FIELD AND LABORATORY PERFORMANCE OF ENGINEERED COVERS ON THE WAITE AMULET TAILINGS[1]

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Abstract: The Waite Amulet Covers Project was initiated in 1990 under the MEND (Mine Environment Neutral Drainage) program to evaluate the effectiveness of engineered soil covers in reducing acid generation in reactive tailings. Two three-layer soil covers (60 cm compacted clay placed between two 30 cm sand layers) with gravel crusts were designed and installed on the partially oxidized sulfidic tailings at the decommissioned Waite Amulet site, near Rouyn-Noranda, PQ. Another test plot was installed in which a 2 mm thick, high density polyethylene replaced the compacted clay. The three covered test plots and a control plot without a cover were instrumented to measure gaseous oxygen concentrations, water contents, pressure heads, temperature, and water quality. Laboratory experiments were also installed to simulate the soil-covered test plots. The laboratory tests contained unoxidized tailings recovered from the saturated zone of the Waite Amulet tailings impoundment. Field and laboratory results indicated that the compacted clay layer in the composite cover remained near saturation (≥93%) even during dry conditions. The soil covers in the laboratory reduced oxygen flux and acid generation by 99.9% and 95.4%, respectively. Infiltration into the covered field plots was equal to 3.9% of total precipitation. The hydraulic conductivity of the clay did not change from its placement value of 1×10^{-7} cm/s during 3 yr of monitoring. Field lysimeters placed beneath each test plot showed a 70 to 91% reduction in sulfate concentrations and an 80 to 93% reduction in iron concentrations, compared with the control plot. These concentrations do not show the same cover effectiveness as the oxygen data because of mixing with surrounding ground water, as the water table rose higher than the top of the lysimeters during spring 1992.

Introduction

A large number of Canadian metal and uranium ore bodies contain sulfide minerals which, when milled, produce tailings which are generally deposited in exposed environments. When iron-bearing sulfide minerals (particularly pyrite and pyrrhotite) contained in the tailings are exposed to oxygen and water, they oxidize and turn receiving surface waters acidic if sufficient alkaline minerals are not present. The solution resulting from this oxidation is characterized by low pH and high concentrations of ferrous iron and sulfate. The overall process of sulfide oxidation may be summarized by the following equation:

$$FeS_2(s) + \frac{15}{4}O_2 + \frac{7}{2}H_2O \rightarrow Fe(OH)_3(s) + 2SO_4^{2-} + 4H^+$$

Naturally occurring bacteria, notably the genus *Thiobacillus ferrooxidans*, catalyze the oxidation reaction (Nordstrom 1982). The ferric iron generated may either be hydrolyzed and precipitated as ferric hydroxide [$Fe(OH)_3$] or oxidize other heavy metal sulfides present such as galena [PbS], sphalerite [ZnS], and chalcopyrite [$CuFeS_2$]. Acid drainage may therefore also contain high concentrations of heavy metals. Rainfall and snowmelt flush the acidic solutions from

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the tailings sites into the downstream environment. If acid drainage is not collected and treated, it could contaminate ground water and local water courses, damaging the health of plants, wildlife, fish, and possibly humans.

Current major tailings management practices for decommissioning are flooding, revegetation of the tailings dam, and treatment of the acid drainage from the tailings area. Flooding requires construction and long-term maintenance of engineering structures such as dams and dikes. Treatment of acid drainage involves the addition of lime to neutralize the acidity and precipitate heavy metals and calcium as hydroxides and sulfates in the form of sludge. Although lime treatment plants effectively prevent adverse environmental impacts from occurring, acid generation may occur for several hundred years following mine closure, therefore necessitating the operation of these treatment plants in near-perpetuity. In 1989, the Canadian Mine Environmental Neutral Drainage (MEND) program began to investigate other technologies, such as engineered soil covers for preventing and controlling acid drainage, in an attempt to find permanent and cost-effective solutions. This effort resulted in a laboratory investigation into the design and construction of soil covers, which was later followed by a field evaluation at the Waite Amulet tailings site, near Rouyn-Noranda, PQ, Canada, during the summer of 1990.

The Waite Amulet Covers Project consisted of a combined field and laboratory study. The main objective of the field program was to evaluate the effects of meteorological changes (such as freezing and thawing), hydrology, and hydrogeology, which are difficult to adequately simulate in the laboratory. The objective of the laboratory study was to evaluate cover performance in a controlled environment where material placement, installation of instrumentation, and monitoring are more convenient.

