



## Long-term evaluation of coal fly ash and mine tailings co-placement: A site-specific study

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### ABSTRACT

This study presents the results of a laboratory investigation conducted to evaluate the efficiency of coal fly ash to control the formation of acid mine drainage (AMD) from mine waste. Site-specific materials, coal fly ash from Atikokan Thermal Generating Station and mine tailings from Musselwhite mine, were mixed at different proportions for the investigation of the drainage chemistry and the optimal mix using static testing (acid–base accounting) and kinetic (column) testing. The acid–base accounting (ABA) results indicated that the fly ash possessed strong alkaline (neutralization) potential (NP) and could be used in the management of reactive mine tailings, thus ensuring prevention of AMD in the long-term. Column tests conducted in the laboratory to further investigate long-term performance of fly ash in the neutralization and prevention of acid mine drainage from tailings similarly showed that mixing fly ash with mine tailings reduces dissolution of many heavy metals from tailings by providing alkalinity to the system. It was found that a fly ash to tailings mass ratio equal to or greater than 15% can effectively prevent AMD generation from Musselwhite mine tailings in the co-placement approach.

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### 1. Introduction

Understanding the physico-chemical properties of mine wastes and predicting their long-term leaching behavior are critical for assessing the long-term environmental impact of mining at a site and for choosing a waste management method to minimize that impact (Benzaazoua et al., 2004; Ritcey, 1989). Given that mineralogy and other factors affecting acid mine drainage (AMD) formation are highly variable from site to site, predicting the potential for AMD can be exceedingly challenging and costly (U.S. EPA, 1994). Static and kinetic tests have been developed and are used on a regular basis, primarily to establish if and when a given material will generate acid. Static tests are designed to determine the overall balance between acid generating and acid neutralizing minerals, and the results provide a preliminary indication of whether a sample is likely to produce acidic drainage in the environment (Sobek et al., 1978; Price et al., 1997). Acid–base accounting (ABA) is the most commonly used static test to predict acid mine drainage from mine wastes. The acid–base accounting evaluates the balance between acid generation processes (oxidation of sulfide minerals) and acid neutralizing processes

(dissolution of alkaline carbonates, displacement of exchangeable bases, and weathering of silicates) (Sobek et al., 1978; Ritcey, 1989). Static tests are fast and cost-effective, but are considered qualitative and have a relatively large uncertainty zone for which it is impossible to state on the long-term acid generation potential (Morin and Hutt, 1994).

Kinetic tests involve weathering of samples under laboratory or on-site conditions, in order to potentially generate net acidity, to determine the rate of acid formation, sulphide oxidation, neutralization, metal dissolution, and to test control and treatment techniques (Campbell et al., 2001). Humidity cells and column tests are the most commonly used kinetic tests. It is generally accepted that leaching column tests tend to simulate actual field conditions more closely than humidity cells (Bradham and Caruccio, 1990). However, achieving the desired observation takes months and may be years (MEND, 1989). Due to the complexity of the physical, chemical and biological processes involved in producing and neutralizing AMD, no individual test (static or kinetic) alone has proven completely adequate, and a combination of static and kinetic methods is usually relied upon to increase prediction accuracy (Filipek et al., 1999; Schafer, 2000).

Various techniques have been developed to prevent AMD formation. One of such techniques is the addition of alkaline materials, by either mixing with the acid generating mine waste or concentrated placement, to inhibit acid formation and to neutralize

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any generated acidity in situ. Various alkaline materials such as limestone, lime, sodium bicarbonate, red mud, and lime kiln dust have been used to control acid mine formation from mine wastes. According to Mylona et al. (2000), limestone (a commonly used alkaline material) may control pyrite oxidation through one or a combination of the following mechanisms: (i) raising the pH of pore water to high values ( $\text{pH} = 6.1\text{--}8.4$ ), thus impairing the activity of the iron oxidizing bacteria *Thiobacillus ferrooxidans* (Nicholson et al., 1988); (ii) enhancing the precipitation of ferric iron in the hydroxide form, thus inhibiting further participation as an oxidizing agent in the dissolution of pyrites (Kelley and Tuovinen, 1988); (iii) enhancing the precipitation of oxidized compounds on the sulphides surface. It is reported that when carbonate minerals are present and available to neutralize the acid produced during the oxidation of pyrite, a protective ferric oxy-hydroxide layer will accumulate around the pyrite grains, impairing its further dissolution (Nicholson et al., 1990); and (iv) enhancing the formation of cemented layers (hardpan) on the stockpile surface. The hardpan consists of the oxidation–neutralization products such as ferric oxy-hydroxide and gypsum that cement the tailings together forming a low permeability mass that acts as an oxygen and water diffusion barrier (Blowes et al., 1991; Tasse et al., 1997).

