Innovative Mine Waste Management Planning at a Site with Multiple Waste Streams

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ABSTRACT

The Metates Project will exploit a large-scale, low-grade gold-silver-zinc deposit located in west-central Mexico in the states of Durango and Sinaloa. A total of 2.3 billion tonnes of ore and waste rock will be excavated at the mine site in Durango (the Metates site) over a mine life of 25 years. The ore will be crushed and sulfides floated, resulting in a concentrate that gets pumped about 120 km to the Ranchito site for additional processing. The concentrate will be pressure oxidized (POX) then cyanide leached to extract the gold and silver. The acidic solution generated in the POX circuit will be neutralized using limestone and lime, resulting in extractable zinc and a significant amount of residue. This process results in significant amounts of four primary waste streams: waste rock and flotation tailings at the Metates site and neutralization residue and cyanide tailings at the Ranchito site. An evaluation of these waste streams was conducted to develop environmentally sound and practical management strategies.

One testing program involved characterizing individual and blended neutralization residue and cyanide tailings. Testing included elemental analysis, acid-base accounting, net acid generation, rinse testing, mineralogy, and humidity cell testing. Additional testing was conducted on various engineered blends to optimize the pH to minimize metals and other constituent leaching from the blended waste material and to evaluate geotechnical stability of the blends.

Results indicate that a blend of neutralization residue, cyanide tailings, and limestone can be designed that has less leaching potential than either of the individual end-member waste materials. The blended residue also has the required characteristics to be geotechnically stable in a dry stack configuration, thereby reducing disturbance and aerial distribution of the waste material.

The resulting operational and closure waste management strategies are more protective of the environment and lower cost than conventional waste facilities for each waste material.

Keywords: closure, metals-leaching, tailings, treatment, blending

INTRODUCTION

The Metates Project is located in northwestern Mexico in the northwestern portion of Durango State, some 160 km northwest of the city of Durango and 175 km north of the coastal resort city of Mazatlan. The Project includes mining of an open pit for 19 years with an additional 6 years of processing, for a total operating mine life of 25 years. Ore will be milled and undergo flotation to produce a bulk sulfide concentrate. The concentrate will be transported via slurry pipeline to the processing site (Ranchito – Figure 1) where the sulfides will be oxidized in a pressure oxidation (POX) circuit prior to cyanidation to recover the gold and silver.

Four primary mine waste streams will be generated; waste rock and flotation tailings at the Metates site, and cyanide tailings (CNT) and neutralization residue (NR) at the Ranchito site. The flotation tailings and waste rock will be co-disposed in a single facility; with the flotation tailings being placed daily in layers, over exposed waste rock to limit oxidation of the waste rock during operations. At the Ranchito site, the two waste streams are to be blended together and placed as a paste in a tailings facility, taking advantage of the neutralizing capacity of the CNT to achieve an optimal paste pH such that metals (and other constituent) mobility is optimized. The blend will also take advantage of the geotechnical character of the NR to minimize infiltration and impacts to the environment.

This paper presents laboratory testing results from the CNT and NR materials which were conducted to identify management options including material blending opportunities.

METHODOLOGY

CNT and NR materials have been generated as part of ore processing development at various phases of feasibility to maximize recovery and reduce processing costs. As of September, 2014, two sets of materials have been generated, and a third set is proposed for early 2015. Results are presented for the first set of materials and some preliminary results for set 2.

The goal of the program is to develop a strategy to manage these waste streams to minimize the potential impacts to the environment while keeping operational costs low, and to design a system that will evolve seamlessly into a robust closure plan and design. Design objectives include:

- Using only a single facility for both waste streams
- Minimizing acid rock drainage and metals leaching
- Minimizing the footprint and disturbance
- Maximizing clean runoff and minimizing contact water quantity
- Minimizing infiltration of precipitation
- Maintaining the ability to execute concurrent reclamation
- Minimizing cost of construction, operations, maintenance, treatment, and closure.