Methods

The design of the composite soil cover focused on the curtailment of oxygen and water to the tailings.To curtail oxygen, cover moisture must remain near saturation, and to inhibit infiltration, the cover must have a low hydraulic conductivity. One method of achieving these two objectives above the water table is by incorporating a capillary barrier in the design of the cover. In a capillary barrier, a saturated, fine-grained soil layer with a low hydraulic conductivity is placed on top of a coarse-grained soil layer (Rasmuson and Eriksson 1986, Nicholson et al. 1989). When the sand base is drained, capillary suction forces prevent drainage of the fine-grained soil cover.

To reduce evaporation from the clay, a layer of sand is placed over the clay. This sand cover also reduces runoff and provides storage of water following infiltration, thereby allowing more water to reach the fine-grained cover to alleviate moisture losses. For maximum reductions in oxygen fluxes, the design aimed at placing the fine-grained cover at a high water content (as close to saturation as practicable). The near-saturation requirement ensures that the diffusive flux of gaseous oxygen through the cover is very low since the diffusion coefficient of gaseous oxygen decreases with moisture content (Yanful 1993).

A gravelly sand layer was selected for the sand base, a compacted varved clay for the fine-grained soil cover, and a fine to medium sand for the sand cover. In the field, a 10 cm thick gravel crust was placed on the sand cover to reduce erosion.

Field Test Plots

Four 20 by 20-m test plots were designed as follows: (1) control plot without a cover, (2) composite plot consisting of upper and lower sand layers and a middle varved clay layer compacted at 93% modified Proctor and a water content of 25%, (3) composite plot consisting of upper and lower sand layers and a middle varved clay layer compacted at 91% modified Proctor and a water content of 26%, and (4) composite plot consisting of upper and lower sand layers and a middle 80-mil (2-mm-thick) high-density polyethylene (HDPE) geomembrane. This design enabled a direct comparison between the performances of the clay and HDPE covers. Each test plot was designed with 3:1 (H:V) end slopes and perimeter drainage ditches to conduct surface runoff away from the plots. The design specified that the slopes be lined with 40-mil HDPE sheets at the clay-upper sand contact to prevent lateral transfer of gaseous oxygen into the covers. For the same reason, a similar lining was specified for all the perimeter ditches.

Based on results of oxygen flux modeling conducted prior to construction of the test plots, the cover was designed with a 60-cm-thick compacted fine-grained layer placed between two sand layers, each 30-cm-thick. A 10-cm gravel crust was placed on top of the covers for erosion protection. It was estimated that this design would reduce oxygen fluxes to very low values.

An integral component of the test plot design was the installation of instrumentation to assess the performance of the covers. The critical parameters for this assessment were identified to be (1) the moisture content of the cover, particularly that of the clay layer and the sand base, (2) the hydraulic heads in the cover and tailings, (3) the concentration of gaseous oxygen in the cover and tailings, (4) the water quality of the tailings porewater, and (5) the temperature of the cover and tailings. Hydrometeorological parameters, such as rainfall and pan evaporation, were also monitored.

To provide information on changes in water quality in the short term, a collection basin lysimeter was installed in the existing tailings directly beneath the cover. The lysimeter was filled with unoxidized tailings recovered from the southern section of the existing impoundment. Each lysimeter wasconnected to a manhole by means of a transfer pipe. The transfer pipe wasconnected to the manhole at a lower elevation to promote drainage by gravity. The field installation was completed in September 1990 and the test plots were monitored from that time until September 1993.