Fly ash has been mixed with mine tailings to control mine tailings oxidation due to its alkaline nature. Ciccù et al. (2003) evaluated the use of fly ash, red mud and bauxite ores for immobilizing metallic and metalloid elements contained in severely contaminated soil samples taken from a tailings pond. Addition of fly ash or red mud, or a combination of the two, to contaminated soils drastically reduced the heavy metal concentrations from effluents, as observed from results of columns containing the mixtures of the additives and the contaminated soil. Studies have also been conducted into the use of fly ash in conjunction with lime for preventing the formation of acidity in sulphidic soils (Golab et al., 2006; Indraratna et al., 2006). Perez-Lopez et al. (2007a,b) similarly showed that addition of fly ash to a mining residue from the Iberian Pyrite Belt resulted in acid neutralization, metal retention in neoformed precipitates, and therefore, the improvement of the quality of the leachates. Under these conditions, Fe-precipitation formed a coating on pyrite surfaces (microencapsulation technology) that may prevent interaction between oxidizing agents and pyrite grains, thus halting pyrite oxidation and AMD production (Pérez-López et al., 2007c). The research conducted by Bayat (1998) also indicated that coal fly ash has potential applications in mine tailings management in view of its chemical and mineralogical properties making the ash a good alkaline binding agent and a possible substitute for gypsum, anhydrite, lime or limestone.

Economic and environmental considerations play a major role in the rapid increase for usages of by-products such as fly ash for various environmental applications such as mine waste management (Yeheyis et al., 2008). Utilization of fly ash reduces disposal costs while actually increasing revenues through the sale of fly ash. The main cost component of coal fly ash is transportation. Moreover, utilization of fly ash for mine waste management can reduce green house gas emission by replacing other alkaline materials such as cement/lime which normally contribute  $\text{CO}_2$  during their production.

In this study, the effectiveness of mixing coal fly ash (alkaline producing material) with mine tailings (acid producing material) to mitigate acid mine drainage was evaluated. The study had three specific objectives; namely, first, to characterize the Musselwhite mine tailings and its acid generation potential; second, to examine whether mixing coal fly ash with mine tailings would affect the overall net neutralization potential, and to determine the optimum fly ash–tailings mixture using static test (acid–base accounting);

and third, to evaluate the long-term performance of the fly ash in the neutralization and prevention of acid mine drainage using column testing.

## 2. Materials and experimental methods

### 2.1. Materials

This study is a site-specific study carried out to assess the suitability of utilizing Atikokan coal fly ash in the management of reactive Musselwhite mine tailings. Atikokan coal fly ash (AFA) is collected directly from the Atikokan Thermal Power Generating Station (Atikokan TPGS) precipitators, which is a lignite coal-fired 200 MW generating facility, located in northwestern Ontario. Musselwhite mine tailings (MT) is obtained from the Musselwhite Mine; a gold mine located 400 km North of Atikokan TPGS. At present, 4000 tonnes of tailings are produced daily and it is projected that more than 20 million tonnes of tailings would be produced by 2012. Currently much of the tailings are disposed under water in a nearby tailings pond. The capacity of the basin under water cover is 13 million tonnes, which means alternative methods for tailings disposal must be implemented for the remaining tailings that will be produced. Co-disposal of the remaining mine tailings with coal fly ash from Atikokan was investigated in this study as one of the alternatives for the on-land disposal of the mine tailings.

### 2.2. Experimental methods

#### 2.2.1. Bulk geochemical and mineralogical compositions

The bulk composition and mineralogy of mine tailings and fly ash materials were studied since both are important in predicting long-term performance during co-placement. The chemical composition (major oxides and trace elements) of AFA and MT samples was determined using X-ray fluorescence spectrometry (XRF), and inductively coupled plasma atomic emission spectrometry (ICP-AES). X-ray diffraction (XRD) spectra of the powder mounts of the AFA and MT were obtained by using a Rigaku powder diffractometer, equipped with a rotating anode and a Co-K $\alpha$  source, operated at 160 mA and 45 kV. The samples were scanned from  $2^\circ$  to  $82^\circ 2\theta$  at a rate of  $10^\circ 2\theta/\text{min}$  and a step size of  $0.02^\circ 2\theta$ .

#### 2.2.2. Geochemical static test (acid–base accounting method)

The acid–base accounting method is conducted on mine tailings and mine tailings–fly ash mixtures to evaluate the effect of coal fly ash on the net neutralization potential of the mixtures, as well as to determine how much coal fly ash is needed to neutralize all of the acid that could potentially be produced from the mine tailings. The procedure used involves a laboratory static test that measures the acid producing potential (AP) and the inherent neutralization potential (NP) of a sample. Mixtures of mine tailings and coal fly ash were prepared, which contained 0, 2.5, 5, 7.5, 10, 12.5, 15, 20, 30, 40 and 50% dry coal fly ash (w/w). The AP of each sample was determined by multiplying the percent of sulphide sulfur (%S) in the sample by a conversion factor ( $\text{AP} = 31.25 \times \%S$ ), assuming 1%S requires approximately 31.25 kg of  $\text{CaCO}_3$  per tonne of material for neutralization (Sobek et al., 1978). The sulphide sulfur in coal fly ash was also assumed to contribute to acid formation and it is included during the calculation of AP of the fly ash–tailings mixtures.

The neutralization potential (NP) of each sample was determined by using the modified Sobek method (Lawrence and Wang, 1997). The NP was determined first by giving each sample a fizz rating (none, slight, moderate, or strong) in order to determine the amount and concentration of acid required to be used in the test. Each sample was then reacted with a known and standardized

amount of hydrochloric acid. The mixture was then shaken for 24 h and back titrated with NaOH to determine how much acid had been consumed by the samples. The net neutralization potential (NNP) or acid–base accounting (ABA) was determined by subtracting the AP from the NP ( $NNP = NP - AP$ ), and used to determine the optimum amount of fly ash needed to provide sufficient alkalinity to neutralize the acidity produced by sulphide oxidation from the mine tailings.

