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Review

Review of closed water loops with ore sorting and tailings valorisation for a more sustainable mining industry

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ABSTRACT

Conservation and management of freshwater resources has become a major challenge of this century. In mining, one should be able to control the quantity of water intake, as well as the volume and quality of effluents. When the water loops in mining industry are closed, new methods for water quality control and optimisation at each process step are required, which facilitates also the recovery of additional valuable elements. The tightly closed water cycles necessitate that the tailings are filtered and stacked dry. Geopolymerisation of remaining tailings has the potential to be used for water and oxygen tight covers on the deposited tailings and for mine back-fill use. Detection of ore types and their classification or sorting by their geo-metallurgical properties before and in mill feed have a significant effect on metals recovery and on the process water quality in flotation. The main objective of this paper is to review the progress made towards a new paradigm shift at mine sites to recycle water and valorise tailings for an improved environmental and economic result, and for increased social acceptance of mine operations.

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1. Introduction

For many projects in the mining sector, access to water is critical for feasibility (Nguyen et al., 2014). Since mining is a water intensive industry, the reduction in water consumption is crucial in achieving the sustainability targets (Gunson et al., 2012). There is a clear need to recycle water in mining operations due to both operational needs and environmental benefits (Driussi and Jansz, 2006; Corin et al., 2011). Typically, various countries have discharge limits on pollutant concentrations as well as on total loads (Northey et al., 2016). In some areas, obtaining water allocation permits can be much easier than obtaining discharge permits (Thomashausen et al., 2018). Recycling of process water minimizes the release of pollutants into nearby waters and lowers the fresh water withdrawals (Lutandula and Mwana, 2014). However, recycling of water may have an impact on plant performance due to increased dissolved ions and increased ionic strength (Levay et al., 2001; Corin et al., 2011). For example, the reuse of process water can have negative or positive effects on the flotation performance and therefore the components in the water need to be assessed. There is an identified need for detailed systematic studies on process water reuse in flotation and responses of the minerals under flotation conditions (Ikumapayi and Rao, 2015).

Ore sorting and thus ore quality will affect the water quality in the subsequent flotation process (Foggiatto et al., 2014). Accurate detecting and sorting i.e. directing higher-grade and lower-grade ore (Duffy et al., 2015) or sulphide and oxidized ore types to flotation and to heap leaching leads to higher flotation recovery and better results in water circulation. Avoiding mixing of sulphide and inert waste rock in mining has significant effect in overall environmental footprint during the mine life cycle. Tools for the reduction of waste rock dilution and ore losses minimize the use of energy, water and consumables in relation to final valuable products and side rock (Lessard et al., 2016).

Tailings storage is the largest water sink in most mines (Gunson et al., 2012) with over 50% of water losses coming from the water trapped in the pores in the tailings (Donoso et al., 2013). Tailings disposal thus needs close attention in the mine water management (Gunson et al., 2012). Tailings and mine water issues should be considered simultaneously, not separately, e.g. with predictive models (Muniruzzaman et al., 2018). Waste rock can be used in novel value creating processes. The finer fractions can be used for geopolymer products as part of mine backfill or tailings area cover. They may even suit to higher value products such as wear parts. A standardized protocol addressing the water related issues in a systematic way would bring benefits both for the design of new plants and for evaluating alternatives to close water loops in already existing plants. The solutions are anticipated to influence the mining operation during the whole lifecycle, since they provide input to the planning and operations of the mine site, as well as to the closure and rehabilitation.

The end-of-pipe solutions aim at cleaning the effluents and storing the waste (Zotter, 2004). This traditional thinking is a challenge both in basic science as well as in engineering. Closed-loop processes provide means to decrease companies' materials requirements significantly (Lovins et al., 1999). Generally, the process-integrated solutions increase the complexity in the production system compared to the end-of-life solutions (Zotter, 2004). There has been very little research on such complex dynamic systems, where the interactions are accounted from a systematic and holistic perspective. Furthermore, there is very scarce understanding of the final balance of a fully recycled water system. The end-of-pipe management also considers usually the effluents and wastes valueless, only accruing extra costs (Zotter, 2004). However, the water and waste streams contain value, which can be utilized. Metals content from recycled water can be recovered (Shadrunova and Orekhova, 2015). Water modified to be suitable to particular process steps will improve the economic value of the ore.