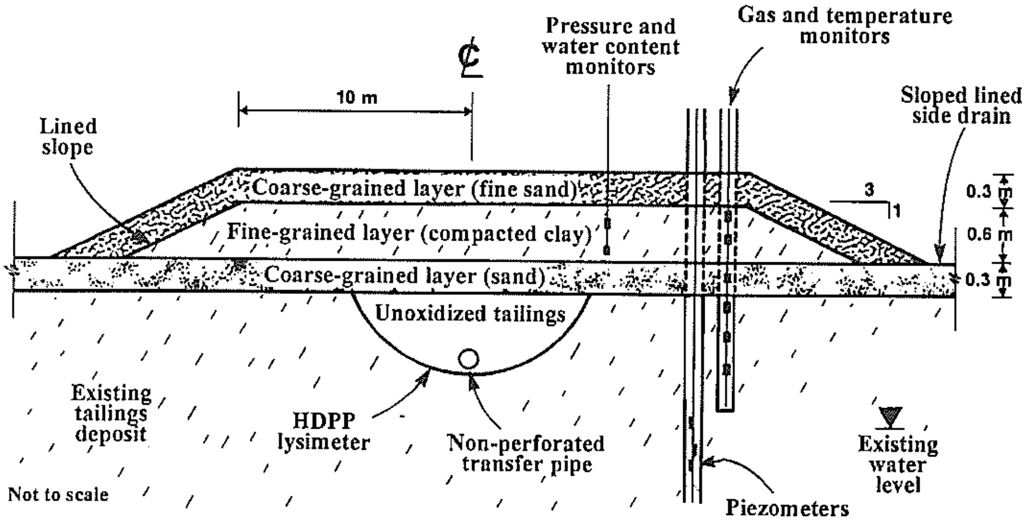

Figure 1. Test plot soil cover.

Cover Simulation Columns

The effectiveness of the three-layer cover in reducing tailings oxidation was investigated by comparing covered tailings with uncovered tailings in laboratory columns. The cover design and soils used in the simulation columns were the same as those used in the field test plots and the drainage column. Tailings used in the evaluation were recovered from the same area as the lysimeter unoxidized tailings. These tailings are rich in sulfides, consisting predominantly of pyrite (15%), pyrrhotite (6%), chalcopyrite, and marmatite.

The columns used in the evaluation consisted of square plexiglass columns (28 cm per side) of 105-cm length. Four such columns were fabricated and installed with soil and tailings materials as follows: (1) two test columns packed with 45 cm of unoxidized tailings overlain sequentially with 15 cm coarse sand, 30 cm clay, and 15 cm fine sand and (2) two control columns packed with 90 cm of unoxidized tailings. Each column was instrumented to measure gaseous oxygen concentrations in the soil voids, soil moisture content, and temperature. The ports were sampled by means of a percent oxygen analyzer with a hand-held sampling trigger and a syringe needle.A detailed description of the column installation is presented by Yanful (1993).

It was soon evident that oxygen was diffusing through the instrumentation in the test columns since the tailings surrounding the sampling ports were oxidizing. Oxidized tailings are easily recognized by their reddish-yellow color, as opposed to the dark-gray color of fresh tailings. Two new test columns were subsequently installed, approximately 200 days after the first set was constructed. These new columns were fabricated from one piece of clear plexiglass with a reduced number of sampling ports, and packing was rigorously controlled to minimize preoxidation of the tailings.

Rainfall and snowmelt were simulated by periodically adding water. Drainage water collected from the two control columns (without covers) was sent for metal and major cation analysis for physicochemical analysis, and [SO_4^{2-}] determination. The test columns (with covers) did not produce any drainage water because the clay layer essentially prevented infiltration. To have a basis for comparison between the control and test columns,the tailings in the test columns were flushed by bypassing the cover and the acidity was measured. The tests were conducted over a period of 760 days.

Results

Water Drainage and Percolation

Cover Simulation Column. The water content profiles in the control columns indicated that the water content of the surface tailings was highly dependent on rainfall and that the deeper tailings were essentially saturated throughout the experiment. The water contents for the test columns showed that the fine sand layer was dependent on rainfall events, while that of the clay remained constant at (or near) saturation (≥95%). The coarse sand below the clay stayed essentially dry except when the columns were flushed to measure acidity. The tailings below the coarse sand layer remained at a constant water content of 30% to 35% until the first column flush, when they became saturated and remained so to the end of the experiment. This data confirm the effectiveness of the upper sand as an evaporation barrier that prevents the clay from losing moisture by evaporation. The bottom sand remained near residual water content, thus preventing the clay from draining by gravity and illustrating its efficiency as a capillary barrier (Nicholson et al. 1989).

The three-layer cover was effective in preventing percolation to the tailings. When precipitation was simulated, most of the added water reported as runoff, some water filled the pores of the sand cover, and no water was collected as drainage. Since the clay presented such an efficient water barrier, it was necessary that flush water bypass the cover in order to obtain acidity results to be compared with the control columns. The columns were flushed four times during the experiment.

