Design and implementation of a field pilot study on using coal fly ash to prevent oxidation of reactive mine tailings

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ABSTRACT
A pilot scale study was conducted on the Musselwhite Mine site to verify the effectiveness of the coal fly ash application to control AMD generation. This paper describes the principles and key aspects of the fly ash application in mine tailings management. The Atikokan fly ash was added to the Musselwhite tailings as a mixture as well as intermediate and/or top layers. The physical, chemical and hydro-geological effects of the two approaches were monitored. The details of the design, implementation, monitoring, sampling and testing over two years are presented.

RÉSUMÉ
A l'échelle pilote, une étude a été menée sur le site de la mine Musselwhite pour vérifier l'efficacité de l'utilisation des cendres volantes de charbon de contrôle AMD à partir de résidus miniers. Ce document décrit les principes et les principaux aspects de l'application des cendres volantes de charbon dans la gestion des résidus miniers. Les cendres volantes Atikokan ont été ajoutées à la Musselwhite comme un mélange de résidus et aussi comme intermédiaires et / ou couches supérieures. Les effets physiques, chimiques et hydro-géologiques de ces deux approches ont été observés. Les détails de conception, de mise en œuvre, de suivi, d'échantillonnage et d'essai sur une période de deux ans sont présentés.

1 INTRODUCTION

The oxidation of reactive mine tailings and subsequent generation of acid mine drainage (AMD) have long been recognized as the largest environmental concern for the mining industry. Coal fly ash is a solid residue from coal combustion in coal-fired power generating facilities. The use of coal fly ash in mine tailings management and AMD treatment shows promise in the literature (Xenidis et al., 2002; Shang et al., 2006; Wang et al., 2006). The addition of coal fly ash is shown to reduce water infiltration, stabilize the heavy metals and control AMD generation. A pilot scale study at the Musselwhite Mine site in northwestern Ontario is undertaken to investigate the beneficial use of coal fly ash in reactive mining tailings management.

The Musselwhite Mine is about 500 km north of Thunder Bay. Currently, the mine is owned and operated by Goldcorp Canada Ltd. The Musselwhite Mine has an expected mine life through to 2026. The mining/milling processes produce a large amount of tailings. It is projected that about 37 million tonnes of mine tailings will be generated by 2026. The tailings storage capacity of the existing tailings pond on the mine site is about 17 million tonnes. Using current tailings disposal methods, the tailings pond will run out of storage space by 2011. The remaining tailings will be stockpiled above the water table in a basin and covered with a non-acid generating solid material. The net neutralization potential of Musselwhite tailings (MT) from acid-base accounting tests is -18 kg $CaCO_3$/t, indicating the acid generating nature of the tailings (Yeheyis, 2008). Signs of oxidation have been observed after more than three years of tailings disposal on the beach of the tailings pond. Therefore, materials of an alkaline nature should be used to prevent tailings oxidation and AMD generation. Coal fly ash is a suitable material for this purpose based on previous studies (Shang et al., 2006; Wang et al., 2006; Yeheyis, 2008).

The overall objectives of the collaborative research program are to develop and evaluate the different approaches of coal fly ash in the control of tailings oxidation and AMD generation. Specific objectives for the evaluation include: optimum mass ratio of coal fly ash and mine tailings, effectiveness in reducing the infiltration of precipitation, and projected long-term durability and performance on tailings oxidation prevention. To meet these objectives, a field pilot study with the following four phases is conducted: Phase I: conceptual design based on the review of laboratory test results; Phase II: detailed design of the field test; Phase III: field test construction; and Phase IV: performance evaluation with available data.

2 PRELIMINARY INVESTIGATION

The pilot study is designed based on the principles of cementitious materials formation and secondary mineral formation by the reactions of coal fly ash and water/AMD. Calcium oxide (CaO), aluminum oxide (Al_2O_3), silicon oxide (SiO_2), and ferric oxide (Fe_2O_3) are major components of a coal fly ash. When coal fly ash is in contact with water, cementitious materials such as calcium silicate hydrates (C-S-H) and calcium aluminate hydrates (C-A-H) are formed (Taylor, 1997). Both of them can bind inert materials together and adsorb heavy metals on the surfaces. Hydroxide ions produced from calcium oxide hydration can neutralize the sulphuric acid (H_2SO_4) from AMD generation and carbonic acid (H_2CO_3) from carbon oxide dissolution (Li et al., 1997).

Apart from C-S-H and C-A-H, secondary minerals such as ettringite are precipitated from the reactions of coal fly ash and AMD. The formation of ettringite is presented by Parkhurst and Appelo (1999). Swelling related to ettringite formation fills the void space among coal fly ash particles. A decreased void ratio results in a decrease in water and air permeation, and further mitigates AMD generation.

