Mine site reclamation Challenge through some examples in Québec (Canada)

ABDELKABIR MAQSOUD
Research Institute in Mine and Environment
University of Quebec in Abitibi-Temiscamingue
675, 1st Avenue, Val-d'Or (Québec) J9P 1Y3
CANADA
Abdelkabir.maqsoud@uqat.ca

Abstract: - The mining industry generates large amounts of solid and liquid waste. These wastes have the potential to adversely impact the environment if not properly managed. Special attention is required when the wastes contain sulfide minerals. The oxidation of sulfides minerals by atmospheric oxygen generates contaminant in the drainage water. This phenomenon is called acid mine drainage (AMD) when the effluents are acidic. In these situations, actions must be taken at the mine site to prevent environmental impacts caused by AMD. For that, reclamation of mine site constitutes the most important challenges for the mining industry and different techniques were developed to control the production of AMD. These techniques are used to eliminate, or to reduce to very low levels, the water flow (hydraulic barrier) and / or oxygen flux (oxygen barrier) to reactive tailings. Under humid climate conditions, the most appropriate techniques to control oxygen flux are: i) cover with capillary barrier effects (CCBE), and ii) monolayer cover with an elevated water table. These techniques were used for mine site reclamation in Abitibi-Témiscamingue (Québec, Canada). The emphasis will be on their characteristics, configuration and performance.

Key-Words: - Mine site reclamation, Cover with Capillary Barrier Effect, Monolayer Cover with an Elevated Water Table

1 Introduction

The extraction of mineral resources plays an important role in the Canadian economy. However, ore extraction generates a large amount of wastes. These wastes include soil overburden, fine-grained mill tailings produced by the ore processing plant, and waste rock extracted to reach the ore body [1]. Mine wastes have the potential to adversely impact the environment if not properly managed. In this regard, special attention is required when they contain iron sulphide minerals, such as pyrite and pyrrhotite. The oxidation of sulphides by atmospheric oxygen tends to acidify meteoric waters; this phenomenon is known as acid mine drainage (AMD) or acid rock drainage (ARD). The main characteristics of AMD are the low pH and high concentrations of dissolved heavy metals and sulfates. As a leading example, pyrite (FeS_2) weathering occurs according to the following overall reaction [2]:

$$FeS_{2(s)} + {}^{15}/_{4}\, O_2 + {}^{7}/_{2}\, H_2O \rightarrow Fe(OH)_{3(s)} + 4H^+ + 2SO_4{}^{2-}$$

In these situations, actions must be taken at the mine site to prevent environmental impacts caused by AMD [3], [4] and [5].

This paper starts by with a brief description of mine site reclamation techniques followed by presentation of two examples of reclaimed mine sites in Quebec (Canada). This paper ends with a conclusion.

2 Mine site reclamation scenarios

When mine wastes are considered acid-generating, different management options and rehabilitation strategies are available to inhibit the acid production. Under the humid climate prevailing in most of the Canadian provinces, techniques to limit oxygen availability are considered to be the most viable option [4] and [6].

For that purpose, it is possible to use a water cover to reduce the availability of oxygen to the underlying acid-generating mine wastes [7], [8] and [9]. An oxygen barrier can also be created by installing a cover made of oxygen consuming materials such as wood waste, straw mulch, or other organic residues [10] and [11].

Another effective way to limit oxygen migration is by the use of a cover with capillary barrier effects (CCBE) [12], [13], [14] and [15]. A CCBE relies on the water retention contrast between two superimposed materials (fine-grained over coarse-grained materials), to create a capillary barrier effect that limits the vertical flow of water at the interface. When overlapped by a coarse material layer, the CCBE maintains the fine-grained material layer near saturation.

Finally, monolayer cover combined with an elevated water table (EWT) can be used as an oxygen barrier; the concept behind a monolayer cover combined with an EWT is to raise or maintain the water table at a position that allows to maintain the reactive tailings at a sufficiently high degree of water saturation to prevent tailings oxidation [16], [17], [18], [19] and [20].