Paste pH tests were also performed on tailings–fly ash mixtures to obtain preliminary information on immediate reactivity of minerals present in each sample using the Sobek procedure (Sobek et al., 1978). Approximately 10 g of sample from each mix was saturated with 10 mL of de-ionized water (1:1 solid:solution ratio) to make a paste. The paste pH was then measured by inserting the pH electrode in to the paste.

### 2.2.3. Kinetic column test

To better simulate the field weathering and evaluate the long-term effect of fly ash addition on the chemistry of mine tailings, four identical translucent PVC laboratory-scale columns (internal diameter 15 cm and height 40 cm) were used. The tops of the columns were open to the atmosphere, and the bottoms were sealed with a PVC lid with a drain outlet in the bottom to allow leachate drainage. The base of each column was equipped with fine mesh grid and geotextile filter to retain solids while allowing leachate to drain. The schematic of the column is shown in Fig. 1.

The columns were packed with approximately 6 kg of air dried mine tailings or fly ash–mine tailings mixtures. One column, which is also referred to as column 1 (C-1) loaded with mine tailings only without any fly ash addition, was used as reference or control column. The other three columns, which are also referred to as column 2 (C-2), column-3 (C-3) and column-4 (C-4), contained homogeneous mixtures of fly ash and tailings containing 2%, 8% and 15% of fly ash (dry weight), respectively. The columns were then watered at the top with 250 mL of distilled water on a batch basis once a week to mimic the annual average precipitation of the study area (maximum annual precipitation of 724 mm). The leachant remained in contact with the solid residue for 48 h and kept dry for the following 5 days on a weekly basis. This simulates the natural weathering process (wet–dry cycle) in order to study the behavior of the tailings/fly ash mixture under unsaturated conditions. The leachant from each column was allowed to flow down through the

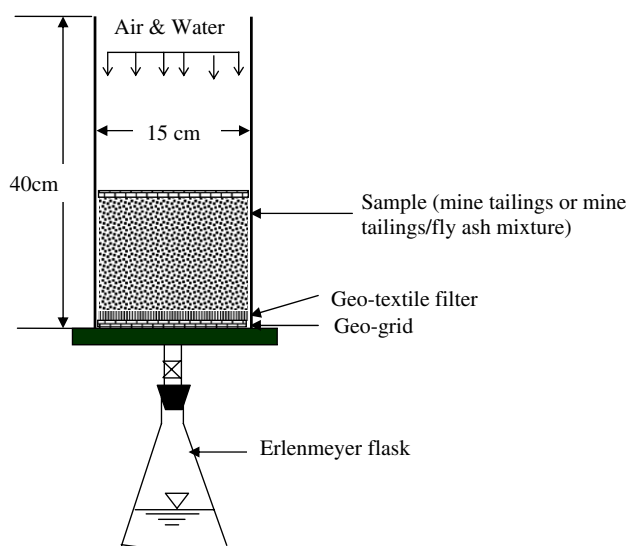


Fig. 1. Schematic of the column design used to evaluate the effect of fly ash addition on oxidation and metal release from mine tailings.

column of material by gravity and was collected in a closed 2-L flask located under the wooden table on which the columns were placed.

Column effluent samples were collected once a week, at the end of the previous cycle and just prior to the next feeding. Leachate was collected and analyzed over the 20-month period. The samples were filtered through 0.45  $\mu\text{m}$  filter papers. During sampling, each sample was split into two portions. One portion was used for the measurement of pH, electrical conductivity and sulphate. The second portion was acidified with nitric acid to pH less than 2 and was stored in a cold room until ICP-OES analysis for metals of interest.

Geochemical modeling was conducted to investigate the possibility of metal precipitation and formation of secondary minerals during the weathering experiment. The geochemical equilibrium model Visual MINTEQ version 2.50 (Gustavsson, 2006), a Windows based version of MINTEQA2 (Allison et al., 1991), was used for saturation indices calculation. The saturation index (SI) for an aqueous solution with respect to a mineral indicates the thermodynamic tendency to precipitate or to dissolve certain phases. The saturation index is defined by:

$$SI = \log(IAP/K_{sp})$$

where IAP is the ion activity product calculated from the water sample, and  $K_{sp}$  is the theoretical solubility product, both adjusted to the temperature of the sample. A negative value of the saturation index indicates that the solution is undersaturated with respect to a particular solid phase and that the solid phase would tend to dissolve if present, whereas a positive value indicates the tendency for a mineral to precipitate. A value close to zero suggests that the mineral is in equilibrium in the solution and may either precipitate or dissolve.

## 3. Results and discussions

### 3.1. Bulk geochemical and mineralogical compositions

The chemical composition (major oxides and trace elements) of Musselwhite mine tailings and Atikokan fly ash are summarized in Table 1. As shown in the table, the tailings consist mainly of Si, Fe, and Al as indicated by the major oxide composition of  $\text{SiO}_2$  (46.2%),  $\text{Fe}_2\text{O}_3$  (35.60%) and  $\text{Al}_2\text{O}_3$  (8.16%). The tailings also contain high concentration of heavy metals and sulfur, which could be a concern if they oxidize. Mineralogical analysis using X-ray diffractometry revealed that the major minerals present in Musselwhite tailings are quartz, chlorite, pyrite, calcite, dolomite, and feldspar (Fig. 2a).