Field Results. The data taken from three years of testing show that the clay remained close its construction water content, with a degree of saturation greater than or equal to 93% throughout the entire experiment. The coarse sand remained at residual water content, and the fine sand varied with precipitation and evaporation. Table 1 presents the 1993 volumetric water contents for the two soil covers and underlying tailings and the sand base and tailings underneath the HDPE cover. These results support the 1990-1992 data and are in complete agreement with results obtained from laboratory and modeling analysis. The water content data of the tailings are probably too high and may be explained by the high ionic strength of the tailings pore water which made it difficult to obtained a well-defined TDR wave for interpretation (Yanful et al. 1993)

The percolation through one of the soil covers was estimated by measuring the discharge from the lysimeter during an eleven-month period (October 1992 to September 1993). It was possible to obtain an good estimate of the infiltration because, unlike the spring of 1992, the water table did not rise above the top of the lysimeters. The collected volume was 82 L, which was equivalent to 37 mm of precipitation. This represents 3.9% of the total precipitation (958 mm) for that period. Duplication of the results was not possible as the transfer pipe from the lysimeter below the other soil cover seemed to have ruptured during the third year. The infiltration in the control plot was estimated to be five times that of the test plot.

Table 1. Volumetric water contents of test plots at Waite Amulet (1993).

Test Plot	Material	Depth (cm)	May 21	June 11	August 19
Soil cover 1	Clay	30-60	43	43	42
	Clay	60-90	46	45	46
	Sand Base	90-120	9	9	9
	Tailings	120-150	50	50	49
	Tailings	150-180	60	60	56
Soil cover 2	Clay	30-80	45	45	44
	Clay	60-90	44	45	43
	Sand Base	90-120	8	9	8
	Tailings	120-150	52	52	52
	Tailings	150-180	57	57	54
HDPE cover	Sand Base	30-60	9	9	--
	Tailings	60-90	53	53	--

Hydrologic Modeling. The Hydrological Evaluation of Landfill Performance (HELP) model is a deterministic water balance model that uses climatic, soil, and design data to determine the water budget of a landfill (Schroeder et al. 1984). The HELP model simulates four hydrologic processes on a daily account: (1) runoff, and hence infiltration, (2) percolation (i.e., saturated and unsaturated vertical flow), (3) lateral drainage, and (4) evaporation. The HELP model was utilized in this project to evaluate the amount of percolation that is expected through the composite soil covers. A small amount of percolation is required for the clay to remain near saturation; however, a large amount of percolation will tend to promote the dispersion of AMD.

The HELP model was run with 20 yr of synthetically generated climatic data. Percolation (39 mm/yr) is slightly greater than the hydraulic conductivity of the clay ($1\text{x}10^{-7}$cm/s or 32 mm/yr). This is possible only when free water is ponded at the surface of the clay. The monthly results indicated these conditions existed and that the predicted soil water content at the end of the 20-yr modeling period was similar to the initial value of 44%.

To validate the HELP modeling, the flow model SEEP/W was used to simulate flow through the composite soil cover at Waite Amulet. The test plot was modelled as a two-dimensional system under steady-state conditions. The top boundary condition was specified as a constant flow of water equivalent to the precipitation minus the runoff and evaporation (240 mm/yr). The results of steady-state flow modeling are only an indication of what one might expect as the average annual flow condition. The transient effects of the system are not depicted.

SEEP/W flow modeling determined that 34.4 mm would percolate through the cover. HELP modeling determined that 39 mm would percolate through the cover. Both modeling programs also indicate that the clay will remain saturated by a perched water table in the upper clay and lower fine sand layers. In the eleven-month period mentioned above, 37 mm of percolation was measured.These converging results between the two modeling methods and the field data confirm the validity of the modeling programs.

Freeze-Thaw. Since the method of measuring water content (time domain reflectometry, or TDR) measures only water and not ice, it can be used to indicate when soils are frozen. The results indicated the tailings under the soil covers did not freeze, while the uncovered tailings froze during the winter. The clay cover also showed freezing during winter. These data agreed with the temperature data, which showed below zero temperatures in the cover and the top 25 cm of uncovered tailings during the winter.

The effects of freeze-thaw on the integrity of the compacted clay layer in the composite cover were investigated. The results showed that most of the negative effects occur during the first two freeze-thaw cycles. Laboratory hydraulic conductivities increased by one to two orders of magnitude after the first two freeze-thaw cycles and then remained steady. Field hydraulic conductivity was measured yearly from 1991 to 1993, and the results indicated a value of ~1.0 x 10^{-7} cm/s, similar to the initial design value. Based on these results and those of the laboratory freeze-thaw studies, it is concluded that freezing and thawing have not adversely affected the cover and that no future negative effects need be anticipated.

