FIELD PERFORMANCE EVALUATION OF SOIL-BASED COVER SYSTEMS TO MITIGATE ARD FOR THE CLOSURE OF A POTENTIALLY ACID-GENERATING TAILINGS STORAGE FACILITY

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ABSTRACT

This paper summarizes field performance results of three engineered soil-based cover systems and one control system intended to mitigate potential acid rock drainage and metal leaching at a tailings disposal site. The field performance evaluation commenced in 2002 on the tailings beach of the Premier Gold Project (PGP) site near Stewart, British Columbia, Canada (~ 56°05’N, 130°00’W). Four 15 m by 15 m test plots were constructed using the barrier layers of either 1) a geosynthetic clay liner (GCL) Bentomat® ST, 2) 0.6 m of local sand and gravel plus 6% EnviroGel® 8 Wyoming sodium bentonite by weight, 3) 0.8-m loose till, or 4) no barrier (control system).

Two years of monitoring results indicate that the barrier layers did not freeze which may be attributed to the insulating effect of approximately 2 m of snow pack at the site. Of the four systems studied, the sand-bentonite (S-B) system performed best when considering performance indicators such as percolation, interflow (lateral drainage above the barrier), and oxygen diffusion. Field and laboratory results indicated that the ‘as-is till’ layer would have to be more than 2 m thick to reduce oxygen diffusion adequately. Field oxygen concentrations and oxygen flux modeling indicated that the GCL system would have to be upgraded substantially (e.g. by incorporating another layer of GCL or a low permeability soil layer) to adequately reduce oxygen diffusion. Unit costs for the as-built S-B cover system without instrumentation were 1.9 and 2.0 times as expensive as the as-built till and the as-built GCL cover systems, respectively.

INTRODUCTION

Acid generation from sulphide-bearing mine waste (tailings, ore, and waste rock) is a very serious financial and environmental issue facing the mining industry and receiving environments. Acid rock drainage (ARD) may form when insufficiently buffered sulphide minerals are exposed to oxidizing conditions in the presence of water. ARD has typically high metal and sulphate concentrations. ARD forms in three stages during which the pH drops from near neutral values to very low values (2.0 and lower). Since oxygen and water are two principal ingredients for sulphide mineral oxidation, their control is usually the goal when covering potentially acid generating (PAG) waste with a soil cover system.

This paper summarizes pertinent results of a pilot study that investigates measures to mitigate potential ARD and metal leaching from a tailings beach of a tailings storage facility (TSF) located at the Premier Gold Project (~ 56°05’N, 130°00’W) near Stewart, British Columbia, Canada (Fig. 1). The closure
The concept for the TSF involves the installation of a soil-based cover over the tailings beach and a shallow water cover over the remainder of the TSF (Klohn Crippen, 2002). Results presented herein are part of the first author’s Ph.D. thesis and related work has also been summarized by Renken et al. (2002, 2003a, 2003b, 2003c, 2004, 2005).

The Premier Gold Project (PGP) site is located in the Mountain Hemlock bio-geoclimatic zone with a total mean annual precipitation of 2,200 mm based on eight years (1989-1996) of climatic records (Mchaina and Zurkirchen, 1998). The PGP mine was comprised of open-pit and underground gold and silver mining and milling works. Pyrite, sphalerite, and galena are the main sulphides and calcite is the most abundant neutralizing mineral in the PGP tailings (Mchaina and Zurkirchen, 1998). Currently, PGP tailings are alkaline (pH 7.5), but they are predicted to become acid generating if left unmitigated (SRK, 2001). Typical sulphur and sulphate concentrations in the tailings were 8.1% and 0.07%, respectively (Renken, 2002). Mineralogical analysis of two PGP tailings samples determined that one sample (#10) contained 24% pyrite and the other sample (#16) contained 52% pyrite plus felsic host rock/gangue material (quartz, plagioclase and sericite) (Harris, 2000).

Research Objectives

The objectives of the laboratory and field studies were to develop and evaluate three soil cover systems and one control system with respect to their: 1) effectiveness to reduce infiltration from precipitation, 2) effectiveness to act as barrier to control oxygen flux into tailings, and 3) costs. To achieve these objectives, a pilot study with the following five phases was implemented: Phase I) conceptual design, Phase II) laboratory study and preliminary modeling, Phase III) detailed design, Phase IV) construction, and Phase V) performance evaluation.

