Sustainable mining through innovation in waste disposal

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Abstract

Economic prosperity depends on exploring new sources of energy and materials along with the development of existing reserves. However, all human activity must ensure that the environment is preserved for current inhabitants and future generations of this planet. Mining of the earth's resources produces waste materials (slurry tailings and waste rocks) of variable nature and extent. Effective management of these waste streams necessitates cost effective, environmentally friendly, and socially viable engineering solutions. Despite several inherent challenges within the mining industry, the waste disposal practice has consistently improved over the years. The main objective of this article is to develop a clear understanding of sustainable development in mining through innovation in waste disposal. Two innovative methods at different development stages and focusing on producing engineered materials with superior geotechnical and geochemical properties are described. The sustainability benefits of tailings thickening and co-mixing of tailings and waste rock are highlighted.

1. Introduction

The World Commission on Environment and Development (1987) headed by G.H. Brundtland defined sustainable development as one that "meets the needs of the present without compromising the ability of future generations to meet their own needs." The United Nations 2005 World Summit Outcome Document identified three interdependent and mutually reinforcing pillars of sustainability as economic development, social development, and environmental protection. These pillars are influenced by various interrelated factors in almost every industrial activity related to products or services.

The mining industry is witnessing an epoch-making revolution due to a growing demand for metals (copper, iron, aluminum, nickel, gold), minerals (clays, gemstones), and energy resources (oil, coal, uranium) all over the world and especially in the emerging economies of China, India, and Brazil. For example, the online data of World Bureau of Metal Statistics indicates that China is currently consuming approximately 25% of the entire world production of base metals. In addition to a general price hike in most of the afore-mentioned commodities, there is a gradual depletion in their available reserves in different parts of the globe. The industry is actively employing improved exploration, enhanced recovery, and novel recycling technologies to address the sustainability issues pertaining to economic development.

Since the companies simultaneously work at mine sites in several countries, the mining industry is essentially global in nature. The employment growth in the industry has been phenomenal over the last five years or so. For example, the average annual employment growth in the Canadian mining sector (that includes surface mining of oil sand in Alberta and Saskatchewan) has stayed above 7% since the year 2001. According to the online data of the Organization for Economic Co-operation and Development, this is the highest among the G-8 and OECD countries. In the Canadian context in particular (and elsewhere in general), there is an acute shortage of skilled professionals in the industry. This is attributed to an aging workforce and a low previous enrolment in Mining, Materials, Environmental, and Geological engineering programs in the universities. These contributing factors, in turn, resulted from the skepticism among the public about the abandonment of mining communities after project completion. A renewed emphasis on the socio-economic well being of the local communities is fundamental for attracting and retaining skilled professionals.

Whereas economic and social development is in the interest of the mining industry, the third pillar of sustainability, namely environmental protection, has to be imposed by the regulatory authorities. The main environmental issues associated with the industry include greenhouse gas emission, energy consumption, water use and recycling, metal leaching and acid rock drainage (ARD), and the geotechnical stability of large volumes of solid wastes. Interestingly, all of the environmental problems are variably affected by climate change that was brought about by industrialization, including the global mining industry, in the first place. Continued pressure from various stakeholders has resulted in stringent environmental criteria and obtaining public licensure for mining is increasingly becoming more costly.

The main objective of this paper is to develop a clear understanding of sustainable development in the mining industry through innovation in waste disposal. First, the generation of waste rocks and slurry tailings in conventional mining operations is described. Next, the inherent challenges in the mining industry to effective waste management are highlighted. This is followed by a description of two most promising innovative waste disposal methods, namely: tailings thickening and co-mixing of tailings and waste rock. The economic, social, and environmental benefits of the two engineering methods are highlighted.

2. **Mine Waste Streams**

Useful materials are obtained from economically profitable ores (possessing sufficient amount and concentration of the commodities) by excavating the earth's crust. To access the ore body, the low-grade overburden rock from different geological facies is removed through blasting. The resulting pulverized materials are sequentially deposited along a hillside to form a waste rock dump. The fragmented ore is further broken down through grinding and washing and the valuable components separated from the gangue using a combination of mechanical, chemical, and thermal treatments (Wills & Napier-Munn 2006). The process residues (tailings) containing large amounts of water and noxious compounds are usually discharged in a valley and contained by dams. The two waste streams continuously grow in volume over the active life of a mine that generally spans over several decades. Given a variety of geoenvironmental issues, the containment facilities have to be managed for several more decades beyond mine closure.