The physico-chemical properties and environmental evaluation of Atikokan coal fly ash for environmental applications are described in detail in Yeheyis et al. (2008). The major constituents of the fly ash are also  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{Fe}_2\text{O}_3$  and CaO. The predominant portion of fly ash sample is poorly crystalline, as shown by a broad diffraction hump between  $2\theta = 15^\circ$  and  $2\theta = 35^\circ$ , with the small crystalline portion of the AFA consisting mainly of quartz, mullite, and traces of calcite, hematite, magnetite and hydrated Ca-sulfate (Fig. 2b).

### 3.2. Geochemical static test results

Fig. 3 shows the paste pH and NNP of tailings–fly ash mixtures plotted as a function of fly ash addition. The paste pH of MT is near neutral mainly due to the addition of lime during the milling process and the presence of carbonates. However, addition of fly ash to mine tailings increased the paste pH of the mixture. The paste pH increased appreciably when the fly ash content increased from 0% to 15%, but increased less as the fly ash content increased

**Table 1**  
Chemical composition of Musselwhite mine tailings and Atikokan fly ash.

Element/compound	Musselwhite mine tailings	Atikokan fly ash
<i>Major oxides (wt. %)</i>		
SiO <sub>2</sub>	46.72	41.50
TiO <sub>2</sub>	0.40	0.71
Al <sub>2</sub> O <sub>3</sub>	8.16	18.91
Fe <sub>2</sub> O <sub>3</sub>	35.60	6.31
MnO	0.46	0.03
MgO	3.47	3.66
CaO	3.34	16.41
K <sub>2</sub> O	0.58	0.86
Na <sub>2</sub> O	0.003	9.12
P <sub>2</sub> O <sub>5</sub>	0.13	0.41
Cr <sub>2</sub> O <sub>3</sub>	0.017	0.003
LOI <sup>a</sup>	–	0.40
Total	98.88	94.27
<i>Minor and Traces (mg/kg)</i>		
Arsenic	151.0	44.2
Barium	89.0	8570.0
Boron	173.0	1800.0
Cadmium	13.7	8.2
Chromium	40.8	32.6
Cobalt	7.0	5.1
Copper	102.0	39.0
Lead	118.0	110.0
Molybdenum	5.3	27.0
Manganese	312.0	158.0
Nickel	38.5	23.5
Vanadium	47.9	110.0
Zinc	26.5	46.7
Total sulfur	11900.0	6670.0

<sup>a</sup> LOI = Loss on ignition.

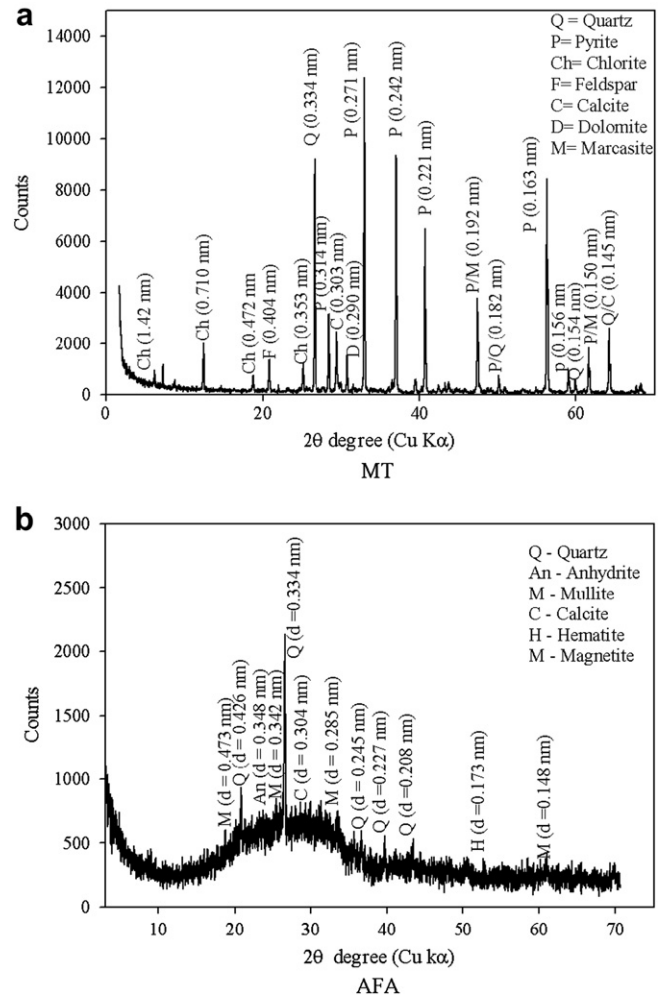
from 15% to 50%. The increase in pH of the mine tailings–fly ash mixture is attributed mainly due to dissolution and hydrolysis of CaO and other major alkali contributing oxides (MgO, Na<sub>2</sub>O, and K<sub>2</sub>O) originally present in fly ash.

Theoretically, a negative net neutralization potential (NNP) indicates that the waste has the potential to generate acid while a positive net neutralization potential indicates that the waste will not generate acid. However, the issue of what values are “safe” to adopt to classify a mine waste as non-acid-generating is not clear-cut and is a source of great controversy. In cases where NNP falls between –20 and +20 kg CaCO<sub>3</sub>/t, the material may be classified as “uncertain” and further kinetic tests are warranted (Brady and Cravotta, 1992; Lapakko, 1992). The NNP of Musselwhite mine tailings was –18.46 kg CaCO<sub>3</sub>/t, which is close to the lower boundary value (–20 kg CaCO<sub>3</sub>/t) of the ABA test “uncertainty” zone. In addition, sign of oxidation has been observed on the in-situ Musselwhite tailings disposal site, which further increase the need to take action to prevent tailings oxidation and AMD generation.