Waste streams were evaluated separately and as a blended product to identify potential opportunities for improving the environmental and geotechnical behavior of the ultimate, placed material and to optimize the placement methodology. The waste material testing included:

- Acid base accounting (ABA) (ASTM D2492-02) (Sobek, 1978).
- Multi-element analysis (MEA) - EPA Method 3050 aqua regia digestion (USEPA, 1992a), and finish method 6010B (USEPA, 1994)

- Rinse testing including synthetic precipitation leaching procedure (SPLP - EPA Method 1312, USEPA, 1996), and shake flask extractions (SFE – ASTM D3987 – 85) and toxicity characteristic leaching procedure (TCLP – EPA Method 1311, USEPA, 1992b)
- Humidity cell tests (HCTs) - ASTM D5744-07 (2007)
- Lime titration
- Mineralogy

A CNT/NR blended tailings sample was titrated with lime (CaO) to raise the pH of the material in steps and develop a dosing curve for the material. A set of 11 samples was then generated at 0.2 pH shifts and sent for additional SPLP testing to evaluate the effect of material paste pH on constituent mobility. The resulting SPLP pH values suggested kinetic/aging effects. Based on this information, an additional blend was generated and analyzed at regular time intervals for mineralogy.

An additional blend of CNT and NR was generated and allowed to rest. A sub-sample of the blend was collected at selected time intervals and analyzed by x-ray diffraction (XRD) to determine the changes in mineralogy that occurs in the sample through time.

RESULTS AND DISCUSSION

Acid Base Accounting

The CNT have 5.5 percent total sulfur, of which 1.63 percent is sulfide. The paste pH value was 9.5. No NAG pH was tested on this sample. The neutralization potential (NP) to acid potential (AP) ratio (NPR) and the net neutralization potential (NNP) are reported well above the potentially acid generating (PAG) cutoffs suggesting the sample is non-PAG. HCT results indicate a pH of 7.44 after 28 weeks with measureable alkalinity (approximately 11 mg/L). 1,040 mg/L sulfate was being produced on the last week of the HCT.

The NR has 13.99 percent total sulfur, but the amount of sulfide sulfur is low at 0.35 percent. The paste pH is 7.9, but despite the low sulfide sulfur, both the NPR and NNP suggest the material may be PAG due to a low NP. Humidity cell data, however, indicate a steady pH of about 7.5 after 28 weeks and consistent production of alkalinity between 15 and 20 mg/L, indicating this sample is non-PAG.

Multi-element Analysis

Not surprisingly, the CNT are the most highly enriched with respect to metals (and other constituents). The CNT are, relative to crustal abundances, elevated in Mo, Pb, Cu, Ca, Cd, Bi, and As. Values of As, Sb, Bi and Pb are three orders of magnitude higher than average crustal values. These materials are depleted in Al, Mg, Na, K and Mn (up to two orders of magnitude compared to crustal values).

The NR is elevated in Cd, S, Ca, and Zn relative to the upper crustal values. Concentrations of As, Cd and S are over three orders of magnitude higher than crustal abundances. They are depleted in P, Na, Al, and K.

Rinse Testing

Results of the SFE tests are summarized in Table 1 and show the CNT, NR, and blended material rinsate chemistries (one test each). Data indicate that the major chemistries of the CNT and NR are very similar and that the blended material rinsate major ion concentrations are typically very similar to the end members; however, the metals and other ion concentrations tended to shift to be either greater or less than the range defined by the end member concentrations rather than in between. The orange cells in Table 1 are those constituent concentrations in the blend that are outside the range and higher, while the blue shaded cells represent those in the blend that are outside the range and lower.

The resulting blend pH is between the two end members, but the effect of this pH change is to shift constituents' solubility. This results in changes in constituent mobility with a relatively small change in the pH; some increasing, while others decreasing. Of those constituents with significant change, with a Mexican water quality standard, all decreased in the blend rinsate relative to the end members except for Cd.

Humidity Cell Tests

The NR HCT had an elevated first flush of sulfate from about 3,300 mg/L to just under 2,000 mg/L, at which point the sulfate concentration stabilized for about 8 weeks (Figure 1). Sulfate then declined to under 1,000 mg/L for about 6 weeks then rose and stabilized at 1,500 mg/L for the remainder of the test; likely in equilibrium with gypsum in the sample. The pH remained very stable, between 7 and 8 for the entirety of the test. Alkalinity was also stable at around 20 mg/L. No net acidity was generated during the test.

The HCT leachate for CNT indicated a relatively high initial sulfate concentration (8,160 mg/L), followed by a steady decline, asymptotically approaching 1,000 mg/L (Figure 2). The pH was in the 9 to 10 range during the first 12 weeks of the test and then declined to between 7.5 and 9 in the second half of the test. The alkalinity started at just above 200 mg/L and declined to stabilize between 10 and 20 mg/L through the test. No net acidity was generated.