The waste rock dumps are constructed by end dumping that uses haul trucks for transportation and disposal and bulldozers for pushing the deposited materials to level the surfaces. This results in material segregation since the coarse chunks travel longer distances than the fine particles. As the dump face advances, the heterogeneity within the dump gradually increases owing to repetitive trafficking of heavy machinery. According to Azam et al. (2007), the internal waste rock configuration evolves over time due to physical processes (abrasion, crushing, crystal growth, slaking) and chemical processes (dissolution, oxidation, hydrolysis, diffusion, precipitation). These weathering pathways are variably affected by the prevalent climatic conditions at a mine site and are maximized under alternate wet-dry cycles (Molson et al. 2005). The slope stability of the man-made mountains along with metal leaching and ARD are the main geoenvironmental issues associated with waste rock dumps.

The tailings are transported through slurry pipelines and are discharged in a disposal area. Segregation of the fine and coarse particles takes place during hydraulic transport and subsequent deposition. The fines remain in suspension and settle under gravity at very slow rates thereby requiring a long-term storage facility. These slimes are contained by an initial starter dyke that is gradually raised by upstream, downstream, or centerline construction to accommodate the increasing waste volume (Vick 1990). The fast-draining coarse fraction is used for stage construction of the dam and forms sandy beaches between the impoundment and the dam. The chemical-rich tailings are environmentally benign when contained under saturated conditions. However, the large volume of such a loose material poses serious geotechnical concerns especially in earthquake active areas. In contrast, the unsaturated sand deposits are quite reactive and produce leaching of acids and metals although efficient drainage is required for the stability of the raised embankments (Wilson 2008).

3. **Challenges In Waste Management**

The mining activity essentially disrupts an existing ecosystem that usually comprises of soil and water and may involve air. The environmental impacts of mining were known from at least the medieval ages. In the first mining textbook, De Re Metallica, Agricola (1556) noted:

> "When the ores are washed, the water which has been used poisons the brooks
> and streams and either destroys the fish or drives them away…. there is greater
> detriment from mining than the value of the metals which the mining produces"

Over the last five centuries, great advances have been made in the mineral and metal processing industry thereby resulting in extensive changes in the nature and extent of the mine wastes. However, an effective management of the wastes is hampered by several challenges associated with the inherent character of the mining industry.

First and foremost is that the wastes are generated as a by-product of the ore beneficiation process where the primary objective is to optimize recovery of metals and minerals. Therefore, the properties of the two waste streams are not consciously designed from a geotechnical and/or a geochemical perspective. This greatly contributes to the generation of marginal waste materials that have to be contained in gigantic storage facilities for very long periods of time. Being economically worthless, the industry cannot justify investing in the wastes and spends capital primarily to ensure environmental compliance. Consequently, only a modest amount of financial assistance is made available for research and development in mine waste management.

The timeframe for mine waste management spans over at least thirty to sixty years in most cases. This time scale is more than the career life of a professional working in mine wastes. The waste disposal lifecycle comprises of exploration and investigation, planning and design, construction and operation, testing and observation, and closure and reclamation. Being the longest across all engineering disciplines, the personnel involved in the initial stages of exploration and investigation would seldom participate in the construction and operation of the containment facilities and so on. This raises serious concerns regarding the efficient knowledge transfer from senior to junior professionals.

The scale of space in containment structures is also one of the largest among the various types of man-made construction. The commonly used SI units to measure the wastes are million tonnes and square kilometers. Enormous waste rock dumps have been constructed at Questa mine (USA), Grasberg mine (Indonesia), and Antamina mine (Peru). Likewise, the world's largest tailings storage facilities include the Alberta Oil Sand (Canada), Minera Escondida (Chile), New Cornelia (USA): the first of which covers an area in excess of 50 km2. The applicability of laboratory-scale and meso-scale tests to field-scale problems is quite implausible.

