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Assessment of chemical stability of Mount Nansen tailings: Column Study

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EXECUTIVE SUMMARY

In the Fall of 2001, the Mining and Mineral Sciences Laboratory (MMSL) initiated a study to assess the chemical stability of impounded tailings at Mount Nansen, Yukon Territory on behalf of Indian and Northern Affairs (INAC). As part of this study, a field investigation program was conducted in November 2001 to assess the site conditions, collect tailings core samples from the current tailings impoundment, sample the pit water, the tailing porewater and the seepage water. The tailings samples brought to Ottawa were subjected to a variety of scientific tests, including column testing to study the release of cyanide and its related species as well as metals. In December 2001, eight columns were set up to simulate following four disposal scenarios (in duplicate): the sulfide tailings under a water cover, the oxide silt tailings under a water cover, the mixed tailings (sulfide/oxide) silt tailings under a water cover and the mixed tailings in flow through conditions. This report summarizes the results of the columns monitoring study for the period December 2001 to January 2003.

The column study demonstrates that total cyanide (CN), thiocyanate (CNS), ammonia-nitrogen (NH_4-N), arsenic (As), manganese (Mn) and possibly antimony (Sb) may be released from the tailings. Sulfide tailings in general released total CN, WAD CN, CNS, and NH_4-N at the column base at higher concentrations compared to oxide and mixed tailings under water cover and mixed tailings in flow through conditions. WAD CN was not released in the water cover and in the porewater of sulfide, oxide and mixed tailings under a water cover. The results suggest that NH_4-N release is likely to continue even after the CNS release is complete. Oxide rich silt tailings are likely to release higher amounts of As, Mn and possibly Sb compared to sulfide silt tailings. However, As and Sb release has not been observed in the current tailings impoundment seepage water. The storm scenario in flow through columns showed that the leaching rates for the parameters of interest will be in the following decreasing order: SO_4 > CNS > NH_4-N > As > Sb > Zn > Cu. Total CN, WAD CN, CNS and NH_4-N are likely to continue leaching from the current tailings impoundment. If the tailings were to be relocated to the open pit, moving the tailings in a relatively dry form may likely have a less significant impact on the water cover quality than transfer of tailings as slurry.

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1.0 PROJECT BACKGROUND

In the Fall of 2001, CANMET-MMSL initiated a study to assess the chemical stability of impounded tailings at Mount Nansen, Yukon Territory under contract from INAC. As part of this study a field investigation program was conducted in November 2001 to assess the site conditions, collect tailings core samples from the current tailings impoundment, sample pit water, tailing porewater and seepage water. The samples collected in the field investigation program were brought to Ottawa for further testing. The tailings samples brought to Ottawa were subjected to a variety of scientific tests including column testing to study the leaching of cyanide and its related species as well as metals. The results of the tests conducted during the period from November 2001 to March 2002 including the column study results were presented in a report entitled “Assessment of chemical stability of impounded tailings at Mount Nansen, Yukon Territory” by Kwong et al. 2002.

In December 2001, eight columns were set up to simulate four disposal scenarios (in duplicate) such as: sulfide tailings under a water cover, oxide silt tailings under a water cover, mixed tailings (sulfide/oxide) silt tailings under a water cover and mixed tailings in flow through conditions. Upon a review of the results obtained from the columns study for the period December 2001 to February 2002, it was decided by INAC to extend the monitoring of the columns for an additional six months. This report summarizes the results of the columns monitoring study for the period December 2001 to January 2003.

2.0 COLUMNS SET – UP AND EXPERIMENTAL DETAILS

Eight plexi-glass columns (15.2 cm inside diameter) were set up (in duplicate) in the week of 3rd December 2001, to investigate the following disposal scenarios:

1. Sulfide silt tailings under a water cover;
2. Oxide silt tailings under a water cover;
3. Mixed (mixture of sulfide and oxide silt tailings) tailings slurried using Brown McDade pit water and placed in the columns with a water cover; and
4. Mixed tailings under flow through conditions.

Only coarse sulfide and oxide silt tailings were used in the columns. Fine clay tailings were not used in the columns due to their low hydraulic conductivity. Sulfide and oxide silt tailings were studied in separate columns to distinctly assess the leaching behaviours of such tailings under water cover as cyanide and related species as well as metals content of their respective porewaters in the tailings impoundment had differing characteristics. Mixed tailings columns were set up to study the leaching behaviour of homogenized tailings mixture under cover. The flow through columns were set up to study the leaching of cyanide and related species as well as metals under storm flushing conditions.

Prior to placing the tailings in the columns, a layer of geo-textile was placed at the base of all of the columns. On top of the geo-textile membrane, a 2.5 cm layer of acid washed (10% HCl solution) quartz with an effective size of 1 mm was placed. The columns were secured on a 45 cm high table. Figure 1 shows the layout of the columns placed on the table with quartz layer overlying the geo-textile. The height of the tailings bed in the columns was approximately 23 to 25 cm. Figure 2 shows the schematic diagram of the column set up. The columns with tailings under a water cover were sampled at the water cover layer, in the pore water layer and at the base of the column. The water cover samples were collected at 5 cm above the water/tailing interface and the pore water samples were collected at 5 cm below the water/tailing interface. Figure 3 shows the water cover, porewater and column base sampling ports. The flow through columns were sampled at the base.

A) B)

Figure 1: A) The layout of the columns, and B) The quartz layer at the base of the column.

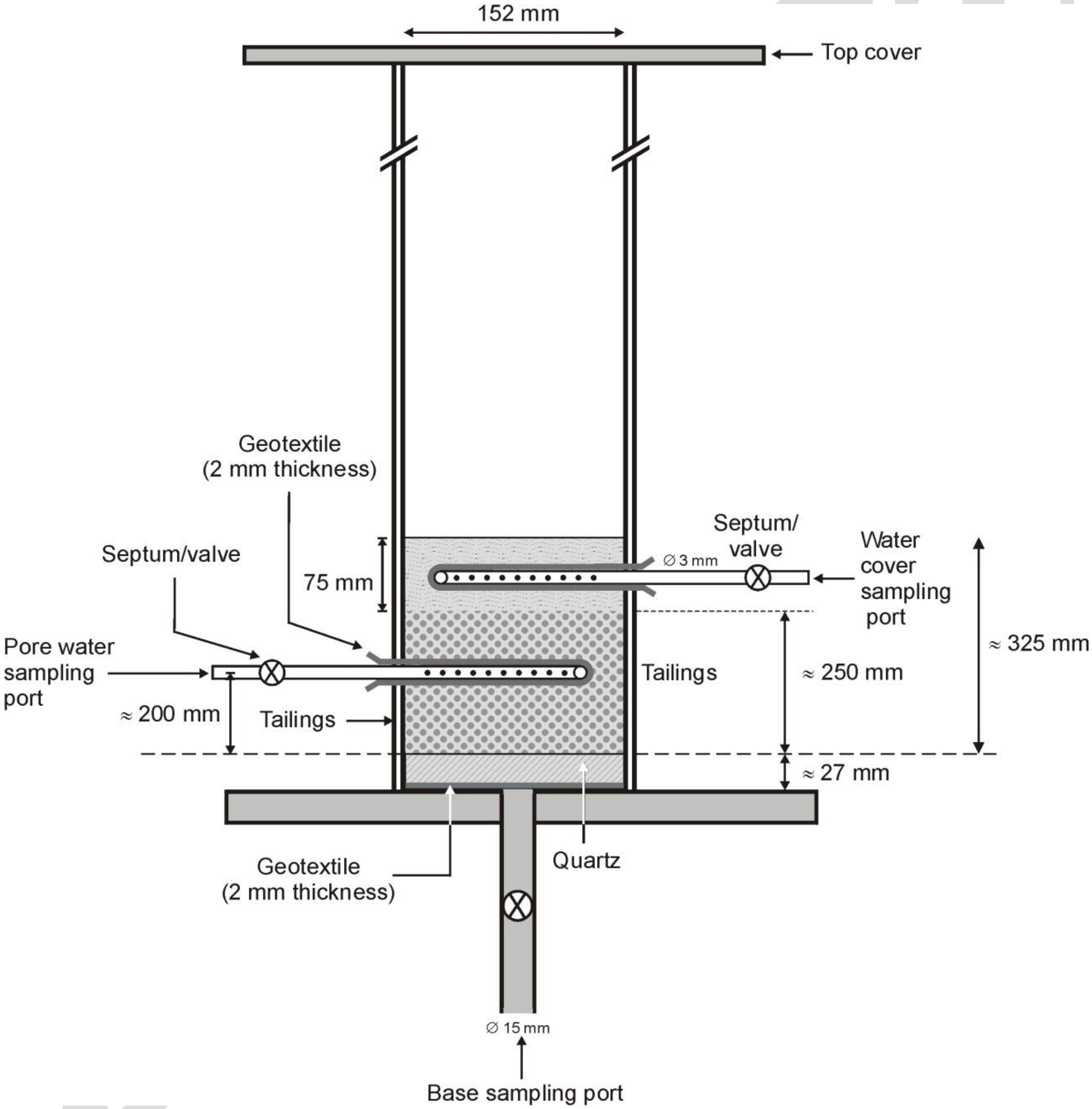
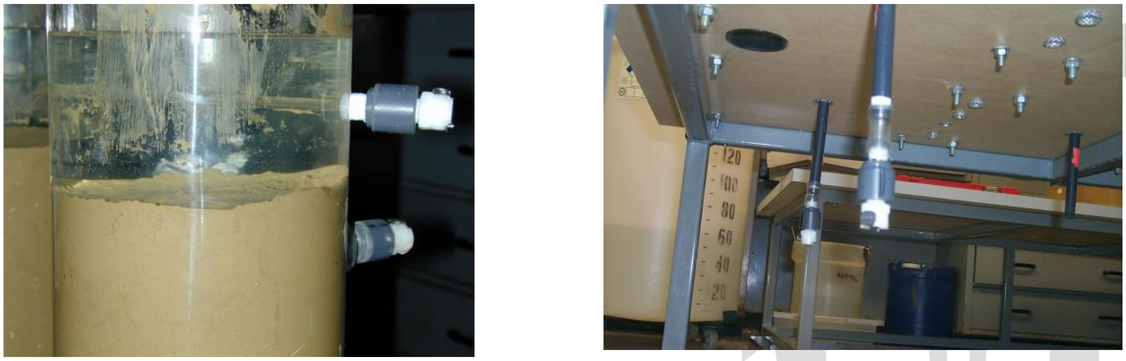


Figure 2: The column set up schematic



A)   B)

Figure 3: A) The sampling port in the water cover and in the tailings for pore water, and B) the sampling ports at the base of the columns.

Coarse tailings were used in the columns. The leaching behaviour of fine tailings was studied using a sequential batch leaching method (Kwong et al, 2002). The coarser tailings were visually inspected and classified as sulfide silt and oxide silt tailings for use in this study. The coarse tailings suitable for the column study was in limited quantity. The sulfide tailings samples from the BH1 – 03, – 04, BH2 – 02, 03, 04, 05, BH 3 – 02, BH 4 – 04, BH 5 – 03, BH 6 – 04, – 06, BH 7 – 07, BH 12 – 02, BH 14 – 03, BH 17 – 01 cores collected from the site in November 2001 (Kwong et al., 2002) were placed in a large bucket and were thoroughly mixed by hand to prepare a composite of the sulfide silt tailings. Similarly, oxide silt tailings from BH 1 – 06, BH 3 –03, BH 15 – 02, 03, and BH 17 – 02 cores collected in November 2001 (Kwong et al., 2002) were used to prepare a composite of oxide silt tailings. Before tailings were placed in the column approximately 0.5 L of Brown McDade pit water was transferred to the columns. The tailings were then placed in 5 to 7.5 cm layers at a time and compacted using a plexi-glass rod to displace air pockets from the tailings bed. When the tailings bed reached the pore water sampling ports, the sampling port were inserted into the columns (Figure 4) and additional tailings were placed on top of the sampling ports to achieve approximately 25 cm of tailings bed. A similar procedure was used for the set up of the columns containing oxide silt tailings. The two sulfide silt tailings columns contained 8.02 and 8.10 kg of tailings. The two oxide tailings columns contained 7.24 and 7.14 kg of tailings. After the tailings were placed in the columns, Brown-McDade pit water was pumped in the columns to obtain a water cover of 7.5 cm. The individual sulfide column required approximately 1400 mL of pit water for 7.5 cm of water cover. The individual oxide column required approximately 1650 mL of pit water for 7.5 cm of water cover.

Figure 4: The sampling port for pore water samples.

The remaining sulfide and oxide tailings were mixed for use in the set up of the additional columns. The mixed tailings were slurried by placing 18.4 kg of tailings in 3.6 L of Brown-McDade pit water. The slurry was then poured into the two columns. The tailings in the columns were allowed to settle and water cover height was adjusted to 7.5 cm. The height of tailings bed in the mixed slurried columns was approximately 25 cm. The sulfide, oxide and mixed columns under the water cover were sampled approximately every four weeks at the water cover, pore water and the base of the column. The sampling event involved collecting 166 mL of water from the water cover, the porewater and the column base for chemical analysis. After collecting the samples, the columns were replenished with an equal volume of the Brown McDade pit water. The Brown McDade pit water sample collected in November 2001 was used for the column set-up/monitoring, it was completely consumed by 17th June, 2002. As a result, after 17th June, the columns were no longer replenished with Brown McDade pit water after the columns sampling event. The water cover served as the source of samples for the subsequent sampling events.