The physical properties, chemical compositions, and mineral contents of Atikokan fly ash (AFA) and Musselwhite tailings (MT) are summarized in previous literature (Wang et al., 2006). AFA is collected from the Atikokan Generating Station (Ontario Power Generation), which is 190 km west of Thunder Bay. The optimum water contents for AFA and MT are 11% and 13%, respectively. It is anticipated that maximum unit weight can be achieved during compaction for both AFA and MT at around 12% water content. AFA contains a large amount of CaO, Al_2O_3, and SiO_2, which indicates its high neutralization capacity and cementitious potential. Wang et al. (2006) present the laboratory results of AFA permeated with water and AMD (pH 3.77). The hydraulic conductivity of an AFA sample increases from 10^{-8} m/s to 10^{-7} m/s during 60 progressive pore volumes (PVs) permeation when permeated with water. However, the hydraulic conductivity of another AFA sample reduces from 10^{-8} m/s to 10^{-11} m/s after 60 PVs AMD permeation. The final pHs of both effluents are above eight after 50 PVs water or AMD permeation. The AFA-MT mixtures with mass ratios from 1:1 to 1:4 are tested in kinetic column leaching tests (Wang et al., 2006). The mixtures are permeated with a weak acid extraction solution of MT. The laboratory tests indicate that the hydraulic conductivities of the AFA-MT mixtures decrease with a mass ratio increase of AFA in MT. The pHs of the effluents for the mixtures are above nine after 90 PVs permeation. The elementals of Cr, Mo and B are stabilized during the tests.

The laboratory tests conducted by Yeheyis (2008) are consistent with the results of Wang et al. (2006). The decrease of hydraulic conductivity can be attributed to the cementitious property of AFA and the formation of ettringite during AMD permeation. Yeheyis (2008) found that AFA has high alkalinity and significant buffering capacity. The net neutralization potential of AFA is 306 kg $CaCO_3$/t. The study further concluded that when used to prevent AMD generation in MT, which has a net neutralization potential of -18 kg $CaCO_3$/t, about 13% AFA should be added.

3 PILOT STUDY

A pilot study was carried out on the Musselwhite Mine site. The selected location of the testing site is near the existing tailings pond, see Fig. 1. The ongoing study was started in 2004. Based on the preliminary investigation, four phases of the study are detailed as follows.

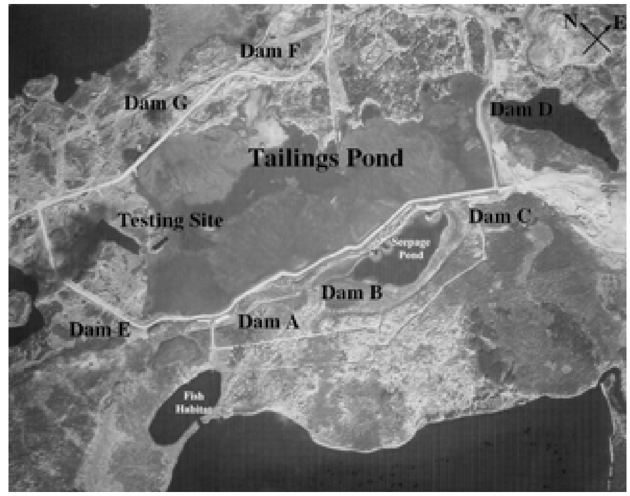

Figure 1. The selected location of the testing site

3.1 Phase I: Conceptual Design

The MT are currently discharged as slurry at 50% solids from the mill to the nearby tailings pond of the Musselwhite Mine via pumping. To reduce the additional operation cost of the coal fly ash application in tailings management, only minor changes can be made to the current tailings transportation system. According to this scenario, the conceptual design of the pilot study is developed based on the following design criteria:

- The initial saturated hydraulic conductivities of the stockpiled materials should be greater than 10^{-6} m/s;
- The final saturated hydraulic conductivities of the materials should be less than 10^{-7} m/s;
- The pH values of the leachate from the tests should be greater than seven;
- The concentrations of the selected dissolved elements in the water discharged from the stockpile should be significantly attenuated;
- The co-placement of AFA and MT should not result in a significant increase in the tailings disposal cost;
- The designs should be easy to construct.

Based on these criteria, two types of AFA-MT co-placement approaches are designed. The first approach involves placing AFA and MT layer by layer. Each layer of MT is covered by a layer of AFA in this stratified approach. The fly ash serves as a separation layer between adjacent lifts of tailings and the cover material at closure stage. The thicknesses of both materials can be calculated from the mass ratio of AFA and MT. When water flows through the fly ash layers, water alkalinity is increased because of the dissolution of alkaline contents in the fly ash. It prevents or mitigates the oxidation of MT beneath the ash layer. This approach is flexible for construction. Each lift of tailings combined with a fly ash layer on top can be considered as a unit. If more tailings need to be discharged, the tailings can be placed on top of the last ash cover and then be covered with another layer of fly ash. Additional equipment would be required to construct the fly ash layer.

