PREDICTION OF EFFLUENT WATER QUALITY FROM WASTE ROCK PILES IN A CONTINUOUS PERMAFROST REGION

D. Blowes[1], L. Smith[2], D. Sego[3], L. Smith[1,4], M. Neuner[2], M. Gupton[2], M. Moncur[1], M. Moore[1], R. Klassen[3], T. Deans[5], C. Ptacek[1], A. Garvie[6] and J. Reinson[4]

[1]Department of Earth Sciences, University of Waterloo, Canada

[2]Department of Earth and Ocean Sciences, University of British Columbia, Canada

[3]Department of Civil and Environmental Engineering, University of Alberta, Canada

[4]Diavik Diamond Mines Inc.

[5]FDA Engineering Ltd.

[6]Australian Nuclear Science and Technology Organization

Abstract

Predicting effluent water quality from mine waste disposal facilities is and important aspect of the design and management of mining operations. Development of water quality predictions required in the early stages of mine planning is challenging because of the lack of detailed information on the rock and its weathering characteristics. These predictions require the selection of rock samples that are lithologically and spatially representative of the rock that will be mined, the implementation of a reproducible characterization protocol and the development of a rigorous approach for scaling from laboratory measurements to the field-scale behaviour. At the Diavik Diamond Mine Inc. operation, open pit mining will lead to the construction of two 200 Mt permanent stockpiles of waste rock. Assessing the long-term environmental implications of storing waste rock in regions with continuous permafrost provides unique opportunities and challenges. The Diavik waste rock research program includes the measurement and comparison of waste rock characteristics across a wide range of scales, varying from samples of less than a kilogram to the construction of three large-scale waste rock piles (15 m in height × 60 m × 50 m) to assess the evolution of the hydrology, geochemistry, temperature, and biogeochemistry of the waste rock piles over time. One test pile contains rock with a sulfide content of < 0.04 wt% S, a second test pile contains rock with > 0.05 wt% S and the third pile simulates a cover scenario proposed for closure of the higher sulfide rock piles. Complementary studies involving conventional static and kinetic tests on small test samples have also been initiated.

Introduction

The prediction of the quality of effluent released from mine wastes is a challenging problem that is important to mining companies, government regulators and other stakeholders that are dependent on the quality of receiving water bodies. Predicting the effluent water quality from new mines is particularly challenging because of the limited understanding of the subsurface geology and the small volumes of samples available. Testing protocols, based on laboratory tests conducted on small volumes of rock, have been developed to assess whether a particular waste rock is potentially acid generating. Extending these small scale tests to provide a quantitative estimates of the concentrations of dissolved constituents anticipated in effluent water are less well developed. An assessment of the value of small-scale tests is required if their results are to be applied to predict if and when low quality drainage may be released from field-scale stockpiles. Scaling issues are critical in the cost-effective and reliable prediction of acid mine drainage risks. Understanding the "scale-up" question is important to designing mine-waste disposal facilities and to develop management plans for new and operating mine sites that will protect the environment.

Objectives

The objectives of this study are to (1) describe the physical, geochemical, and microbiological processes affecting the weathering of waste rock in large stockpiles in cold climates, and (2) determine the relationship between laboratory dissolution test results and geochemical behaviour of full-scale sulfide-bearing waste rock stockpiles. This paper up dates and extends Blowes et al. (2006), and describes the construction of test piles, and testing underway to quantify the relationship between weathering rates in laboratory dissolution tests and those in waste rock piles in the field.

Methods

1. Site Description

The Diavik Diamond Mine Inc. is located 300 km northeast of Yellowknife, NT (Fig. 1). Open pit mining will lead to the eventual development of two 200 Mt permanent stockpiles of waste rock to retain the excavated country rock that surrounds the diamond-bearing kimberlite pipes. The country rock consists of granite averaging <0.04 wt.% S and biotite schist averaging >0.08 wt.% S. Both rock types contain low concentrations of carbonate minerals.