The remaining mixed tailings were used to set up the flow through columns to simulate storm accelerated flushing conditions. Both flow-through columns contained 6.2 kg of mixed tailings each. The tailings bed in the each column was approximately 18 cm. For even distribution of the pit water, a layer of glass wool covered by a filter paper, was placed on the tailings. The Brown-McDade pit water was applied at the top of the tailings layer at the rate of five times the average annual precipitation of 25 cm per year at the Mount Nansen. The Brown McDade pit water was applied at top of the tailings layer twice a week (190 mL each time @ 6 mL/min) and the samples were collected at the base of the columns. As of 23rd May 2002 (day 169) the pit water used in these columns was replaced by deionized water with pH adjusted to pit water pH of 8.2 to 8.3. The water samples collected during the week were mixed together and the composite sample was analyzed for the various parameters.

Figure 5 shows all the eight columns set up to study the four disposal scenarios. The water samples collected were analyzed for pH, conductivity, total and WAD cyanide (CN), thiocyanate

(CNS), cyanate (CNO), ammonium-nitrogen (NH_4-N), nitrate-nitrogen (NO_3-N), nitrite-nitrogen (NO_2-N), sulfate (SO_4), and dissolved metals by ICP AES/MS Metal scan. The sulfide, oxide, and mixed tailings columns with the water cover were sampled ten times with the last sampling occurring on the 6th January 2003. The flow-through tailings columns were sampled a total of thirty-six (36) times with the last sample collected on 27th September 2002.

Figure 5: The eight columns set up to study the four disposal options

On 7th of January, 2003 the columns were dismantled. All the columns were drained and the top portion of the column was cut-off approximately five inches above the surface of the tailings prior to collecting the tailings core samples. For each column, two core samples were collected as shown in Figure 6. The cores collected were then sliced in 2 cm long sections at 2.5 cm below the tailings/water interface and 2.5 cm above the base of the tailing bed. The tailings samples sliced at 2.5 cm below the top from the two cores of a column were mixed and analyzed for total CN. A similar procedure was followed for tailings samples sliced at 2.5 above the base of the tailings bed. The results from the monitoring and sampling of columns are presented in Section 3.0.

A)

B)

Figure 6: A) Core sampling of the columns, and B) the core samples collected.

3.0 COLUMN STUDY RESULTS

Table 1 shows the Ag, Au, C, S and moisture content of the sulfide, oxide and the mixed tailings that were used to pack the columns. The total sulfur content of the sulfide and oxide tailings was 2.81% and 2.14 % respectively. The total carbon content of the sulfide tailings was significantly higher than the oxide tailings. The results obtained from the column study are presented in the following sections.

Table 1: Characteristics of composite tailings samples used in the column study.

Tailings Type	**Ag (ppm)**	**Au (ppm)**	**C (%)**	**S (%)**	**Moisture Content (%)**
Sulfide	24.4	1.34	0.38	2.81	21.2
Oxide	24.7	2.67	0.18	2.14	17.8
Mixed	25.2	2.20	0.34	2.34	20.5

3.1 Sulfide Columns

Figure 7 shows the average pH and conductivity observed in the water cover, porewater and at the base of columns containing sulfide tailings over the experimental period. At the end of the study, the pH in the porewater and at the base of the columns was 8.0 and 7.8. The water cover pH decreased from an initial value of 7.8 to 7.3. The conductivity of the water cover and porewater increased to more than 2000 µS/cm.

Total CN was not observed in the water cover or in the porewater. However, total CN concentration in the water samples collected at the base of the column ranged from 0.053 mg/L on day 16 to a maximum of 1.74 mg/L on day 226 (Figure 8). The total CN leaching at the column base was observed to be lower than the average total CN concentration of 3.9 mg/L observed in the sulfide silt pore water samples collected from the tailings impoundment in November 2001 sampling program (Kwong et al., 2002). WAD CN was not observed in the water cover. At the column base, WAD CN was detected only in samples collected on day 226 at an average concentration of 0.50 mg/L. The CNO was observed in the samples collected in the water cover, porewater and at the base of the column on only two occasions (day 43 and 75). In the porewater and at the base of the column, CNO at maximum concentration of 25 mg/L was observed. In the water cover the CNO concentration was 3 mg/L.

Figure 9 shows the profile of the cumulative amounts of the CNS, NH_4-N, and SO_4 that leached from the sulfide columns at the water cover, the porewater, at the base of the column and the total amounts that leached from the columns. The data shown in Figure 9 was estimated using the following equation:

Cummulative mass (%) leached = $\sum_{i=1}^{n}(C_{wi} \times V_{wi} + C_{pi} \times V_{pi} + C_{bi} \times V_{bi})$

where, C_{wi}, C_{pi}, C_{bi} = average concentration of the chemical parameter of interest in the water cover, porewater and base of a column type respectively on a sampling event i, mg/L;

V_{wi}, V_{pi}, V_{bi} = volume of sample collected from the water cover, the porewater and at the base of the column respectively on a sampling event i (L); and
n = number of sampling events.

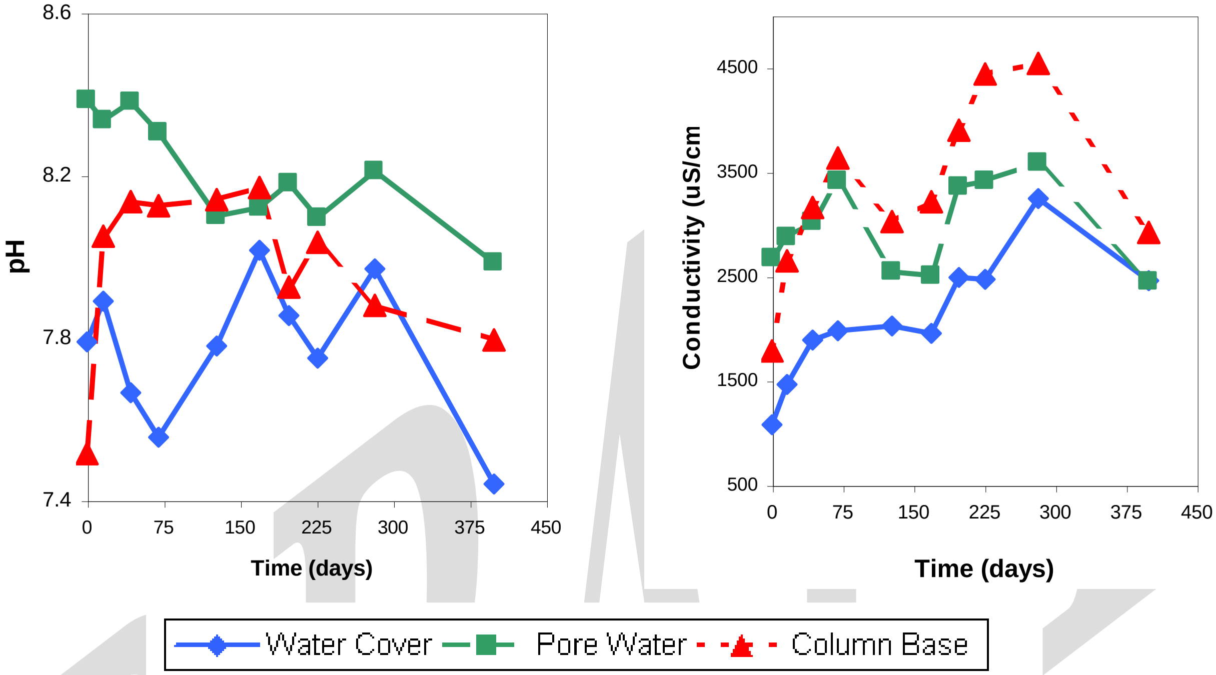


Figure 7: The pH and conductivity profile for sulfide columns.

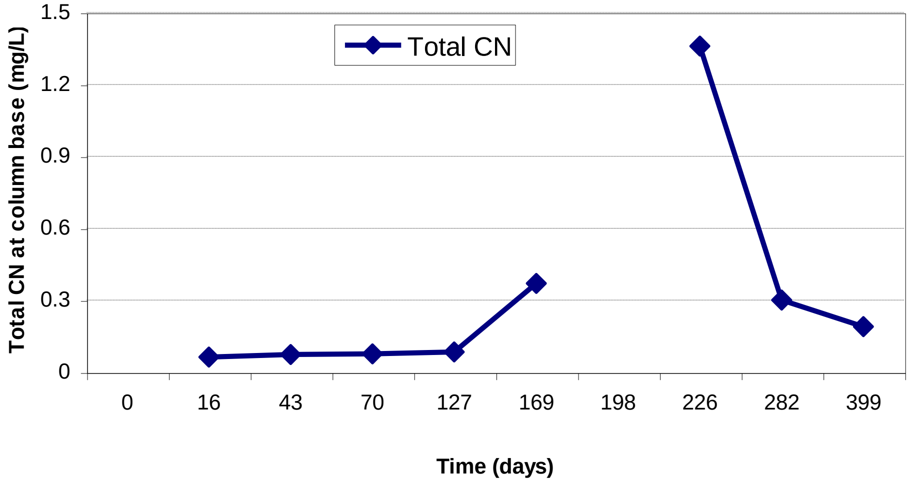


Figure 8: The total CN leaching at the base of the sulfide column with a water cover.

The percentage of the total amount of CNS leached from the column in the water cover, pore water and at the column base was approximately 3.5%, 25 % and 71.5% respectively. The concentration of CNS in the water cover, porewater and column base prior to column dismantling was < 2, < 2 and 37 mg/L respectively. The percentage of NH_4-N leached from the water cover, porewater and at the column base was 16%, 34% and 50% respectively. The initial porewater CNS and NH_4-N concentrations were 167 and 31 mg/L respectively compared to CNS and NH_4-N concentrations of 104 and 32 mg/L observed in the porewater of the sulfide silt samples collected from tailings impoundment in November 2001 (Kwong et al. 2002). In the water cover, the maximum NH_4-N concentration was 17.5 mg/L during initial 127 days. Algae growth in the water cover was observed after 127 days and after that the NH_4-N concentration in the water remained at < 0.8 mg/L. The NH_4-N present in the water cover may have served as a nitrogen source for the algae. The amount of CNS and NH_4-N leaching at the base of the column increased and did not change significantly after day 226. The SO_4 leaching in the porewater and at the column base was higher than that leached in the water cover. Figure 10 shows the CNS, NH_4-N and SO_4 leaching rates observed for the high sulfide columns. The leaching rate was estimated based on the total amounts (µg) of the CNS, NH_4-N and SO_4 leached from the columns. The CNS, NH_4-N and SO_4 leaching rates have decreased with time. The CNS and SO_4 leaching is likely to be influenced by porewater flushing, however NH_4-N leaching in addition to flushing would also be controlled by the degradation rate of cyanide in the columns and release of NH_4-N sorbed on the tailings. The total amount of CNS, NH_4-N and SO_4 that leached during the study from the high sulfide columns was 27.0, 11.4 and 1221 mg/kg of tailings respectively.

Upon columns dismantling, tailings samples were collected at approximately 2.5 cm below the tailings water interface and 2.5 cm above the base of the columns and analyzed for total CN. The initial total CN associated with tailings was 34.5 µg/g of tailings. The average total CN in samples from the top and the base of the columns was 14.9 and 23.1 µg/g respectively. Based on the average of total CN in the samples at the top and at the base, approximately 55% of the total CN was released from the tailings. Total CN was not released to a significant degree in the aqueous phase as the total CN was present only in the samples collected at the column base at concentrations not exceeding 1.74 mg/L. It is likely that the total CN associated with the tailings was released via formation of CNS or microbial mediated natural degradation to CNO that was subsequently degraded to NH_4-N or through volatilization as HCN. Table A1 (in appendix A) provides the raw water chemistry data for the samples collected from the high sulfide columns.

The NO_2-N concentration in general was below the detection limit. The NO_3-N was not present in the porewater and at the base of the column. However, NO_3-N was present in the water cover at concentrations ranging from 0.68 to 6.5 mg/L indicating that partial nitrification of NH_4-N in water cover occurred. The dissolved oxygen (DO) measured on day 282 in water cover and porewater was 3.87 mg/L and 0.86 mg/L respectively. The DO could not be measured accurately at the column base.

Figure 11 shows the cumulative amount of dissolved As, Cu, Sb and Zn that leached from the sulfide columns at the water cover, porewater, and the column base and the total amount leached from the columns. Figure 12 shows leaching rates of dissolved As, Cu, Sb and Zn observed for the high sulfide columns. The leaching rate was estimated based on the total amount of the metal leached from the columns.