3 Examples of mine site reclamation

Under humid climate conditions, the most appropriate techniques to control oxygen flux are CCBE and monolayer cover combined with EWT.
The materials used in these engineered covers can be natural (e.g., sand and silt) or recycled (e.g., non-reactive tailings). Also, the monolayer cover material can be constructed using fine or coarse grained soils. Two examples were selected, with the objective to illustrate these types of reclamation (CCBE and EWT).

The main objective of the mine site reclamation was to prevent further reactive tailings oxidation and therefore inhibit the production of new acid mine drainage. The emphasis will be on their characteristics and performance.

3.1 Lorraine mine site

The Lorraine mine site is located near Latulipe, in the Temiscamingue region, Québec, Canada (see Fig. 1). The main ore minerals mined from 1964 to 1968 were chalcopyrite and pentlandite. Approximately 600 000 tonnes of ore were treated at the mill generating approximately the same amount of tailings ([21]). There was little work done for closure at the end of the operation and the abandoned tailings were left exposed for 30 years. This led to the oxidation of sulphides minerals and AMD was observed at the toe of the pervious dykes ([22]).

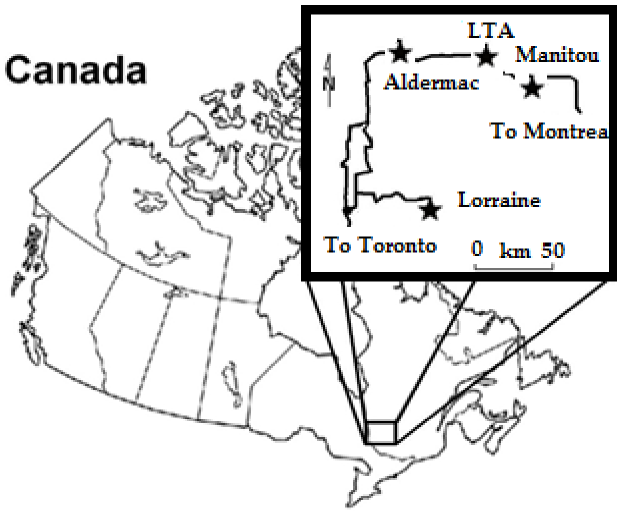

Figure 1: Mine site locations

3.1.1 Mine site reclamation and monitoring program

Rehabilitation work was performed at the Lorraine tailings impoundment in 1999 by installing a cover with capillary barrier effects (CCBE). The Lorraine CCBE which extends over 15-hectares is made of three layers [22], [23] and [16]: i) a 0.3 m thick capillary break layer made of sand material; ii) a 0.5 m thick moisture retaining layer (MRL) made of natural silty material; and iii) a protective layer 0.3 m thick made of sand and gravel material.

In parallel with the construction of the layer cover, 3 limestone drains were constructed near the base of the south dyke to treat the acidic exfiltration seeping from the dykes [24]. Different monitoring stations were installed with the objective to evaluate volumetric water content and suction at strategic locations. Measurements of volumetric water content and suction were performed using Ech$_2$O probes and Watermark sensors respectively. Also, piezometers were equipped with logger to monitor piezometric level variations.

The performance evaluation of the Lorraine CCBE was based on its ability to maintain the MRL at a high degree of saturation. Maintaining the MRL at a high degree of saturation allows for the reduction of the production of the acid mine drainage. Also, this effect minimizes the movement of water through the CCBE and across the reactive tailings. In other words, the cover with the lowest flux was deemed the best performer.

3.1.2 Monitoring results

Typical volumetric water content measurements are presented in Figure 2. This Figure shows the volumetric water content values measured in the capillary break layer (EC 1-1- in sandy layer) and near the bottom of the MRL (EC 2-1). One can see that the volumetric water contents in the MRL are much larger than in the capillary break layer. The θ value in the moisture-retaining layer stayed above 0.40 during the entire study period. The θ values in capillary break layer stayed lower than 0.2 during the same period. The contrast between these values reflects the presence of capillary barrier effects.