SYNOPSIS OF THE PILOT STUDY

Phase I – Conceptual Design: The soil-based cover system at the PGP site is intended to lower the phreatic line below the tailings beach to ensure that it runs through the lower half of the seal zone of the main tailings dam and to minimize oxygen ingress. Design criteria for the barrier in the soil cover systems included: 1) saturated hydraulic conductivity of less than $10^{-7}$ to $10^{-6}$ cm/s, 2) a soil saturation (percentage of soil pores that is filled with water) of greater than 85%, 2) an effective oxygen diffusion coefficient, $D_o$, of $1\times10^{-8}$ m$^2$/s or lower, 3) an air entry value (AEV) that is significantly larger than the maximum matric suction that is experienced by the barrier layer, and 4) very low oxygen flux through the cover. Oxygen flux through the cover system should be as low as possible to minimize sulphide oxidation. Aubertin et al. (1999) suggested a target oxygen flux of 20 to 50 g/m$^2$/year.
Phase II – Laboratory Study and Preliminary Modeling: Laboratory work involved preliminary and detailed material characterization, and QA/QC testing during and after test plot construction. Material characterization included grain size analyses; compaction tests; flexible wall, falling head and constant flow hydraulic conductivity tests; specific gravity tests; soil water characteristic curve tests; specific surface area tests; acid base accounting; ICP metal scans, and oxygen diffusion tests. QA/QC soil testing included the parameters of bulk density and water content. Preliminary modeling included HELP (Hydraulic Evaluation of Landfill Performance) modeling, SWEEP/W (saturated/unsaturated) flow modeling, and oxygen flux modeling (Renken et al., 2002, 2003a, 2003b, 2003c).

Phase III – Detailed Design: A detailed design was developed for the field test plot construction based on Phase II results. The detailed design included material specifications; site layout and design; construction drawings; monitoring equipment selection and specifications; monitoring objectives, parameters, and schedule; and cost estimates. The cover systems contained the barrier layers of either 1) a geosynthetic clay liner (GCL) Bentomat® ST (3.6 kg bentonite/m²), 2) 0.6 m of local Minus ¾” (1.905 cm) sand and gravel plus 6% EnviroGel® 8 Wyoming sodium bentonite by weight, 3) 0.8 m loose PGP till, or 4) no barrier (control site). EnviroGel® 8 was a coarse granular sodium bentonite, supplied by Wyo-ben Inc. (2003). Soil layers in the test plots are detailed in Table 1.

Phase IV – Construction: Test plot construction occurred between August 7 – September 28, 2002 according to construction drawings developed in Phase II (Renken, 2002; Renken et al., 2003b). Separate, duplicate field percolation columns (2 columns per test plot) were also set up to investigate the one-dimensional percolation rate of the soil cover systems. These columns were commissioned on Jun. 13, 2003. A weather station was installed and commissioned in the fall of 2001.

The PGP test plots were instrumented to facilitate comprehensive field performance evaluation. Automated instrumentation was installed to continuously monitor soil moisture, matric suction, and soil temperature in the test plots and underlying waste material in all test plots at two locations (Nests 1 and 2) and several depths (Fig. 2). Soil moisture was assessed continuously in two profiles per test plot with EnviroScan® sensors and bi-weekly to monthly with one Diviner 2000® portable capacitance probe in 5 profiles per test plot). These devices, manufactured by Sentek Pty Ltd., S. Australia, were frequency domain reflectometry (FDR) sensors. Soil temperature and matric suction were determined with Campbell Scientific 229 thermal conductivity sensors (8 per test plot). Runoff and interflow were monitored continuously in the non-winter months with five water level meters (OTT Thalimedes Float Operated Shaft Encoders). Pore gas was collected at three locations (Nests 1, 2, and 3) and 5 depths per test plot with 0.3-m long, hollow, horizontal, slotted (10 mil) PVC pipes approximately every six weeks from June to October in 2003 and 2004. Soil water samplers (suction lysimeters) were installed in the tailings of the Control and GCL Plots (10 per test plot). Approximate locations of the Instrumentation Nests and the access tubes used for soil moisture assessment are depicted on Fig. 2.

Phase V – Key Findings and Discussion of Results: Key findings of the pilot study are summarized below in the following order: 1) laboratory results, 2) constructability of covers, 3) construction costs, and 4) field performance results (climate, soil temperature, and selected test plot results). Selected test plot results include volumetric water content, matric suction, runoff and interflow, oxygen concentrations and estimated oxygen fluxes, and expected freeze-thaw susceptibility of the barrier layers. To prevent
drainage of the barrier layer, matric suction experienced by the barrier has to be less than the barriers’ air entry value (AEV). The AEV is equal to the smallest matric suction at which water starts draining from a soil. The AEV can be inferred from the soil water characteristic curve (SWCC) in which matric suction is graphed versus volumetric soil water content. The SWCC can be measured with a Tempe cell or a pressure plate apparatus in the laboratory. A typical SWCC is flat for saturated soils (i.e. volumetric water content is 100%) until the matric suction exceeds the AEV after which the SWCC declines sharply until the residual soil water content is reached.