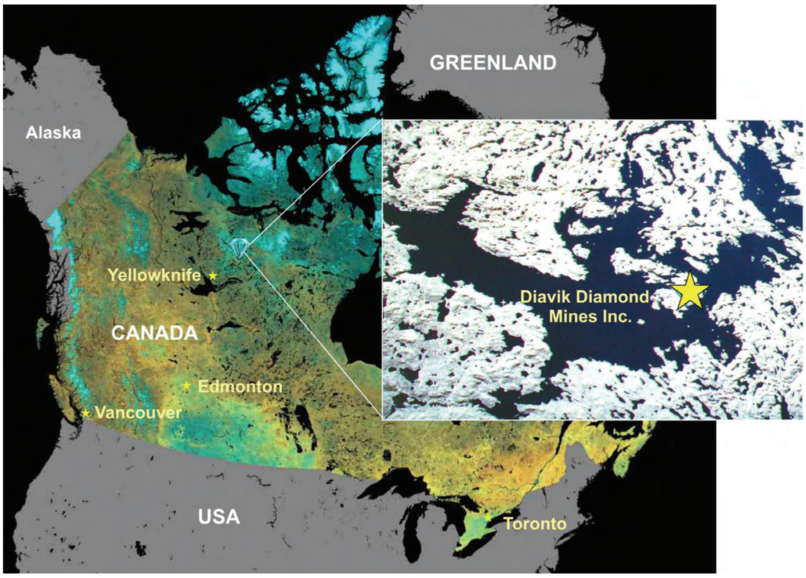

Figure 1. Location map for Diavik Diamond Mines Inc.

2. Experimental Approach

This study includes the construction of two large-scale waste rock piles (15 m in height × 60 m × 50 m) to assess the evolution of the hydrology, geochemistry, temperature, and biogeochemistry of the waste rock piles over time. One test pile contains waste rock with a sulfide content of < 0.04 wt.% S and the other test pile contains rock with > 0.05 wt.% S. A third waste rock pile was constructed to evaluate the cover strategy proposed to prevent the release of dissolved constituents from the waste rock piles.

Each test pile is constructed on an impermeable liner to capture and measure all infiltrating water. During construction of the pile, a comprehensive instrumentation network was installed within the interior of each test pile. Instrumentation includes thermistor strings, gas sampling ports for measurement of gas concentrations and pore gas pressures, soil suction lysimeters, collection lysimeters, time domain reflectance probes, tensiometers, and access ports for thermal conductivity measurements and microbiological sampling.

Humidity cell tests (ASTM, 2000; Lapakko, 2003) Type I (<0.04 wt.% S), Type II (>0.04 >0.08 wt.% S) and Type III (> 0.08 wt.% S) rock samples are underway. These tests will provide measurements of the rate of sulfide oxidation and the rate of release of dissolved metals. Humidity cells use run-of-mine rock sieved to a grain size of less than 1 cm, which is similar to the grain size used in the Diavik baseline environmental program. Three samples of Type I (<0.04 wt.% S_T), three samples of Type II (>0.04 and <0.08 wt.% S) and three samples of Type III (>0.08 wt.% S_T) rock are being tested. Each sample is being tested in duplicate at room temperature (20 °C) and at a temperature representative of field conditions using cold rooms (4 °C). These samples also are being tested in duplicate at each temperature with bacterial inoculation.

3. Analysis of Solids and Leachates

Samples of rock were collected for humidity cell tests and mineralogical study at the initiation of the project in 2004, duplicate samples were collected in 2005, during the early stages of the construction of the test piles. Examination of these samples is underway, using X-ray diffraction (XRD), optical microscopy, secondary electron microscopy (SEM) coupled with energy dispersion X-ray analysis (EDXA). The static test analyses have been conducted on samples split from the humidity cell charges. These tests include paste pH, slurry pH (surface rinse pH), total sulfur, sulfate sulfur, sulfide sulfur, neutralization potential (NP), total carbon (LECO induction furnace), and Net Acid Generation (NAG) testing. Acid base accounting (ABA) was conducted using the Sobek technique (Sobek et al., 1978). Previous studies have indicated that finely crushed rock exhibits greater neutralization potential than coarse-grained samples of the same material (Jambor, 2003). Acid-base accounting tests, using the Sobek technique will be conducted on various grain sizes of materials to assess the relationship between particle size and ABA measurements. In addition to static test analyses, the elemental composition of the rock was determined by whole-rock analysis. At the end of the humidity cell testing, the weathered rock will be re-examined for physical, chemical, and mineralogical characteristics. Surface analytical techniques including X-ray photoelectron spectroscopy (XPS) will be applied.