As shown in Fig. 3, addition of coal fly ash to Musselwhite tailings increased the neutralization potential of the mixture and resulted in much higher net neutralization potential, thus ensuring the prevention of acid generation in the long term. For example, the NNP of mine tailings increased from –18.46 kg CaCO<sub>3</sub>/t to 0 kg CaCO<sub>3</sub>/t due to the addition of 8% fly ash, showing the tailings–fly ash mixture may or may not produce AMD. Error bars have been included to reflect the uncertainty range during ABA interpretation of NNP (a standard deviation of ±20 kg CaCO<sub>3</sub>/t). Based on ABA results and interpretation, at least 13% of Atikokan fly ash is required to be added to Musselwhite mine tailings to obtain a non-acid-generating mixture.

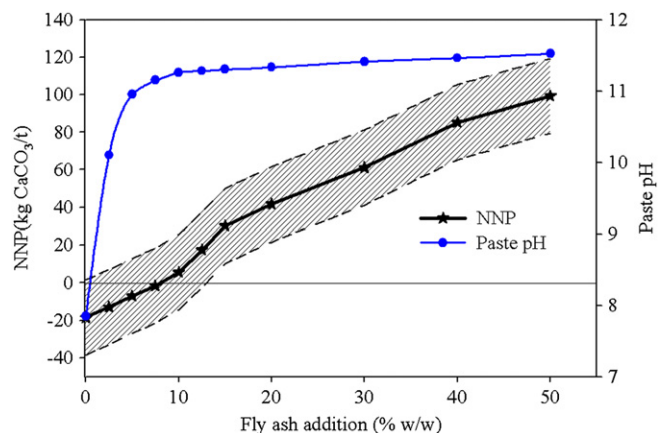
### 3.3. Column test results

In addition to the control column (C-1) which contained only mine tailings, the fly ash–tailings mix ratios of the remaining three



**Fig. 2.** X-ray diffraction patterns of Musselwhite mine tailings (MT) and Atikokan fly ash (AFA).

columns were chosen based on the results of the ABA tests. Column 2 (C-2) contained 2% fly ash added to the tailings and corresponded to an NNP value of –15.5 kg CaCO<sub>3</sub>/t, which is slightly higher than the lower boundary value (–20 kg CaCO<sub>3</sub>/t) and falls in the “uncertainty” zone of the ABA tests. Column-3 (C-3) contained 8%



**Fig. 3.** Paste pH and NNP of Musselwhite mine tailings–Atikokan coal fly ash mixture (error bars show NNP standard deviation of ±20 kg CaCO<sub>3</sub>/t).

dry weight fly ash, and corresponds to an NNP of 0 kg CaCO<sub>3</sub>/t. The fourth column (C-4) contained 15% fly ash added to tailings and corresponds to an NNP value of 30.14 kg CaCO<sub>3</sub>/t, which is slightly higher than the upper boundary value (+20 kg CaCO<sub>3</sub>/t) in the “uncertainty” zone of acid–base accounting results. The column tests ran for a total of 80 weeks, and the results of the leachate chemistry are presented below.

### 3.3.1. pH, conductivity and sulphate

Fig. 4 shows the pH of leachate solutions from columns containing mine tailings with and without fly ash as a function of weathering (leaching) time (weeks). Comparisons between the columns show that the effluent pH from fly ash amended columns is generally higher than that of the control column containing mine tailings only; indicating that addition of fly ash has contributed long-term alkalinity to the system. It is noted that the effluent pH from the control column (C-1) remained near neutral due to the presence of calcite and dolomite and the addition of lime to mine tailings during milling. The pH of the effluent from fly ash amended tailings showed a significant drop especially during the first 40 weeks of the tests. This drop in pH is due to the dissolution or depletion of alkaline materials from fly ash. The pH of effluent from columns containing lower fly ash to tailings ratios (C-2 and C-3) decreased faster than that of C-4 which remained well above pH 8 throughout the test period. Although the static method is generally considered a conservative approach in predicting acid drainage formation, the mixture containing 15% fly ash can be considered a safe choice due to the depletion of alkalinity from fly ash in the other columns that contained lower fly ash ratio to tailings mix ratio.

Figs. 5 and 6 show the electrical conductivity and sulphate concentrations measured in the leachates from columns plotted versus the weathering time (weeks). In the early weeks of weathering (leaching) test, both electrical conductivity and sulphate from all samples decreased significantly before stabilizing after 5 weeks. This is due to the dissolution of readily soluble salts present in the fly ash and tailings materials. The slight decrease in pH as well as the slight increase in electrical conductivity and sulphate in the control column after 65 weeks of weathering could indicate increase in tailings oxidation. The results suggest that a fly ash–tailing mixture containing 15% Atikokan fly ash is required in order to decrease the formation of acid mine drainage in Musselwhite mine tailings.