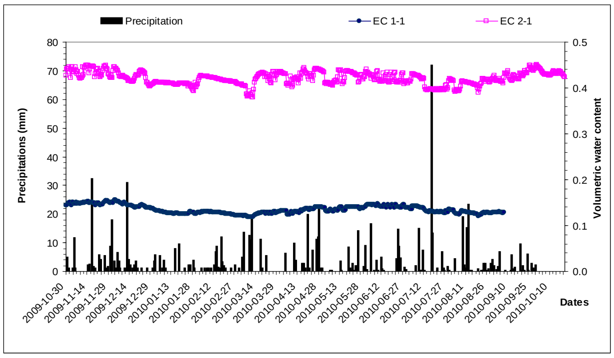

Figure 2: Volumetric water content measurements

Suction (ψ) measurements result are presented in Fig. 3. Except the freezing period (FP), the ψ values measured in the bottom and in the top of the MRL are usually lower than 20 kPa, that is lower than the air entry value (about 30 kPa). These measurements indicate that MRL remain close or near the saturation. The suction measurements in the bottom of the MRL are in accordance with those of the volumetric water contents (see Fig. 2).

The difference in suction values between the sensors located near the top and near the bottom of the MRL is included between 0 and 2 kPa. This difference is mainly attributed to the 20 cm difference in elevation of the Watermark probes. This difference becomes larger during the winter period (see Fig. 3) because the top of the MRL is more affected by freezing.

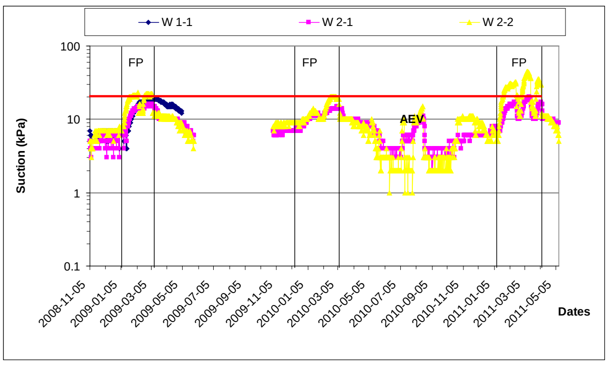

Figure 3: Suction measurements

During the freezing period (FP), the ψ values measured in the bottom and in the top of the MRL increase and can exceed the AEV; this effect is attributed to temperature effect. So the declining temperature tends to increase suction (a phenomenon known as cryo-suction) particularly near the frost front. When the water in the sensor is all frozen, the readings reach the maximum value (250 kPa). This value is not necessarily a real suction value. As a final remark, Fig. 3 shows that the freeze effect was more important during winter 2011 than during winter 2010 and 2009.

3.1.3 Oxygen flux evaluation

Volumetric water content measurements were used in the calculation of the oxygen flux. The oxygen flux through the Lorraine CCBE was evaluated by calculating the diffusive oxygen fluxes and using the first Fick's law ([25], [26], [27], [28). Calculation results are presented in Figure 4.

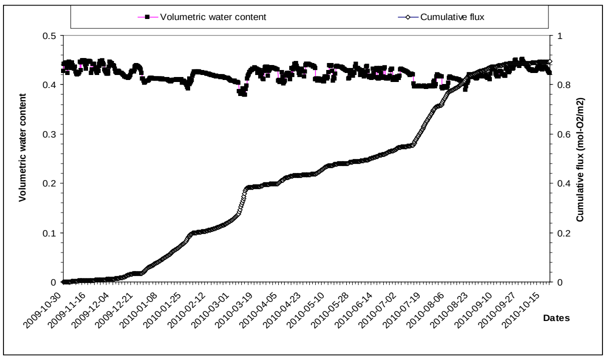

Fig. 4: Cumulative flux

The oxygen flux is included between 2.48×10^{-5} and 2.23×10^{-2} mol O_2/m^2/day. However the annual cumulative flux is about 0.89 mol O_2/m^2/year (see Fig. 4). This cumulative flux was calculated for the entire year, were one can see that during winter, the cumulative flux until the end of March is about 0.4 mol-O_2/m^2 although the oxygen flow can be considered as nil because there is a snow cover and the ground is frozen during this period. Finally one can conclude that the measured flux is considered as comparable to those measured through water covers.