ITERAMS project (iterams.eu) develops new holistic water and waste concepts and a procedure to assess the overall sustainability of mine operations with the ultimate aim to develop a water recycling testing protocol for the mining industry. Conventionally water, ore and tailings have been considered separately from each other. When closing the water loops, the plant is technically isolated from the surrounding water systems. All water will be recycled within the plant and tailings are deposited filter dry. This complete water recycling requires a new holistic water management paradigm based on three major cornerstones: the water, ore sorting and geopolymerisation of tailings, which are discussed in the following chapters with the ambition to improve the sustainability of mining. Moreover, the transformation of current challenges related to water effluents and tailings into a business case follows the circular economy principles and can improve the overall performance of the mining sector.

2. Method

The review was done using the scientific literature recovered from databases and search engines, such as Google Scholar and eKnowledge Search including EbscoHost, Scopus, Science Direct, Knovel, IEEE, Springer Nature, Taylor&Francis and Wiley. Since a narrative review has a broader focus than a systematic review, it was selected as the method with the focus to find the most relevant literature from a wide range. Words such as water + recycling + mining, water + recycling + flotation, ore sorting, geopolymer, mining + sustainability + environmental were used in the search. Since the literature was selected based on the title and a short description, it is possible that some relevant literature was not retrieved from the search. Publications were searched only in English.

Typically in the literature, water, ore and tailings have been considered separately from each other. We have mapped the content of the literature into three main groups. Section 3 collects information on water use of mining, closing the water loops and water closure effects on flotation. Section 4 describes the possibilities to decrease the amount of tailings and water use via ore sorting. Section 5 focuses on getting the tailings dry in order to recover the water content for water recycling and the mineral residue to be used as geopolymers in various applications. Sustainability aspects of closed water loops and the importance of first industrial examples are highlighted in sections 6 and 7, respectively. Finally, we have integrated the three topics into one holistic water recycling paradigm for mining industry.

3. Closing the water loops

3.1. Water use and management in the mining industry

Conservation and management of freshwater resources has become a major challenge of our societies globally. Mining operations are not the biggest users of water in the global scale. Around 1–2% of the total water consumption in the USA, Canada and Australia is due to the mining industry (Norgate and Lovel, 2004; Gordon-Smith, 2012; USGS, 2013). However, the local usage of water of the mining industry can be very high, even dominating (Northey et al., 2016). For example, approximately 65% of water is used in mining operations in the arid Antofagasta area in Chile (Donoso et al., 2013). The amount of water used for mining operations is expected to further increase with subsequent decrease in the ore grades and increase of metals demand (Mudd, 2010), and in some areas there can be incentives to look for alternative water sources (Northey et al., 2017). Seawater sourced from dozens of kilometres has been used in some mining areas (Ihle and Kraht, 2018). For example, Las Luces plant in Chile has used only seawater and no fresh water for fifteen years (Moreno et al., 2011).

The first industrial trials in the mining sector to evaluate and implement fresh-water saving technologies started already in 1970's with the increasing pressure put on the industry by the limited availability of water, civil actions, government regulations, and the corporate sustainability policies and goals (Bailey, 1970; Pickett and Joe, 1974). Since then, the pressure to save more water and to build zero-emission concentrators has become even more critical due to further depletion of freshwater resources, competition by other industries, farmers, local communities and environmental pollution issues (Ridoutt and Pfister, 2010). The issue is all the more acute for the mining sector since a given plant needs to secure a stable water supply (Thomashausen et al., 2018) and limit the volume of its discharges (Mudd, 2010), whilst it is not able to change its location to adapt to the regional water composition and availability (Askham and Van der Poll, 2017). Hence, the economic value of water depends on water availability at the site (Ossa-Moreno et al., 2018). Different mining sites in various climatic areas face challenges of too much or too little water (Gao et al., 2017) leading to either insufficient water for production or discharges during the rainfalls (Kunz and Moran, 2016). Many mines also experience both water scarcity and excess water at various times (Ossa-Moreno et al., 2018). As a result, the clear majority of the mining companies analyzed in the study of Askham and Van der Poll (2017) had reduction targets for water consumption, because the water crisis can have a far more significant effect on the business of mining companies in the future than has been anticipated.