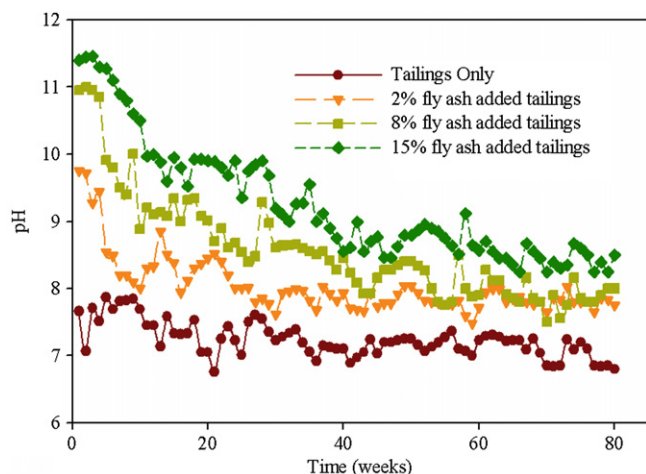


Fig. 4. Temporal variation of pH from tailings columns amended with and without fly ash.

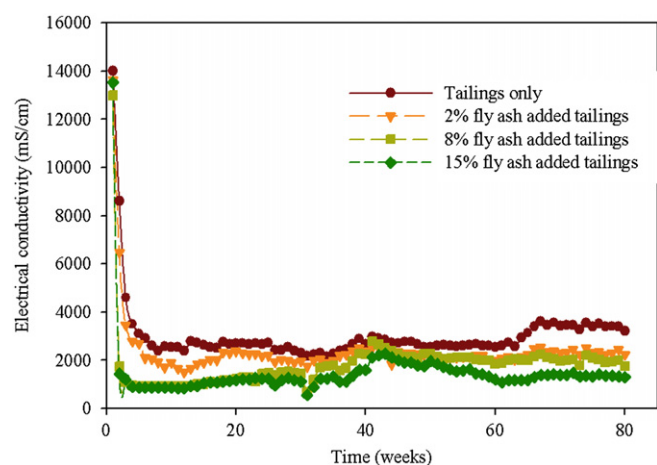


Fig. 5. Temporal variation of electrical conductivity from tailings columns amended with and without fly ash.

### 3.3.2. Leachate trace metal concentration

Fig. 7a–f show the concentrations of trace elements in effluents monitored during weathering. The concentrations of the investigated heavy metals were generally found to be lower in columns containing fly ash amended tailings compared to the control column containing tailings only. Given that Atikokan fly ash has a significant amount of calcium oxide and is classified as Class C fly ash, the calcium oxide could react with the siliceous and aluminous materials (pozzolans) of the fly ash itself and form cementitious materials (calcium–silicate–hydrate (CaO·SiO<sub>2</sub>·H<sub>2</sub>O) and calcium–alumina–hydrate (CaO·Al<sub>2</sub>O<sub>3</sub>·H<sub>2</sub>O)), which could be responsible for stabilization of contaminants from mine tailings (Yeheyis et al., 2007). Unlike other regulated metals, the concentration of chromium from fly ash amended tailings was slightly higher compared to the control column due to additional chromium added from fly ash. However, the concentrations of chromium in the leachate from all columns were below the Ontario Regulation 558 (MOE, 2000) leachate criteria limit of 5 ppm.

Furthermore, geochemical modeling of the leachate composition during the weathering period using visual MINTEQA2 showed the possibility of metal precipitation and formation of secondary minerals mainly in fly ash amended tailings columns. Generally, the geochemical calculations indicated similar secondary mineral

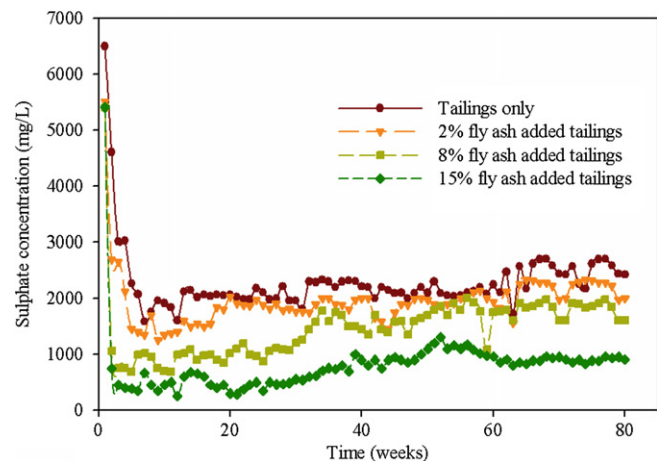


Fig. 6. Temporal variation of sulphate from tailings columns amended with and without fly ash.