Figure 2. Photo showing waste rock sampling procedure at the tip face. Four tip faces were be sampled for each pile.

The oxidation of sulfide minerals in mine waste is catalyzed by chemolithotrophic bacteria of the *Thiobacillus* and *Acidithiobacillus* groups. Although *Acidithiobacillus ferrooxidans* is a mesophile (growth occurs from 10 to 35 °C), some isolates have been shown to be capable of growth and iron oxidation at temperatures as low as 2 °C (Leduc et al., 1993). These bacteria may play an important role in the oxidation of sulfide minerals at the Diavik site. Observations made in waste rock piles at the nearby Ekati Diamond Mine indicate that temperatures within the pile decreased rapidly to less than 0 °C, and that low temperatures prevail for most of the year. The viability and activity of sulfide-oxidizing bacteria under these extreme conditions are not well known. To assess the behaviour of bacteria in the test piles, samples of the test pile materials were collected during construction, and will be collected during the monitoring phase and at the end of the experimental period.

Using the samples collected during pile construction, three groups of iron- and sulfur-oxidizing bacteria were enumerated at two different temperatures, 20 °C and 4 °C. The three groups consist of acidophilic iron oxidizing bacteria (*Acidithiobacillus ferrooxidans*), acidophilic sulfur oxidizing bacteria (*Acidithiobacillus thiooxidans*) and neutrophilic sulfur oxidizing bacteria (*Thiobacillus thioparus*). The media compositions, incubation conditions, and enumeration procedure are described in detail in Blowes et al. (1995). The samples analysed at 20 °C and at 4 °C were incubated for one month and four months, respectively, prior to enumeration. Bacterial populations were also enumerated for the humidity cell tests and column leaching experiments following the same procedures as above and will be re-examined at the end of the study.

The leachate from the test piles, humidity cell tests and leaching column experiments are analysed for pH, Eh, electrical conductivity, total dissolved solids, acidity/alkalinity, sulfate, major ions, and trace metals.

Results and Discussion

1. Construction of the Waste Rock Piles

1.1. Pad Construction

The dimensions of the basal pads for the Type 1 and Type 3 test piles are 50 m × 60 m. The basal pad for the Test Cover (TC) pile is 80 m × 125 m. The pads are constructed from waste rock overlain by crushed kimberlite for the Type 1 pile or esker sand for the Type III and the TC pads. Each pad was graded to a 0.5 to 1.5 % slope for the collection of infiltrating meteoric water. To determine the temperature profile in the underlying bedrock, three boreholes were drilled vertically through each pad across the center to a depth of 10 m. Thermistor strings with sensors at 1 m intervals were installed into each borehole. In addition, thermistor strings were laid horizontally in trenches across the pad to record development of the active layer, in which freeze-thaw fluctuation occurs, along with the temperature variation beneath the pile during the changing seasons. A single 10 m borehole was drilled away from the test pads to record the background temperature of the bedrock. After the foundations of the test pads were graded to the design slope, an impermeable high density polyethylene (HDPE) liner was installed so that all water infiltrating to the base of the test pile would be captured, and isolated from the underlying esker sand or crushed kimberlite. For protection during pile construction, geotextile was placed over the HDPE liner followed by a 0.3 m layer of 5 cm minus crush composed of Type I rock (Fig. 3).

Figure 3. Photo to the left shows crushed rock being place over the impermeable liner of the Type I rock pad. Photo to the right shows the positions of the Type I pad (left) and Type III pad (right). The dimension of each pad is 50 m × 60 m. The L-shaped ramp adjacent to the test pads in the foreground will be used to tip rock onto the pads for construction of the waste rock piles. The arrow to the right of the photo is pointing North.

1.2. Basal Drainage System

Infiltrating water is collected from each test pad using 15 cm perforated PVC pipes that contains heat trace, which is regulated to between 2 °C and 5 °C to prevent the water from freezing. The Type I pad and the TC pad were constructed to allow water to collect diagonally along the center of the pad and discharge through the SW and NW corners respectively (Fig. 4). Water flow across the Type III pad is directed from the center of the pad to the perimeter, discharging through the SW and NW corners. Paddle-wheel flow meters and tipping bucket rain gauges are installed to maintain a continuous record of flow from the basal pads.