The process-integrated solutions tend to significantly increase the complexity of the process compared to the end-of-pipe technologies (Zotter, 2004). The approach behind any attempt at increasing the water recirculation rate at a given mining plant must integrate several interrelated variables (Levay et al., 2001). The availability status of water, as a scarce or an abundant resource, is frequently the first item to consider. It is defined by the surrounding environment of the mine in terms of hydrogeological setting and climatic conditions, but also by diverse competitive uses. Inside the plant itself, water streams of various qualities and volumes are handled: i) fresh water from the pits or from surrounding watercourses, ii) process waters produced during the plant operation, which have to be treated before discharge, and iii) wastewaters from tailings deposits, dams and seepage waters, which may, or may not, need treatment (Kauppila et al., 2011). When treatments are needed, they have to be designed based on the quality of water, bearing in mind that quality is defined by the chemical composition of the water as well as the specifications of the process unit where it is recirculated (DWAF, 2006a). In addition to the water requirements of unit operations, evaporation, seepage or retention in tailings and concentrates occur (Gunson et al., 2012; Ihle and Kraht, 2017).

The most important aspect in water recirculation is to ensure that the quality of process waters is kept constant (Slatter et al., 2009). Managers in mining sites have knowledge of water use in their department, but often lack the knowledge of the effects of water quality and quantity on the production chain (upstream and downstream). Often, the water flows at the site are not accurately known, and additional monitoring should be conducted to better understand the water usage (Kunz and Moran, 2016.) New technologies and solutions to meet the water issues targeting closed water loops are needed in the mining operations.

3.2. Recycling water in flotation operations

Flotation is the most common method used for concentrating the ore and it is one of the biggest water consuming unit processes in the mine (Gunson et al., 2012). According to Donoso et al. (2013), over 70% of water in the copper mining operations in Chile is consumed in flotation. A pre-processing step before flotation is to grind the ore with water to a particle size where the different minerals become liberated. The solids density in flotation is typically 25–35% by mass. As a result, approximately 1.9–3.0 m^3 of water per tonne of processed ore is needed in flotation, if water is not reused or recycled (Gunson et al., 2012). The particle surface properties are crucial for successful separation in flotation. Collectors are used to enhance hydrophobicity of valuable minerals, whereas depressants are used to get the gangue particles hydrophilic. Frothing agents are utilized for stable froth needed in the transportation and recovery of valuables. Changes in the composition of the pulp may have an effect on the behaviour of flotation reagents (Moimane et al., 2016). Froth flotation is affected by the quality of the water as it employs the different surface properties (hydrophobicity) of the minerals in order to separate them. Flotation is also sensitive to fluctuations in water quality, so the fluctuations should be diminished (Levay, 2001; Muzenda, 2010).

Without recirculation, complex physicochemical, concentration-dependent and transient-time interactions already take place at the flotation stage between the dissolved inorganic and organic reagents, the colloidal species, the microorganisms and the solid-liquid and gas-liquid interfaces, all mediated by pH, redox potential, electrical conductivity and temperature (Levay et al., 2001). The direct consequence of recycling water in the process is the increase of the ionic concentration over time. Previous research has shown both positive and negative effects of water recycling and increased ionic concentration on flotation.