Titrations and Mineralogy

Figure 3 shows the original titration results for the blended material from the bench measurements (bench paste pH). The titration curve shows a regular and linear trend. However when the subsequent individual samples were generated and sent for SPLP testing, the resulting pH values were much lower than the original pH values and much less linear.

Table 1 - SFE results summary
(orange shading indicates an increase in concentration relative to the end members; blue indicates a decrease)

Parameters	Units	Instrument/Method	Reportable Detection Limit	NR	CNT	NR/CNT Blend
Wt. of sample used	g	Weighing balance	0.01	50	70	50
Volume of DI water used	ml	Graduated Cylinder	0.01	1000	1400	1000
Final pH (18h)		pH Meter	0.5	7.90	9.7	9.09
Electric Conductivity (18h)	µS/cm	Conductivity Meter	0.5	3370.0	3380	2650.0
Acidity (pH 4.5)	mg/L	PC Titrator	0.5	<0.0005	<0.5	<0.0005
Acidity (pH 8.3)	mg/L	PC Titrator	0.5	3.2	<0.5	1.9
Alkalinity (Total)	mg $CaCO_3$/L	PC Titrator	0.5	28.9	29	14.1
Bicarbonate (HCO_3)	mg HCO_3/L	PC Titrator	0.5	35.2	21	17.3
Carbonate (CO_3)	mg CO_3/L	PC Titrator	0.5	<0.0005	6.8	<0.0005
Hydroxide (OH)	mg OH/L	PC Titrator	0.5	<0.0005	<0.5	<0.0005
Sulphate (SO_4)	mg/L	UV-Vis.	5	1710	1760	1530
Chloride (Cl)	mg/L	IC	0.5	4.3	7.0	1.8
Fluoride (F)	mg/L	SIE	0.01	0.10	0.10	1.50
Dissolved Analytes by ICP-MS						
Aluminum (Al)	mg/L	ICP-MS	0.001	0.005	0.007	0.099
Antimony (Sb)	mg/L	ICP-MS	0.0001	0.0169	0.0152	0.0013
Arsenic (As)	mg/L	ICP-MS	0.0001	0.118	0.130	0.004
Barium (Ba)	mg/L	ICP-MS	0.0001	0.0638	0.0736	0.0576
Beryllium (Be)	mg/L	ICP-MS	0.00005	<0.00005	<0.00005	<0.00005
Bismuth (Bi)	mg/L	ICP-MS	0.00003	<0.00003	<0.00003	<0.00003
Boron (B)	mg/L	ICP-MS	0.3	<0.3	<0.3	<0.3
Cadmium (Cd)	mg/L	ICP-MS	0.00003	<0.00003	<0.00003	0.00008
Calcium (Ca)	mg/L	ICP-MS	0.3	557	539	554
Cesium (Cs)	mg/L	ICP-MS	0.0003	0.0004	0.0005	0.0037
Chromium (Cr)	mg/L	ICP-MS	0.0005	0.0247	0.0272	0.0061
Cobalt (Co)	mg/L	ICP-MS	0.00003	0.00139	0.00139	0.00039
Copper (Cu)	mg/L	ICP-MS	0.0003	0.0085	0.0174	0.008
Iron (Fe)	mg/L	ICP-MS	0.005	0.207	0.248	0.032
Lanthanum (La)	mg/L	ICP-MS	0.0003	<0.0003	<0.0003	<0.0003
Lead (Pb)	mg/L	ICP-MS	0.00003	0.00004	0.00005	0.0001
Lithium (Li)	mg/L	ICP-MS	0.003	<.003	<0.003	14
Magnesium (Mg)	mg/L	ICP-MS	0.3	1.17	0.7	24.8
Manganese (Mn)	mg/L	ICP-MS	0.0003	<0.0003	<0.0003	2.2
Molybdenum (Mo)	mg/L	ICP-MS	0.0003	0.0176	0.0171	0.0223
Nickel (Ni)	mg/L	ICP-MS	0.0001	0.0001	0.0002	0.0007
Phosphorus (P)	mg/L	ICP-MS	0.01	0.028	0.02	0.043
Potassium (K)	mg/L	ICP-MS	0.3	172	168	46.7
Rubidium (Rb)	mg/L	ICP-MS	0.0003	0.301	0.274	0.137
Selenium (Se)	mg/L	ICP-MS	0.0002	0.0024	0.0025	0.0026
Silicon (Si)	mg/L	ICP-MS	0.5	5.73	5.9	0.688
Silver (Ag)	mg/L	ICP-MS	0.00003	0.00162	0.00265	0.00024
Sodium (Na)	mg/L	ICP-MS	0.3	163	165	41.6
Strontium (Sr)	mg/L	ICP-MS	0.0003	0.418	0.398	0.34
Tellurium (Te)	mg/L	ICP-MS	0.0001	<0.0001	<0.0001	<0.0001
Thallium (Tl)	mg/L	ICP-MS	0.00001	0.00251	0.00329	0.00127
Thorium (Th)	mg/L	ICP-MS	0.00003	<0.00003	<0.00003	<0.00003
Tin (Sn)	mg/L	ICP-MS	0.00005	<1	<0.00005	<1
Titanium (Ti)	mg/L	ICP-MS	0.003	<3	<0.003	<3
Tungsten (W)	mg/L	ICP-MS	0.00005	0.00024	0.00023	0.00014
Uranium (U)	mg/L	ICP-MS	0.00001	<0.01	<0.00001	<0.01
Vanadium (V)	mg/L	ICP-MS	0.001	<0.001	<0.001	<0.001
Zinc (Zn)	mg/L	ICP-MS	0.0005	<0.0005	<0.0005	0.0063