1) **Laboratory Results:** Key laboratory results are summarized in Table 2 and Fig. 3. Estimates of the effective oxygen diffusion coefficients for the tailings and potential barrier materials, illustrated in Fig. 3, include best-fit and upper bound equations proposed by MacKay (1997).

2) **Constructability of Covers:** Construction at the end of August and in September, 2002 was often interrupted due to heavy rains; and therefore, more time consuming than originally planned. The most time consuming and tedious construction was the S-B Plot construction. Mixing the S-B was labour intensive and ensuring that the pre-mixed S-B mixture remained close to the optimum water content for compaction was tedious during storage, installation and compaction. The Till Plot was the fastest and easiest to install. Originally it was planned to install the till barrier at its optimum to 2% wet of optimum water content for compaction. However, the locally available till proved to be too wet for compaction and even too wet for trafficability. The lack of trafficability of the till required that all layers, the till and covering sand and top soil layers, needed to be placed and shaped prior to moving the leveling equipment to a new location. Construction of the GCL cover system had to be postponed several times due to wet weather conditions which proved to be one of the main constraints in the GCL plot construction. Screening of fine sand for 0.1-0.15 m thick cushion layers above and below the GCL was also very slow due to the low fines and high moisture content in the sand and gravel (fine earths remained adhered to the larger granules).

3) **Construction Costs:** Construction costs for the test plots were approximately Can$216,400. These costs include test pad construction costs of approximately $26,000 and cost-savings of $51,200 arising from the industry/government/university (Boliden/NSERC/UWO) collaboration (Table 1). Approximate unit costs ($/m²) for test plot construction without instrumentation was $275 for the S-B plot, $178 for the Control Plot, $145 for the Till Plot, and $139 for the GCL Plot (Table 1). Please note that unit costs for the Control Plot include loading, hauling, and placing of 0.5 m sand and gravel and 0.1 m of top soil. The unit costs for the GCL Plot construction include the placement of 0.75 m tailings below the GCL cover system which was approximately $8.40/m².

4) **Field Performance (1. October 2002 – November 23, 2004) and Discussion of Results:**

4) a) **Field Performance - Climate:** The cumulative rainfall from June to October ranged from 586 mm to 627 mm (3.8 to 4.2 mm/day) and averaged 610 mm during the 2001-2004 monitoring period. The cumulative precipitation was approximately 23% lower than was reported in the Canadian Climate Normals for the Stewart Airport Climate Station (Environment Canada, 1981) and about 14% lower than was recorded at the PGP Mill site during 1989-1996 (Mchaina and Zurkirchen, 1998). The maximum and minimum air temperatures were 32°C and -19°C, similar to what was recorded by Environment Canada
(1981) and reported by Mchaina and Zurkirchen (1998). The average monthly relative humidity ranged from 68% to 96% with an average relative humidity above 75% for all months except April, May and June. In the winters of 2001-2002, 2002-2003 and 2003-2004, the depth of the annual snowpack at the PGP site ranged from 2.0 to 2.3 m. On average, snowmelt started at the end of March and continued until the middle of May.

4) b) Field Performance - Soil temperatures: Soil temperature varied seasonally in response to the average air temperature in all test plots. Soil temperatures declined over the winter months to 0.2-1.1°C and rose in the summer to 15.7-21.9°C. None of the 32 temperature sensors measured freezing soil temperatures, which may be attributed to the insulating effect of snowpack at the site.