Oxygen Diffusion

Field Results. The diffusion of oxygen in water is a very slow process, compared with its diffusion in air (2.5×10^{-9} m^2/s in water and 1.8×10^{-5} m^2/s in air). This implies that a layer of water placed above tailings could severely limit the available oxygen for tailings oxidation. The oxygen diffusion coefficient in a saturated soil is equal to the diffusion coefficient in water multiplied by the tortuosity factor of the soil, since the oxygen must travel through the water in the pores of the soil. Since a tortuosity factor is smaller than 1, the diffusion of oxygen through a saturated soil is therefore lower than that in water.

The computer program POLLUTE (Rowe and Booker 1990) was used to determine the flux of oxygen into the covered and uncovered tailings. Modeling results showed that, in July 1992, the flux of oxygen into the uncovered tailings was 2.76 g O_2/(m^2·day), compared with 4.96×10^{-4} g O_2/(m^2·day) for the covered tailings. This represents a cover effectiveness of over 99.9%.

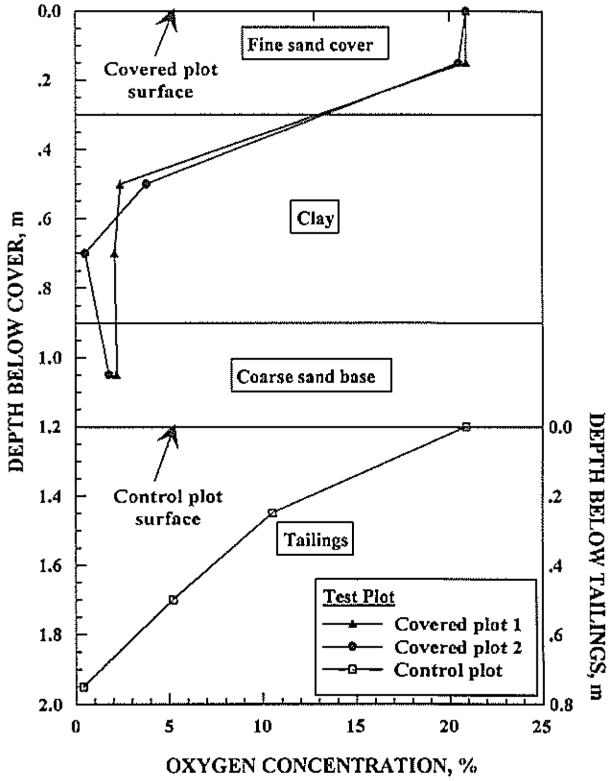

Figure 2. Field O_2 concentrations.

Figure 2 presents gaseous oxygen profiles measured in July 1992 on both covered test plots as well as the uncovered control plot. These profiles show that the covers have a significant effect on the oxygen concentration at the surface of the tailings. When the tailings are not covered, the oxygen at the surface of the tailings is at atmospheric conditions (20.9% O_2). When the three-layer cover is placed over the tailings, the oxygen concentration is reduced to 2.0%. This represents a 90% efficiency in reducing oxygen availability.

The bacteria that catalyze the oxidation reaction are aerobic and may therefore not be capable of survival where oxygen concentrations are low. Below a soil cover, this would represent a greater decrease in oxidation rate than that due to the reduction in oxygen concentration alone, since biological oxidation is eliminated. For example, a 90% decrease in oxygen availability could conceivably imply a 97% decrease in tailings oxidation rate.

During 1992, oxygen measurements at the membrane-covered test plot were consistently 20.9% above, and 6% below, the geomembrane. The fact that the concentration was not lower than 6% below the geomembrane indicated a constant supply of oxygen in the sand base layer. Horizontal inflow of oxygen from the edge of the cover was most likely responsible for the oxygen observed in the sand base.

Simulation Column Results. In the test columns, the oxygen concentration in the fine sand at the surface remained essentially constant near atmospheric value (20.9%). In three of the four test columns, the oxygen concentration beneath the soil cover remained below 1%. In the fourth test column the concentration ranged from 6% to 15% oxygen. As the cover was intact and the tailings in the fourth column did not oxidize (the tailings remained gray and very little acidity was measured), the sampling port was considered defective. The oxygen concentrations measured in all covered tailings were always below 1%.

In the control columns, an oxydation front was formed and gradually descended farther into the tailings as the upper layers oxidized. The oxidation rate decreased with time because the oxygen had to diffuse through the upper layers of oxidized tailings to reach the fresh tailings below. Near the end of the test period (~650 days), oxygen concentrations greater than 2% were observed at the 31-cm depth. This suggests that the tailings above the 30-cm depth must have been oxidized.