The second approach is to mix AFA with MT at a specific mass ratio. In this mixing approach, the fly ash can be added into the tailings slurry in the mill directly, and pumped through the existing tailings transportation system to the tailings pond. Only mixers are required for this procedure.

To keep the balance of maximizing the storage capacity of tailings in the tailings basin and to optimize the long-term performance of AFA-MT co-placement, the mass ratio of the ash-tailings should be determined beforehand. The laboratory tests indicate that the optimal dry mass ratio of AFA-MT should be between 10:90 and 15:85 (Wang et al., 2006; Yeheyis, 2008).

3.2 Phase II: Detailed Design

A detailed design of the pilot study is developed based on the preliminary investigation and the conceptual design. The pilot study is composed of four testing tanks each with a diameter of 2.5 m and height of 3.6 m. The material profiles of the four in-situ testing tanks are shown in Fig. 2.

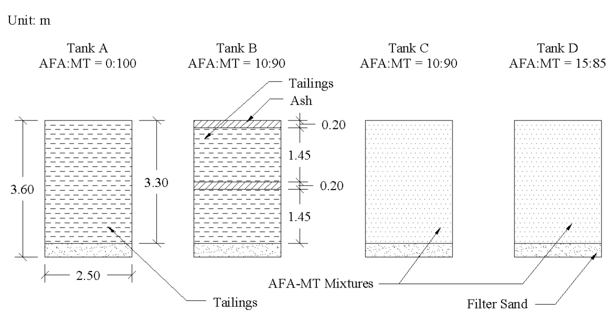

Figure 2. Material profiles of the four tanks

Tank A contains pure MT overlying a filter sand layer with 0.3 m thickness. The thickness of MT is 3.3 m. This tank is regarded as the control test. In Tank B, the sequence of containing materials is AFA, MT, AFA, MT and filter sand from top to bottom. The thicknesses of each layer are 0.2 m, 1.45 m, 0.2 m, 1.45 m and 0.3 m, respectively. The dry mass ratio of AFA to MT is 10:90, and the stratified approach is implemented in this tank. Tank C contains the same mass ratio of AFA and MT as in Tank B. The mixing approach is implemented in Tank C to compare the water permeation and neutralization effects with those from Tank B. Considering the uncertainty of in-situ conditions, an elevated ash addition to the tailings is applied in Tank D, and reaches to 15:85. With a 5% increase in AFA, the storage capacity of the tailings basin is estimated to reduce 5.5% for MT. Both Tank C and Tank D have a 0.3 m thick filter sand layer at the bottom of the tank.

Currently, the MT is uncovered and thus is exposed to air and precipitation in the existing tailings pond. To simulate the in-situ condition, no soil cover or other covers are placed on top of the tanks. Thus, oxygen and rainfall can contact the materials filled in the tanks directly.

To confine the boundaries of different materials, a geotextile is used on the bottom of each tank and between the adjacent materials. The selected geotextile is produced by GSE Lining Technology, Inc. (Product code: GEO1008002). The filter sand layer is used to simulate the drainage condition for the potential application of AFA in MT. A local inert sand is selected for the filter sand layer construction. The respective grain size of filter sand (d_{15}) is less than 0.405 mm, which can prevent the migration of both AFA and MT particles into filter sand.

3.3 Phase III: Field Test Construction

The testing tanks described in the detailed design were constructed in July 2006 with the assistance of the staff of the Musselwhite Mine. The major construction activities included: 1) testing site selection; 2) site and material preparation; 3) material filling into the tanks; 4) field monitoring and sampling equipment installation.

3.3.1 Testing Site Selection

The selected testing site is located at the high end corner of the west side of the tailings pond, between Dam E and Dam G, see Fig. 1. The main considerations of site selection include site capacity, site topography, duration and site accessibility.

The selected testing site is about 20 m long by 6 m wide, ensuring that the site has enough space to handle four 2.5 m diameter tanks and construction equipment. The layout of Tanks A, B, C and D follow the alphabetical sequence from the east to the west. The elevation of the selected site is about 3.5 m above the tailings surface in July 2006. According to the tailings disposal schedule of Musselwhite Mine, this site will not be disturbed by tailings disposal until 2011. Vehicle and construction equipment can access the site through the existing ground surface from Dams E and G.

3.3.2 Site Preparation and Material Preparation

Site preparation of the field tests included the access road construction, soil excavation, tank preparation and installation, and soil backfill surrounding the tanks. This work was completed in the first half of July 2006. In order to protect the tanks from rainfall erosion and the pore water of the testing materials, the tanks were coated with a rustproof material before being embedded at the testing site.