4) c) Field Performance - Control Plot:
- Estimates of volumetric water content (VWC) were based on gravimetric, EnviroScan® and Diviner 2000® soil moisture measurements in all test plots. Samples for gravimetric measurements were collected from one profile per test plot in the spring of 2003 and from two profiles per test plot in the spring and fall of 2004. Inferred VWCs in the Control Plot tailings ranged from 25 to 65%.
- Matric suction in the Control Plot tailings ranged from 4 to 30 kPa. These matric suctions were either equal to or higher than the air entry value (AEV) for the PGP tailings, which was estimated to be 5-6 kPa. Thus, air entered the Control Plot tailings in 2003 and 2004 and oxidation of the tailings likely occurred during the summer months. There appeared to be an approximate time lag of 6-8 days between the onset of dry periods (no rainfall) and the onset of increased matric suction in the tailings.
- Runoff and interflow results were indicative of an effective hydraulic conductivity of $1 \times 10^{-6}$ cm/s to $3 \times 10^{-6}$ cm/s for the tailings based on HELP modeling (Table 2).
- Measured oxygen concentrations in the Control Plot are illustrated on Fig. 4. Based on these concentrations, the oxygen flux was calculated as outlined in Renken et al. (2003c). The estimated oxygen flux in the Control Plot was 27.6 kg/m²/year in 2003 and 25.5 kg/m²/year in 2004 assuming that the effective oxygen diffusion coefficient, $D_e$, was $2.0 \times 10^{-6}$ m²/s year-round. These oxygen fluxes were of similar order of magnitude as was previously reported (Tibble and Nicholson, 1997; Li and St. Arnaud, 1999).

4) d) Field Performance - GCL Plot:
- Inferred VWCs in the GCL Plot tailings ranged from 22 to 67% in 2003 and 2004 based on gravimetric, EnviroScan® and Diviner 2000® soil moisture measurements. This range was essentially the same as was measured for the Control Plot tailings.
- Matric suction ranged from 4 to 20 kPa in the GCL Plot tailings and was very similar to Control Plot results (i.e. the matric suction was close to or higher than the tailings’ AEV). Matric suction in the sand and gravel, measured 0.1 m above the GCL, ranged from 3 to 30 kPa. This matric suction might have been higher than the AEV for the GCL, because several of GCL samples exhumed in October, 2004, had an AEV of less than 10 kPa. However, the AEV for the majority of the exhumed GCL samples ranged from 70-80 kPa.
- Runoff and interflow results showed that measurable interflow occurred only during periods of substantial rainfall (e.g. Aug. 1-10, 2004, Sept. 10 – Oct. 17, 2004). In the wetter months of September and October, 2004, the percentage of precipitation that either evapotranspired or infiltrated into the GCL ranged from 19 to 29%. Based on these and HELP modeling results, the effective
The hydraulic conductivity of the GCL was inferred to be $1 \times 10^{-8}$ to $2 \times 10^{-8}$ cm/s, approximately one magnitude higher than is often assumed for GCLs (Estornell and Daniel, 1992; Hewitt and Daniel, 1997; CETCO, 2002). Chamberlain et al. (1997) also found that the field hydraulic conductivity of GCLs was higher than is typically reported in the literature.

- The performance of the GCL cover system with respect to oxygen diffusion was not as good in 2004 as in 2003 (Fig. 4). The estimated 2003 oxygen flux in the GCL Plot tailings was 0.196 kg/m²/year assuming that the effective oxygen diffusion coefficient, $D_e$, was $1.9 \times 10^{-10}$ m²/s, and 0.089 kg/m²/year, if $D_e$ was $8.57 \times 10^{-11}$ m²/s. In 2004, the estimated oxygen flux in the GCL Plot was 0.167 kg/m²/year, if $D_e$ was $1.9 \times 10^{-10}$ m²/s, and 0.076 kg/m²/year, if $D_e$ was $8.57 \times 10^{-11}$ m²/s. However, $D_e$ for the GCL would have been much higher (say $1 \times 10^{-7}$ m²/s), if the GCL dried out partially in the summer of 2004 as seems to be indicated by three of the performance indicators. Partial hydration of the GCL seems to be indicated by 1) higher oxygen concentrations in the GCL Plot tailings observed in two out of three soil profiles in 2004 (Fig. 4), 2) GCL Plot runoff and interflow results, and 3) AEV values of less than 10 kPa for some exhumed GCL specimens. Assuming that $D_e$ was $1 \times 10^{-7}$ m²/s, the estimated 2004 oxygen flux might have been 40.4 kg/m²/year at a depth of 15 cm below the GCL. Thus, the oxygen flux would have been of the same order of magnitude as estimated for the Control Plot tailings, at least during the time span when the GCL was only partially hydrated. The above-mentioned estimates of $D_e$ for GCLs were based on the work of Aubertin et al. (2000) and Bouazza et al. (2002). Aubertin et al. (2000) reported a $D_e$ of $8.57 \times 10^{-11}$ m²/s for 100% saturated Bentofix GCL (3.3 kg bentonite/m²) and Bouazza et al. (2002) recorded a $D_e$ of $1.9 \times 10^{-10}$ m²/s for 93% saturated Bentofix X2000 (3.1 to 3.8 kg bentonite/m²).