Figure 11 shows that the As leaching was an order of magnitude higher than the amounts of Cu, Sb and Zn that was leached. The amount of As leaching at the base of the column was higher than the As leaching in the water cover and the porewater. The As concentration in the water cover and the porewater did not change significantly after 226 days, however the As leaching at the base of the column increased with time. In the water cover, a maximum As concentration of 1.33 mg/L at day 127 decreased to 0.176 mg/L at day 399. However, in the porewater the As concentration ranged from 1.04 mg/L to 1.52 mg/L during this study. At the column base, the As concentration increased with time from 0.323 mg/L at the start to 3.49 mg/L prior to column dismantling. Higher concentrations of Sb and Zn were observed in the water cover compared to the porewater and at the base of the column. The Brown-McDade pit water used as a source for water cover contained As, Cu, Zn and Sb at concentrations of 0.024 mg/L, 0.065 mg/L, 0.738 mg/L and 0.035 mg/L respectively. Sb concentration in the water cover increased from 0.052 mg/L at the start of the study to 0.234 mg/L prior to column dismantling. The Sb concentration in the porewater and at the column base was less than 0.089 mg/L and 0.018 mg/L respectively after day 16. The Zn concentration in the porewater and the column base was less than 0.042 mg/L after the 16 days. A maximum Cu concentration of 0.176 mg/L was observed in the porewater initially, subsequently the Cu concentration was generally < 0.07 mg/L. The rate of As leaching was highly variable compared to the leaching rates of Cu, Sb and Zn (see Figure 12). The total amount of As, Cu, Sb and Zn that leached during the study from the high sulfide columns per kg of tailings was 0.890, 0.017, 0.083 and 0.055 mg/ kg of tailings respectively

Table A2 and A3 presents the AES and MS scans for the samples collected in the water cover, the porewater and at the base of the high sulfide columns. The data shows that there is a potential for mobilization of Mn, since a maximum Mn concentration of 6.97 mg/L was observed at the column base. The results show that Pb was not leached to any significant degree, as the maximum Pb concentration of 62 µg/L at the start of the column study was reduced to less than 1 µg/L subsequently.

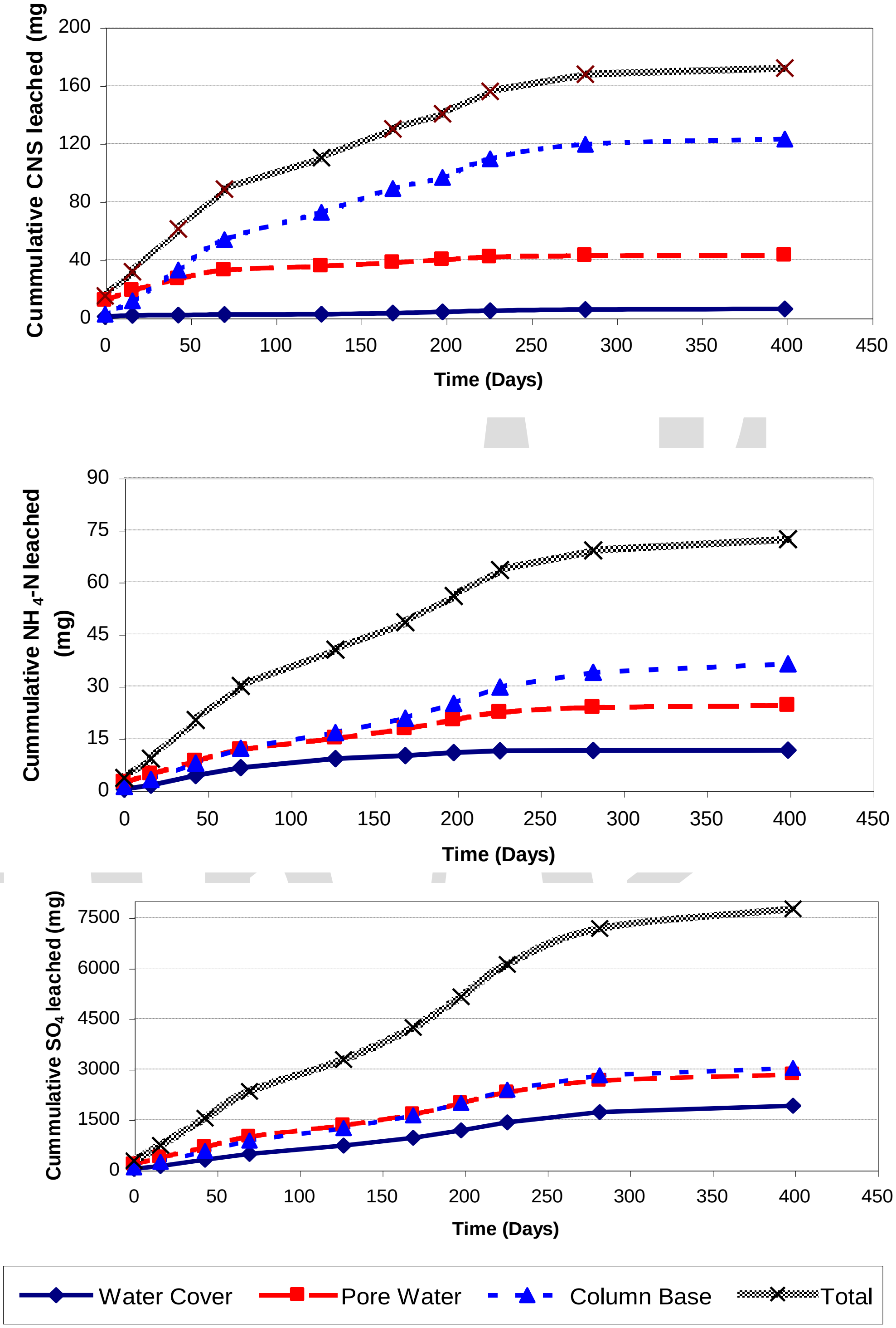


Figure 9: Profile of total cumulative amount of CNS, NH_4-N and SO_4 that leached from the sulfide tailings columns with a water cover.

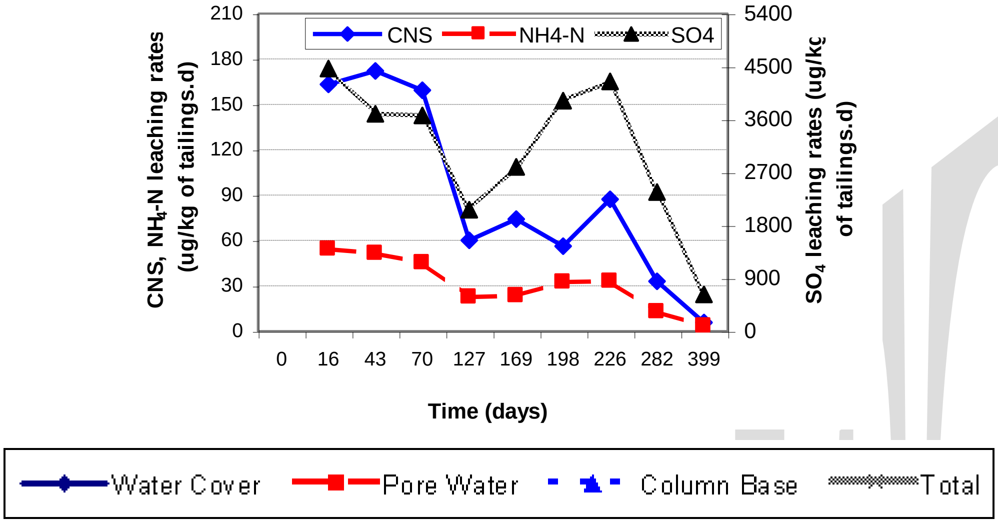


Figure 10: The leaching rate profiles of CNS, NH4-N and SO4 from sulfide tailings columns with a water cover.

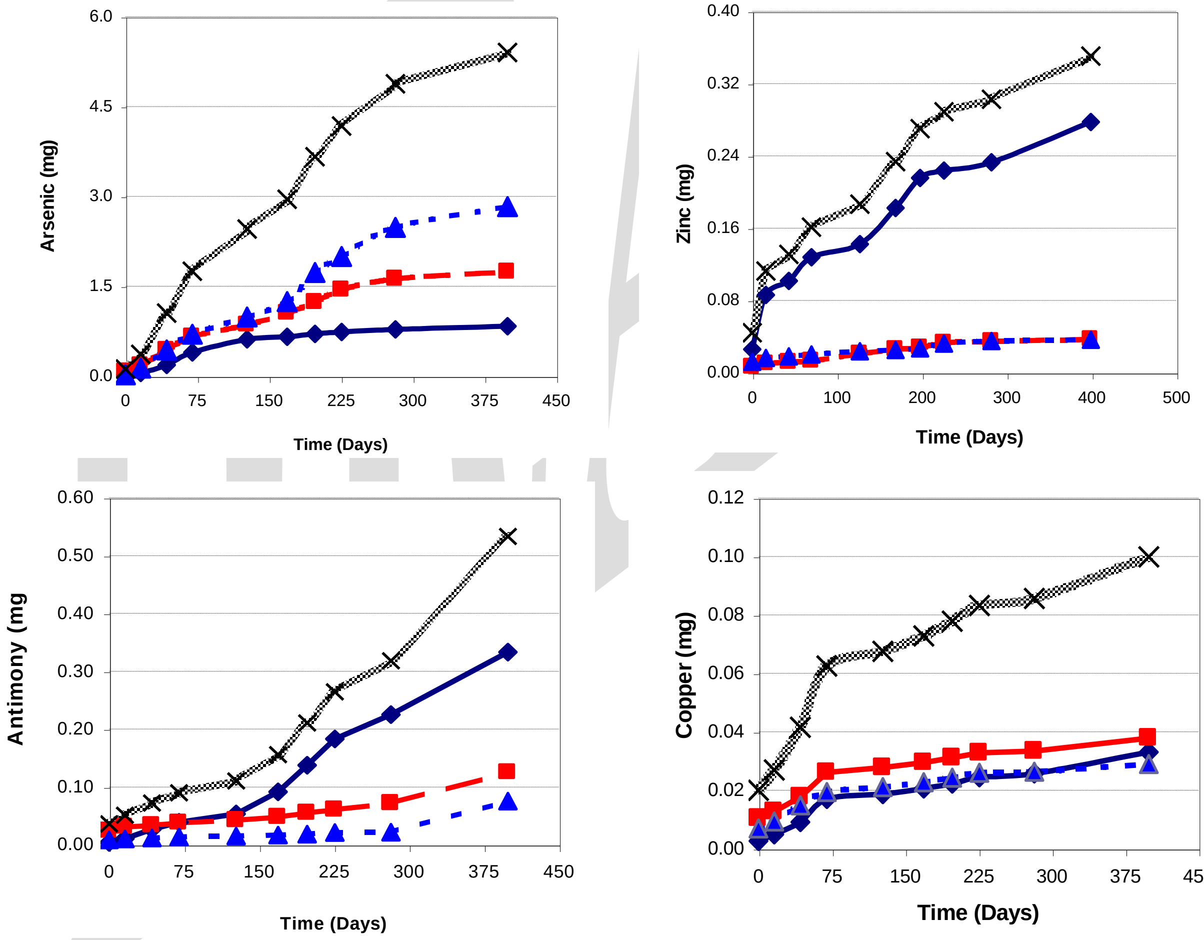


Figure 11: The profile of total cumulative amounts of As, Cu, Sb and Zn that leached from the sulfide tailings columns with a water cover.

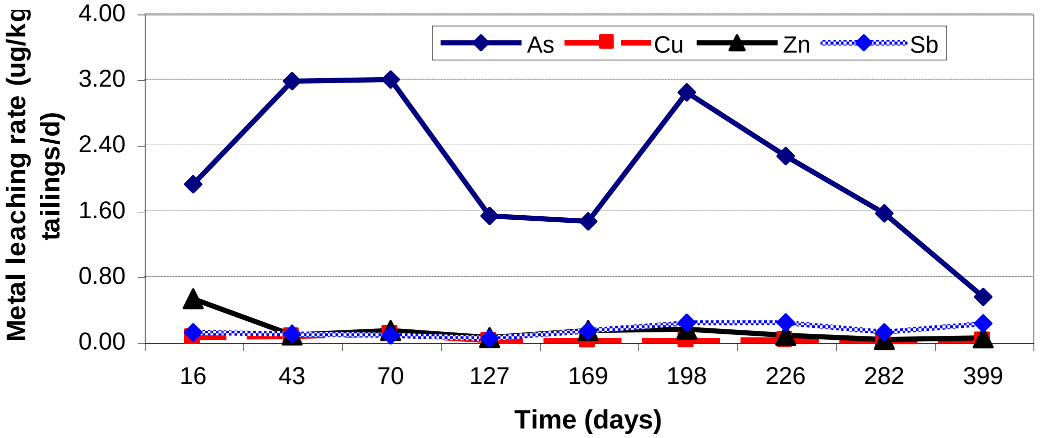


Figure 12: Profile of As, Cu, Sb and Zn metal leaching rates from the sulfide tailings columns with a water cover.