3.3 Aldermac mine site

The Aldermac abandoned mine site is located in the Abitibi region; in the province of Québec about 15 km west of Rouyn–Noranda city (see Figure 1). This abandoned mine site has been exploited for its rich deposits of zinc and copper between 1931 and 1943. The mine produced nearly 1.5 million tons of acid-generating tailings, which covered an area of about 60.3 hectares. The Aldermac site was reclaimed between 2008 and 2009 ([29]. Thus, two different techniques have been used for the reclamation of the abandoned Aldermac mine site: low saturated hydraulic conductivity cover made of an HDPE geomembrane and a monolayer cover combined with an elevated water table (EWT).

The success of the reclamation of the northern area of the abandoned Aldermac mine site using the EWT is based on the possibility to maintain permanently the EWT close to the interface between the mono-cover layer cover and the reactive tailings.

To evaluate the performance of this type of reclamation technique, a network of 6 piezometers (T1 to T6) was installed during field work reclamation (see fig. 5). The depths of these piezometers are close to the interface between the granular cover and the underlying reactive tailings.

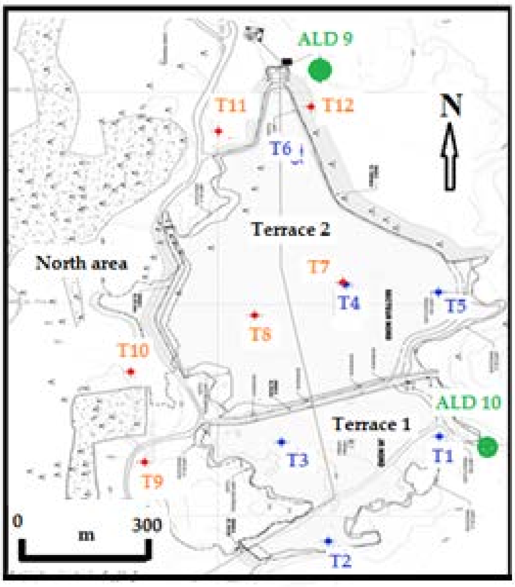

Fig. 5: Localisation of different sectors of the Aldermac mine site

These piezometers are used for groundwater sampling and for piezometric level measurements. So, for each year, three measurement campaigns are performed and measurement results are presented in Fig. 6. This figure shows that the lowest levels of the EWT were measured during August, while the highest were usually measured during November. These behaviors are linked respectively to the decline of the water table that occurs during the summer and water table recharge that occurs during the fall period.

Piezometric measurements are also used for the evaluation of the EWT location by comparison to the soil surface and the interface between reactive tailings and monolayer cover.

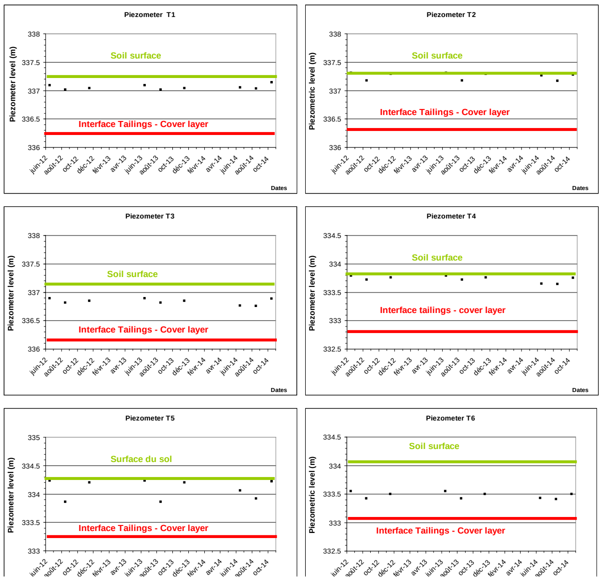

Fig. 6: Piezometric level measurements in various piezometers installed in the Aldermac mine site