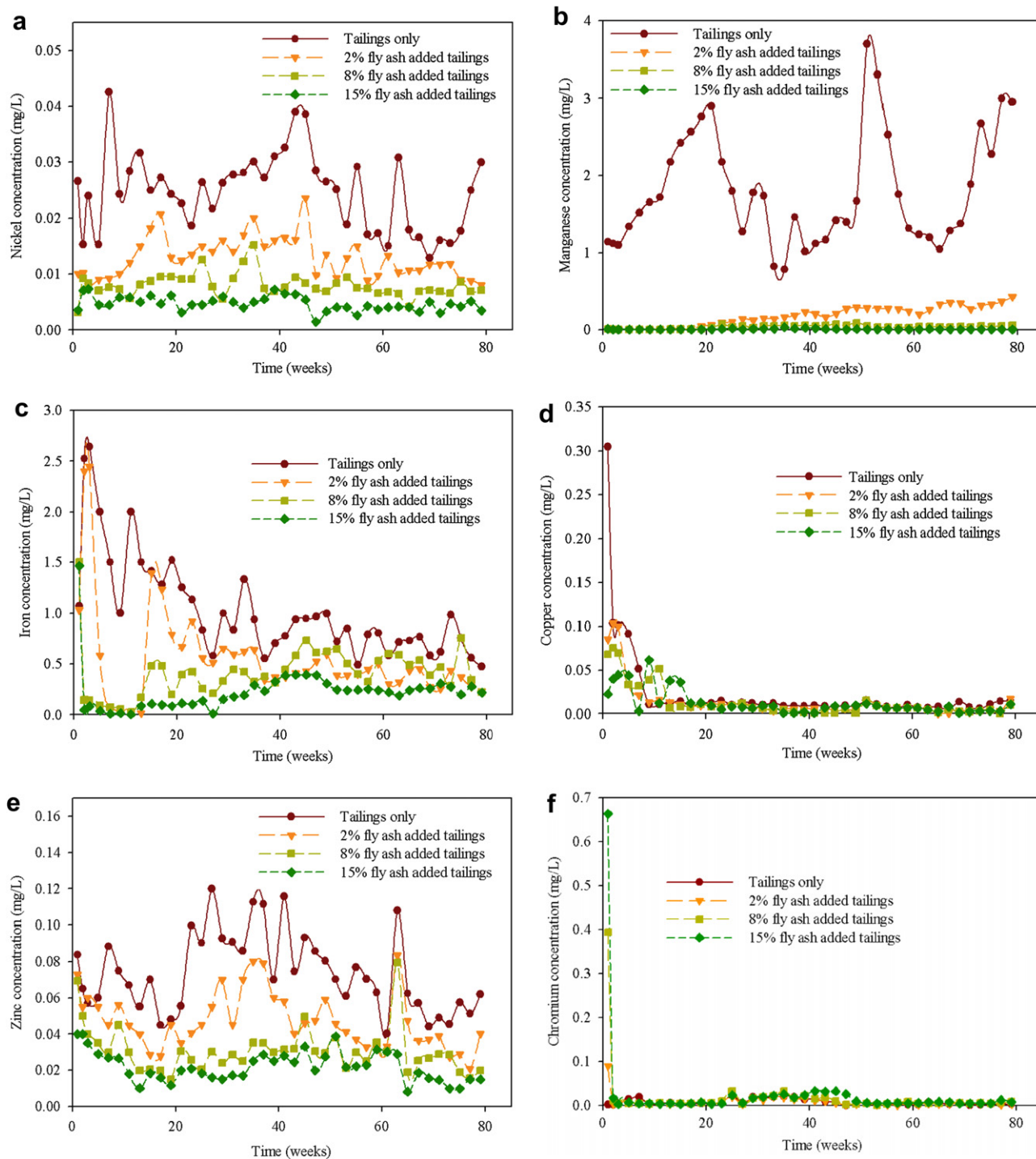


Fig. 7. Concentrations of trace elements in effluents monitored during weathering. (a) Ni; (b) Mn; (c) Fe; (d) Cu; (e) Zn; and (f) Cr.

formations in all fly ash amended samples, except that higher saturation indices correspond to higher fly ash–tailings mix ratios. As a result, geochemical modeling results and discussion of the effluent chemistry are presented for control column (C-1) and the mixture containing 15% fly ash sample only (C-4).

Table 2a and b present the calculated saturation indices (SI) for some minerals that can affect the solubility of metals from C-1 and C-4, respectively. As indicated in Table 2a, the control column was

generally undersaturated with respect to the various minerals examined. However, the leachate from the control column was close to or oversaturated with respect to gypsum ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ) throughout the test. The formation of gypsum was also observed in similar laboratory column study by Perez-Lopez et al. (2007a) but only at the onset of the experiment. In early weeks of weathering test, the leachate from control column was near or at saturation with respect to brochantite ( $\text{Cu}_4(\text{SO}_4)(\text{OH})_6$ ), and crystallized

**Table 2**

Summary of saturation indices of minerals as predicted by vMINTEQ for (a) control column (C-1) and (b) 15% fly ash amended tailings (C-4).

