A Holistic Approach of Green Mining Innovation in Tailings Reprocessing and Repurposing

Terry C. Cheng
CanmetMINING, Natural Resources Canada, Ottawa, ON, Canada

Fodhil Kassimi
CanmetMINING, Natural Resources Canada, Ottawa, ON, Canada

Janice M. Zinck
CanmetMINING, Natural Resources Canada, Ottawa, ON, Canada

ABSTRACT: The rate of tailings generated at Canadian mines is on the order of 200–250 million tonnes per annum. The accumulative sum of the tailings from the last three decades has amounted to over 6 billion tonnes; most of which have been retained in tailings impoundment areas (TIA). TIA represent huge environmental and social liabilities to the mineral and metals industries as well as to governments and communities. One of the priorities of Green Mining Initiative at Natural Resources Canada is to facilitate the development and deployment of new technologies to minimize the footprint of tailings, and at the same time to examine options to utilize mining wastes as resources in other applications. This paper outlines the main areas of research in addressing the technological gaps prior to the wide adoption of tailings reprocessing and repurposing.

1 INTRODUCTION

1.1 *Environmental liabilities*

The management of tailings has been evolving rapidly in the past hundred years, from uncontrolled haphazard disposal to today's well designed and constructed tailings impoundment areas (TIA). The proper management of tailings remains a constant challenge to minerals and metals sector largely due to the mass of the material generated and the chemical and mineralogical complexity of the material. Records indicated that over 6 billion tonnes of tailings had been generated in Canada in the last 30 years; of which 90% originated from metal mines with base metals, iron and gold mines to be the major contributors as shown in Figure 1 (Barter, 2011). The typical tonnage of tailings generated in each commodity industry varies largely depending on the primary metal mined. For example, as shown in Table 1, about 400 tonnes of tailings is generated per kg of gold produced, 125 tonnes per tonne of copper produced, and 2 tonnes per tonne of iron produced (Barter, 2011). Apparently, these ratios will continue to climb as high grade ores become scarce, while the continuous advancement of technologies is allowing industry to process lower grade ores. The rate of tailings generated in Canada was estimated to be between 200 and 250 million tonnes per annum (Barter, 2011).

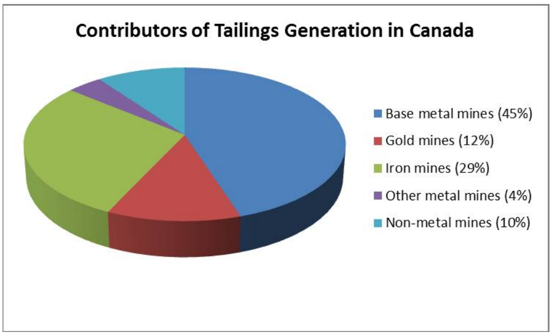

Figure 1. A snap shot of tailings generation by mines in Canada (Barter, 2011).

Despite the overall reduction in TIA failures globally in recent years, the severity of these failures is steadily trending upwards. According Bowker & Chamber (2015), almost half of all recorded "serious and very serious"[1] failures from 1940-2009 have occurred since 1990. The liability of these TIA is significant. The cost of remediation for TIA failures worldwide within this decade (2010-2019) alone is estimated to be US$ 6 billion (Bowker & Chambers 2015).

Table 1. Ratios between tonnage of tailings generated and the mass of metal produced (Barter, 2011).

Commodity	**Year**		
	2006	**2007**	**2008**
Gold *tonnes of tailings per kg gold*	391	384	397
Copper *tonnes of tailings per tonne copper*	125	118	122
Iron *tonnes of tailings per tonne iron*	2	2	2

1.2 *Declining grade*

Couple the decline in easy to access high grade ores with a growing global middle class; it is clear that the demand for minerals and metals will increase in coming years. The challenges of finding high grade ores in politically stable regions are more difficult. The project time for new exploration is getting longer due to the fact that uncertainties associated with permitting and gaining social license to operate are numerous (Ramji, 2016). The option to reprocess historical tailings becomes an attractive and potentially economically viable alternative to new mine development.