Figure 4. Photo to the left shows the basal drainage ditch excavated diagonally across the center of the Type I pad exiting through the SW corner. Photo to the right shows the basal drainage ditches excavated around the perimeter of the Type III pad exiting though the SW and NW corners.

1.3. Cluster Lysimeters

Three clusters of different-sized basal lysimeters were placed at the base of the test pads to permit an examination of scale effects in flow variability and solute loadings. Each lysimeter cluster contains two 4 m × 4 m lysimeters and two 2 m × 2 m lysimeters (Fig. 5). The minimum height between the pad of the lysimeter and the top of the lysimeter wall is 0.6 m to prevent wicking effects. Each lysimeter is lined with an impermeable HDPE membrane that drains into a 3.8 cm PVC pipe housed in an insulated pipe. The bottom of each lysimeter pad and the 3.8 cm drainage pipe contains heat trace, which is regulated to between 2 °C and 5 °C to prevent ice buildup on the pad and blockage of the drainage pipes.

Figure 5. Photo to the left shows three lysimeter clusters constructed over the Type III test pad. Loops of wire on the lysimeter pads are heat trace cable. The black 25.4 cm insulated pipe house the 3.8 cm drainage pipes exiting from each lysimeter. The photo to the right shows a completed cluster lysimeters with an impermeable HDPE liner.

Drainage pipes exiting each lysimeter are sloped across the rock pad and feed into a heated instrumentation shack located adjacent to the pads (Fig. 6). Inside the instrumentation shack, water discharging from the basal and cluster lysimeter drainage pipes flows into individual flow-through for geochemical sampling and continuous measurement of pH and electrical conductivity. Water is then directed into tipping bucket rain gauges where discharge is continuously measured. Paddle wheel flow meters are installed on all basal drain systems to measure any flow events that are beyond the tipping bucket range. Water from the tipping bucket rain gauges is then collected in sample containers for subsequent determination of the bulk geochemistry of the drainage from the basal drain. All samples will be analysed for pH, Eh, EC, TDS, acidity/alkalinity, sulfate, major ions, and trace metals.

Figure 6. Photo to the left shows cluster lysimeter drainage pipes directed into the instrumentation shack. The instrumentation shack is situated between the Type I and Type III rock pads. The photo to the right shows lysimeter drainage pipes entering the instrumentation shack.

1.4. Pile Construction

During construction of the waste rock piles, material was pushed or tipped outward from the top of the ramp (see Fig. 3, photo to the right) onto and across the basal pads. Four tip faces were instrumented with thermistors, soil suction lysimeters, tensiometers, gas sampling ports, time domain reflectance (TDR) probes and access ports for thermoconductivity profiling and microbiological sampling (Fig. 7). In addition to instrumentation on the tip faces, four continuously-draining collection lysimeters, each two meters in diameter, will be placed two meters below the top surface of the platform adjacent to the test piles, near the anticipated base of the active zone. Two additional collection lysimeters with vertical sampling ports will be placed in two meters of waste rock and will be capped by till and run-of-mine thermal covers. We plan to deconstruct the Type III test pile in year four or five of this study, to permit internal sampling of waste rock and to observe the spatial characteristics of any ice formation that may develop within the pile.

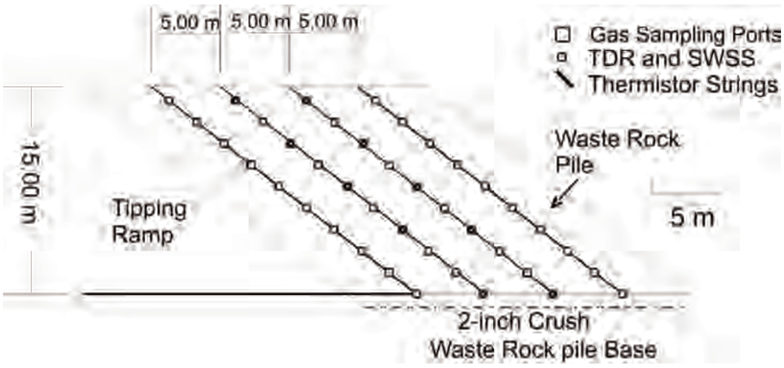

Figure 7. Cross-section of a waste rock pile showing the instrumentation along the tip faces (TDR = time domain reflectance probes and SWSS = soil water suction sampler).