Week	Brochantite	Cr(OH) <sub>2</sub>	Cu(OH) <sub>2</sub>	Fe(OH) <sub>2</sub> (am)	Fe(OH) <sub>2</sub> (c)	Ni(OH) <sub>2</sub> (c)	Tenorite (c)
<i>a. Control column (C-1)</i>							
1	3.66	-5.65	-0.32	-3.88	-3.17	-2.64	1.32
3	2.49	-5.13	-0.50	-3.07	-2.47	-2.39	1.15
7	1.85	-4.44	-0.55	-2.98	-2.38	-1.81	1.10
11	-2.46	-5.39	-1.82	-3.60	-3.00	-2.74	-0.17
15	-2.68	-5.51	-1.94	-4.00	-3.40	-3.04	-0.29
19	-4.46	-5.89	-2.54	-4.54	-3.94	-3.63	-0.89
23	-2.04	-5.26	-1.74	-3.91	-3.31	-2.97	-0.09
27	-1.45	-5.16	-1.51	-3.86	-3.26	-2.56	0.14
31	-3.49	-5.02	-2.16	-4.32	-3.72	-3.08	-0.51
35	-4.99	-5.19	-2.68	-4.77	-4.17	-3.55	-1.03
39	-4.73	-5.30	-2.59	-4.81	-4.21	-3.44	-0.94
43	-5.19	-5.59	-2.72	-4.76	-4.16	-3.43	-1.07
47	-4.13	-6.97	-2.37	-4.43	-3.83	-3.25	-0.72
51	-3.51	-5.68	-2.25	-4.67	-4.07	-3.41	-0.60
55	-3.94	-5.78	-2.30	-4.59	-3.99	-3.10	-0.65
59	-5.06	-6.24	-2.71	-4.92	-4.32	-3.88	-1.06
63	-4.10	-5.41	-2.31	-4.37	-3.77	-3.02	-0.66
67	-5.88	-5.98	-2.90	-4.82	-4.22	-3.76	-1.25
71	-6.43	-6.71	-3.15	-5.40	-4.80	-4.26	-1.50
75	-3.89	-5.87	-2.34	-4.61	-4.01	-3.51	-0.69
79	-5.28	-6.22	-2.86	-5.49	-4.89	-3.97	-1.21
<i>b. 15% Fly ash amended tailings (C-4)</i>							
1	-5.30	0.66	-0.67	1.34	1.94	0.41	0.98
3	-5.12	-1.57	-0.37	0.08	0.68	0.65	1.28
7	-6.49	-2.00	-1.04	-0.51	0.09	0.75	0.61
11	-0.41	-3.05	0.05	-2.46	-1.86	1.04	1.70
15	1.66	-3.08	0.53	-0.13	0.47	1.02	2.18
19	-0.30	-2.73	0.06	-0.24	0.37	1.02	1.71
23	-1.23	-3.22	-0.29	-0.52	0.08	0.79	1.36
27	-1.08	-2.87	-0.16	-1.28	-0.68	0.91	1.49
31	0.74	-3.12	-0.10	-1.24	-0.64	-0.06	1.55
35	-3.57	-2.56	-0.99	-0.31	0.30	0.61	0.66
39	-1.65	-3.39	-0.92	-1.71	-1.11	-0.66	0.73
43	0.09	-3.48	-0.52	-1.98	-1.38	-1.08	1.13
47	0.29	-3.65	-0.54	-2.17	-1.57	-2.05	1.11
51	1.51	-3.87	-0.08	-1.63	-1.03	-0.69	1.57
55	0.23	-4.07	-0.45	-1.84	-1.24	-1.04	1.20
59	0.41	-4.17	-0.45	-2.03	-1.43	-1.09	1.21
63	-0.85	-4.22	-0.84	-2.49	-1.89	-1.45	0.81
67	0.60	-3.95	-0.37	-1.94	-1.34	-1.16	1.28
71	-1.41	-4.43	-1.02	-2.42	-1.82	-1.72	0.63
75	-1.14	-4.22	-0.85	-2.19	-1.59	-1.17	0.80
79	0.55	-4.37	-0.60	-2.85	-2.25	-2.00	1.05

am = amorphous; c = crystallized.

tenorite. Due to the strong alkaline nature of Atikokan fly ash, the leachate from fly ash amended tailings was at or near saturated with respect to various metal oxides and hydroxides examined (Table 2b). Model calculations indicate that leachates from fly ash amended tailings are at or near equilibrium ( $-2.05 \leq SI \leq 1.04$ ) with respect to crystallized nickel Ni(OH)<sub>2</sub> suggesting nickel hydroxide is among the dominant phases controlling the concentration of nickel. The leachate is also oversaturated ( $0.61 \leq SI \leq 2.18$ ) with respect to crystallized tenorite (CuO), at or near to equilibrium with respect to copper hydroxide (Cu(OH)<sub>2</sub>), brochantite (Cu<sub>4</sub>(SO<sub>4</sub>)(OH)<sub>6</sub>), and antlerite (Cu<sub>3</sub>SO<sub>4</sub>(OH)<sub>4</sub>). The leachate is also saturated or slightly oversaturated with respect to both crystallized and amorphous iron hydroxide (Fe(OH)<sub>2</sub>) during the first 23 weeks or so, after which time, slight under saturation occurred. The geochemical modeling results also showed that gypsum (CaSO<sub>4</sub>·2H<sub>2</sub>O) was the only mineral found in the leachate from the control column to be at near or saturation condition.

#### 4. Conclusions

This paper presents the results of laboratory investigation conducted to evaluate the effectiveness of coal fly ash in controlling the formation of acid mine drainage (AMD) from mine waste. A coal fly

ash from Atikokan thermal generating station and tailings from Musselwhite mine, were mixed at different proportions and the leachate chemistry and the optimal mix were investigated using static testing (acid–base accounting) and kinetic (column) testing. The acid–base accounting (ABA) results indicate that Atikokan fly ash possessed strong alkaline (neutralization) potential (NP) and can be used in the management of reactive mine tailings, thus ensuring prevention of AMD in the long-term and subsequent release of heavy metals into the environment. Column tests conducted in the laboratory to further investigate the long-term performance of fly ash in the neutralization and prevention of acid mine drainage of tailings similarly showed that mixing fly ash with mine tailings reduces dissolution of some heavy metals from tailings by providing alkalinity to the system. It was found that a fly ash to tailings mass ratio equal or greater than 15% can effectively control AMD generation on the Musselwhite mine tailings disposal facility.

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