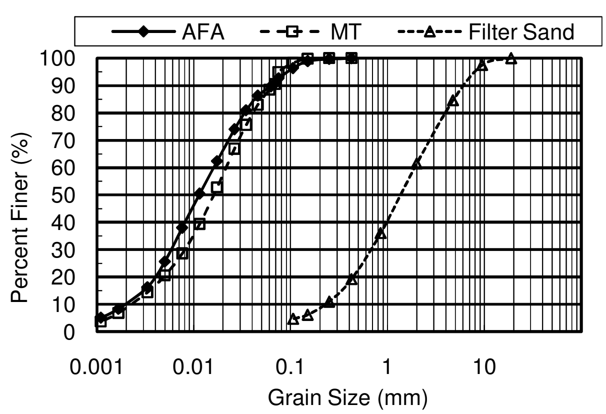

Figure 3. Grain sizes of AFA, MT and filter sand

The AFA, MT and filter sand were moved to the testing site during this same period. The AFA used in the tests was fresh fly ash from Atikokan Generating Station. The distance between the station and the mine is about 800 km. The water content of the AFA was about 0.25%. The tailings were collected from the tailings pond. The age of the tailings was three to four month old. The water in the tailings was drained before construction. The measured water content of the tailings during construction varied between 10% and 14%. The filter sand was classified as sand, some gravel, trace silt. The grain size distributions of these materials are shown in Fig. 3.

3.3.3 Material Filling

For quality control, field tests and laboratory tests were carried out on the samples collected from different depth, including the water content, dry unit weight, void ratio, specific gravity, sulphur content of tailings solids, and the initial water tables. The results are summarized in Table 1.

Table 1. Initial setting of the materials in four tanks

	Tank A	Tank B	Tank C	Tank D
Material	MT	AFA-MT	AFA-MT	AFA-MT
Mass ratio of AFA:MT	0:100	10:90	10:90	15:85
Co-placement design		stratified	mixing	mixing
Water content				
AFA		9.3%		
MT	10.3%	12.2%		
AFA-MT mixture			13.2%	12.9%
Dry unit weight, γ_d (kN/m^3)				
Depth 0.0 m	13.48	10.96	14.39	14.17
Depth 0.9 m	14.88	14.81	14.95	14.31
Depth 1.8 m	16.12	11.32	15.22	14.59
Depth 2.7 m	17.68	14.67	15.60	14.73
Void ratio, e				
Depth 0.0 m	1.46	1.25	1.20	1.24
Depth 0.9 m	1.26	1.25	1.16	1.22
Depth 1.8 m	1.07	1.25	1.12	1.19
Depth 2.7 m	0.88	1.25	1.08	1.16
Specific gravity, Gs				
Depth 0.0 m	3.37	2.51	3.23	3.24
Depth 0.9 m	3.44	3.40	3.30	3.23
Depth 1.8 m	3.41	2.60	3.29	3.26
Depth 2.7 m	3.39	3.37	3.31	3.25
Sulphur content, S% (wt/wt)				
Depth 0.1 m		0.53%		
Depth 1.0 m	1.75%	1.69%	1.58%	1.22%
Depth 1.7 m		0.51%		
Depth 3.0 m	1.78%	1.69%	1.53%	1.15%

Material filling occurred between July 26 and August 1, 2006 in accordance with the detailed design in Phase II. The followings are the construction procedures of the four tanks.

In Tank A, a layer of geotextile was laid out on the bottom of the tanks to protect the tank surface from damage by the filter sand. On the top of the geotextile, 0.30 m of filter sand was placed in one lift. The filter sand layer was thin and confined by the tank and no significant settlement was expected. No compaction was carried out on this layer. Then, another layer of geotextile was laid out on top of the filter sand to separate the different materials. A 3.30 m thick layer of tailings was installed in eleven lifts on top of the second layer of geotextile. Each lift of tailings was compacted with human trampling. The construction procedures in Tanks C and D were similar to that of Tank A. The difference was that Tanks C and D contain the AFA-MT mixtures. The mass ratio of AFA and MT were 10:90 and 15:85 for Tanks C and D, respectively.

The construction of the filter sand layer and the underlying geotextile layer in Tank B were the same as in Tank A. The construction occurred in four phases. In the first phase, a geotextile and 1.45 m thickness of tailings were placed. The tailings were compacted with human trampling in five lifts. In the second phase, a geotextile and 0.20 m of AFA were placed. The AFA layer was compacted in one lift with human trampling. The construction procedures of the third and fourth phases were the same as those in the first and second phases, respectively.

3.3.4 Monitoring and Sampling Equipment

The four testing tanks were instrumented to facilitate a comprehensive field performance evaluation. This section summarizes the selection, installation and location of the monitoring and sampling equipment.

According to the design criteria, the following parameters are monitored:

- climatic parameters (temperature and rainfall),
- surface condition,
- temperature,
- water content,
- water table,
- water chemistry, including pH, electrical conductivity (EC), dissolved oxygen (DO) and elemental concentrations of the pore water and leachate,
- solids properties, including major oxides, elemental concentrations, and hydraulic conductivity,
- other relevant field observation.

One EM5 Datalogger was used to record the climatic temperature and rainfall. The climatic temperature was monitored with ECT, ECH2O Temp, Air and Soil Temperature Sensor. The rainfall at the site was measured using a tipping bucket rain gauge. The model of the rain gauge is ECR, ECH2O Rain, Precipitation Gauge. The rain gauge could not record the snow precipitation.