Results show that for all the studied period from November 2011 until October 2014, the EWT was maintained over the interface tailings - sand and gravel. For this period, the minimum of the water column height ranges from 0.34 m (T6) to 0.85 m (T2); ii) the maximum the water column height varies from 0.48 m (T6) to 0.99 m (T2); and iii) the average the water column height varies from 0.40 (T6) and 0.93 m (T2).

Piezometer T4 was instrumented during 2012 using data logger for continuous measurements of the groundwater level pressure. Piezometric level measurement results and precipitations measured at the climatic station of Rouyn-Noranda, (Canada) are presented in Fig. 7. One can observe that after each precipitation event, the piezometric level increases; against, the absence of precipitation induced decreases in the piezometric level.

It is also observed that the maximal elevation of phreatic surface is observed during April (April 22, 2013 and April 23, 2014) following snowmelt. Following the spring freshet, the level of that table presented a downward trend, which corresponds to the periods of decline and depletion. After these periods, there is a further increase in the groundwater level during the late summer and early fall. Finally, during the winter, a slight tendency to decrease was observed. This behavior is quite normal and is typical of groundwater close to the soil surface. Indeed, their behavior is directly influenced by climatic conditions: i) the significant rainfall generated an increase in the water table; ii) the lack of precipitation and evaporation or drainage generates a decline in the water table.

For the piezometer T4, the piezometric level remained close to the soil surface and even the water at soil surface was observed during the spring flood (see Fig. 7). However, the lowest piezometric levels were observed during July 15, 2012, 31 July 2013 and 29 June 2014 and, therefore, the water column height above the interface had respectively a thickness of 0.43, 0.63 and 0.68 m. These thicknesses are well below those that were evaluated using manual measurements of piezometric level, confirming the need for continuous monitoring of the phreatic surface.

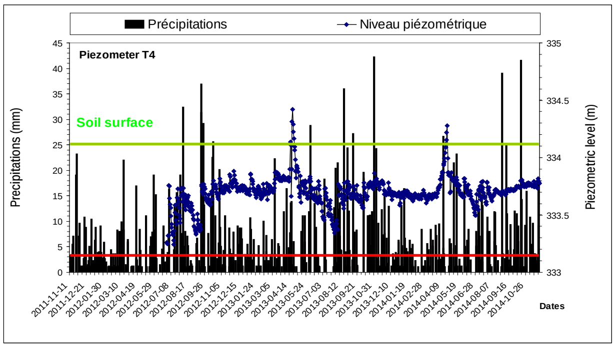

Fig. 7: Piezometric level measurements using sensor performed in the piezometers T4

Therefore, one can consider that the tailings were constantly covered by EWT and, thereby, the tailings oxidation process should be inhibited.

To evaluate this hypothesis, water samplings were performed in different piezometers for chemical and physical analysis. Measurement results of the water electrical conductivity (EC) are shown in Fig. 8