In the studies of Xu et al. (2012), the zinc concentrate, tailings waters and effluent had a negative effect on the flotation of galena, whereas lead concentrate water showed positive effects on flotation. Positive effects of water recycling were shown in the studies of Ikumapayi and Rao (2015), in which chalcopyrite, galena and sphalerite recoveries were higher in reused process water compared to tap water. In the study of Nuorivaara et al. (2019), pyrite flotation from tailings remained unaffected throughout ten cycles using recycled water, even though the concentrations of several elements increased over time. Rabieh et al. (2017) had no clear effect of water quality on the flotation of pyrite between tap water and synthetic process water. However, most of the studies have shown negative effects on flotation with recycled water. Ikumapayi et al. (2012) studied the effect of calcium and sulphate ions on the flotation of galena, since these ions are very common elements in the process water, when sulphide minerals are floated. Calcium was shown to adsorb onto the surfaces, which would reduce the xanthate adsorption on galena and affected its flotation in a negative way (Ikumapayi et al., 2012). Gypsum in the recycled water has shown to decrease the flotation recovery in sphalerite flotation due to retarded uptake of copper and SIPX (Deng et al., 2013). Also Moimane et al. (2016) showed that a change in ionic strength of the plant water had an effect on the behaviour of xanthate. A competitive adsorption of xanthate ions and cations on the mineral surface was suggested (Moimane et al., 2016). In the tests of Lutandula and Mwana (2014), bicarbonate ions in the recycled water clearly disturbed the flotation process of oxidized ores of copper and cobalt. Bicarbonate ions increase the recovery of minerals from the gangue and depress the minerals containing the metals of interest. The presence of bicarbonate ions also overconsumes reagents through oxidation (Lutandula and Mwana, 2014). The accumulation of thiosulphate ions has been shown to decrease copper and cobalt recovery in the flotation of oxidized ore. Thiosulphate ions deplete dissolved oxygen content from the pulp and alter mineral surface properties and potentially also contribute to the dissolution (Shengo et al., 2014). Corin et al. (2011) have suggested a maximum ionic strength, after which the effects become constant and stable. The up to 3-fold increase in ionic strength did not affect the recovery of sulphide minerals in their studies, but the grades slightly decreased as a result of more naturally floatable gangue introduction to the final concentrate (Corin et al., 2011).

In addition to the accumulation of chemical components, there is a clear need to understand the potential accumulation of microorganisms and their effects on the closed water system (Levay et al., 2001). According to Liu et al. (2013), there is a lack of understanding of the risks of microbiology on flotation efficiency. They showed the decrease in flotation efficiency in the presence of microorganisms in the water. Bacteria-laden water can be received, when using e.g. treated effluent in the processes (Liu et al., 2013) or bacteria may start to accumulate, when the water is recycled in the process. On the other hand, microorganisms may also bring positive effects to the flotation.

3.3. *Complexity increases in closed water loops*

Creating recycling water loops somewhere in the process will increase the magnitude of the interactions in the floated slurry, as well as decrease the residence time of the water storage before reuse – from weeks or months to hours – so that water will be out of the thermodynamic equilibrium (Muzenda, 2010). In addition, the local hydrogeological and climatic setting of the mine can also modify the composition of the recycled water. For instance, snowmelt and rain precipitation will dilute the waters pumped back from a tailings dam to the process plant.

In this context, closing the water loop turns into a loss of information and understanding on what flows inside and outside a given plant (VTT, 2016). The objective is then to determine how much and which kind of water can be extracted from (or discharged to) the surrounding water resources, stored or recirculated internally, and in which internal unit operations. While this objective may appear to be challenged by the fact that every mine operation faces site-specific issues, there are ways to progress on the issues. The first one is the development of causal loop diagrams to qualitatively model the aspects relevant for the sustainability in the specific mine site (Di Noi and Ciroth, 2018). These diagrams help to understand the interrelations in the mine, with a changed water regime, and to focus detailed analyses on those areas that are important. One first choice for detailed models are numerical models for a proper water accounting at the mine scale. Such models would allow (i) establishing water mass balances, (ii) predicting the accumulation of elements in the recycled water (Westerstrand and Öhlander, 2011), (iii) relating the quality of water to the kinetics and recoveries of flotation units, and (iv) providing technological water treatment options to reach the optimal water compositions. This development would represent a conceptual shift in the way the water issue is dealt in mine operations, from a conventional deterministic approach – systematic and separate studies of the effect of each process component to infer predictive laws – to a systemic approach, considering the water system in its totality and its own dynamics.

In turn, this important aspect requires proper water metering technologies and methods, such as on-line cost-effective sensors, followed by their commissioning on the process lines (DWAF, 2006b). The sensors do not need to be very accurate, but they must provide almost real-time information of relevant data, such as the conductivity value or the concentration in colloids, whilst withstanding the rough conditions of the industrial processes.