1.3 *Mine waste metal value*

To illustrate the significant amount of metal value available in tailings, the metal value in Canadian gold tailings was estimated and is depicted in Figure 2. The estimate is based on the expected 1 billion tonnes of gold tailings disposed of in Canada since 1985. The metal grades are evaluated at 0.01–0.5 g Au/t, 0.5–50 g Ag/t and 100–1000 g Cu/t, respectively while the metal prices are taken at a discounted rate of 65% of the respective average market price in 2015 (Kitco, 2016). From this, it is conservatively estimated that the total metal value in Canadian gold tailings is of the order of US$ 10 billion.

[1] According to the definition used by Bowker & Chamber (2015), a TIA failure with loss of life and/or release of semi-solids discharge equal or greater than 100,000 m^3 is categorized as "serious", and with multiple loss of life (~20) and/or release of semi-solids discharge equal or greater than 1,000,000 m^3, and/or release travel of 20 km or more is categorized as "very serious".

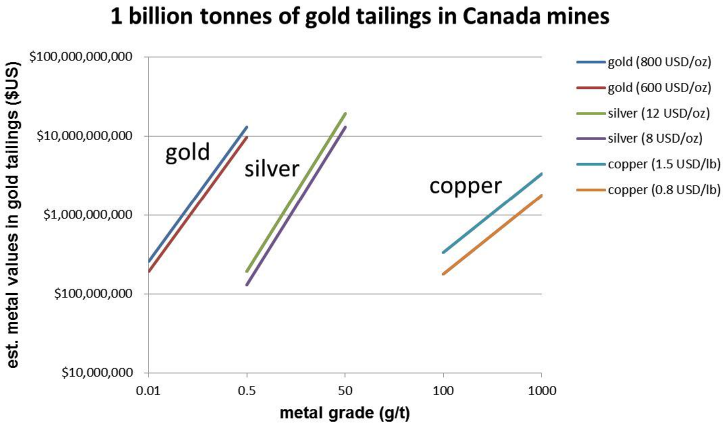

Figure 2. Estimation of the metal values (gold, silver & copper) contained in the estimated one billion tonnes of gold tailings in Canada.

2 RESEARCH

2.1 *Rationale*

Despite the significant metal value contained in mine waste, reprocessing of it is unconventional. In general, the remaining metal value present in tailings is considered as a process loss and does not warrant any further effort to be recovered mostly due to economics, environmental liability and regulation or technological deficiencies.

Tailings and other mine waste pose a long-term liability to mine operators. Besides holding long-term insurance bonds, mine operators are actively engaged in developing best practices in tailings management (Environment Canada, 2009; MAC, 2011a, 2011b, 2011c, & 2015) to mitigate the risks associated with these wastes. Furthermore, mine waste management efforts and objectives are often formulated around reclamation and mine closure, not targeting at reaping potential economic benefits through waste reprocessing and repurposing.

2.2 *Variability of tailings*

Tailings are often a mixture of finely ground rock and water. Because of the diversity of ore bodies and technologies employed to process them, the resulting tailings are very much site specific. The physical and chemical properties of tailings of every site at every point of time are unique. The mineralogy of tailings can be grouped into three broad categories, namely gangue, sulphide-oxide, and secondary mineral fractions. Within a tailings impoundment area, it is common to see mineralogical variation among tailings samples collected at different locations and depths as a result of particle size segregation, secondary chemical reactions, process and feed changes, and weathering effects (Wang, et. al., 2014). Thus, the capability of handling variable feed conditions is essential to the successful implementation of tailings reprocessing technologies.

2.3 *Knowledge gaps*

Tailings are very fine solids which can be classified by their particle size as sand, silt, and clay. For example, according to Canadian oil sands classification system, sand is less than 44 μm, silt is between 2 and 44 μm, and clay is less than 2 μm (Masilyah, et. al., 2011). As the inherent characteristics of fine solid particles, there are two undesirable phenomena often related to tailings processing/reprocessing: water capture and slow solids settling (Wang, et. al., 2014).