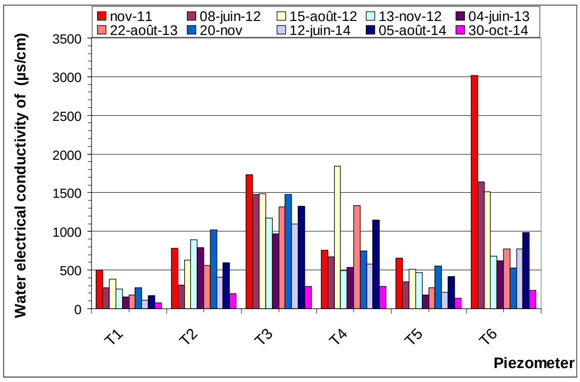

Fig. 8: Electrical conductivity of water

This last Fig. shows that the highest EC were measured in the piezometer T3 with an average value of 1234 µS/cm, whereas the lowest conductivities have been measured in the piezometer T1 with an average value of 237 µS/cm (see Fig. 4). It can be seen that the EC for the piezometer T6 placed close to the final effluent terraces, decreases continuously; indeed, it decreased from 3020 µS/cm (First measure in 2011) to 240 µS/cm (2014 - last measure). These results confirm that the EWT inhibit the tailings oxidations.

4 Conclusion

Different management options and rehabilitation strategies are available to inhibit the AMD production. Despite the development of these techniques, there is still work to do to improve their performance both technically and economically.

In the context of sustainable mining development, it is important to consider the climatic change impact in the cover design. It is why reclamation of mine sites is the most important environmental challenge for the mining industry.

References:

[1] M. Aubertin, B. Bussière, L. Bernier, *Environnement et gestion des résidus miniers*. Les Presses internationales Polytechnique, Montréal, *2002*, CD-ROM.

[2] W. Stumm, JJ. Morgan, *Aquatic chemistry, chemical equilibria and rates in natural waters*, 3rd edn. JohnWiley & Sons, Inc., New York, p 1022, 1996.

[3] GM. Ritcey, *Tailings Management, Problems and Solutions in the Mining Industry*, 1989, Amsterdam: ELSEVIER.

[4] Steffen, Robertson and Kirsten Inc. (SRK) Draft acid rock drainage technical guide, Volume I. Report prepared for British Columbia Acid Mine Drainage Task Force. *Bi-Tech Publishers Ltd.*, Vancouver, B.C., 1989.

[5] MEND Mine environment neutral drainage (MEND) manual, Vol. 4: Prevention and Control, MEND 5.4.2d, Canada Centre for Mineral and Energy Technology (CANMET), Canada. 477 p, 2001.

[6] WW. Fraser, JD. Robertson, Subaqueous disposal of reactive mine waste: an overview and update of case studies - MEND/Canada. *Proceedings of the International Land Reclamation and Mine Drainage Conference and 3rd International Conference on the Abatement of Acidic Drainage*, Pittsburgh, vol. 1, 1994, 250-259.

[7] D. Amyot, S. Vézina, Flooding as a reclamation solution to an acidic tailings pond - the Solbec case. *Proceedings of the 4th*

International Conference on Acid Rock Drainage, Vancouver, vol. 2, 1997, 451-464

[8] PH. Simms, EK. Yanful, L. St-Arnaud, B. Aubé, A laboratory evaluation of metal release and transport in flooded preoxidized mine tailings, *Applied Geochemistry* 15, 2001 1245-1263

[9] A. Cabral, I. Racine , F. Burnotte, G. Lefebvre Diffusion of oxygen through a pulp and paper residue barrier, *Can Geotech J* 37, 2000, 201-217

[10] N. Tassé, D. Germain, Performance of forestry wastes for the treatment of acid mine drainage through a reactive barrier. *Proceedings of the 7th International Symposium on Environmental Issues and Waste Management in Energy and Mineral Production*, 2002, pp. 723-730.

[11] RV. Nicholson, RW. Gillham, JA. Cherry, EJ. Reardon, Reduction of acid generation in mine tailings through the use of moistureretaining cover layers as oxygen barriers. *Can Geotech J, 1989*, 26:1–8

[12] M. Collin, A. Rasmuson, Mathematical modelling of water and oxygen transport in layered soil covers for deposits of pyritic mine tailings, *Acid Mine Drainage: Designing for Closure*, Annual Meeting, 1990, pp 311–333

[13] B. Bussière, R. Potvin, AM. Dagenais, M. Aubertin, A. Maqsoud, J. Cyr, Restauration du site minier Lorraine, Latulipe, Québec : Résultats de 10 ans de suivi. *Revue Déchets, Sciences et Techniques*, 2009, 54 : 49-64

[14] A. Maqsoud, B. Bussière, M. Mbonimpa, M. Aubertin, M. Chouteau, Suction break to control slope-induced effects in covers used as gas barrier, *Can Geotech J*, 48, 2011, 53–71

[15] AM. Dagenais (2005) *Techniques de contrôle du drainage minier acide basées sur les effets capillaires*, Thèse de doctorat, École Polytechnique de Montréal, 2005, 444 p.