4. Ore sorting decreases the amount of tailings and water use

Ore has a crucial effect on water and tailings quality. Ore sorting targets to remove the non-valuable material in the beginning at a coarse particle size to avoid the processing of barren material below the cut-off grade, where the processing would cost more than the value of the metal (Duffy et al., 2015; Gülcan and Gülsoy, 2017). Sorting subsequently reduces the amount of material to be milled and thus the energy costs (Lessard et al., 2014). If we consider the fact that comminution has an energy efficiency of approximately 1–2% (Donoso et al., 2013), most of the energy is consumed for inefficiencies. Ore characteristics affect the possibility to use ore sorting. If valuable minerals have the preferential mineralization, then the sorting is likely effective (Foggiatto et al., 2014). For example, in Somincor before the grade control, approximately 20% of waste was processed as ore, and also approximately 20% of ore was considered as waste (Duffy et al., 2015). In the sorting tests of Grotowski and Witecki (2017) in the Rudna mine, ore sorting was evaluated to be able to remove 20–30% of ore calculated as final tailings resulting in 70–80% primary ore mass in flotation with minor copper losses in tailings.

The amount of waste rock is expected to increase exponentially, since the ratio of excavated waste rock to valuable metals has increased over time (Mudd, 2010). Ore sorting results in higher-grade feed material sent to flotation and in minimization of waste (Cutmore et al., 1998; Lessard et al., 2014), reduces the water consumption at the beneficiation plant, enables selective beneficiation and produces coarse dry waste (Foggiatto et al., 2014). When the head grade of the feed increases, energy, water and reagent consumption decrease (Lessard et al., 2016). Water consumption per ton of product decreases, when less tons of ore at a higher grade are processed. This results also in the decreased production of wet tailings (Duffy et al., 2015). The ore sorting test work needs to take into account all processing circuit stages, since the ore sorting can influence recoveries in flotation, when the contaminants are removed into the waste in sorting (Foggiatto et al., 2014).

Typically, the mines blend out the ore variation on purpose to make a stable feed to the plant (Duffy et al., 2015) despite the potential benefits of sorting. In many mines, ore variability causes surprises in mining (Ashley and Callow, 2000) and in estimated reconciliation resulting in big variations in metals recovery in the flotation. Even in cases where the monthly grades of a mine are at estimated levels, the daily ore types and ore geo-metallurgy variations are continuously challenging in flotation and the concentrate in smelter feed is not consistent. Today, sensors and automation in flotation plants have helped to reach levels at which metallurgists are able to adjust metals recovery to optimum in cases, where ore grades are known and consistent. However, even when best conventional mining methods are used, ore types and their variability cause problems. The solution is typically based on bigger (if possible) intermediate piles at the rom pad, which are mixed into the crusher with the best estimation. First indication is on-line analysis assays in flotation feed, if the grade is not the desired one.

Ore sorting technologies include X-ray fluorescence, X-ray transmission, and radiometric and optical sorting (Lessard et al., 2016). In modern mining, ore is characterized with very sophisticated and accurate geo-physical and geo-metallurgical methods even before the decisions to start the mining are made. Later, geological data and feasibility studies give good estimates for the ore types and grades and ore location with inherent estimated amount of side rock and dilution. Desired results are confirmed in feasibility studies with the ore. However, such studies are very difficult to perform with the material including ore variability and side rock dilution. Mining and refining methods and equipment are designed, and the whole operation commissioned and ramped up in few years. The mine operation is monitored with best practices and flotation process is automatically monitored and controlled to get optimum metallurgical recovery.

The difference between the concentrator and mining control is obvious (Ashley and Callow, 2000). Sensors and on-line control of the ore quality along the mining process are missing almost completely, even though continuous ore sorting is a mature technology. The understanding of the implementation and economic impact of ore sorters is lacking (Lessard et al., 2016). Mining equipment (drills, loading machines, trucks) are monitored with sophisticated sensors, and data from machine is sent in real-time to local supervisors or to the control room at the head office. The valuable ore quality is based on early estimates and sparse data from the ore benches, which are mined. The ambition is to study and develop methods to accurately monitor and sense in real-time ore and ore types (and waste and waste types) and their geo-metallurgical properties along the mining process from mine benches to the flotation feed. The aim is also to minimize the use of energy, water and consumables in relation to final valuable products by being able to physically manipulate the mill feed stream properties. There is a need to study and develop methods to accurately analyze ore grade in benches with 3D data to be able to optimize blasting, to estimate ore movement, grade and location in the muck-pile, to monitor ore loading into the crusher and to the mill feed and to the flotation, thus providing valuable on-line real-time information for forward control in grinding and in flotation.