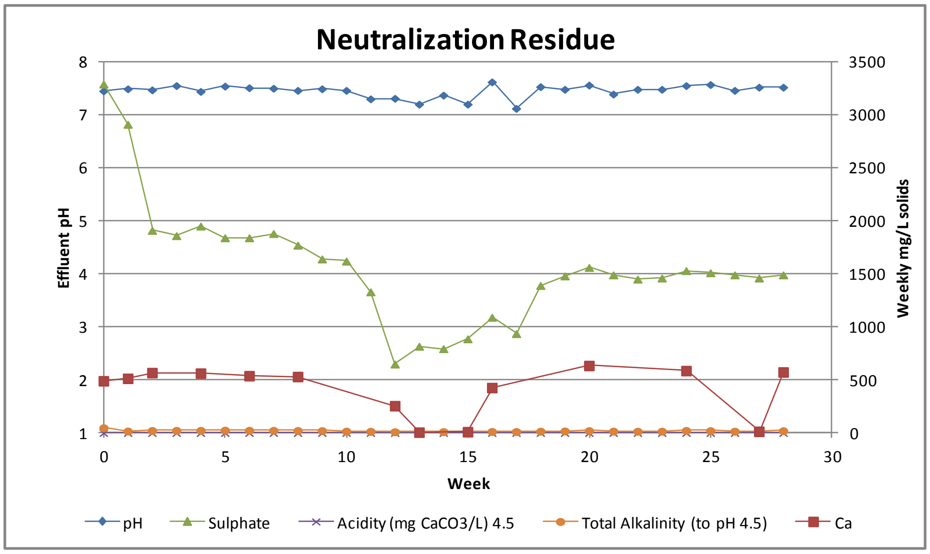

Figure 1 - NR HCT Results

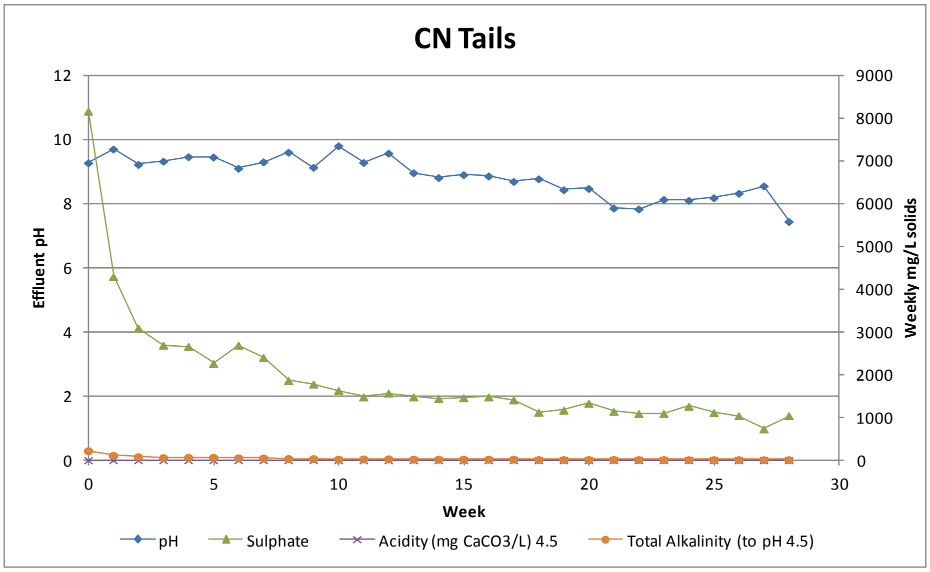

Figure 2 - CNT HCT Results

The difference noted between the bench titration and the SPLP suggests that the samples evolved chemically through time and consumed alkalinity, lowering the pH. Figures 4 and 5 show the major and trace analyte concentrations. Major ions were generally constant over the range of pH values tested in the SPLP except for aluminum concentration, which increased with increasing pH, and iron, which varied between 0.04 mg/L and 0.18 mg/L. Trace analytes were also largely below detection and somewhat insensitive to the relatively small change in pH tested by the SPLP. Arsenic increased slightly from 0.0046 mg/L to 0.0076 mg/L, likely reflecting the weaker sorption at higher pH values. Antimony and thallium decreased slightly with increasing pH.