Conclusions

The experiments described in this paper are designed to provide a rigorous examination of the hydrologic and thermal conditions inside the test piles and to document waste rock weathering observed in both laboratory and field settings. Samples will be subjected to detailed physical, chemical, mineralogical, and microbiological characterization before and after testing. Numerous field samples were systematically collected for these analyses. During field tests, temperature, gas composition, and moisture conditions will be determined with a relatively high degree of spatial and temporal intensity. The reactions occurring will be reflected by (1) analysis of drainage collected at the base of the piles, and (2) analysis of weathered solids upon termination of the experiment. Thus, the reactants, reaction conditions, and reactions occurring in both the small-scale and field-scale tests will be described in detail. The test-pile instrumentation will also provide a detailed description of the spatial and temporal variation of hydrologic conditions within the piles, as well as insight on the distribution of drainage at the base.

The results from this study will quantify the release of acidity, metals, and other solutes from sulfide-bearing mine waste stockpiles in the Arctic environment. Our findings should promote more reliable evaluation of waste rock management systems. Scientific outputs from this project will include the development of a conceptual model of water flow in large, unsaturated piles; understanding the different physical mechanisms leading to cooling of large stockpiles in cold climates, including advective gas flow; a quantitative assessment of the value of small-scale measurements in providing information that can be used in predicting the physical and geochemical behaviour of full-scale sulfide-bearing stockpiles; and rigorous testing of the application of models of physico-chemical processes to full-scale systems by comparing the predictions with field data. The scale-up aspects of the program will contribute to the development of protocols based on a sound scientific understanding of scale relationships. Application of the conceptual models will allow more rigorous predictions of the behaviour of waste rock piles over time spans of many decades, which will be valuable in the assessment of the potential effects of climate change on system response.

Acknowledgements

This research is made possible through funding provided by Diavik Diamond Mines Inc. (DDMI), the Canada Foundation for Innovation (CFI), the Natural Science and Engineering Research Council of Canada (NSERC), the International Network for Acid Prevention (INAP), and the Mine Environment Neutral Drainage (MEND) program. In-kind support provided by Environment Canada is greatly appreciated. We thank Diavik Diamond Mines Inc. and FDA Engineering for their technical support and patience during the construction phase. We appreciate the support and assistance that we have received from G. MacDonald and S. Wytrychowski, Diavik Diamond Mines Inc., throughout the project.

References

ASTM (2000). D5744-96, Standard test method for accelerated weathering of solid materials using a modified humidity cell. In: Annual Book of ASTM Standards, 11.04. American Society for Testing and Materials, West Conshohocken, Pennsylvania, 257-269.

Blowes D.W., Al T., Lortie L., Gould W.D., Jambor J.L. (1995). Microbiological, chemical, and mineralogical characterization of the Kidd Creek mine tailings impoundment, Timmins area, Ontario. Geomicrobiol. J. 13, 13-31.

Blowes D., Moncur M., Smith L., Sego D., Bennett J., Garvie A., Gould D., Reinson J. (2006). Construction of two large-scale waste rock piles in a continuous permafrost region. ICARD, 2006, Proceedings of the Seventh International Conference on Acid Rock Drainage, March 2006, St. Louis, MO, USA.

Jambor J.L. (2003). Mine-waste mineralogy and mineralogical perspectives of acid-base accounting. In: Jambor J.L., Blowes D.W, Ritchie A.I.M. (eds.), Environ. Aspects of Mine Wastes. Mineral. Assoc. Can. Short Course Vol. 31. Ch 6, 117-145.

Lapakko K.A. (2003). Developments in Humidity-Cell Tests and their Application. In: Jambor J.L., Blowes D.W, Ritchie A.I.M. (eds.), Environ. Aspects of Mine Wastes. Mineral. Assoc. Can. Short Course Vol. 31. Ch 7, 147-164.

Leduc L.G., Trevors J.T., Ferroni G.D. (1993). Thermal characterization of different isolates of *Thiobacillus ferrooxidans*. FEMS Microbiology Letters 18, 189-194.

Sobek A.A., Schuller W.A., Freeman J.R., Smith R.M. (1978). Field and laboratory methods applicable to overburdens and mine soils. U.S. Environmental Protect. Agency, EPA-600/2-78-054.