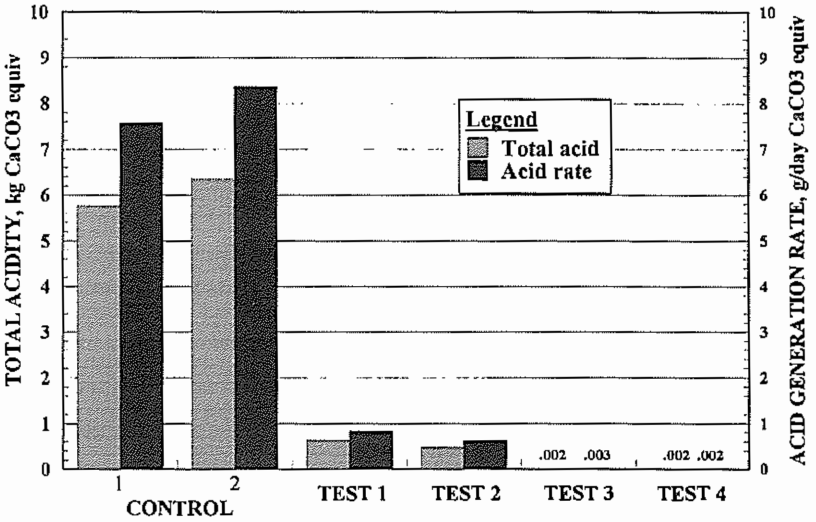

Figure 3. Total acidity and acid production rate in laboratory columns.

Chemistry

Simulation Column Results. Total acidity was used as a basis for assessing soil cover effectiveness during the simulation column experiments. The total acidity was determined as the product of the acidity as $CaCO_3$ equivalent, in grams per liter, and the respective volume of drainage water through the columns. For the control columns, this included both simulated rain and flush water. For the test columns, only flush water was measured since the simulated rain water did not permeate through the clay. The acidity data are presented in figure 3 for the uncovered and covered tailings. The data indicate that the soil cover decreased acid production from the tailings by an average of 95.4%. Reduction of acid production in test columns 1 and 2 was not as high as in columns 3 and 4, because of oxidation resulting from test artifacts, as previously mentioned.

The oxidation rate calculated for the uncovered tailings was about 10 mg/(d·cm^2) of $CaCO_3$. This oxidation rate could not be related to field oxidation rates since laboratory conditions were almost optimal for microbial activity (22° C). However, the laboratory results provide an estimate of the maximum acid flux generated by a tailings with similar mineralogy.

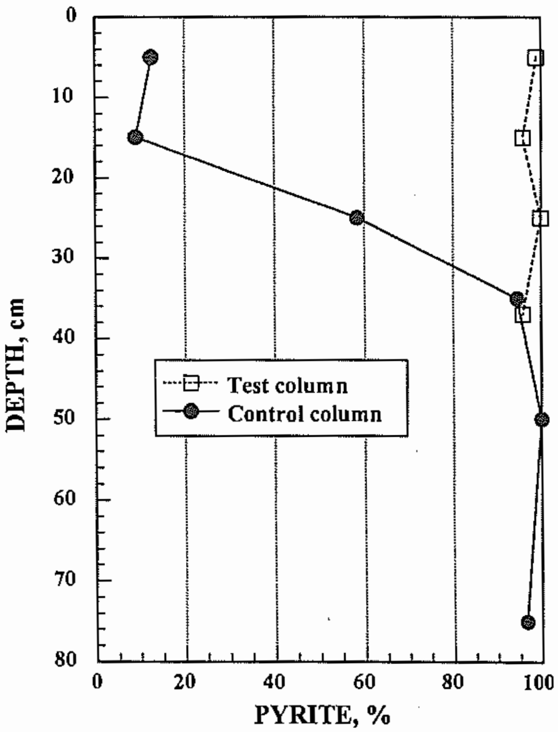

Figure 4. Percentage of initial pyrite.

At the end of the tests, solid tailings samples were removed from the columns and sent for analysis. Pyrite content was considered to be a good basis for verification of the degree of oxidation since it is quickly oxidized and represented 12% to 18% of the fresh tailings. The results in figure 4 were obtained by dividing the final concentration of pyrite at the specific depths by the initial concentration of the tailings taken when the columns were packed. These results clearly show that the control column tailings had been mostly oxidized in the first 20 to 30 cm of depth, and that the covered tailings were virtually intact.