3.2 Oxide Columns

Figure 13 shows the average pH and conductivity profile in the water cover, the porewater and at the base of the oxide columns. The pH in the water cover, porewater and the column base was 7.7, 7.6 and 7.3 respectively at the end of the column study. The conductivity of the water cover and the column base more than doubled. The conductivity at the column base was slightly higher than at the water cover and the porewater. Table B1 (in appendix B) provides the raw water chemistry data for the samples collected from the oxide columns. Total CN was not detected in the water cover and the porewater of the oxide columns. The total CN at the column base was detected only in 4 sampling events, at concentrations ranging from 0.054 to 0.41 mg/L. WAD CN was detected only once in the sample from column base at a concentration of 0.14 mg/L. CNO presence was observed only in two of the ten sampling events at concentrations ranging 2 mg/L (in water cover) to 8 mg/L (in pore water).

Figure 14 shows the profile of the cumulative amounts of CNS, NH_4-N and SO_4 that leached from the oxide columns. In the oxide columns, CNS did not leach in the water cover and the porewater samples. CNS was present at the base of the column at a maximum concentration of 12 mg/L. The amount of NH_4-N leaching was observed to be highest at the column base and lowest in the water cover. The maximum NH_4-N concentration in the water cover was 5.4 mg/L and reduced to <0.8 mg/L on day 169 onwards. Algae growth in the water cover and top surface of the tailings occurred during days leading up to day 169 sampling event. The NH_4-N concentration at the column base and in the porewater was 16.3 mg/L and 4.3 mg/L respectively at the end of the column study. The SO_4 leached at comparable amounts in the porewater and at the column base. The total amount of CNS, NH_4-N and SO_4 that leached from the oxide columns per dry weight of tailings was 1.59, 7.26, and 1129 µg/kg of tailings respectively. The CNS leaching rates (Figure 15) were observed to be lower than NH_4-N leaching rates, in contrast to the high sulfide columns that exhibited higher CNS leaching rates.

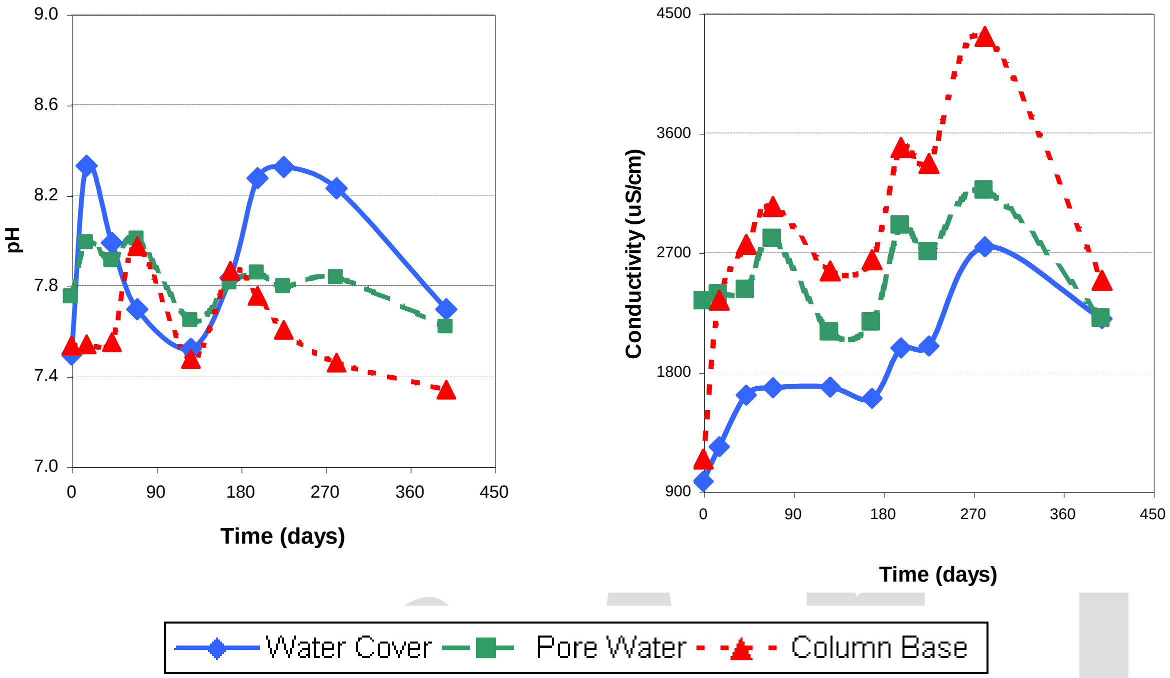


Figure 13: The pH and conductivity profile for the oxide columns.

The initial total CN associated with the oxide tailings was 9.6 µg/g of tailings. The average total CN in the core samples collected at the top and base of the columns after columns dismantling was 8.0 and 9.1 µg/g respectively. The results show that limited total CN leaching and degradation took place during the column monitoring study. The total CN was not released to a significant degree in the aqueous phase in the water cover and or in the porewater. The total CN was present only in the samples collected at the column base at concentrations not exceeding 0.41 mg/L. NO_2-N was not observed in the columns. The NO_3-N was not present in the porewater and at the base of the column. However, NO_3-N was present in water cover at concentrations up to 7.0 mg/L, indicating that nitrification of NH_4-N may have occurred in the water cover. A decrease in the NO_3-N concentration coincided with the presence of algae in the water cover. The dissolved oxygen (DO) measured on day 282 in the water cover and the porewater was 5.65 mg/L and 1.11 mg/L respectively.

Figure 16 shows that leaching of As, Cu, Sb and Zn was in the following order: As > Sb > Zn > Cu. As leached in higher amounts at the base compared to leaching in the porewater and the water cover. At the end of the column study, the As concentration in water cover, porewater and at the base of the column was 0.469, 1.53 and 5.18 mg/L respectively. Copper leaching was observed at similar levels in the water cover, porewater and at the column base. The Cu concentration was generally < 0.045 mg/L except for one sample at the base with a concentration of 0.107 mg/L. Sb and Zn leaching was at higher amounts in the water cover compared to the porewater and at the column base. The Zn concentration in the water cover decreased from 0.584 mg/L to 0.057 mg/L. Initial higher Zn concentrations in the water were due to the higher Zn concentration (0.738 mg/L) in the Brown-Mcdade pit water which was used as the water cover. Zn concentration in the porewater and at the base of the column were < 0.042 mg/L in samples

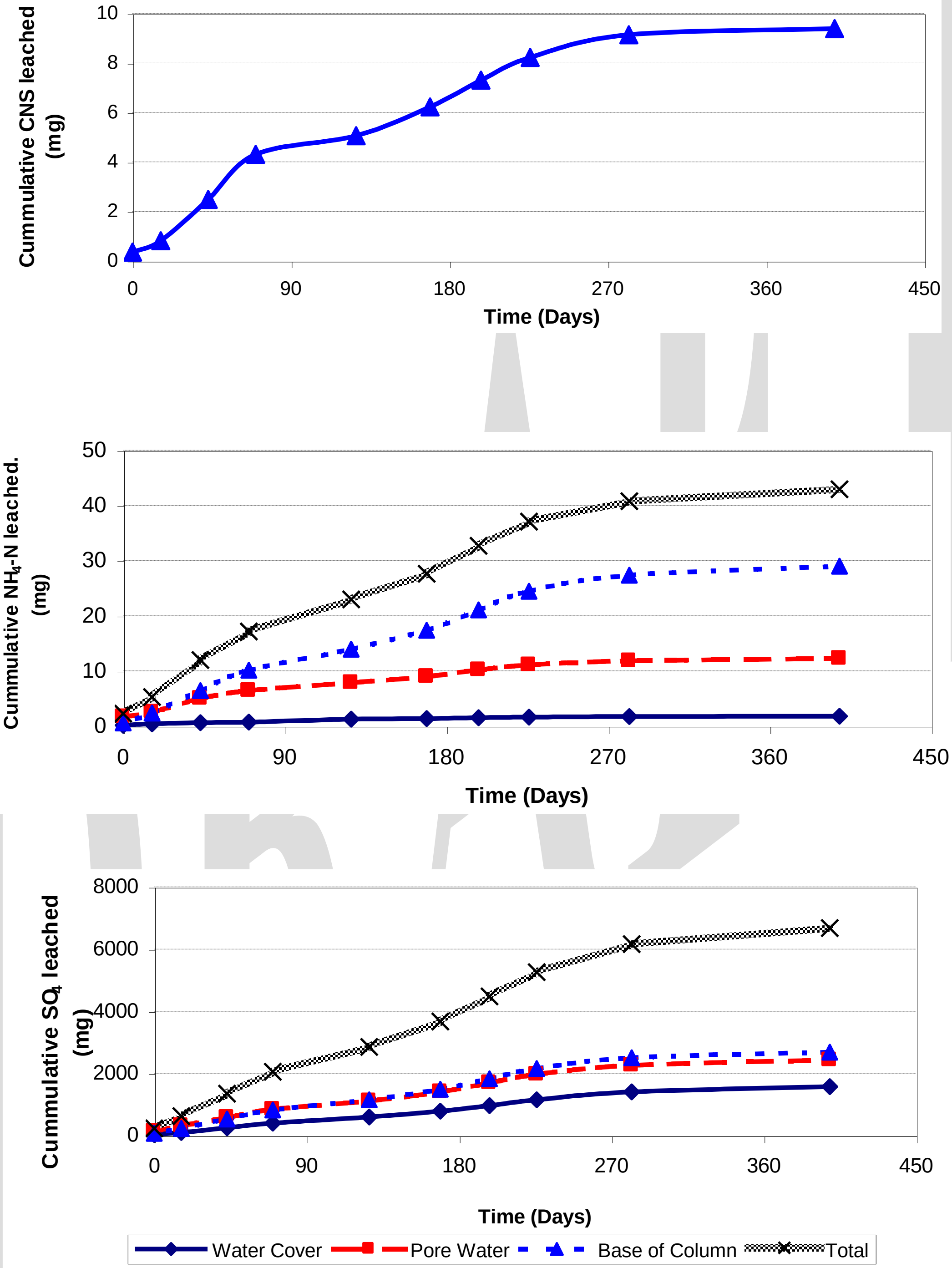


Figure 14: Profile of total cumulative amounts of CNS, NH_4-N and SO_4 leaching from the oxide tailings columns with a water cover.

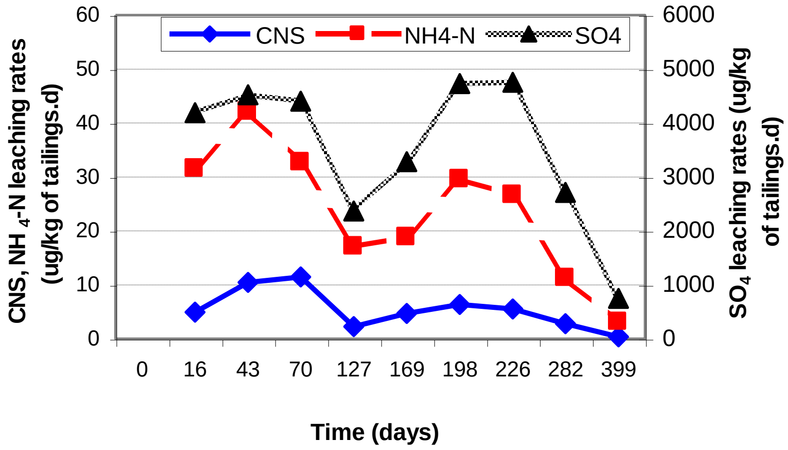


Figure 15: The profiles of CNS, NH_4-N and SO_4 leaching rates from the oxide tailings columns with a water cover.

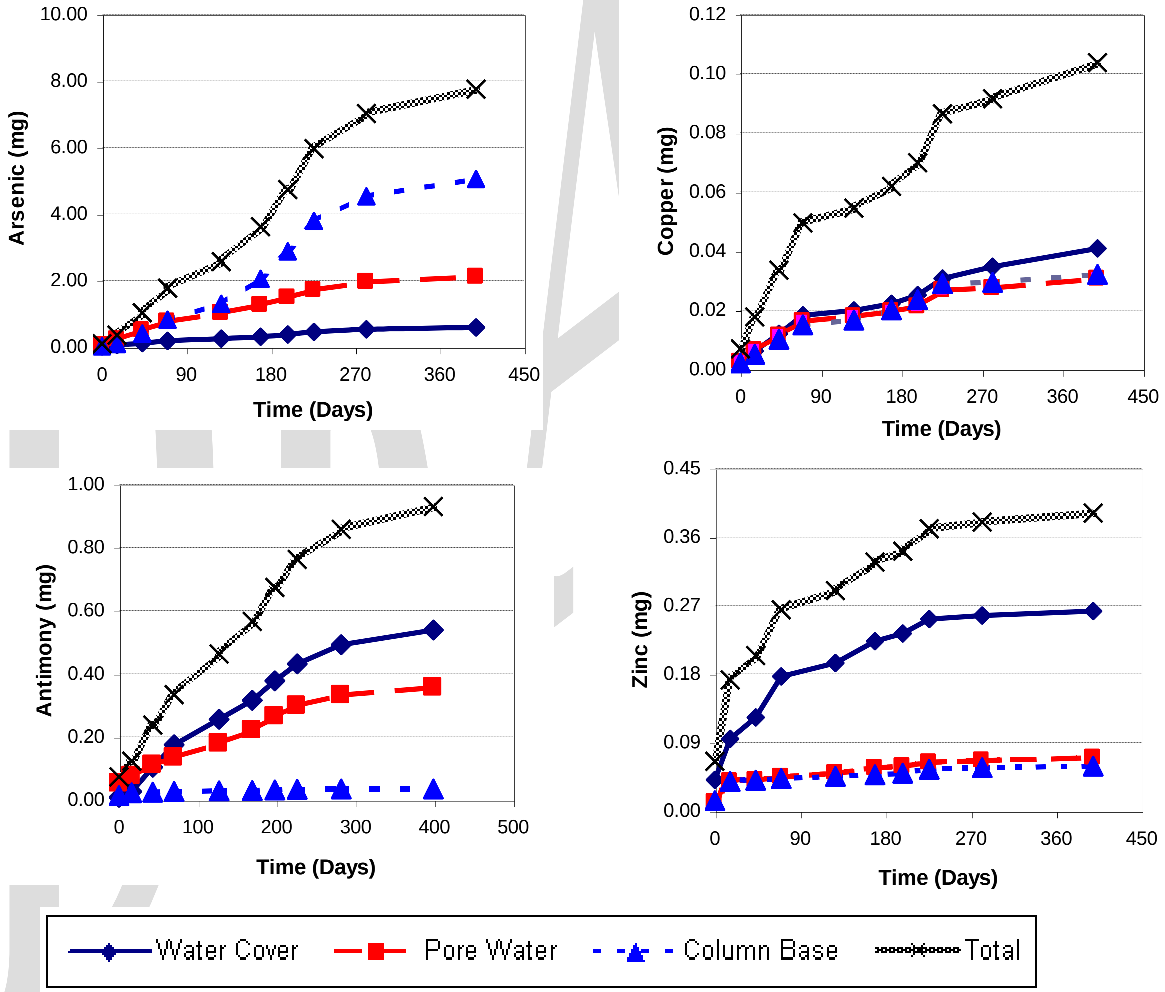


Figure 16: The profile of the cumulative amount of As, Cu, Sb and Zn leached from the oxide tailings columns with water cover.