Each tank was equipped with an EM5 Datalogger to collect data of temperatures and volumetric water content. Two temperature sensors were embedded in each tank at depths of 0.9 m and 2.7 m. The model of these sensors was the same as that used to monitor atmosphere temperature. The volumetric water contents of the solids in the tanks were monitored by EC-20, ECH2O Probes. The measurement of volumetric water content is based on the apparent capacitance of the solids that surrounds the sensor. Three volumetric water content sensors were embedded in each tank at different depths.

Water samples were collected from the tanks for chemical analysis. Two UMS SPE20 lysimeters were installed in each tank to collect the pore water samples at depths of 1.8 m and 2.7 m. The leachate from four tanks was collected from eight-inch diameter high-density polyethylene standpipes installed in the tanks. This material can efficiently resist both alkaline and acidic erosion. The screen of the standpipe was along its circumference with 0.30 m height from its bottom. A one-inch diameter piezometer was installed in each tank to monitor the water table and perform the slug tests for the hydraulic conductivity measurement. The piezometer screen was 0.30 m in height. Dipper-T water level meter was involved in the water table measurement.

Solid samples of each tank were collected to analyze the major oxides and elemental concentrations. The Eijkelkamp Auger Set was used to drill and take samples of the solid samples.

The installation of the monitoring equipment in the four tanks followed the same procedure. Figure 4 shows the locations and depths of the monitoring equipment in the tanks. All monitoring equipments were installed during construction. A pole was placed in the center of the tank to locate the three nests. One volumetric water content sensor and one temperature sensor were installed in the Nest I. Nest II held one volumetric water content sensor and one lysimeter. Nest III contained one volumetric water content sensor, one temperature sensor and one lysimeter. The sensors were calibrated with 12 AFA and MT samples before installation. The cables of all the sensors and the pipes of the lysimeters were bound on the pole. Two-inch PVC pipe was used to protect the cables and pipes from potential damage from wildlife. The frequency of data collection for all data loggers was every six hours.

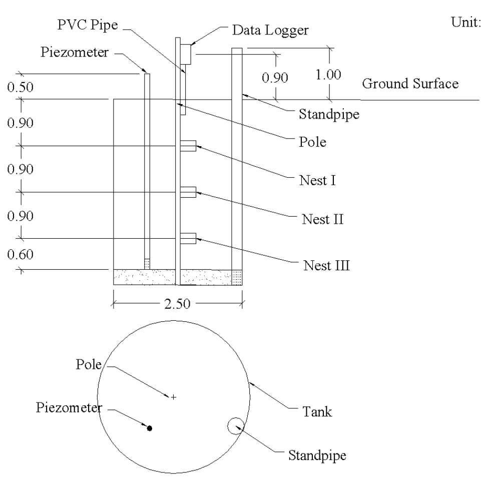

Figure 4. Monitoring equipment in the tanks (a) front view (b) top view

3.4 Phase IV: Performance Evaluation

The pilot study tested three AFA and MT co-placement systems and one control system. The three co-placement systems contain either stratified AFA and MT, or AFA-MT mixtures. The control system contained MT only. The goal of the ongoing pilot test was to evaluate the performance of different co-placement approaches at field scale and, to recommend a practical technology for the mine tailings.

A discussion of performance evaluation was based on the following data:

- 24 months of climate records;
- 23 months of temperature and volumetric water content measurements of the materials in the tank;
- 18 months of surface observation of four tanks;
- 13 months of major oxide and elemental concentration analysis results of the solid samples;
- 15 months of chemical analysis results of water samples;
- 17 months of hydraulic conductivity measurements of the solids.

3.4.1 Climate Conditions

An understanding of climatic conditions at the pilot study site is important in the determination of the time and type of climatic stresses that exist naturally at the site. For example, heavy rain might result in the rise of the water table in the tanks, and further affect the water content and oxygen distribution in the tailings. A dry period might desiccate the top layer of AFA in Tank B, and lead to cracking at the surface of the coal fly ash due to shrinkage.

Figure 5 presents the air temperatures from July 2006 to July 2008 at an elevation of 308 m. The maximum and minimum air temperatures are 33.2^oC and -16.7^oC, respectively. The average temperature between April and October is observed to be above 0^oC for every year.