- Freeze-thaw susceptibility of GCLs was not assessed in this study, but others have found that the hydraulic conductivity of GCLs does not increase after freeze-thaw episodes (Koerner and Daniel, 1997; Chamberlain et al., 1997).

- The current design for the GCL cover system would have to be upgraded based on the performance results in order to provide an effective oxygen diffusion barrier, for example, by reducing the effective oxygen diffusion coefficient or increasing the diffusive path length. Several scenarios of required layer thickness (h) and associated $D_e$ values were modeled, but are not discussed in this paper. For example, placing a second GCL on top of the first one and keeping both GCLs highly saturated with $D_e$ of $8.57 \times 10^{-11}$ m²/s or lower would reduce the annual oxygen flux to 46 g/m²/year. However, whether this performance is achievable in a field setting at the PGP site or elsewhere would need to be investigated further.

4) e) Field Performance - Sand and Bentonite Plot:

- The volumetric water content (VWC) of the S-B barrier ranged from 21 to 29% and the corresponding soil saturation ranged from 58 to 77% based on physical soil samples. Temperature corrected EnviroScan® VWCs ranged from 18 to 36% and the corresponding soil saturation ranged from 48 to 97%. Please note that the EnviroScan® measurements (scaled resonance frequencies) were very well correlated with summer soil temperatures in the S-B barrier (Renken et al., 2004). This observed temperature dependent behaviour was investigated further and was attributed to the temperature dependency of the electrical permittivity of bentonite clay minerals.

- Matric suction in the S-B Plot ranged from 8 to 80 kPa excluding start-up measurements. Maximum matric suction in the S-B barrier was approximately 30 kPa below the air entry value for the S-B
material, and therefore, S-B might be a suitable barrier material to limit oxygen ingress at the PGP site. Matric suction in the sand and gravel, measured 0.1 m above the S-B barrier, ranged from 3 to 30 kPa, and therefore, was well below the air entry value for the S-B mixture.

- Runoff and interflow rates were indicative of an effective hydraulic conductivity of $3 \times 10^{-7}$ cm/s for the S-B barrier based on HELP modeling. This hydraulic conductivity was similar to the average 2003 and 2004 percolation rate of $4 \times 10^{-7}$ cm/s measured with the S-B field percolation columns (Table 2).
- Measured oxygen concentrations in the S-B barrier ranged from 0 to 20.9% (Fig. 4). The majority of the S-B plot sensors were flooded after installation (83% in the first year and 92% in the second year), which is indicative of saturated soil conditions. In order to achieve an oxygen flux of 50 g/m²/year or lower, modeling indicated that it is essential to have a 0.2 m thick layer with a $D_e$ of $1.0 \times 10^{-9}$ m²/s or lower. Achieving and maintaining a $D_e$ of $1.0 \times 10^{-9}$ m²/s or lower in a 0.2 m thick layer of S-B seems feasible at the PGP site, because 1) the site is characterized by a high net annual water surplus (i.e. high recharge potential), 2) S-B has a relatively high AEV (i.e. has resilience during dry spells), and 3) laboratory studies indicated that a $D_e$ of $1.0 \times 10^{-9}$ m²/s is achievable under nearly saturated conditions (soil saturation > 90%). Laboratory tests determined a $D_e$ of $4.6 \times 10^{-9}$ m²/s to $1.0 \times 10^{-8}$ m²/s for a soil saturation of 80 to 85% (Fig. 3).
- Freeze-thaw susceptibility of S-B was not assessed in this study, but others have found that the hydraulic conductivity of S-B does not increase after freeze-thaw episodes (Wong and Haug, 1991; Chamberlain et al., 1997; Williams, 2004).

4) f) Field Performance - Till Plot:

- Based on physical and EnviroScan® moisture measurements, the volumetric water content (VWC) in the Till Plot ranged from 16 to 30% and the corresponding soil saturation ranged from 56-100%. However, the Diviner 2000® VWC measurements varied widely from 5 to 32% corresponding to a soil saturation ranging from 18 to 112%. Based on the Diviner measurements, the PGP till would not be saturated enough to adequately reduce oxygen diffusion.
- Matric suctions were lower than the estimated suction at 85% soil saturation (45-70 kPa) for the PGP till, except for one of the sensors closest to the soil surface (‘T2-S1’ in Nest 2; 12-60 kPa). Based on these matric suction measurements, the till might be suitable as a barrier material to limit oxygen ingress to the PGP tailings.
- Based on the Till Plot runoff and interflow data, the portion that either evapotranspired or infiltrated into the test plot ranged from 3 to 23%. Based on these and HELP modeling results, the inferred effective hydraulic conductivity was $5 \times 10^{-7}$ cm/s for the till (Table 2).
- The freeze-thaw susceptibility of PGP till was evaluated in the laboratory with flexible wall hydraulic conductivity tests (ASTM D 5084) conducted in triplicate and in the field with two percolation columns. Hydraulic conductivity for the PGP till was $4.2 \times 10^{-8}$ cm/s before freezing, $1.3 \times 10^{-7}$ cm/s after 3 freeze-thaw cycles, and $1.1 \times 10^{-7}$ cm/s after 9 freeze/thaw cycles in the laboratory (i.e. the hydraulic conductivity increased approximately by an order of magnitude after 3-9 freeze/thaw cycles; Table 2). The average percolation rate in the field was $6.3 \times 10^{-7}$ cm/s in the first summer and $6 \times 10^{-6}$ cm/s in the second summer after construction (~ i.e. the hydraulic conductivity increased by about one order of magnitude after one winter!). Other workers (for example, Viklander, 1998) also found that glacial tills are susceptible to freeze-thaw events.
Oxygen concentrations measured in the Till plot varied widely from 0 to 20.9% (Fig. 4). Approximately 73% of the sensors were flooded in 2003 and 77% in 2004. In the laboratory, $D_e$ for the PGP till was estimated to be $5.6 \times 10^{-8} \text{m}^2/\text{s}$ for a soil saturation of 80 to 88% (Fig. 3). Assuming a $D_e$ of $5.6 \times 10^{-8} \text{m}^2/\text{s}$, a 9-m thick layer of till would be required to reduce the oxygen flux to less than 52 g/m²/year.

A $D_e$ lower than $5.6 \times 10^{-8} \text{m}^2/\text{s}$ is theoretically achievable for the PGP till, if it could be maintained in a saturated state at all times. Lower $D_e$ results might also be achievable, if the PGP till could be compacted close to its optimum water content.

As was found for the S-B barrier, a 0.2 m thick layer of PGP Till with a $D_e$ of $1.0 \times 10^{-9} \text{m}^2/\text{s}$ or lower seems to be required to achieve an oxygen flux of 50 g/m²/year or lower. Achieving and maintaining a 0.2 m thick layer of PGP till with a $D_e$ of $1.0 \times 10^{-9} \text{m}^2/\text{s}$ or lower seems questionable at the PGP site based on laboratory diffusion test results (Fig. 3).

Prior to making any decision on whether to select till as a barrier material, it is recommended to determine which one of the soil moisture measurements was the most representative of field conditions by carefully establishing the actual water content for numerous soil profiles in the Till Plot. Soil moisture measurements should be confirmed, because matric suction and Diviner® 2000 results were conflicting.

**SUMMARY AND RECOMMENDATIONS**

This paper summarizes key elements of a pilot study of three engineered soil-based cover systems and one control system intended to mitigate potential acid rock drainage (ARD) and metal leaching. The field performance evaluation commenced in 2002 on the tailings beach of the Premier Gold Project (PGP) site near Stewart, British Columbia, Canada (~ 56°05'N, 130°00'W). Four test plots were constructed that contained the barrier layers of either 1) a geosynthetic clay liner (GCL) Bentomat® ST, 2) 0.6 m of local sand and gravel plus 6% EnviroGel® 8 Wyoming sodium bentonite by weight, 3) 0.8 m loose till, or 4) no barrier (control system). Two years of monitoring results indicated that the barrier layers did not freeze which may be attributed to the insulating effect of approximately 2 m of snow pack at the site. Of the four systems studied, the sand-bentonite (S-B) system performed best when considering performance indicators such as percolation, interflow (lateral drainage above the barrier), and oxygen diffusion. Unit costs for the as-built S-B cover system without instrumentation were 1.9 and 2.0 times as expensive as the as-built till and the as-built GCL cover systems, respectively. Hydraulic modeling for the cover systems based on the performance results is currently in progress and results are not included in the following summary. Advantages and drawbacks of the four cover systems are summarized below:

**Control System - Do nothing option (leave PAG tailings covered with sand and gravel only):**

- If tailings were to be left unmitigated, ARD generation is predicted, because 1) tailings were classified as potentially acid generating (SRK, 2001), 2) both oxygen and water are available for oxidation, 3) the matric suction was higher than the tailings’ AEV, and 4) the measured oxygen concentrations indicated sufficient oxygen for oxidation down to a depths of 0.6 to 0.7 m.
S-B Cover System:

- The S-B cover system has potential to reduce oxygen ingress and limit percolation, because 1) achievement of low enough $D_e$ seems feasible, 2) freeze-thaw susceptibility is low, 3) a low hydraulic conductivity is achievable, and 4) the AEV for S-B was approximately 30 kPa higher than the maximum measured matric suction in the S-B barrier. However, drawbacks of a S-B barrier are labour-intensiveness in installation and high construction cost (the as-built S-B system was approximately twice as expensive as the till and GCL cover systems). Also, failures of S-B bottom liner systems have been reported (Chapius, 1992; Wong and Haug, 1991).