As most conventional milling and extraction technologies have been developed and biased towards handling of coarser particle size materials, numerous difficulties in processing fine-grained materials such as tailings are faced stemming from equipment blockages to poor process performance. The interfacial phenomena between fine solid particles and aqueous media in transient multi-component systems are rather complex. The advancement in nanoscience and microfabrication technologies could be very well a source of reference and inspiration, particularly in the understanding of the fundamental theories of surface chemistry involved. Equally important is to build up application knowledge and a database by working with tailings materials taken directly from across a wide range of mines and TIA. There is no substitute but to evaluate extensively lab- and pilot-scale tests and performance data available from relevant vendors before reliable and economically viable tailings reprocessing and repurposing processes can be successfully implemented (Wang, et. al., 2014; Consortium of Tailings Management Consultants, 2012).

3 CASE STUDES

3.1 *Copper-molybdenum tailings*

Amerigo Resources, a Canadian junior exploration company, has successfully demonstrated significant economic benefit by reprocessing tailings from one of the world largest copper mines, Codelco's El Teniente in Chile, whereas historical and fresh tailings were graded at about 0.3% and 0.12% Cu, respectively (Williams, 2010). Amerigo Resources has a wholly owned subsidiary, Minera Valle Central (MVC) operating a tailings reprocessing plant next to a 200 Mt historical tailings impoundment of Colihues. This tailings reprocessing plant is a low capital cost investment with secondhand equipment re-engineered to suit MVC's specific high throughput and very low grade requirements. The plant has eight ball mills to grind the tailings, cyclones and a large flotation section. Some 130,000 t/d of fresh tailings are delivered to the plant via a 40 km tailings launder from the El Teniente mine, while about 30,000 t/d of historical tailings of Colihues are mined and sent directly to the concentrator using water monitors and pumps. The operation relies heavily on a gravity flow system feeding the slurried tailings to ball mills, followed by flotation to produce copper concentrate, which also contains molybdenum and silver. In 2008, MVC produced about 35 million pounds (16 Mt) of copper and 769,000 pounds (350 kt) of molybdenum, and the cost of producing a pound of copper was around US$ 1.30, which proved to be economically viable at the time (Williams, 2010). Despite the current downward pressure of commodity prices, MVC has continued its tailings reprocessing operation in Chile and produced 37 million pounds (17 Mt) of copper in 2015 (Amerigo Resources, 2016), which is higher than a number of primary copper mining operations today.

3.2 *Carolin Mine gold tailings*

The Ladner Project of New Carolin Gold Corp. in BC, Canada has amplified the potential economic benefits brought by re-examining the metal values in gold tailings. As per its NI 43-101 compliant resources estimate (standards of disclosure for mineral projects in Canada) completed in 2011, for the tailings portion of the property, the indicated mineral resource of 445,000 tons (403,695 t), grading 1.83 g/t for a contained gold ounces estimate of 24,000 ozt and the inferred mineral resource of 93,000 tons (84,367 t), grading 1.85 g/t for a contained gold ounces estimate of 5,000 ozt, were reported (Pearson, 2015).

As the gold content in the Carolin tailings is relatively high, the investigators, Daniel and Downing (2011), are interested in determining why the original mill failed to extract the gold which remained contained in the tailings and whether 25 years of weathering has had an effect on the tailings ability to be concentrated. The prefeasibility test work showed recovery problems experienced by the original Carolin Mill was attributed to the larger grind size used in the old plant (i.e., P80 of 180 μm) compared to the reduced grind size of 53 μm used in the testwork. The testwork also demonstrated clearly that the material could be concentrated by 10 times the original feed grade with a 3-stage flotation circuit using potassium amyl xanthate (PAX) and aeroflot 208. It also showed the positive effect of using reagents such as sulphuric acid to re-activate the material's surface for better flotation sensitivity. Finally, the leaching tests on the flotation concentrates of the tailings (gold grade of 19.2 g/t) achieved an overall gold recovery of at least 80% using sodium cyanide of concentration as low as 3 g/L in total leach time of 24 hours (Daniel & Downing, 2011).

3.3 *Desulphurization of tailings*

For the past two decades, a considerable amount of effort has been put into desulphurization of tailings aiming at prevention and risk mitigation of acid mine drainage (AMD); some of the relevant technical reports and guidance documents can be found in the Mine Environment Neutral Drainage (MEND) depository available to the public, http://mend-nedem.org/ (Tremblay & Hogan, 2015).