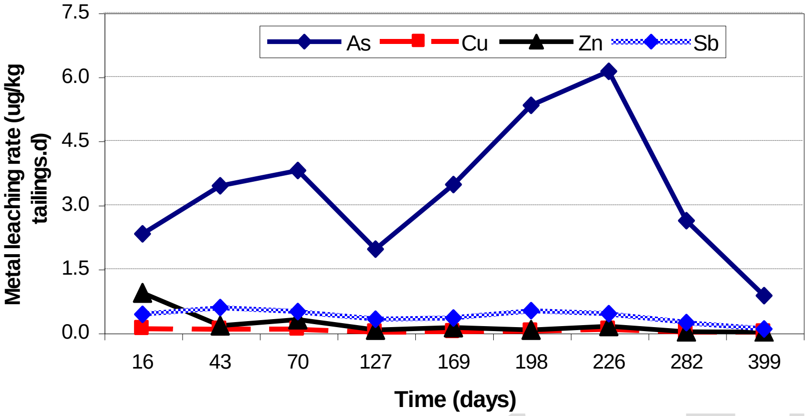


Figure 17: Profile of As, Cu, Sb and Zn leaching rates from oxide columns.

collected after 169 days. The Sb concentration in the water cover increased from 0.118 mg/L at the start to 1.03 mg/L. However, porewater Sb concentration decreased from 0.746 mg/L at the start to 0.198 mg/L at the end of the study. At column base, Sb concentrations remained <0.010 mg/L after 169 days. Figure 17 shows that total As leaching rates were higher than leaching rates observed for Cu, Sb and Zn. The total amount of As, Cu, Sb and Zn that leached during the study from the oxide columns per kg of tailings was 1.13, 0.002, 0.157 and 0.066 mg/ kg of tailings. Table B2 and B3 (in appendix B) show the AES and MS scans obtained for the samples collected from the oxide columns. Mn leaching was observed, at the column base the Mn concentration increased from 0.685 mg/L at the start to a maximum of 9.32 mg/L at the end of the study. Pb was not leached to any significant degree from oxide columns.

3.3 Mixed Tailings Slurry Columns

Figure 18 shows the average pH and conductivity profiles for the mixed tailings slurry columns. After 399 days, the pH in the columns ranged from 7.5 to 7.8. The conductivity of the water cover was higher initially and decreased with time compared to the conductivity of the water cover in the oxide and the sulfide columns. The tailings were deposited into the columns in a slurry form and as a result higher water cover conductivity was observed at the beginning of the column study.

Total CN was present in the porewater at concentrations ranging from 0.052 to 0.082 mg/L. At the column base, the total CN concentration ranged from 0.054 mg/L at day 16 to 0.30 mg/L on day 282. WAD CN was not detected in the samples collected in the water cover, porewater and at the column base. Figure 19 shows the profile of cumulative amounts of CNS, NH_4-N and SO_4 that leached from the columns. The majority of CNS leaching occurred at the column base. The CNS concentration in the water cover decreased from 68 mg/L to 7 mg/L in initial 16 days after the columns set up. In the porewater, CNS decreased from 67 mg/L at the start to 7 mg/L in approximately 200 days. The NH_4-N leaching in the water cover of the mixed slurry tailings columns was higher than those measured in the sulfide and oxide columns. In the water cover, the NH_4-N concentration decreased from an initial concentration of 21.8 mg/L to <0.8 mg/L in 127 days. Decrease in water cover NH4-N concentration coincided with the growth of algae in the water cover and on the tailings surface. The NH_4-N concentration in the porewater and at the column base at the end of the column monitoring was 8.5 and 19.4 mg/L respectively. SO_4 leaching in the porewater and at the column base was at comparable and higher than water cover. Total CNS, NH_4-N and SO_4 that leached in the mixed slurry tailings column was higher than that leached in the oxide columns and lower than that leached in the sulfide columns with water cover. The total amounts of CNS, NH_4-N and SO_4 leached from mixed slurry tailings column was 11.3, 8.1 and 1022 mg/kg of tailings respectively.

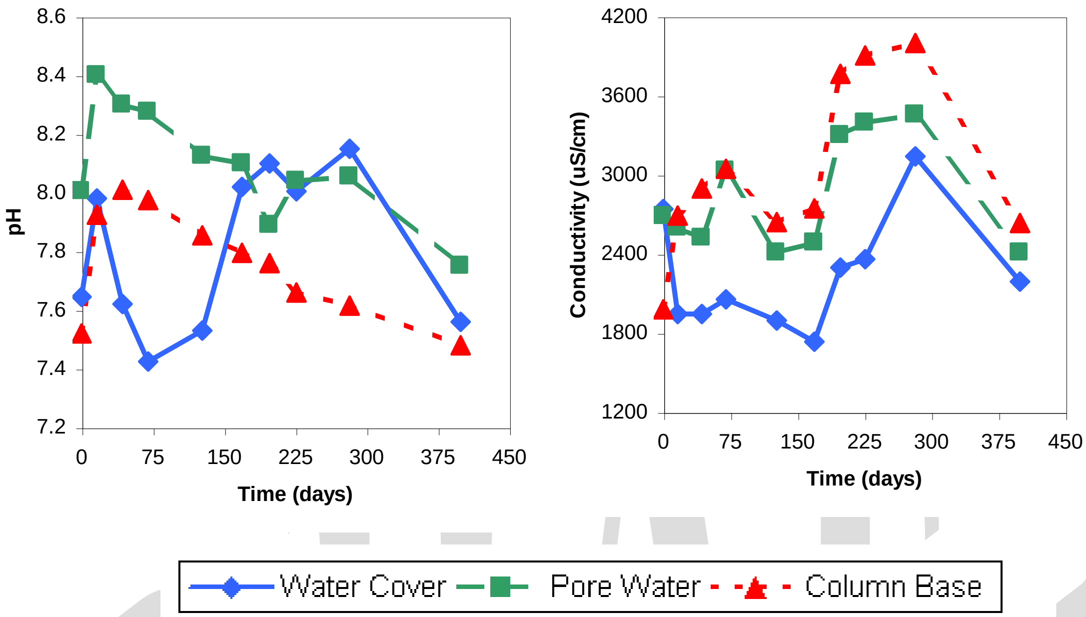


Figure 18: The pH and conductivity profile for mixed slurry tailings column.

Figure 20 shows that initially, CNS leaching rates were higher than those of NH_4-N, and after 127 days CNS and NH_4-N leaching rates were at comparable levels. SO_4 leaching rates decreased significantly with time. Table C1 (in appendix C) presents the raw water chemistry data for samples collected from the mixed slurry tailings column under water cover. NO_2-N was not present in the samples collected from the columns. NO_3-N was not present in the porewater and at the base of the column. Nitrification of NH_4-N was not observed in the water cover. The DO measured on day 282 in water cover and porewater was 4.91 mg/L and 0.94 mg/L respectively. Lower DO in the porewater compared to the water cover suggests that bacterial activity and chemical reactions associated with degradation of cyanide and related species were consuming oxygen from the porewater.

The initial total CN associated with the mixed tailing was 30.8 mg/kg. The average total CN in the core samples collected towards the top and at the base after the columns were dismantled was 16.0 and 15.2 mg/kg. Approximately 50% of the total CN associated with the tailings was leached. In the water cover, total CN was not detected, thus CN removal would have likely taken place via degradation to NH_4-N, since NH_4-N was present in the water cover, the porewater and at the column base. CNO, an intermediate product of CN natural degradation to NH_4-N, was present at the column base confirming CN degradation. At the column base, total CN was present in the aqueous phase at concentrations ranging from 0.054 to 0.30 mg/L, indicating that some CN leached from the tailings.

Dissolved As leaching was higher by more than an order of magnitude compared to the total amount of dissolved Cu, Sb and Zn leaching (Figure 21). The initial As concentration in the water cover was 0.929 mg/L and it decreased to 0.197 mg/L at the end of the column study. At the column base, As concentration increased from 0.517 mg/L at the beginning to 3.36 mg/L at the end of the study. The profile of the cumulative As leaching curve at the column base indicates that As leaching had not yet reached a steady state and is likely continue. Cummulative Sb leaching profiles indicated that Sb leaching in the porewater and at the column base was fairly constant after approximately 226 days, however Sb leaching in water cover continued at increasing cumulative amounts with time. The leaching of Cu was significantly lower than Sb and Zn leaching. The Cu leached at approximately similar levels in the porewater and at the column base with concentrations generally below 0.049 mg/L. In the water cover, a maximum Cu concentration of 0.072 mg/L was observed at the start of the column study. The Sb concentration was observed to be highest in the water cover compared to the porewater and at the column base. Water cover Sb concentrations ranged from 0.100 mg/L to 0.366 mg/L. In the pore water, the initial Sb concentration was 0.218 mg/L and decreased to approximately 0.035 mg/L or below. At the column base the Sb concentrations were <0.023 mg/L after 16 days. The average Zn concentration in water cover was highly variable and ranged from 0.053 mg/L to 0.340 mg/L with no consistent increasing or decreasing pattern observed. The average porewater Zn concentrations were below 0.094 mg/L, and at the column base the Zn concentration was less than initial concentration of 0.141 mg/L. The total amount of As, Cu, Sb and Zn that leached during the column study from the mixed tailings slurry columns was 1.13, 0.013, 0.038 and 0.060 mg/kg of tailings respectively. Figure 22 shows that As leaching rates between sampling periods were variable and were significantly higher than Cu, Sb, and Zn leaching rates.

Table C2 and C3 show the AES/MS scan for the samples collected from the mixed slurry tailings column under water cover. At the column base Mn leached at increasing amounts from 1.75 mg/L at the beginning to 11.25 mg/L at the end of the study. Leaching of Pb was observed in the water cover at a maximum concentration of 89 µg/L on day 19 and subsequently reduced to below detection levels.

3.4 Mixed Tailings In Flow Through Columns

The flow through columns were set up to study the leaching of various water quality parameters at five times the annual precipitation on site. Figure 23 shows the leaching profile of CNS, NH_4-N, SO_4 and the pH in the samples collected at the base. The pH of the water samples collected from the base of the column ranged from 7.6 to 8.2 except on two occasions where the pH was 6.4 and 6.8. The conductivity increased from 1920 µS/cm initially to approximately 3000 µS/cm at the end of the study. Total CN was observed at a maximum concentration of 0.1 mg/L during the initial few weeks. WAD CN was not detected in the water samples collected. CNO was detected only in the sample collected on day 63, at a concentration of 14 mg/L. The majority of CNS leaching from the columns was achieved in approximately 30 days after the column step. The NH_4-N leaching at the start was significantly higher, at concentrations ranging from 15 to 30 mg/L during the first three months. NH_4-N leaching thereafter was observed at slower rates and at a concentration of 2 mg/L at the time of column dismantling. The initial NH_4-N release from the columns may have been due to the flushing of NH_4-N present in the porewater and to some degree from the degradation of CN and related species. NH_4-N leaching continued towards the end of the column study at lower concentrations (2 to 5 mg/L) and may have resulted from the degradation of CN and its related species being adsorbed on the tailings and/or also from the release of NH_4-N adsorbed onto the tailings. The CNS and NH_4-N leaching profiles suggests that CNS leaching from tailings is likely to cease earlier than NH_4-N leaching. The CNS and NH_4-N leaching profile suggest that the washing of the tailings in a stirred tank reactor may be able to remove significant amounts of CNS from the tailings and labile NH_4-N present in the tailings. The sulfate concentration in the samples collected at the column base ranged from 1600 to 1800 mg/L after two months of leaching. Table D1 (in appendix D) presents the water chemistry of samples collected from the flow through columns. Figure 24 shows that CNS leaching rates significantly decreased from approximately 2000 µg/kg of tailings/day within a month. However, NH_4-N leaching rates decreased from approximately 550 µg/kg of tailings per day to below 55 µg/kg tailings per day after initial three months of column monitoring. The total amount of CNS, NH_4-N and SO_4 leaching from tailings was 32.0, 34.0 and 4842 µg/kg of tailings.