Currently, there are no methods for the economic analysis of ore losses. Fig. 1 shows the results of the ore sorting campaign conducted in a sulphidic mineral mine in Finland. The ore loss is 5%–10% at contact, and as the waste quality is not known, some sulphide waste is piled wrongly in the inert waste area. This latter case may eventually lead to contaminated water leaks in the environment. Further, economics of ore pre-concentration is studied by analyzing ore feed variations immediately after the primary crusher. Fig. 1 shows that the occasional truckloads of below cut-off ore are being fed into the process. The other more frequent situation is that too conservative loading of ore leads to ore losses and possible misplacement of waste types. Low-grade truckloads contain low-level ore, which is not economic to process. Low-grade ore can be sorted out with bulk ore sorting method. Economic calculations can be done to estimate, how much below cut-off ore can be sorted out, and how much higher ore grade is in the feed. When considering the positive possibilities associated with ore sorting, the technology adoption of ore sorting has been surprisingly slow (Lessard et al., 2016).

5. Dry tailings for water recovery and geopolymers

Closing water loops in the processing plant requires that the mining operation has to deal with dry tailings as a consequence. For sulphidic ores (and sulphidic host rock) a subaerial deposition (i.e. dry deposition) of tailings will lead to oxidation of the sulphides and to the subsequent formation of acid mine drainage. Therefore, the deposition of these tailings is one of the major challenges when closing water loops in the mineral processing plant. However, in case the tailings contain considerable amounts of aluminium and silicon, they could be used as solid precursor materials for alkali-activated materials or geopolymers. As a result, these tailings can be used for various applications rather than being deposited as a waste material. Besides an ecological benefit, this could also result in an additional economic value of the tailings management.

5.1. *Tailings*

The mining industry is the largest producer of waste globally with 51 billion tonnes of waste rock and 14 billion tonnes of fine particle (less than 120 μm) tailings in 2010 (Jones and Boger, 2012). Since the ores are getting lower grade, the amount of tailings production is going to go up (Jones and Boger, 2012; Adiansyah et al., 2015). Tailings is the non-economical part (Adiansyah et al., 2015) removed from the valuable part of the ore. Tailings contain different soluble species such as dissolved metals and reagents depending on the ore type and selected production process (Edraki et al., 2014; Wang et al., 2014). Fresh tailings often contain silicates, carbonates and sulphides (Lindsay et al., 2015). Tailings slurry can be disposed into lagoons, ponds or mine sites, where the separation of solids and process water proceeds under gravity (Wang et al., 2014). Tailings have the potential to release acidity and heavy metals into the environment resulting in concerns of the tailings dam stability (BRGM, 2001; Simate and Ndlovu, 2014; Asif and Chen, 2016). Wang et al. (2014) noted, that even though the role of tailings processing management may be minor related to the operation's OPEX and CAPEX, tailings are a significant liability issue to the mining companies. New approaches are needed to prevent the challenges related to tailings storage and to recover the potential business value related to tailings (Kinnunen and Kaksonen, 2019).

Removing water from the tailings and recycling are steps forward in sustainable mining (Jones and Bogar, 2012). Most mines use the conventional disposal method for tailings in the tailings dam requiring a significant content of water. In addition to conventional tailings, there are also technologies and existing applications for thickened tailings and tailings paste (Adiansyah et al., 2015.). Moolman and Vietti (2012) considered 50–59% solids as conventional tailings, 60–70% solids as thickened tailings, and >70% solids as paste. The advantages of removing to thickened tailings are the recovery of water and process reagents, as well as the possibility for mine backfill, reduction in acid mine drainage potential and risk for a dam failure (Jones and Bogar, 2012). Reducing the water content in the tailings is a possibility to increase water efficiency and recycling and subsequently reduce the risks associated with dam failures (Adiansyah et al., 2015). Based on the work of Ihle and Kraht (2017), the production of thickened tailings and the corresponding recovery of more water is a more energy efficient option compared to the production of conventional tailings with the needed water make-up. The use of paste or thickened tailings could also result in the elimination of a significant part of