The presence of sulphide minerals in the tailings is directly related to the onset of acid generation due to the bacteria catalyzed oxidation of sulphides. The successful separation of sulphides and non-sulphide portions of the tailings would allow better management and repurposing of the material. For one, the total amount of sulphide-containing tailings which requires high cost and high maintenance acid proof lining and water cover would be significantly reduced. Second, the non-sulphide portion of the tailings may have added values to be valorized or repurposed for other applications. Finally, in the process of separating the sulphide and non-sulphide portions of the tailings, the metal values locked up in the tailings may very well be concentrated or liberated, which certainly add further economic values to support the business case.

A comprehensive review study on separating sulphides from mill tailings was conducted by Cominco Engineering Services Ltd. using four mill tailings samples taken from three operating mines at the time, Placer Dome – Detour Lake Mine, Lac Minerals – La Mine Doyon, and Les Mines Selbaie (Cominco Engineering Services Ltd., 1994). The study examined the effectiveness of separating the samples into sulphide and non-sulphide fractions by testing an array of gravity and flotation separation processes. One of the common observations on the characteristics of the tailings from the four different locations was that the sulphide minerals tended to be concentrated in the fine size fractions (< 74 µm), and were well liberated from the gangue minerals making separation by direct flotation a viable option. Table 2 shows the selected results of the flotation tests highlighting on the possibility of clean separation of sulphide and non-sulphide minerals portions of the tailings, and at the same time the great opportunities of concentrating metal values – gold, silver, copper and tellurium, in these cases.

Table 2. Summary of the flotation tests results on the four mill tailings (Cominco Engineering Services Ltd., 1994).

Sample: Placer Dome
Test mode: CN destruction prior to flotation

Description	Assays		
	Au (g/t)	Cu (wt.%)	S_T (wt.%)
Cu prefloat	1.05	5.09	21.10
Bulk sulphide float	0.51	0.47	25.10
Tails	0.31	0.02	0.98
Head	0.33	0.15	2.35

Sample: Lac Minerals
Test mode: Flotation using PAX after CN destruction

Description	Assays		
	Au (g/t)	Te (ppm)	S_T (wt.%)
Flot 1	0.78	11.00	42.53
Flot 2	0.51	14.00	29.62
Tails	0.26	8.00	0.65
Head	0.12	8.36	4.17

Sample: Selbaie-1
Test mode: flotation at low pH

Description	Assays		
	Au (g/t)	Ag (g/t)	S_T (wt.%)
Flot 1	0.18	49.50	49.10
Flot 2	0.25	56.20	19.40
Tails	0.05	3.00	0.76
Head	0.12	0.15	22.97

Sample: Selbaie-2
Test mode: Use PAX as collector

Description	Assays		
	Au (g/t)	Ag (g/t)	S_T (wt.%)
Bulk sulphide float	0.52	52.70	28.13
Tails	0.21	0.73	0.39
Head	0.24	6.56	3.50

4 OPTIONS TO REPROCESS AND REPURPOSE

The concept of treating tailings as resources is not new (Bean, 1972; Rampacek, 1982; Shaw, et. al., 2013; van Zyl, 2014), and has been successfully applied in some areas such as reusing tailings as an oxygen barrier to treat contaminated soil and turning bauxite residues into marketable products for road construction or neutralizing agent in agricultural soils. These solutions are among the 100 innovations highlighted in the mining industry in a recent publication by Minalliance (Minalliance, 2012). Generalized flowsheets for tailings reprocessing have been proposed and studied by various researchers looking for long-term solutions for better environmental, social and economic outcomes (Struthers, *et al.*, 1997; Edraki, *et al*., 2014). However, for the wider adoption of the technologies in tailings reprocessing and repurposing by the industry, a cost-effective, environmentally sound, holistic approach supported by multiple stakeholders from industry, regulatory and policy organizations, and academia must be developed and demonstrated.