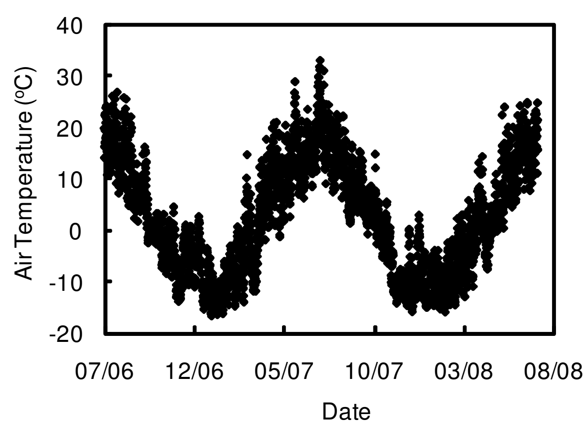

Figure 5. Air temperature of the ground surface of the testing site

Rainfall during August 2006 – October 2006, April 2007 – October 2007, and April 2008 – July 2008 at the same elevation is presented in Fig. 6. The operation period of the rain gauge in each year is from April to October. The maximum hourly precipitation of 7.5 mm occurs in the summer of 2007. The cumulative rainfall from April to

October in 2007 was 0.60 m. The precipitation in winter is estimated from the depth of snowpack at the site which ranges from 0.31 to 0.35 m. The depth of snowpack is not presented in the figure. Assuming that 10 mm of snow is equivalent to 3.7 mm of water (Renken, 2006), the snowpack is equivalent to 0.11 to 0.13 m of water.

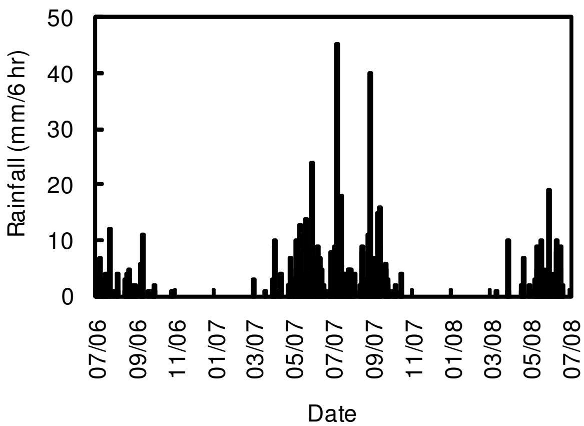

Figure 6. Rainfall of the ground surface of the testing site

3.4.2 Surface Conditions and Settlements

The surface condition of ash-tailings co-placement is one of the most important concerns in field testing. If water ponds at the surface, it may be the result of the water table rising to the ground surface or the hydraulic conductivity of the underlying material being lower than 10^{-9} m/s. The tailings contain about 3% pyrrhotite (Wang et al., 2006). When tailings oxidized, the released AMD has a colour range of orange, red or yellow-brown depending on the iron concentration. Thus, the colour of the water samples collected in the test tanks' standpipes may be used as a visual test for the status of tailings oxidation. The cracks developed on the tailings surface change the distribution of water and oxygen in the tanks, and further affect the tailings oxidation. Using the stratified approach, if the cracks develop with time, the ambient air and water would pass through the top fly ash layer and come into the contact with tailings directly. Therefore, the expected hydraulic barrier function and neutralization function of the coal fly ash layer to tailings may not be achieved. On the other hand, when the mixing approach is implemented, the AFA and MT mix evenly at specific mass ratios. The tailings particles are protected by the nearby ash particles. Thus, the impact of cracks on the surface of testing tanks in the mixing approach is less than in the stratified approach.

The water accumulation, water discoloration and cracking at the surfaces of the four tanks are monitored. There is no water accumulation on the surfaces of the tanks, indicating that the rainfall has infiltrated into the MT, AFA, or AFA-MT mixtures. There is no colour change in all the water samples over a 27-month observation period, which implies the tailings have not oxidized. No cracks are seen on the surfaces of the tanks from August 2006 to October 2008.

The settlements of the four tanks over 27 months are summarized in Table 2. It was found that the settlements in the four tanks increased with time. The settlement in Tank B was comparable with that in Tank A and resulted from the comparable thicknesses of MT layers in both tanks. The settlements of Tanks A and B were higher than those in Tanks C and D. The cementitious property of coal fly ash leads to the increase in the compression strength of the AFA-MT mixture and reduced settlement.

Table 2. Settlements of four tanks

Date	Tank A (m)	Tank B (m)	Tank C (m)	Tank D (m)
08/01/2006	0.000	0.000	0.000	0.000
06/15/2007	0.017	0.014	0.002	0.002
08/21/2007	0.023	0.022	0.003	0.002
10/30/2007	0.025	0.026	0.004	0.005
06/25/2008	0.037	0.035	0.009	0.009
10/28/2008	0.042	0.036	0.011	0.011

3.4.3 Temperature Profiles

The temperature readings measured in the four tanks were very similar. Figure 7 shows a typical solid temperature distribution in the tanks. The temperatures at depths of 0.9 and 2.7 m were comparably high at the beginning of the curves. This was attributed to the exposure of AFA and MT during material preparation before construction. The recorded temperatures at depths of 0.9 and 2.7 m declined over the winter and rose in the summer. Compared with Fig. 5, it was clearly illustrated that the solid temperatures increased and decreased seasonally in response to the air temperature at the ground surface of the testing site.