Porewater samples were extracted (by squeezing) from approximately 200 g of tailings and analyzed for pH and for metals and sulfur by the inductively coupled plasma method. The results showed that iron concentrations in the control columns were more than 100 times higher than iron concentrations in the test columns. The oxidation front in the control columns was also well defined at around 30 cm, with iron concentrations of 15 g/L compared with 5 g/L near the surface. Table 2 presents some water quality data for the uncovered (Control 1) and covered (Test 4) tailings. Details of the water quality data from the columns are presented and discussed in detail in the MEND report on the project (Yanful et al. 1993).

Bacteria count was also performed on tailings samples to evaluate the population of iron-oxidizing microorganisms such as *Thiobacillus ferrooxidans*. The results indicate that the bacterial population in the covered tailings (test columns) ranged from $1x10^2$ to approximately $1x10^5$ cells, while the uncovered tailings (control columns) showed a maximum number of cells of $1x10^7$ near the oxidation front, at a depth of 30 cm.

Table 2. Post-testing pH and species concentrations (mg/L) in tailings pore water.

Depth (cm)	**pH**	**Fe**	**Fe^{3+}**	**Zn**	**Cu**	**SO_4^{2-}**	**Al**
Uncovered Tailings (C1)							
5	1.87	4,970	3,590	13.5	80.7	22,380	1,300
15	1.89	4,150	4,130	15.7	136	21,240	1,300
25	2.02	15,800	14,270	67.2	158	49,500	2,700
36	2.87	11,600	11,680	184	52.2	34,500	2,240
50	3.31	9,230	9,320	432	15.9	27,690	1,730
75	4.06	1,330	70	72.5	<0.02	3,840	5.3
Covered Tailings (T4)							
5	4.12	5.31	2.31	11.6	0.1	2,610	1.87
15	5.45	1.42	0.7	2.48	0.03	1,950	0.58
25	5.41	7.58	0.7	8.31	<0.02	1,980	0.69
37	5.29	0.9	1.75	12.4	<0.02	2,250	0.51

Field Results. The chemistry of the drainage water from the control lysimeter indicated rapid oxidation of the exposed tailings in the uncovered lysimeter. Immediately following installation in October 1990, the pH of drainage water decreased from 3.78 to 3.33 within a month. Concentrations of Fe and other heavy metals (Zn, Cu, and Cd) were higher than those observed in the saturated tailings surrounding the lysimeter. After the initial flushing of the tailings, the concentrations of sulfate and metals apparently decreased in 1991. Further oxidation during the following summers produced more acid, and concentrations of sulfate and metals have increased in 1992 and 1993.

The lysimeters underneath the soil covers did not produce any drainage water until after a year of monitoring. Unoxidized tailings were placed in the lysimeters at residual saturation prior to covering. Following installation, it was calculated that the lysimeters underneath the soil covers would not report water until after 14 months, based on the hydraulic conductivity of the compacted clay and the residual water content of the tailings. When the lysimeters finally reported water, the water table below the test plots was found to have risen above the level of the lysimeter as a result of high rainfall. This was evident from hydraulic head data, ponding observed on the control test plot and water collected from the lysimeter below the geomembrane. Analysis of the lysimeter water and pore water of the surrounding tailings supported the inference that ground water had contaminated the fresh tailings inside the lysimeters by rising above the the sand base and into the lysimeters. This contamination would affect the collected water from both the control and the soil covered test plots. Ferric ions (Fe^{3+}) in the tailings pore water could subsequently oixidize the fresh tailings below the covered plot and worsen the water quality in the lysimeter, before collection. The chemistry of the lysimeter drainage water was therefore not considered a useful measurement of the acid generation rate. A different design for the lysimeter system could have averted the problem associated with the water table elevation. Also, the problem would not occur in a full-scale soil cover application, in which covering of the entire tailings deposit would lower the net infiltration in the tailings, and hence lower the water table.