The initial total CN associated with the mixed tailings was 30.8 mg/kg. The average total CN in the core samples collected at the top and at the base was 19.1 and 17.6 mg/kg respectively. Approximately 40% of the total CN associated with the tailings was removed in the flow through column. WAD CN was detected in samples collected at the column base. However, CNO and NH_4-N, the natural degradation products of CN were observed in samples collected at the column base, suggesting that the removal of CN associated with the tailings was likely due to its natural degradation to NH_4-N.

Figure 25 shows the cumulative amount of As, Cu, Sb and Zn released from the flow through columns containing mixed tailings. The As and Sb are being steadily released from the columns as evident by the upward slope of the cumulative amount profile versus time. Cu and Zn leaching has been at significantly lower amounts compared to As and Sb and appears to be have reached a plateau. The concentration of As, Cu, Sb and Zn at the end of the column study were 1.48 mg/L, < 0.022 mg/L, 0.039 mg/L and < 0.010 mg/L respectively. The total amount of As, Cu, Sb and Zn leached was 3.30, 0.062, 0.322 and 0.098 µg per kg of dry tailings. Figure 26 shows the As, Cu, Sb, and Zn leaching rates for the flow through columns. A maximum As release rate of 20.7 µg/kg/d was observed at the beginning which decreased to below 5 µg/kg/d approximately 90 days and again subsequently increased to around 15 µg/kg/d. Sb leaching rate appears to have stabilized at 0.3 to 0.4 µg/kg/d after initial leaching rates as high as 7.5 µg/kg/d. Cu leaching rates in the range 0.10 to 0.3 µg/kg/d have been observed after approximately 150 days of column monitoring. The Zn leaching rates have been highly variable and ranged from 0.10 to 0.95 µg/kg/d in last two months of the column study.

Tables D2 and D3 (in Appendix D) show the AES and MS scan for the samples collected from flow through columns. The results show Mn was consistently leached at the column base in concentrations ranging from 3.5 to 6.5 mg/L. Pb was observed at a maximum concentration of 115 µg/L during first week of the study and reduced to levels less than 8 µg/L.

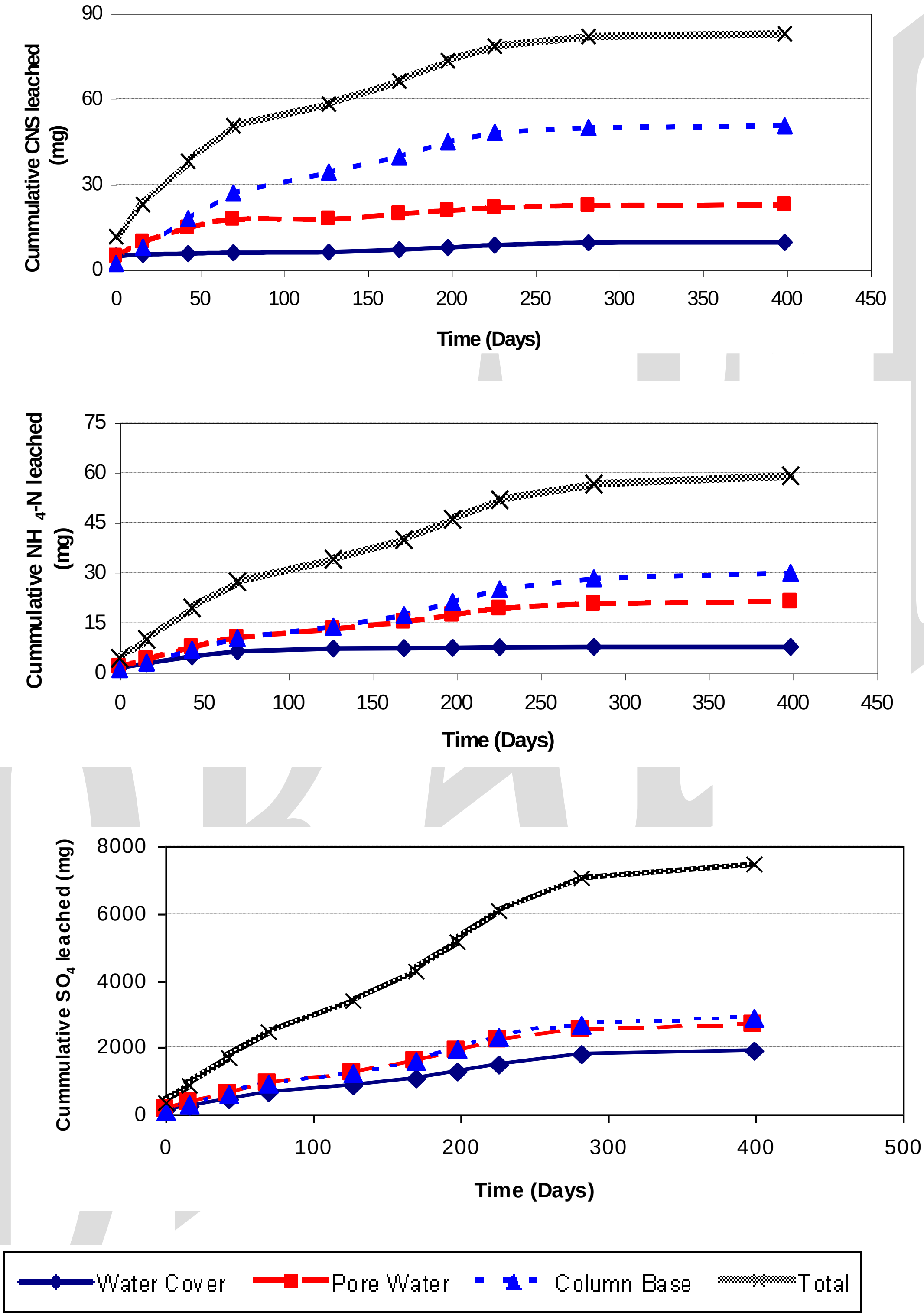


Figure 19: Profile of cumulative amounts of CNS, NH_4-N and SO_4 leaching from the mixed slurry columns with a water cover.

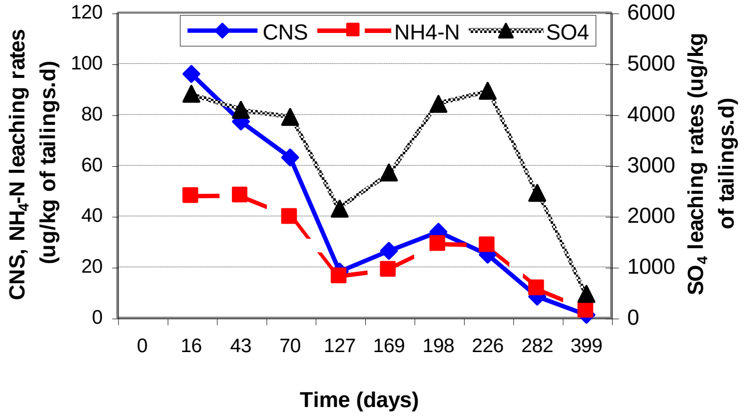


Figure 20: The profiles for CNS, NH_4-N and SO_4 leaching rates from the mixed tailings slurry column with a water cover.

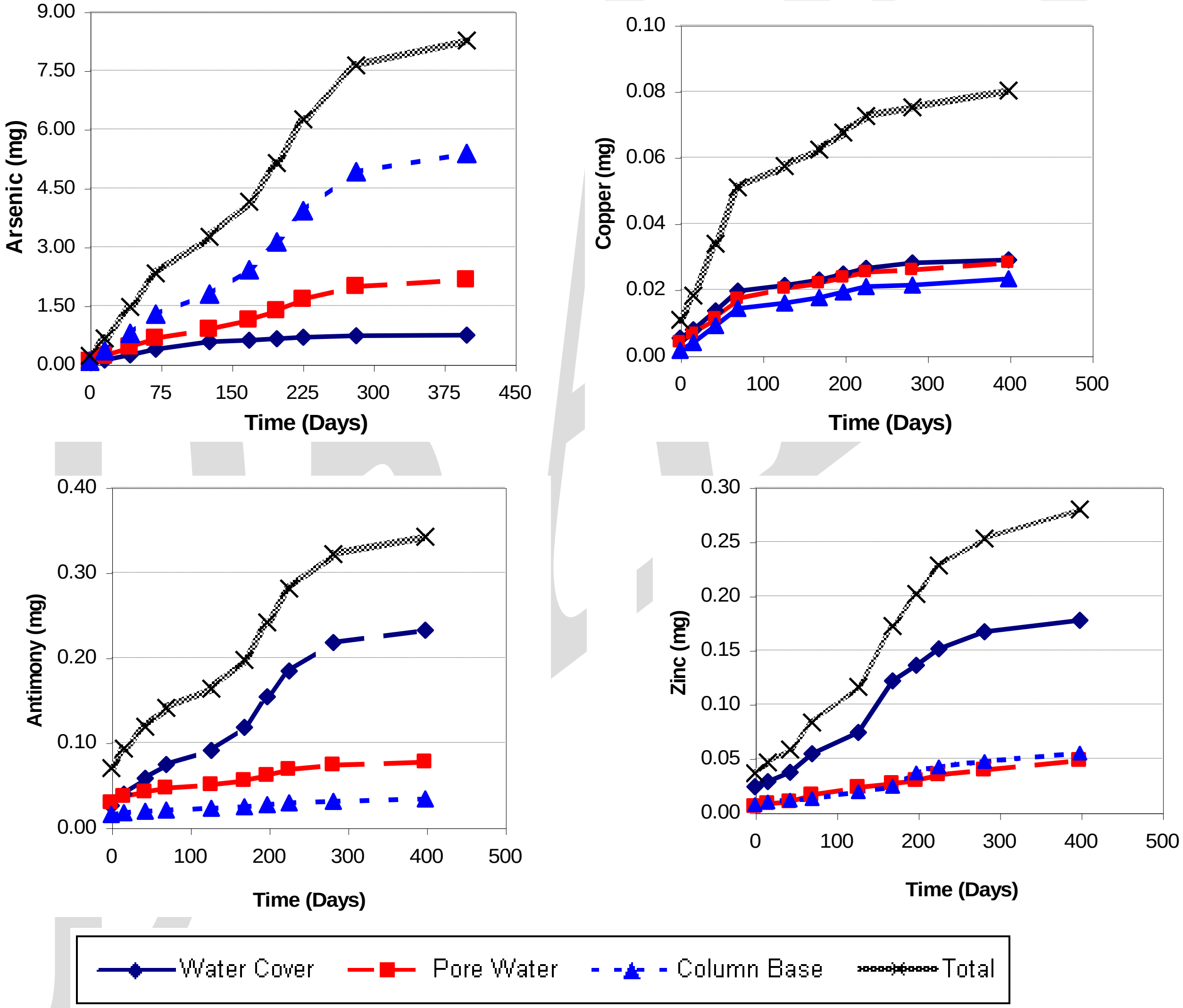


Figure 21: The profile of total cumulative amounts of As, Cu, Sb and Zn that leached from the mixed tailings slurry columns with a water cover.

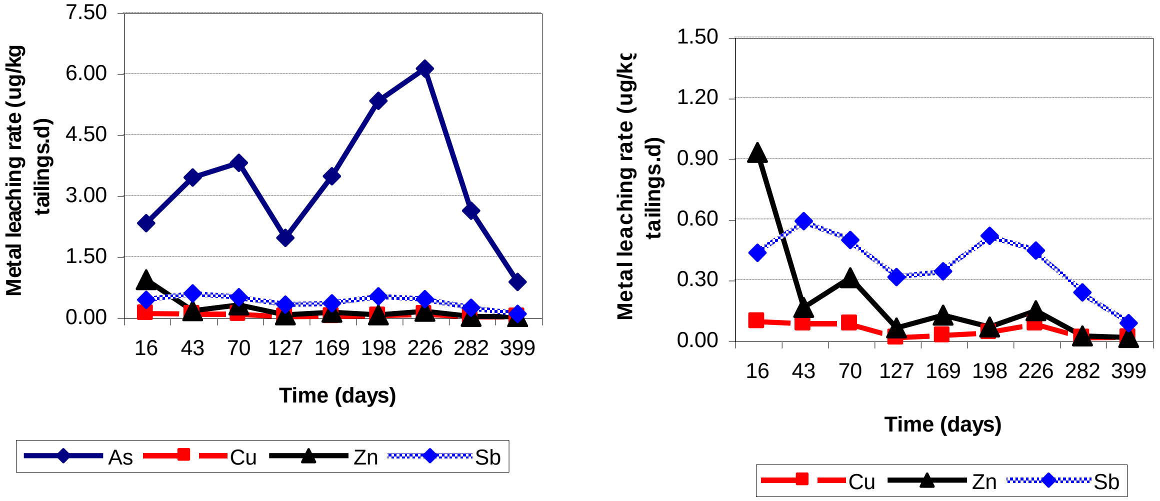


Figure 22: Profile of As, Cu, Sb and Zn leaching rates observed for the mixed tailings slurry columns with a water cover.