There is a great degree of variability in the wastes among materials from different mines as well as among those retrieved at different times from the same mine. This variability can be attributed to several factors: (i) parent geology (inherent properties, mineral composition); (ii) mining operation (blasting, sequencing, slurry preparation, ore processing); (iii) containment construction (transportation, dumping); and (iv) climatic conditions (temperature, precipitation, humidity, wind). The time and space scales along with the site-specific and time-dependent nature of the wastes have largely precluded the development of a generalized framework to evaluate and improve the two waste streams. It is safe to state that the basic science (physics and chemistry) of the large-scale systems is not well understood. Recognizing this shortcoming, extensive research work has been carried out using applied mathematics. However, predictions based on numerical modeling are not thoroughly validated by empirical in situ data.

The mining industry is not always conducive to adopting research and development in the waste management realm. This is primarily attributed to the fact that the wastes (types, properties, and volumes) depend on the factors listed earlier and the teams responsible for carrying out different tasks within a company often have opposing mandates. Therefore, the waste management groups have traditionally operated the containment facilities using an observational approach. This mindset generally precluded the acceptance of new knowledge through innovation and the retention of existing knowledge through training.

The above issues have cumulatively resulted in incremental research and breakthrough progress (similar to that in the computer industry) was seldom witnessed in mine waste disposal. The innovative methods, described in this paper, are developed based on previous experience and improvements in components and subsystems. Therefore, most of the new developments should be considered as the second generation methods of mine waste management.

4. **Innovative Waste Management Methods**

Driven by an acute stakeholder pressure, a culture of innovation is gradually emerging in the mining industry. At the company level, there is an increased understanding of the organizational culture (including attitudes, beliefs, values, and norms that govern the behaviour of individuals and teams (Cummings et al. 2005)) and organizations are defining unique metrics for their innovation (changes in paradigms, processes, or services that result in progress (Mckeown 2008)). Increased communication, collaboration, experimentation, and accountability within the industry have contributed to the evolution of the innovation culture. Consequently, there is a wide variety of novel mine waste disposal methods at different stages of research, development, and implementation (Bussière 2007). The most promising among these methods are the ones focusing on engineering the waste streams to produce materials possessing superior geotechnical and environmental properties.

Thickening is the process by which slurries are converted to non-segregating, paste-like materials that can be pumped (Robinsky 1999). The method involves the removal of most process water originally used in metal/mineral extraction by passing the solid-liquid mixture through gravity thickeners. Depending on material type and the operation method, the solids content of the thickened slurry can range from 45% to 65% for ultrafine bauxite residues and up to 70% for typical base metal mine tailings. The tailings stream modified through physicochemical reagents fulfills one or more of the following objectives: (i) reclaim process water and/or chemical reagents; (ii) maximize the solids content of the tailings in the storage facility; (iii) minimize the potential for contamination; (iv) balance water consumption at various stages in the ore beneficiation process; and (v) develop suitable materials for surface deposition, mine backfilling, or sub-aqueous discharge (Azam 2004).

The engineered materials create a self-supporting conical deposit thereby reducing the land footprint and eliminating the need for settling basins and large retention dams. Upon release in the disposal area, the highly viscous homogenous tailings flow and eventually attain a slope of 2% to 6%. The slope is governed by the degree of thickening and is intended to improve surface runoff. A low mud wave develops at the toe of the thickened tailings deposit as it expands during deposition. The drainage system is designed to ensure that each layer of the deposited tailings mass attains the shrinkage limit (water content pertaining to minimum soil volume). Precipitation along with the small amount of extruded process water is redirected to a pond located near the ore processing plant that uses the recycled water. The pond typically receives about 33% of the amount of process water that would flow in conventional tailings disposal thereby substantially reducing infiltration from the deposited mass into the underlying soil and/or rock formations. In most cases, the disposal area is progressively reclaimed during the operational life of the mine (Jewell & Fourie 2006).

The absence of a settling basin containing large volumes of loose materials means a reduced failure risk and minimal ecological damage in case of local failure. Fresh deposits can liquefy but would not flow excessively because of an insufficient amount of water in the material. Following deposition, the thickened tailings undergo self-weight consolidation and the flow eventually stops. Additional consolidation takes place due to the gradually increasing tailings load as new material is deposited on top of the existing layers. This increases the shear strength of the deposited material owing to an increase in solids content. The continuous burial of the exposed surfaces with fresh slurries and effective bonding within the engineered tailings also minimizes potential erosion problems. Generally, the stacking heights can be at least doubled through the use of thickened tailings discharge.