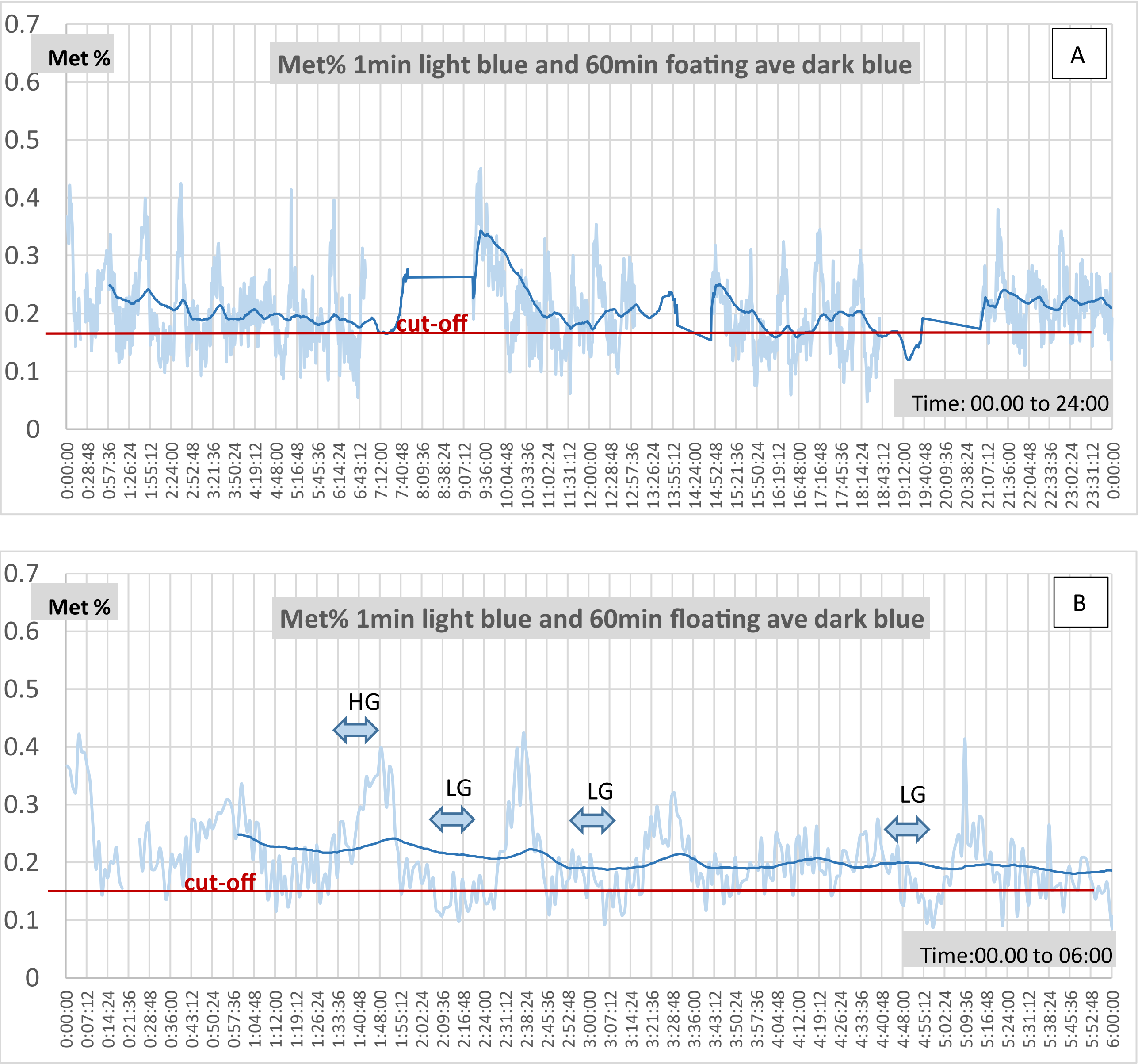

Fig. 1. a) Study on metal content (%) during 24 h period showing 1 min (light blue) and 60 min (dark blue) floating average from primary crushed ore. b) During six morning hours 3 truckloads could have been sorted out, representing about 10% of total feed (1 load high grade HG, 3 loads low grade LG). Arrow in the figure shows approximately the time in which one of those truckloads is processed in the Primary Gyratory crusher. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

the tailings ponds (Jones and Bogar, 2012). As the water and electricity costs are expected to increase, the high-density tailings disposal options are getting more interesting and economical (Moolman and Vietti, 2012).