The tailings from the two soil covered and control test plot lysimeters were removed and examined after 3 yr of monitoring, to assess the extent of oxidation. The tailings from the control lysimeter showed some discoloration due to oxidation, whereas the samples removed from beneath the covered tailings were gray and seemingly unoxidized. Chemical analysis for sulfate and metals indicated oxidation in the control tailings but little or no oxidation in the covered tailings. For example, total Fe concentration in the uncovered tailings pore water ranged from 5,000 to 20,000 mg/L, compared with 1,000 to 1,500 mg/L in the covered tailings. Sulfate concentrations in the uncovered tailings pore water were about 16,000 to 63,000 mg/L compared with 5,000 to 5,700 mg/L in the covered tailings. These data do not indicate the same soil cover effectiveness as the gaseous oxygen and hydraulic data and are believed to be influenced by mixing from surrounding ground water which overtopped and contaminated lysimeters hosting the tailings. It is estimated that, at the time of sampling, the ground water that had contaminated the covered lysimeters had not yet been flushed from the lysimeter pore water. In fact, only about 1/6 of the total tailings pore volume (in the soil-covered lysimeters), had been flushed. Details of the water quality data are presented by Yanful et al. (1933b).

After three years of monitoring, pore water sulfate concentrations in soil-covered tailings (lysimeters) were 9 to 30% those of uncovered tailings. Total iron concentrations in the covered tailings were 7 to 20% of those observed for the uncovered tailings.

Conclusions

The three-layer soil cover, consisting of one fine-grained (clay) saturated layer placed between two coarse-grained (sand) layers, is an efficient method of inhibiting acid mine drainage generation. Field and laboratory tests have shown that the clay barrier will remain near saturation ($\geq 93\%$) even under dry conditions. Oxygen profiles measured in the laboratory and the field showed that the oxygen flux could be reduced by up to 99.9%. The reduction in oxygen flux in the laboratory columns reduced the activity of the bacteria which catalyze the oxidation reaction by 99.0%. The curtailment of oxygen and biological oxidation resulted in a reduction of the rate of acid generation of 95.4% in the laboratory.

Field water balance measurements indicated that only 3.9% of precipitation percolated through the cover. This was confirmed by hydrologic modeling. This infiltration is equal to approximately one fifth the infiltration into uncovered tailings. After three years of monitoring, the hydraulic conductivity of the compacted clay had not changed from the initial value of 1.0×10^{-7} cm/s.

Literature Cited

Nicholson, R.V., R.W Gillham, J.A. Cherry, and E.J. Reardon. 1989. Reduction of acid generation in mine tailings through the use of moisture-retaining cover layers as oxygen barriers. Can. Geotech. J., 26(1): 1-8.
`http://dx.doi.org/10.1139/t89-001`

Nordstorm, D.K. 1982. Aqueous pyrite oxidation and the consequent formation of iron minerals. p. 37-56. In Acid Sulphate Weathering. Soil Sci. Soc. America. Spec. Pu. 10.

Rasmuson, A. and J.C. Eriksson. 1986. Capillary barriers in covers for mine tailings dumps. National Swedish Environmental Protection Board Report 3307.

Rowe, R.K., and J.R. Booker. 1990. POLLUTE v.5.0 1-D pollutant migration through a non-homogeneous soil—user manual. Geotechnical Research Centre, Faculty of Engineering Science, University of Western Ontario. Report GEOP 90-1.

Schroeder, P.R., J.M. Morgan, T.M. Walski, and A.C. Gibson. 1984. The hydrologic evaluation of landfill performance (HELP) model. U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Washington, DC.

Schroeder, P.R., and R.L. Peyton. 1984. Verification of the hydrologic evaluation of landfill performance (HELP) model using field data, U.S. Environmental Protection Agency, Washington, DC.

Woyshner, M.R. and E.K. Yanful. Hydrologic analysis and prediction in a composite soil cover. Joint CSCE-ASCE National Conference on Environmental Engineering (Montreal Canada, July 12-14, 1993)

Yanful, E.K. and L.C. St-Arnaud. 1992. Migration of acidic pore waters at the Waite Amulet tailings site near Rouyn-Noranda, Quebec, Canada. Canadian Geotechnical Journal, Vol. 29: 466-476.
http://dx.doi.org/10.1139/t92-051

Yanful, E.K, 1993. Oxygen diffusion through saturated soil covers on sulphidic mine tailings. ASCE J. Geotech. Eng., Vol. 119, No. 8, pp. 1207-1228.
http://dx.doi.org/10.1061/(ASCE)0733-9410(1993)119:8(1207)

Yanful, E.K., M.R. Woyshner, and B.C. Aubé. 1993. Field evaluation of the effectiveness of engineered soil covers for reactive tailings.Report for MEND, DSS contract 23440-0-9061/01-SQ.