Thickened tailings disposal minimizes ARD and metal leaching in reactive deposits through curtailment of potential diffusion of atmospheric oxygen. A low hydraulic conductivity along with high moisture retention and a high air-entry value of the engineered material provide suitable hydrological conditions necessary for maintaining a saturated tailings profile (Barbour et al. 1993). During active mining, a small amount of contaminated water is collected as surface runoff that is mainly recycled with the remainder duly treated prior to its release to the environment. At closure, a soil cover can maintain saturated conditions in the sulphide bearing tailings deposits. The land could be easily reclaimed by vegetation that would facilitate an innate balance between evapotranspiration, infiltration, and runoff.

Co-mixing of tailings and waste rock produces a blended waste stream with improved engineering properties: low hydraulic conductivity, high water retention capacity, high air entry value, high shear strength and low compressibility (Wickland et al. 2006). The method involves arranging the coarse waste rock particles in a loose contact and filling the voids with thickened tailings. Depending on material type and blending method, mixing ratios of 20:1 through 1:1 (waste rock to tailings) can be achieved. The new materials can be used for the construction of post-mining landforms above ground or in open pits (improved geotechnical stability) and for reducing metal leaching and ARD (improved geochemical stability).

The co-mix material has a much higher density than either conventional tailings or waste rock deposits thereby reducing the total waste volume and surface area requirements for impoundment construction. Likewise, their superior hydraulic properties can result in eliminating oxygen intake by advection/convection (primary oxygen transport mechanisms in waste rock dumps) and even reduce oxygen supply through diffusion thereby minimizing oxidation and metal leaching in sulphide bearing materials. Laboratory testing, meso-scale experiments, and field-scale trials using selected blends of waste rock and thickened tailings were conducted for the Porgera Mine, Papua New Guinea and the Copper Cliff Mine, Canada (Wilson et al. 2008). The hydraulic conductivity values for co-mixes were found to be comparable to consolidated thickened tailings with volume change characteristics similar to waste rock. Further, field lysimeter measurements demonstrated that the infiltration and drainage rates are reduced by two orders of magnitude when co-mixes are used to construct cover systems on tailings.

The most important factor affecting co-mixing is the method employed to blend thickened tailings and waste rock. The use of a concrete transit mixer has proved to be successful for experiments at a small to intermediate scale. At the field-scale, combined pumping of tailings and crushed waste rock at a ratio that limits segregation of fine particles and minimizes the risk of pipe blockages seems to be the most promising way to transport and mix the two waste types. Alternatives such as blending in a haul truck or a conveyor belt, mixing at the dump crest, and injection of tailings in waste rock are being considered. Several other aspects of co-mixing are being investigated to facilitate its implementation in the mining industry. Some of these include the following: (i) impact of mixing ratio and additives (clay, slag, cement) on material properties; (ii) infrastructure requirement for efficient mixing; (iii) design of storage facilities such as dyke and drainage structure; (iv) co-mix rheology when combined pumping is planned; and (v) acid generation rates of sulphide rich materials.

6. **Summary and Conclusions**

The mining industry has been developing innovative waste disposal methods over the years. Sustainable methods involving materials with superior geotechnical and geochemical properties include tailings thickening and co-mixing of tailings and waste rock. Given a reduced life cycle cost along with an improved physical and environmental stability, thickening has been adopted by several mines around the world such as Kidd Creek copper/zinc mine (Canada), Alcoa World alumina mine (Australia), and Bulyanhulu gold mine (Tanzania). Co-mixing is in the testing stage and is potentially a more sustainable technology particularly in base metal mining. The growing needs of the industry have forced universities and academic institutions to conduct high quality research on different aspects of the engineered materials. The number of conferences and seminars on tailings thickening and acid rock drainage vividly exhibits enhanced information sharing. The engineering and scientific community, the regulatory authority, and the public at large are embracing the use of thickening and co-mixing at an accelerated pace and their use appears to be the norm rather than the exception in the very near future.

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