The chemical changes suggested from the titration data were investigated further by aging a blended CNT/NR sample and analyzing samples' mineralogy at increments. Figure 6 shows the mineralogical composition through time. The results indicate that the majority of the material is gypsum, with lesser amounts of amorphous phases and silicates (predominantly mica and quartz). The quantity of amorphous material decreases from about 27 percent to about 10 percent over the course of 10 days, with a corresponding increase in gypsum content.

The geotechnical characteristics of the blended material that had been aged for only 12 days suggested significantly increased strength (compressive strength increased from 10 kPA to 440 kPa) and low hydraulic conductivity (1x10^{-7} cm/s) is achieved.

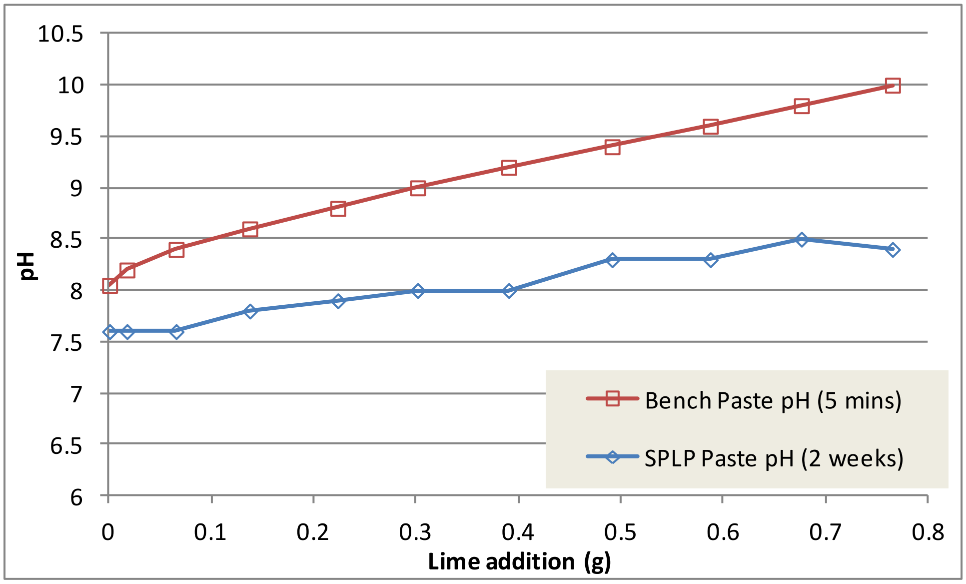

Figure 3 - Lime titration results

DISCUSSION AND IMPLICATIONS FOR MATERIAL MANAGEMENT

NR is a relatively inert material consisting predominantly of gypsum from the neutralization of sulfuric acid by lime in the process.

