cover materials indicate that the desulfurised cover system generally reduces oxygen fluxes to the underlying tailings to less than 2 moles/m²/yr.

An overall assessment of acidity and metals production from the cover and tailings profile requires consideration of the net

infiltration rate, the oxygen diffusion rate, the location of acidity production and the buffering capacity of the cover and tailings material. Coupling of net infiltration rate data and oxygen diffusion rate predictions was not undertaken as part of this study. Linking this data with a reactive geochemical model would permit an assessment of the total ARD load at the Detour Lake mine tailings facility.

The results obtained in this study are specific to the near neutral conditions recorded at the Detour Lake mine facility. The development of the numerical method in Equations 1 to 8 is based upon research into kinetics under these conditions. Consideration of other desulfurised tailings sites would require derivation of kinetic oxidation rates specific to those sites.

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