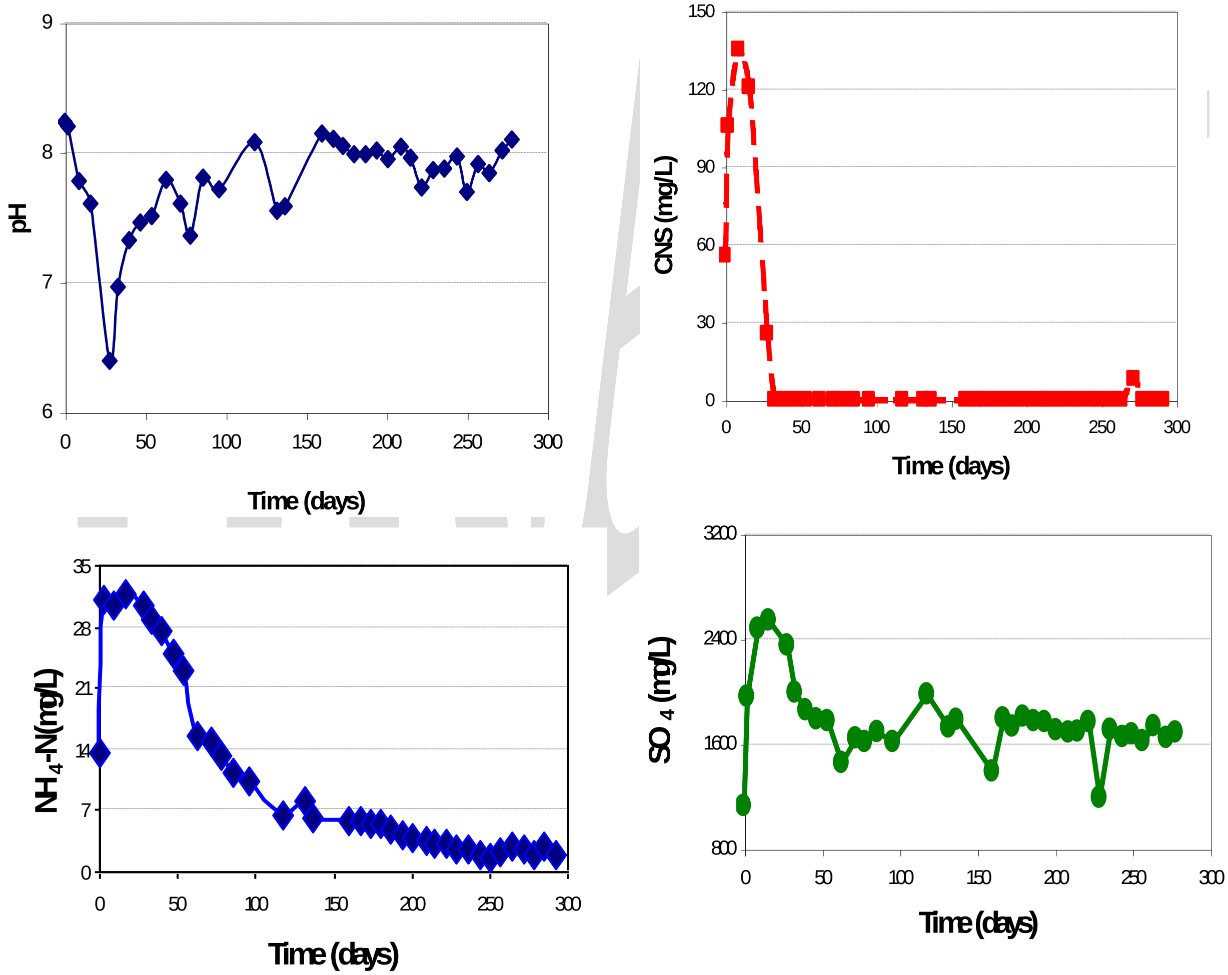


Figure 23: Profile of average pH, CNS, NH_4-N and SO_4 leaching from the mixed tailings in the flow through columns.

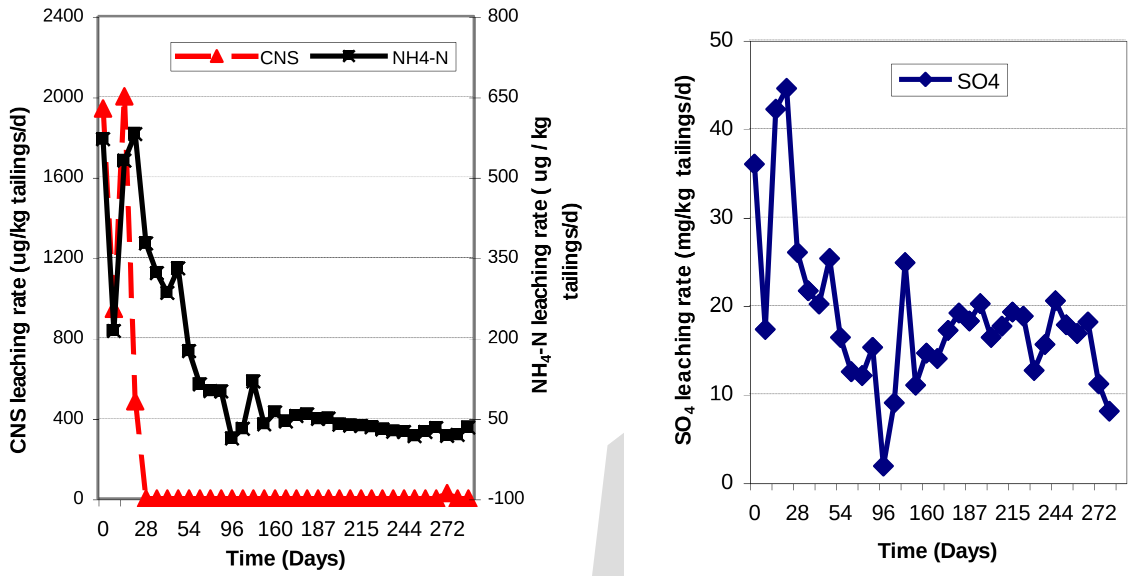


Figure 24: Profile of CNS and NH_4-N leaching rates for the mixed tailings in the flow through columns.

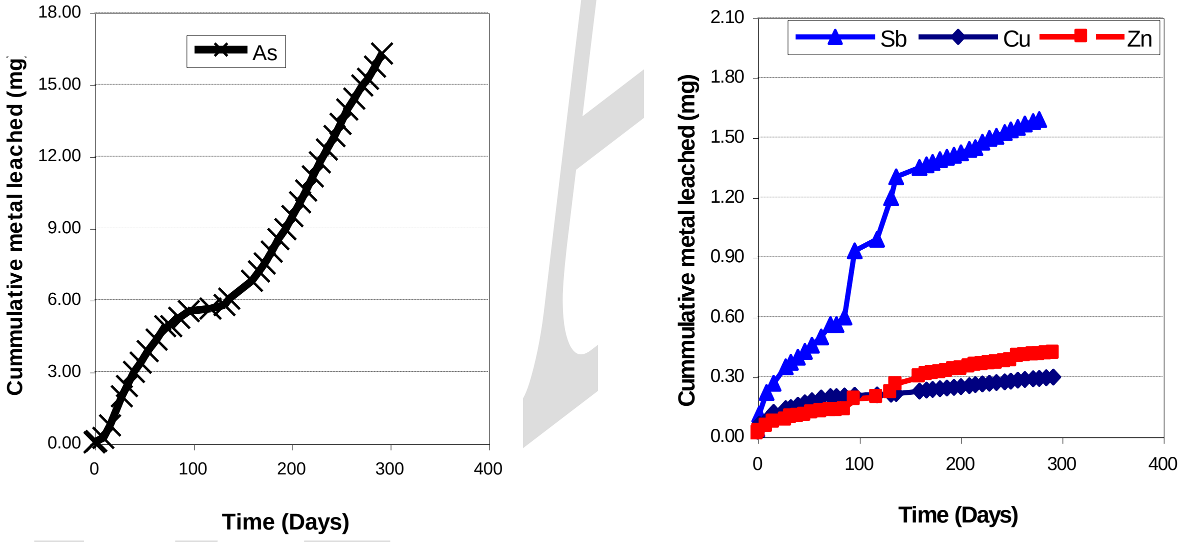
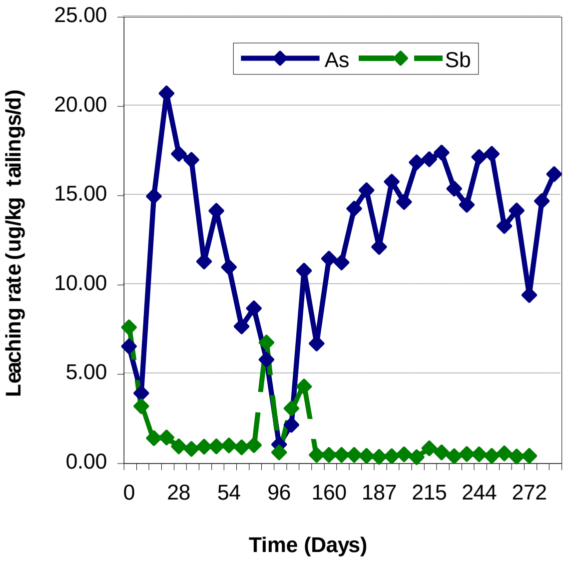


Figure 25: The profile of total cumulative amounts of As, Cu, Sb and Zn that leached from the mixed tailings in the flow through columns.



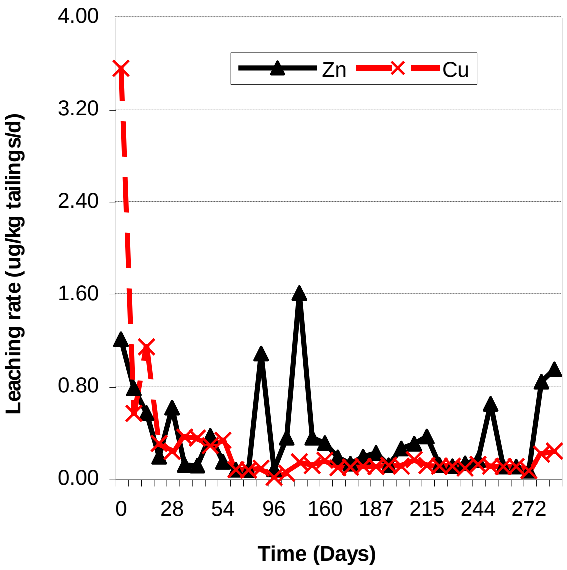


Figure 26: Profile of As, Sb, Cu and Zn leaching rates for the mixed tailings in the flow through columns.

3.5 Comparison of column results to the current tailings impoundment seepage return water

Table 2 presents the water chemistry of the last sample collected from the flow through column after 292 days of leaching and the tailings impoundment seepage return water. The average total CN in the seepage return water is comparable to the concentrations observed at the column base of the sulfide columns under a water cover. In the flow through columns, total CN leached for a short duration at a maximum concentration 0.1 mg/L. However, the mobilization of total CN upon disturbance of the tailings is likely to be influenced to a greater extent by the total CN in porewater compared to the total CN sorbed on the tailings. In the column studies, WAD CN was observed at a maximum concentration of 0.6 mg/L at the base of the sulfide columns. CNS leached from the flow through columns for approximately 30 days, however the CNS concentrations in the seepage return water is at levels comparable to those observed at the base of sulfide columns at day 399 of monitoring. NH_4-N concentration observed in the seepage return water was at lower concentration than at the base of the columns with a water cover on last day of column monitoring study. However, NH_4-N leaching in flow through columns appears to be approaching completion. Arsenic release in the laboratory columns was at much higher concentrations than that observed in the seepage return water. The average Fe concentration in seepage return water was higher than in flow through columns by an order of magnitude. There is a possibility that Fe present in the seepage return water may be playing some role in immobilizing As by precipitation in the tailings impoundment. Sb also appears to be at a higher concentration in the water cover of the laboratory columns and at the base of the flow through columns compared to seepage return water. Zn leaching in the porewater and at the base of the columns occurred at a much lower concentration compared to the seepage water. Cu leaching in the columns was generally lower than Cu concentration in the seepage return water and in the tailings impoundment porewater samples collected at the site. The tailings impoundment porewater results indicated a strong relationship between Cu and WAD CN concentrations (Kwong et al. 2002). Cu, total and WAD CN were not found in the column samples at concentrations comparable to the tailings pond pore water results. The WAD CN (predominantly as copper-cyanide complex) may have undergone degradation with the redox potential changes and other secondary reactions led to the formation of a variety of precipitates such as Cu (I, II) and ferri/ferro cyanide complexes, which are highly insoluble (Smith and Mudder, 1991). Most cyanide complexes associated with tailings remain inert. Compounds such as hexacyanoferrates are usually tightly bound to the tailings solids. They are thermodynamically stable and do not dissociate readily. In an iron-rich medium containing excess ferric, ferrous and copper ions an insoluble metal hexacyanoferrate often precipitates. This could also explain why total CN was not released to any significant degree in the columns aqueous phase directly as cyanide. However, Mn concentration at the base of the oxide and mixed columns with a water cover is higher than in the tailings impoundment seepage water, but in flow through columns Mn concentration was below that of seepage return water.