- Other methods that do not rely on the measurement of the electrical permittivity to infer soil moisture should be investigated, if a S-B barrier system were to be selected as a final cover system for the PGP site. Frequency domain reflectometry (FDR) and time domain reflectometry (TDR) devices should be avoided or only used with temperature correction for S-B mixtures.

- It should be investigated whether more cost-effective methods of preparing and installing an S-B mixture are suitable for the PGP site.

Till Cover System:

- Prior to making any decision on whether to select till as a barrier material, apparently conflicting results of Diviner® 2000 soil moisture measurements and matric suctions should be addressed.

- Use of the ‘as-is PGP till’ to limit oxygen ingress to below 50 g/m²/year would require a 9-m thick layer assuming that the effective diffusion coefficient, $D_e$, is equal to $5.6 \times 10^{-8}$ m²/s. A thinner till layer than that may be used if $D_e$ can be reduced for example by compacting the till close to its optimum water content for compaction or keeping the till saturated at all times.

- Use of PGP till as barrier material in a final soil cover system would require several modifications. To protect the till from freeze-thaw effects, it should be covered with a frost protection layer even if the till did not freeze under the current climatic conditions, as global warming may lead to a thinner snowpack with less insulating capacity. For compaction of the PGP till close to its optimum water content, it would have to be dried and large rocks and woody and other debris should be removed prior to compaction.

GCL Cover System:

- The as-built GCL cover system would have to be upgraded to act as an effective oxygen diffusion barrier, for example, by ensuring that the diffusive path length is increased and that the GCL(s) stay(s) saturated at all times.

General Recommendations

It is recommended to confirm effective oxygen diffusion coefficients of the barrier materials in a separate and independent study. It is recommended to continue test plot monitoring with installed automatic monitoring equipment as long as possible to obtain a more comprehensive database. However, continued monitoring should not delay closure activities for the TSF at the PGP site. Monitoring data should be periodically interpreted to update performance results.
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REFERENCES


Table 1. Test Plot Layering and Construction Costs

<table>
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<tr>
<th>PARAMETER</th>
<th>S-B Cover System</th>
<th>TILL Cover System</th>
<th>GCL Cover System</th>
<th>CONTROL Cover System</th>
<th>TOTAL COSTS</th>
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<td>0.5 m S&amp;G</td>
<td>0.3 m S&amp;G</td>
<td>0.3-0.4 m S&amp;G</td>
<td>0.5 m S&amp;G</td>
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<tr>
<td></td>
<td>0.6 m S-B geotextile</td>
<td>0.8 m till geotextile</td>
<td>0.1 m S&amp;G</td>
<td>0.1 m S&amp;G GCL</td>
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<tr>
<td></td>
<td>0.75 m tailings geotextile</td>
<td></td>
<td>0.75 m tailings geotextile</td>
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<tr>
<td>Construction Costs:</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Instrumentation Costs ($)</td>
<td>$17,400</td>
<td>$17,400</td>
<td>$17,400</td>
<td>$17,400</td>
<td>$69,600</td>
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<tr>
<td>Instrumentation Installation Costs ($)</td>
<td>$3,000</td>
<td>$3,000</td>
<td>$3,000</td>
<td>$3,000</td>
<td>$12,000</td>
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<tr>
<td>Test Pad Construction Costs($)</td>
<td>~$6,500</td>
<td>~$6,500</td>
<td>~$6,500</td>
<td>~$6,500</td>
<td>~$26,000</td>
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<tr>
<td>Test Plot Construction Costs ($)</td>
<td>$22,730</td>
<td>$7,830</td>
<td>$7,840</td>
<td>$5,800</td>
<td>$44,200</td>
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<tr>
<td>General Equipment Costs ($)</td>
<td>$2,000</td>
<td>$2,000</td>
<td>$2,000</td>
<td>$2,000</td>
<td>$8,000</td>
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<tr>
<td>Cost Savings ($)</td>
<td>$12,800</td>
<td>$12,800</td>
<td>$12,800</td>
<td>$12,800</td>
<td>$51,200</td>
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<tr>
<td>Incidentals ($)</td>
<td>$880</td>
<td>$880</td>
<td>$880</td>
<td>$880</td>
<td>$3,520</td>
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<tr>
<td>Tailings Curtain ($)</td>
<td>$470</td>
<td>$470</td>
<td>$470</td>
<td>$470</td>
<td>$1,880</td>
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<tr>
<td>Total Construction Costs</td>
<td>$65,780</td>
<td>$50,880</td>
<td>$50,890</td>
<td>$48,850</td>
<td>$216,400</td>
</tr>
<tr>
<td>Test Plot Area (m^2)</td>
<td>165</td>
<td>210</td>
<td>220</td>
<td>160</td>
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<tr>
<td>Grand Unit Costs ($/m^2)</td>
<td>399</td>
<td>242</td>
<td>231</td>
<td>305</td>
<td></td>
</tr>
<tr>
<td>Unit Costs (without instrumentation) ($/m^2)</td>
<td>275</td>
<td>145</td>
<td>139</td>
<td>178</td>
<td></td>
</tr>
<tr>
<td>( \frac{\text{Unit Cost}}{\text{Unit Cost} - \text{Ratio without instrumentation}} )</td>
<td>1.55</td>
<td>0.82</td>
<td>0.78</td>
<td>1.00</td>
<td></td>
</tr>
</tbody>
</table>