A conceptual flowsheet for tailings reprocessing and repurposing is depicted in Figure 3. There are four desired outcomes:

(1) Reduce the environmental liabilities posed by the existing tailings;

(2) Recover the metal values in the tailings;

(3) Produce benign tailings residue; and

(4) Utilize tailings as resources.

Tailings A shown in Figure 3 is the whole of historical tailings generated from metal mines in the past. Tailings A composes of tailings of variability with site specific constraints and material properties. A set of assessment criteria which is required to form a basis (i.e. decision gates 1, 2 & 3) to qualify the individual tailings material for reprocessing must first be developed with the end goals of reaching one of the four desirable outcomes. The ultimate goal is to reduce substantially the amount of potentially hazardous tailings in the tailings impoundment area (i.e. Tailings B << Tailings A) and so are the environmental liabilities associated with it. The resulting tailings from reprocessing, Tailings C, are benign and should pose minimum risks to the environment. Strategically, tailings reprocessing opens up new resources for industrial minerals which do not require costly exploration and lengthy commissioning time. Importantly, the reprocessed tailings itself can be turned into various value-added products such as backfill, top soil or other applications.

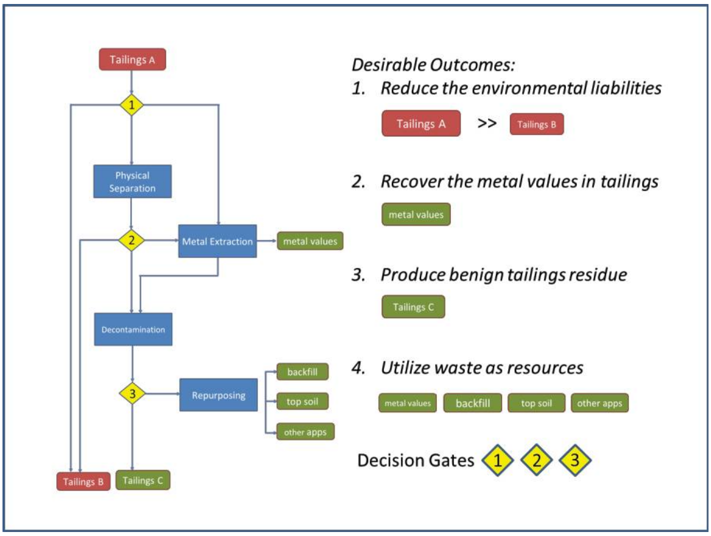

Figure 3. A conceptual flowsheet for tailings reprocessing and repurposing.

5 CONCLUSIONS

As an integral part of the five-year (2016–2020) Green Mining Innovation Research Plan at CanmetMINING, this project pursues the ultimate goal of waste minimization through active utilization of tailings as resources. Over 6 billion tonnes of tailings have been generated in the Canadian mines for the last thirty years; of which 90% result from metal mining where base metals and gold mines are the major contributors. The metal values in the gold tailings alone were estimated to be in the order of US$ 10 billion. This project employs a holistic approach to facilitate the development and deployment of green mining solutions in tailings reprocessing and repurposing. Its objectives are not only to reclaim the metal values locked up in the waste but also to alleviate the environmental liabilities and social burdens associated with the management of the tailings facilities.

REFERENCES

Amerigo Resources, 2016. <http://www.amerigoresources.com/.> (accessed June 2016).
Barter, S., 2011. Tailings inventory project 2011. CanmetMINING internal project.
Bean, J.J., 1972. Tailings as an ore body. In: Aplin, C.L., Argail, G.O., (Eds.), Tailing Disposal Today. Proceedings of the First International Tailing Symposium, Tucson, Arizona. Miller Freeman Publications Inc., San Francisco, USA. pp. 606-614.
Bowker, L.N., Chambers, D.M., 2015. The risk, public liability, and economics of tailings storage facility failures. Center for Science in Public Participation. <http://www.csp2.org/technical-reports> (accessed June 2016).
Cominco Engineering Services Ltd., 1994. Separation of sulphides from mill tailings - Phase I. MEND Report 2.45.1a. <http://mend-nedem.org/category/uncategorized/> (accessed June 2016).
Consortium of Tailings Management Consultants, 2012. Alberta Innovates – Energy and Environment Solutions, Project reports: Oil sands tailings technology deployment roadmap and action plan. <http://www.ai-ees.ca/reports/> (accessed June 2016).