Table 2: Water chemistry of samples collected from the flow through columns (on day 292) and tailings impoundment seepage return water.

Parameter	**Flow Through Columns on Day 292 (average for two columns)**	**Tailing Impoundment Seepage Return (average for the period 29th August 2001 to 15th January 2003)**
pH	8.1	7.1
Total CN	< 0.1	0.97
WAD CN	< 0.05	0.21
CNS	< 5	48.9
NH_4-N	2	13.0
As	1.48	0.054
Cu	< 0.022	0.143
Sb	0.039	<0.02
Zn	< 0.010	0.044
Mn	5.10	8.83
Fe	0.867	12.2

Note: All values are in mg/L except for pH.

4.0 DISCUSSION

Total and WAD CN were not leached into the water covers of the sulfide, the oxide and the mixed tailings columns. Only the mixed tailings columns with a water cover had total CN in the porewater at concentrations ranging from 0.02 to 0.82 mg/L. Total CN was observed at the base of the columns with the water cover at concentrations ranging from 0.053 to 1.74 mg/L. The sulfide tailings in general released total CN at higher concentrations. In general, WAD CN concentrations at the column base were generally < 0.1 mg/L except for one sampling event with a concentration of 0.5 mg/L at the base of sulfide columns. In the flow through columns, total CN release was observed only in the initial 30 days of the column set up at concentrations ranging from 0.054 to 0.1 mg/L. WAD CN was not detected in samples collected from the flow through columns. The pH in the columns was generally above 7.0. Table 3 shows amounts of CNS, NH_4-N, SO_4, As, Cu, Sb and Zn that leached from the columns simulating four disposal scenarios.

Table 3: Amounts of total CN (associated with tailings), CNS, NH_4-N, SO_4, As, Cu, Sb and Zn that leached from the columns under a water cover and the flow through conditions.

Parameters	**Columns With a Water Cover (mg/kg of dry tailings)**			**Flow Through Columns With Mixed Tailings (mg/kg of dry tailings)**
	Sulfide Tailings	**OxideTailings**	**Mixed Tailings Slurry**	
Degradation of total CN associated with tailings	15.5	1.0	15.2	12.4
CNS	27.0	1.59	11.3	32.0
NH_4-N	11.4	7.26	8.1	34.0
SO_4	1221	1129	1022	4842
As	0.890	1.13	1.13	3.3
Cu	0.017	0.020	0.013	0.062
Sb	0.083	0.157	0.060	0.322
Zn	0.055	0.066	0.038	0.098

CNS, NH_4-N, SO_4, As, Cu, Sb and Zn leached in higher amounts from the flow through columns compared to the columns with a water cover. Degradation of total CN associated with tailings was slightly higher in columns with water cover compared to flow through columns. Removal of the total CN associated ranged from 40 to 50% in the columns containing sulfide and the mixed tailings. For columns with a water cover, CNS, NH_4-N, and SO_4 leaching was higher from sulfide columns compared to the oxide and mixed slurry tailings columns. Natural degradation of CN involves its oxidation to CNO, an intermediate degradation product that is unstable and is degraded to NH_4-N, and also to nitrogen and carbon dioxide under extremely oxidative conditions. CNS presence in the columns suggests the interactions of cyanide and sulfides present in the tailings are likely producing CNS also. CNS is also known to degrade to CNO, that degrades to NH_4-N. These cyanide degradation reactions are assisted by microbial action. CNO was observed in porewater and at the base of columns with the water cover during the initial couple of months of the column tests. For columns with a water cover, CNS and NH_4-N concentrations were higher at the base of columns compared to the porewater and in the water cover. The flushing of porewater from the upper regions of the columns through extraction of water samples at the base of the column may have contributed to the observed increases in CNS and NH_4-N concentration at the column base. Initially, the water cover of the mixed slurried columns exhibited higher NH_4-N concentrations compared to the sulfide and the oxide columns due to the slurry deposition of the mixed tailings in the columns. CNS leached from the flow through columns within a month. NH_4-N leaching from the flow through columns occurred in two phases: an initial high leaching rate within 90 days of columns set-up and was followed by a slower leaching rate (Figure 24). An initial higher NH_4-N leaching rate phase may have taken place due to flushing of NH_4-N present in porewaters and degradation of CN species in the column. The slower NH_4-N leaching rate phase may have resulted from NH_4-N generated by the degradation of the total CN sorbed on the tailings.

More As, Sb and Zn leaching occurred in the oxide columns compared to the sulfide columns with a water cover. Arsenic leached at equal amounts from the oxide and mixed tailings columns under water cover. In general, the amount of leaching of As, Cu, Sb and Zn was exhibited in the following decreasing order for all of the columns studied: As > Sb > Zn > Cu. The concentration of As in the columns with a water cover was highest at the base and lowest in the water cover. The average dissolved As concentration in the water cover of the sulfide, oxide and mixed slurry tailings columns on day 399 was 0.176, 0.469, and 0.197 mg/L. The oxide columns under a water cover exhibited the highest average dissolved As concentration of 5.18 mg/L at the base. Sb leaching in the columns with a water cover was higher in the water cover compared to Sb leaching in the porewater and at the column base. The maximum Sb concentration observed in the water cover of the low sulfide column was 1.03 mg/L. In the flow through columns, Sb concentration towards the end of the column study was than 0.070 mg/L. Higher Zn concentrations were observed in the water cover compared to the porewater and at the column base, likely due to higher Zn concentration (0.734 mg/L) in the Brown McDade pitwater that was used as a source for the water cover in this study. Dissolved Zn in the porewater and at the base of the columns with the water cover decreased with time to concentrations below 0.07 mg/L. Lower dissolved Zn in the porewater and at the column base suggests that Zn was removed by precipitation/sorption on mineral surfaces as overlying water was being drawn downward for sample collection. In the water cover of high sulfide columns, a maximum dissolved Cu concentration of 0.070 mg/L was observed at the end of the study. Generally, the dissolved Cu concentration in the water cover, the porewater and the column base was below 0.05 mg/L, except on certain sampling events.

Persistence of total CN in aqueous media is likely to be for longer durations under low oxygenated conditions as evidenced by the presence of total CN in porewater and especially at the base of the columns under the water cover. Cyanide degradation in aqueous media occurs at enhanced rates under oxic conditions compared to low oxygen/anaerobic conditions. Release of As was also observed to be higher at the column base compared to leaching in the porewater and in the water cover (DO of 5.65 mg/L) of the oxide columns. A shallow water cover is likely to provide oxygenated conditions in the water cover and at the top tailings layer, which may limit the persistence CN and extent of As release in the water phase. It is suggested that the effect of

DO on total CN and its related species, As, Mn and Sb leaching be confirmed using simple batch tests. However, it should be noted that cyanide degradation will produce CNS, CNO and NH_4-N that will ultimately be released in the water phase.

In section 3.0 the actual leaching rates observed for the parameters of interest over the sampling periods were presented in Figures 10, 15, 17, 20, 22, 24 and 25 for the columns. Using a linear regression technique, overall leaching rates of CNS, NH_4-N, SO_4, As, Cu, Sb and Zn were estimated based on the cumulative amounts released from the flow through columns containing the mixed tailings and these presented in Table 4. Since the columns studies were conducted at room temperature (considerably higher than on-site temperature conditions), the leaching rates obtained were likely enhanced due to higher temperatures, in addition these rates were obtained at a precipitation rate five times the site precipitation. The rates presented below show that leaching rates from the tailings impoundments under flow through conditions will be in the following order: SO_4 > CNS > NH_4-N > As > Sb > Zn > Cu.

Table 4: Overall estimated leaching rates based on the amounts leached from the flow columns at room temperature.

Parameter	**Estimated Leaching Rates Using Linear Regression Technique (µg/kg tailings/day)**	**Comments**
CNS	1270	Leaching achieved in approximately 30 days after column set up
NH_4-N Phase 1: Initial leaching at higher rates	366	Leaching period: Within 90 days of column set up
Phase 2: Subsequent slower leaching rate	35.5	Leaching period: 90 - 292 days of column monitoring
SO_4	18,328	Estimated over the entire monitoring period of 292 days
As	10.5	
Cu	0.24	
Zn	0.32	
Sb Phase 1: Initial leaching at higher rates	1.78	Leaching period: Initial 150 days after column set up
Phase 2: Subsequent slower leaching rate	0.43	Leaching period: 150 to 292 days of column monitoring

The initial leaching of total CN upon disturbance of the tailings is likely to be influenced to a greater extent by its concentrations in the porewater compared to the total CN sorbed on the tailings. The CNS and NH_4-N leaching profile from the flow through columns suggests that washing of the tailings in a stirred tank reactor may likely remove significant amounts of CNS and labile NH_4-N associated with the tailings and the porewater. In the current impoundment, CNS and NH_4-N leaching is likely to continue. The results show that NH_4-N leaching from the columns is likely to continue even after CNS leaching is complete. The results also show that there is a potential for As, Sb and Mn mobilization to occur. The cumulative profile of As leached from flow through columns suggests that As leaching is likely to continue even after the majority of NH_4-N release from the flow through is achieved. The movement of tailings from its current impoundment will involve agitation and exposure to an oxidizing environment that is likely to enhance volatilization, mobilization and degradation of CN and related species. The disturbance of the tailings is likely to enhance some of the total and WAD CN degradation, resulting in elevated concentrations of CNO, NH_4-N and CNS in aqueous phase. Moving the tailings from its current location to the Brown McDade open pit in a slurry form is likely to have an impact on the resulting water cover compared to transferring the tailings in a dry form. The columns results have shown that oxide silt tailings are likely to leach higher amounts of As, and possibly Sb compared to the sulfide silt tailings, and the sulfide silt tailings are likely to leach higher amounts total and WAD cyanide, CNO, CNS and NH_4-N compared to oxide silt tailings. This leaching behavior of the sulfide and oxide tailings will have to be taken into consideration in selection of a permanent site for tailings placement. If the tailings were moved to a new location, the differences in the leaching of various contaminants from the oxide and the sulfide tailings will have to be recognized in developing a tailings deposition plan at the site.

5.0 CONCLUSIONS

The column study project on the Mount Nansen coarse sulfide and oxide silt tailings aims to evaluate the release of cyanide and it's related species and metals in order to provide technical data to aid in making decisions for permanent disposal of the tailings. Based on the column study results obtained for this project, the following conclusions are drawn:

1. Sulfide tailings columns in general released total CN and WAD CN at the column base at higher concentrations compared to oxide and mixed tailings under a water cover and mixed tailings in flow through conditions. WAD CN did not leach into the water cover and in the porewater of sulfide, oxide and mixed tailings under a water cover.

2. Total CN sorbed on the tailings will undergo natural degradation and ultimately produce NH_4-N.

3. CNS and NH_4-N leaching was observed at higher concentrations in the porewater and at the column base compared to the water cover over sulfide, oxide and mixed tailings. In the flow through columns, CNS leached in approximately 30 days. The flow through column results suggests that NH_4-N leaching is likely to continue even after CNS leaching is complete.

4. The column results show that As, Mn and possibly Sb are susceptible to leach from the tailings. Oxide silt tailings are likely to leach higher amounts of As, Mn and possibly Sb compared to sulfide silt tailings.

5. Data collected from this study indicate that leaching rates will generally be in the following decreasing order: SO_4 > CNS > NH_4-N > As > Sb > Zn > Cu.

6. Total and WAD CN, CNS, CNO, and NH_4-N are likely to continue leaching from the current tailings impoundment. The movement of tailing to a new location in a slurry form may result in undesirable impacts on the quality of the water overlying the tailings.

6.0 RECOMMENDATIONS FOR FURTHER WORK

In order to fully understand the long-term leaching behaviour and disposal options, further work on the following aspects is recommended.

1. The column test work has been conducted at room temperature. The leaching rates estimated and observed may not be truly representative of the leaching rates taking place in the field. It is recommended to construct a model experiment at the site in order to obtain leaching profile and rates representative of the site conditions.

2. Leaching of cyanide and its related species and degradation products such as CNS, CNO and NH_4-N is likely to continue for sometime. It is therefore recommended to review and test technologies that will be effective in treating water containing undesirable amounts of toxic cyanide and related species.

3. It is recommended to study the impact of dissolved oxygen and redox potential on the release of cyanide and its species, As, Sb and Mn in simulated batch tests at controlled temperature conditions.

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APPENDIX A

Sulfide Tailings Columns

APPENDIX B

Oxide Tailings Columns

APPENDIX C

Mixed Tailing Slurry Columns

APPENDIX D

Mixed Tailings Flow Through Columns