Notes:  
S&G Sand and gravel  
S-B Sand and bentonite
Table 2. Grainsize distribution and hydraulic conductivity of PGP soils and tailings

<table>
<thead>
<tr>
<th>Grainsize distribution</th>
<th>Hydraulic conductivity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Sample Size N</strong></td>
<td><strong>MATERIAL</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Tailings</strong></td>
</tr>
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<td></td>
<td></td>
</tr>
<tr>
<td><strong>Average PGP Sand</strong></td>
<td><strong>PGP till</strong></td>
</tr>
<tr>
<td>and Gravel**</td>
<td></td>
</tr>
<tr>
<td><strong>Average Minus 3/4&quot;</strong></td>
<td></td>
</tr>
<tr>
<td><strong>PGP Sand and Gravel</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Average PGP</strong></td>
<td></td>
</tr>
<tr>
<td>Till**</td>
<td></td>
</tr>
<tr>
<td><strong>Average PGP</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Tailings</strong></td>
<td><strong>inferred from runoff and interflow</strong></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Sand &amp; Gravel</strong></td>
<td><strong>Sand &amp; Gravel</strong></td>
</tr>
<tr>
<td>+ 6% Envirogel 8**</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>GCL</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| **Grain Size**         | **% Sand Size**  | **% Silt Size**  | **% Clay Size** |
|                        |                  |                  |                  |
| **D10** (mm)           | 0.7              | 0.5              | 0.0013           |
| **D20** (mm)           | 1.8              | 1.4              | 0.2900           |
| **D50** (mm)           | 5.53             | 3.60             | 1.2750           |
| **C_u = D_{60}/D_{10}**| 8.3              | 6.7              | 27.8             |
| **C_c = D_{20}^2/(D_{10}D_{60})** | 0.94              | 1.04             | 0.90             |
| **Liquid Limit**       |                  |                  |                  |
| **Plastic Limit**      |                  |                  |                  |
| **Plasticity Index**   |                  |                  |                  |
| **USCS Classif.**      |                  |                  |                  |

**Table Notes:**
- **sample size:** N = 3
- **min. of 23 flexible wall tests:** 4.0E-07
- **max. of 23 flexible wall tests:** 7.0E-08
- **inferred from percolation columns:** 1.0E-08 to 2.0E-08
Legend:

- C-, G-, S-, T- => Control Plot, GCL Plot, Sand & bentonite Plot, Till Plot
- D1-D5 => location of Diviner 2000® access tubes (5 per test plot)
- EnviroScan 1, 2 => location of EnviroScan® access tubes (2 per test plot)
- Suction => location of soil suction sensors (4 per profile, 2 profiles per test plot)
- Gas => location of gas assessment profile (5 per profile, 3 profiles per test plot)
- Lysim. => location of suction lysimeters (10 per Control and GCL test plot)
Figure 2. Location of Instrumentation Nests and access tubes

Figure 3. Effective Oxygen Diffusion Coefficients
Figure 4. Field oxygen concentrations in the PGP test plots