- NR is considered PAG by ABA because the net neutralization potential is -5.7 and NPR is 0.5, however sulfide sulfur is only 0.35 percent of the total 13.99 percent total sulfur so acid production is expected to be low or unlikely. Paste pH is 7.9.
- HCT data show that the final pH of the NR is 7.52 after 28 weeks with no acid generation. Elevated amounts of sulfate were generated, but this is likely due to the high gypsum content of the material.
- Multi-element analyses by aqua regia show this material is elevated in 9 metals over crustal abundances (at least four times crustal abundance) including sulfur.
- Rinsate chemistry has a circumneutral pH, and is a calcium-sulfate type with generally low-to moderate metal and metalloid concentrations.

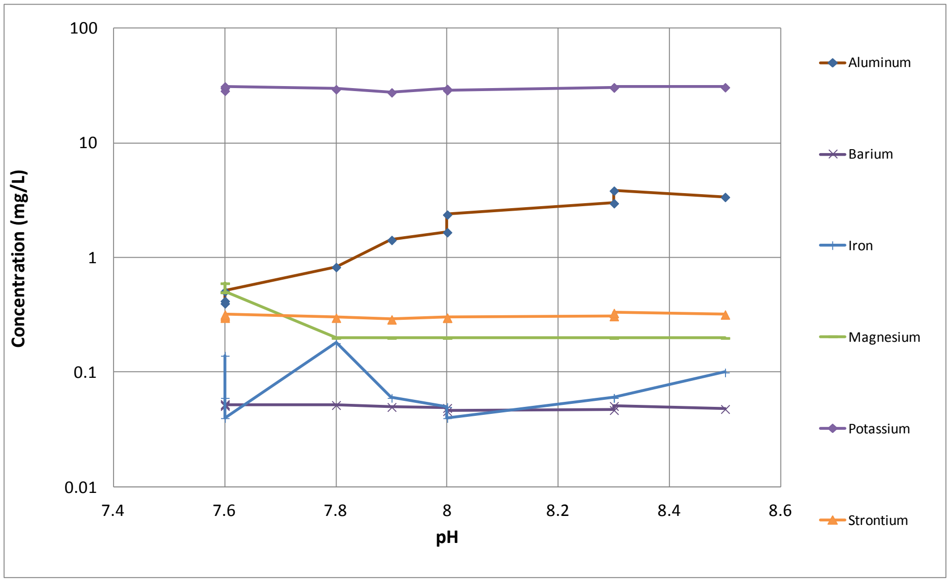

Figure 4 – Major analyte concentrations in SPLP extract

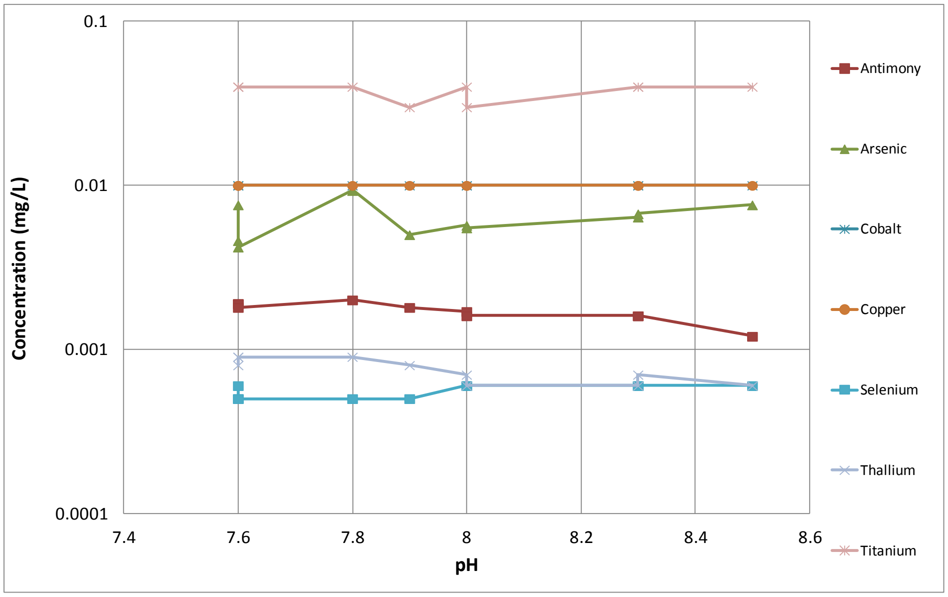

Figure 5 – Minor and trace analyte concentrations in SPLP extract

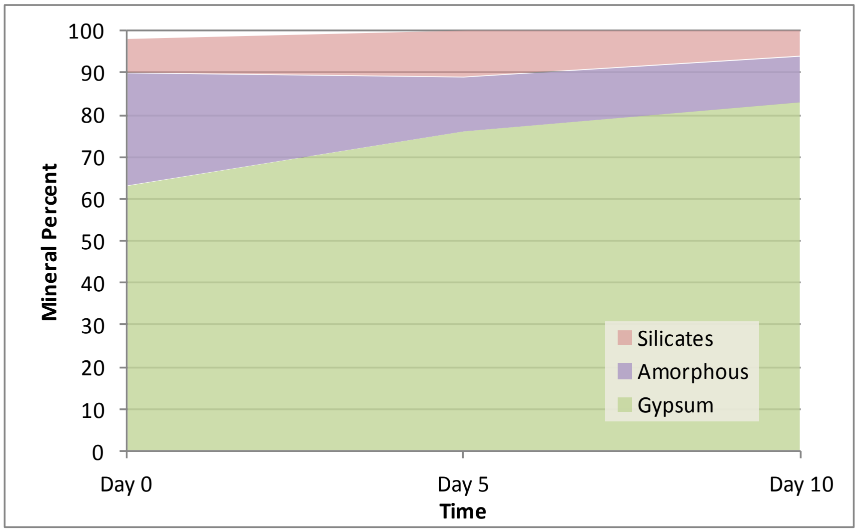

Figure 6 - Evolution of mineralogy through time of NCT/NR blend

CNT are generally alkaline due to the lime addition during the process, with some elevated metal and metalloid concentrations in leach and rinse testing. CNT have the following characteristics:

- CNT are considered non-PAG by ABA testing because NNP is 48.2 and NPR is 1.9. Paste pH is 9.5.
- While total sulfur is 5.5 percent and sulfide sulfur is 1.63 percent, the material does not exhibit acid production in HCT. Final pH was 7.44 after 28 weeks.
- Multi-element analysis indicates this material is elevated in 9 metals over crustal abundances (at least three times crustal abundance) including sulfur.
- Rinsate has an elevated pH (9.7) but a similar major ion chemistry as the CNT with a calcium-sulfate water type.

The CNT/NR blended material is geochemically stable with a circumneutral pH and low metal/metalloid leaching potential:

- Blended material had an NNP of 20.5 and an NPR of 3.2 which would categorize this material as non-PAG. Paste pH was 8.3.
- Total sulfur was 11.26 but the sulfide sulfur was 0.29. Because of this, acid generation is very low or negligible.
- Multi-element analyses by aqua regia show this material is elevated in 11 metals over crustal abundances (at least four times crustal abundance) including sulfur.