Daniel A., Downing B.W., 2011. Investigating the reprocessing of Carolin Mine Tailings. In: Tailings and Mine Waste 2011, Norman B. Keevil Institute of Mining Engineering, University of British Columbia, Vancouver, BC. pp.1-13. <http://www.infomine.com/library/publications/docs/Daniel2011.pdf> (accessed June 2016).

Edraki, M., Boumgartl, T., Manlapig E., Bradshaw, D., Franks, D.M., Moran, C.J., 2014. Designing mine tailings for better environmental, social and economic outcomes: a review of alternative approaches. J. Cleaner Prod. 84, 411-420.

Environment Canada, 2009. Environmental Code of Practice for Metal Mines. <https://www.ec.gc.ca/lcpe-cepa/default.asp?lang=En&n=CBE3CD59-1> (accessed June 2016).

Kitco, 2016. Metal commodity prices. <http://www.kitco.com/finance/metals/> (accessed June 2016).

MAC, 2011a. Developing an operation, maintenance and surveillance manual for tailings and water management facilities. The Mining Association of Canada. <http://www.mining.ca/> (accessed June 2016).

MAC, 2011b. A guide to the management of tailings facilities. The Mining Association of Canada. <http://www.mining.ca/> (accessed June 2016).

MAC, 2011c. A guide to audit and assessment of tailings facility management. The Mining Association of Canada. <http://www.mining.ca/> (accessed June 2016).

MAC, 2015. MAC Tailings Management Initiatives. The Mining Association of Canada. <http://www.mining.ca/> (accessed June 2016).

Masilyah, J.H., Czarnecki, J., Xu, Z., 2011. Handbook on Theory and Practice of Bitumen Recovery from Athabasca Oil Sands: Theoretical Basis, vol. I. Kingsley Knowledge Publishing, Canada.

Minalliance, 2012. 100 Innovations in the Mining Industry. <http://www.minalliance.ca/pdfs/Minalliance_100_innovations_en.pdf > (accessed June 2016).

Pearson, C.A., 2015. Technical report on the New Carolin Gold Corporation - Ladner Gold Project. Reported submitted to New Carolin Gold Corp. on May 29, 2015. pp.1-88 <http://www.newcarolingold.com> (accessed June 2016).

Ramji, K., 2016. Strategic risk assessment and management of Indigenous issues in the extractive sector. CIM Journal, 7(1), 52-60.

Rampacek, K., 1982. An overview of mining and mineral processing as a resource. Resour. Conserv. 9, 75-86.

Shaw, R.A., Petavratzi, E., Bloodworth, A., 2013. Resources Recovery from Mine Waste. In: Hester, R.E., Harrison, R.M. (Eds.), Issues in Environmental Science and Technology, 37 Waste as a Resource. The Royal Society of Chemistry, London, UK. pp. 44-65.

Struthers, S., Brumle, J., Taylor, G., 1997. An integrated system for recycling base metal tailings. Paper presented at the 1997 Annual Meeting of the American Society for Surface Mining and Reclamation, Austin, Texas, May 11-16. pp. 579-592.

Tremblay G.A., Hogan, C.M., 2015. The Canadian MEND program – the first twenty-five years. In: The 10th International Conference on Acid Rock Drainage & IMWA Conference. <https://www.imwa.info/docs/imwa_2015/IMWA2015_Tremblay_265.pdf> (accessed June 2016).

van Zyl, D., 2014. A perspective of innovations in tailings management. In: Anderson C.G., Dunne, R.C., Uhrie, J.L. (Eds.), Mineral Processing and Extractive Metallurgy – 100 Years of Innovation. The Society of Mining, Metallurgy & Exploration, Colorado, USA. pp. 629-637.

Wang, C., Harbottle, D., Liu, Q., Xu, Z., 2014. Current state of fine mineral tailings treatment: A critical review on theory and practice. Miner. Eng. 58, 113-131.

Williams, L., 2010. Teniente tailings provide good revenue stream. International Mining. January 2010, 58-60.