[16] M. Ouangrawa, M. Aubertin, JW. Molson, B. Bussière, G. Zagury, Preventing acid mine drainage with an elevated water table: longterm column experiments and parameter analysis. *Water Air Soil Pollut* 213, 2010, 437–458

[17] MP. Ethier, B. Bussière, M. Aubertin, Maqsoud A, I. Demers, J. Dionne, Field investigation results of the elevated water table technique combined with a monolayer cover on reactive tailings, *Proceeding of the GeoRegina, Regina*, 2014, SK, Canada

[18] A. Maqsoud, M. Mbonimpa, B. Bussière, M. Benzaazoua, The hydrochemical behaviour of the Aldermac abandoned mine site after its rehabilitation. *Proceeding of the Canadian Geotechnical Conference, GeoQuébec*, 2015, QC, Canada

[19] M. Maqsoud, M. Mbonimpa, B. Bussière, J. Cyr, Réhabilitation du site minier abandonné Aldermac, résultats préliminaires du suivi de la nappe surélevée, CD-Rom, The 66th *Canadian Geotechnical Conference and the 11th Joint CGS/IAHCNC Groundwater Conference*, 2013, Montréal, QC, Canada

[20] AM., Dagenais, M. Mbonimpa, B. Bussière, M. Aubertin, The modified oxygen consumption test to evaluate gas flux through oxygen barrier covers. *Geotechnical Testing Journal, ASCE*, 35, 2012, 150-15.

[21] AM. Dagenais, M. Aubertin, B. Bussière, L. Bernie, J. Cyr, Monitoring at the Lorraine mine site : a follow up on the remediation plan. *National Association of Abandonned Mine Land Annual Conference*, 2001, CD-ROM.

[22] M. Nastev, M. Aubertin, Hydrogeological modelling for the reclamation work at the Lorraine mine site Québec, *1st Joint IAH-CNC-CGS Groundwater Specialty Conference*, 2000, Montréal, Québec, pp. 311-318, 2000

[23] A. Maqsoud, B. Bussière, M. Aubertin, B. Plante B, J. Cyr, Tracer test to evaluate hydraulic residence time in limestone drains: case study of the Lorraine site, Latulipe, Québec, Canada. *International J Mining, Reclamation and Environment*, 4, 2012, 275-291

[24] RV. Nicholson, RW. Gillham, JA. Cherry, EJ. Reardon, Reduction of acid generation in mine tailings through the use of moisture-retaining cover layers as oxygen barriers. *Can Geotech J*, 26, 1989, 1-8.

[25] M. Aachib, M. Aubertin, RP. Chapuis, Étude en laboratoire de la performance des barrières de recouvrement constituées de rejets miniers pour limiter le drainage minier acide - Un état de la question. Rapport EPM/RT-93/32, 1993, École Polytechnique de Montréal,

[26] EK. Yanful Oxygen diffusion through soil cover on sulphidic mine tailings. *J Geotech Eng*, 119, 1993, 1207-1228.

[27] M. Aubertin, RP. Chapuis, M. Aachib, B. Bussière, JF. Ricard, L. Tremblay, Évaluation en laboratoire de barrières sèches construites à partir de résidus miniers. *MEND/NEDEM Report 2.22.2a, CANMET*, 1995, Ont.

[28] SNC-Lavalin 2010. Restauration du site minier Aldermac, Ministère des Ressources naturelles et de la Faune Rouyn-Noranda, 2010, Québec, SNCLavalin.