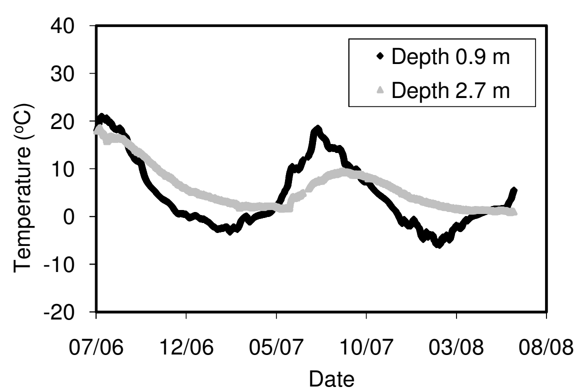

Figure 7. The typical temperature distribution of the tanks

It was found from Fig. 7, that the maximum and minimum temperatures at a depth of 0.9 m in year 2007 were 18.5°C and -3.2°C, respectively. The average temperature at the same period was 4.7°C. The maximum, minimum and average temperatures during 2007 at a depth of 2.7 m were 9.6°C, 1.6°C and 5.3°C, respectively.

The fluctuation of the temperature at depth 2.7 m was less than that at 0.9 m.

3.4.4 Water Tables and Gravimetric Water Content Profiles

Water serves as both a reactant and a survival medium for bacteria in the tailings oxidation process. As well, it transports dissolved metals and other oxidation products among tailings particles or to an adjacent soil and water system. Water content distribution in the tailings also affects oxygen diffusion. Oxygen is important to maintain rapid bacterially catalyzed oxidation. If the concentration of oxygen in the pore spaces of mining tailings is less than one or two percent, oxidation of sulphides can be significantly reduced (U.S. EPA, 1994).

The water tables in the four tanks are measured periodically with a water level meter. Table 3 presents the measured water tables during August 2006 to October 2008. The table illustrates that the tailings in Tank A accumulates the rainfall in summer, and the water table reaches its peak at -1.8 and -2.1 m in October 2007 and 2008, respectively. Precipitation decreases during winter, and the tailings dry out because of its poor water retention capacity. The water table decreases to the bottom of tank in Tank A in June 2008. When AFA is involved in either the stratified approach or the mixing approach, the water tables are more stable than that in the control tank. The water tables of Tanks C and D are lower than that in Tank B after October 2007, which may indicate that the cemented AFA layer on top of MT has prevented water evaporation from the MT layer.

Table 3. Water tables of four tanks

Date	Tank A (m)	Tank B (m)	Tank C (m)	Tank D (m)
08/01/2006	-3.60	-3.60	-3.60	-3.60
06/17/2007	-3.06	-3.06	-3.04	-3.08
08/21/2007	-2.34	-2.84	-2.71	-2.88
10/30/2007	-1.83	-2.33	-2.31	-2.57
06/24/2008	-3.60	-2.67	-3.11	-2.94
07/23/2008	-2.23	-2.10	-2.63	-2.64
08/05/2008	-2.20	-2.09	-2.49	-2.56
10/28/2008	-2.09	-2.05	-2.45	-2.53

The volumetric water contents at different depths in the tanks are measured using sensors. The measured data are converted to gravimetric water content. Figures 8 through 11 show the gravimetric water contents at depths 0.9, 1.8 and 2.7 m for the tanks. All water contents in the four tanks range from 1% to 22%. In general, the maximum water content occurs in the summer, and the minimum water content occurs in winter for all tanks.

Figure 8 illustrates that the gravimetric water contents in Tank A are in agreement with the measured water table. The saturated water contents at depth 2.7 m for 2006 and 2007 are approximately 19% and 17%. The decrease between the saturated water content is attributed to the settlement which reduces the void space among solid particles.

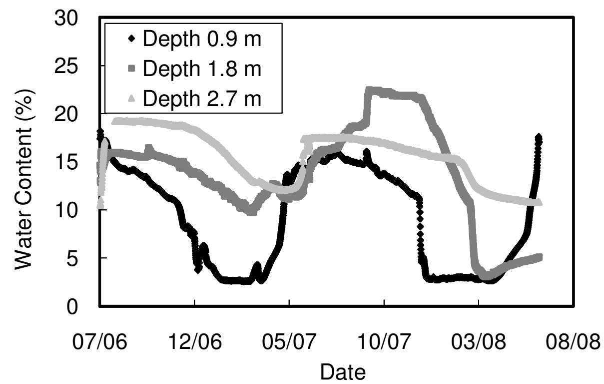

Figure 8. Gravimetric water content distribution of Tank A

It can be noted from Fig. 9 that the volumetric water content sensor at depth 1.8 m was damaged in May, 2007. A new sensor was installed at depth 1.9 m to replace the damaged one. The tailings at depth 2.7 m reached the saturation in September 2007, and remained at saturation. The saturated water content at this depth decreased slightly over time due to settlement development. Low water contents at a depth of 1.9 m occurred, i.e. ~ 5%, during February and March 2008. The sensor embedded at this depth was just under the AFA layer between 1.65 and 1.85 m. The low hydraulic conductivity of the overlying AFA layer and the high hydraulic conductivity of MT could be the cause of the low water content.