- Rinsate has an elevated pH (9.1) and was a calcium sulfate water type but constituent concentrations tended to shift (either up or down) compared to the CNT and NR.

Rinsate constituents from the CNT/NR blend generally show non-linear relationship (i.e., concentrations are not showing conservative behavior). For example, iron concentration declined to 0.032 mg/L from 0.21 and 0.25 mg/L (NR and CNT, respectively). Speciation modeling using PHREEQC (Parkhurst, 1995) indicates that all three waters are supersaturated with respect to various iron oxy-hydroxide phases (e.g., goethite), but that the blend was less supersaturated. This suggests that iron oxy-hydroxide precipitation occurred in the blended material, providing sorption substrate for various other metals/metalloids in the process. Modeling results also suggests that the rinsate waters were kinetically unstable (relatively labile phases were indicated as being supersaturated) indicating that additional aging of the samples could result in significant mineralogical maturation and environmental behavior. These processes will continue to be investigated in ongoing studies.

Overall, data suggest the blended CNT/NR material will be a physically and chemically stable product that will be suitable for long-term storage. The blended material has physical and chemical properties that have environmental and geotechnical benefits which outperforms either end-member material. The material matures quickly resulting in a high-strength, low permeability material that is easily handled as a dry-stacked material, resulting in more streamlined operational management and lower risk environmentally both during operations and closure. Material can be blended at the run-of-mine production rates and placed in a single facility, with the high gypsum content acting to encapsulate and reduce metals mobility in the material. No acid generation and only minor metals leaching is expected from the material. Some elevated sulfate concentrations may require limited water management but will generally be suitable for reclamation using standard best engineering and closure practices.

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