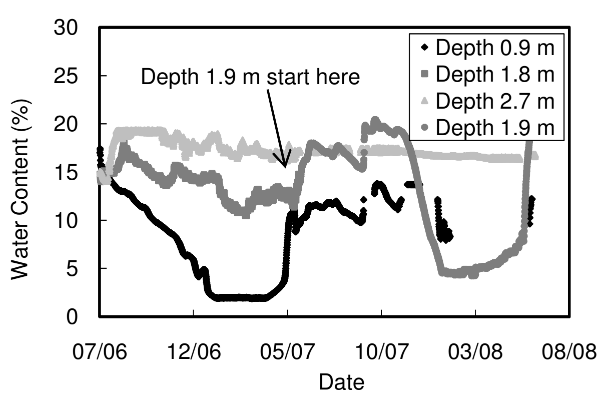

Figure 9. Gravimetric water content distribution of Tank B

In Fig. 10, the water content decrease began at 0.9 m, followed by at 1.8 m, and finally at 2.7 m for Tank C in the winter of 2006 and 2007. This can be attributed to the evaporation gradient along the depth as more evaporation was anticipated near the ground surface than at the bottom of the tanks. The water content distribution in Tank D is similar to in Tank C, see Fig. 11.

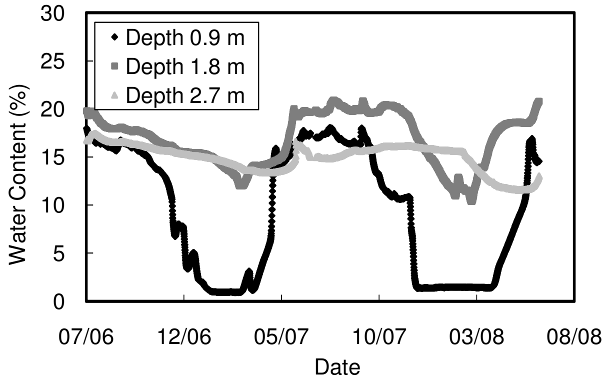

Figure 10. Gravimetric water content distribution of Tank C

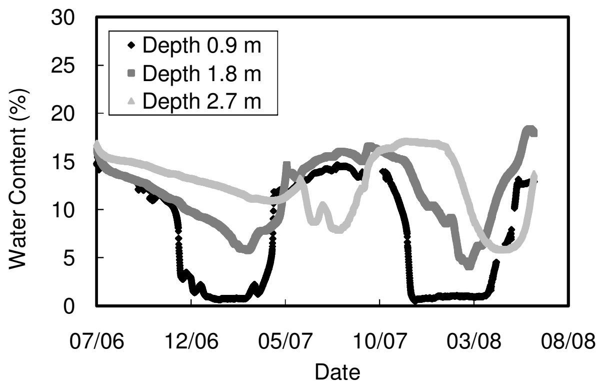

Figure 11. Gravimetric water content distribution of Tank D

3.4.5 Chemical Analysis of the Solid Samples and Water Samples

Solid samples in the four tanks were collected by drilling twice every year. Three groups of samples have been analyzed thus far. The major oxides of the samples were determined by X-Ray Fluorescence (XRF) analysis, and the trace element concentrations of the solids were determined by aqua-regia digestion and Inductively-Coupled Plasmaspectrometer (ICP) analysis. The results of analysis indicate the major oxides and trace element concentrations of the materials in the four tanks had no notable changes at the same depth of the same tank during the testing period.

From the chemical analysis of water samples, it is observed that the addition of AFA resulted in a significant decrease of EC during the first 12 months. The average EC in Tank A during August 2006 and June 2007 was about 1.5 mS/cm, while the average EC in Tanks B, C and D during the same period were approximately 0.12, 0.10, 0.12 mS/cm, respectively. This may due to precipitation and adsorption of dissolved metals in the pore water in the alkaline environment.

4 SUMMARY

A pilot study for the application of the AFA in the management of the MT was carried out at the Musselwhite Mine site. The stratified approach and the mixing approach were adopted in the design. Four tanks were implemented for long-term performance evaluation. As of October 2008, oxidation was not observed in all four tanks. The pilot study will continue for the long-term study. The preliminary test results over a period of two years include:

1) No water accumulation or cracks were formed on top of four tanks;
2) The settlements of the mixing approaches were lower than that of the stratified approach;
3) The temperature distributions in the four tanks were comparable, and the solid temperatures deeper in the tanks were less impacted by air temperature;
4) When MT was covered or mixed with AFA, the water contents at 0.9, 1.8 and 2.7 m in Tanks B, C and D were more stable than those in Tank A; and
5) The EC of pore water was significantly reduced during the first 12 months in both stratified approach and the mixing approach.

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