5.2. Geopolymers

When a solid material gets in contact with a solution, various elements can be dissolved from the solid material. If e.g. aluminium or silicon is present in the solid, an alkaline solution can dissolve these elements. The relative amount of dissolved species depends on the stability of the solid phase in which the specific element is incorporated. As an example, silicon dissolves rather easily from a glassy structure, whereas it is almost insoluble in the form of quartz with a three-dimensional network structure. Therefore, besides the chemical composition of a material, the mineralogical composition is crucial for the dissolution of certain species in alkaline conditions. Regarding the dissolution behaviour of naturally occurring raw materials containing aluminium and silicon, natural calcined clays are the most suitable precursor materials for geopolymers. Furthermore, ground granulated blast furnace slag and various fly ashes are materials with a favourable dissolution of aluminium and silicon. Depending on their chemical and mineralogical composition, other industrial waste materials (e.g. smelter slags, mine tailings, sludges) might be acceptable precursor materials for alkali-activated materials under certain circumstances or additional treatment (e.g. mechanical, chemical, or thermal activation).

When dissolved in an alkaline solution, Al and Si are in tetrahedral coordination and can precipitate as aluminosilicate monomers when saturation limits are reached. These monomers can further condense into more complex structures to form 2D or even 3D aluminosilicate structures by further forming Si—O—Si or Si—O—Al bonds. The negative charge of the AlO_4 tetrahedra is counterbalanced by alkali cations within the cavities of the network structure. The resulting precipitates can be considered a nano gel similar to the calcium-silicate-hydrates that form when an Ordinary Portland cement (OPC) is mixed with water. As a result, the material develops strength comparable to OPC. In contrast to hydrated OPC, alkali-activated materials and geopolymers can show more rapid setting and hardening and have the ability to incorporate toxic metal ions into the structure. They can therefore be used to stabilize potentially hazardous substances. Furthermore, the resulting materials show an improved resistance to elevated temperatures and acidic conditions compared to OPC (Glukhovsky, 1994; Davidovits, 1994). The process of geopolymerisation using an aluminosilicate raw material is schematically shown in Fig. 2 (Obenaus-Emler et al., 2017).

Initially, when geopolymers were invented, metakaolin (i.e. calcined kaolinite) and fly ash were used as the only solid precursors. In the past years, numerous other mineral raw material sources (e.g. natural minerals, calcium rich fly ash, metallurgical by-products as well as their mixtures) have been investigated as precursors for alkali-activated materials and geopolymers (Rao and Liu, 2015). With these alternative raw materials, other chemical species are introduced into the process of dissolution and precipitation. The main difference between a geopolymer and an alkali-activated material is the chemical composition of the resulting precipitate, where geopolymers are viewed as a subset of alkali-activated materials in many instances. Geopolymer precipitates are highly coordinated and almost exclusively aluminosilicates with a very distinct chemical composition - in order to enable the formation of a network structure, the amount of reactive calcium has to be low. Alkali-activated materials in general can also show lower coordinated structures, like chain structures (Provis, 2014). The precipitates in a geopolymer have a chemical composition with a ratio of M:Al:Si of roughly 1:1:4, where M represents an alkali element, and show an aluminosilicate network structure. The precipitates of alkali-activated materials are considered to have a wider compositional range and also incorporate other chemical species, like Calcium, into the structure.

The principle of alkali-activation has been tested as a possible mechanism for the valorisation of mine tailings as well as a route to immobilise heavy metals often contained in tailings. Since the host rock of many mining operations contain aluminosilicates at least to some extent, the tailings of these mineral processing plants may show potential to be alkali-activated. Depending on the mineralogical origin of Al and Si in the tailings, the original rock itself might not show a favourable dissolution behaviour of these crucial elements. However, the fine particle size distribution of the tailings is advantageous for dissolution mechanisms compared to the natural rock. Additionally, the reactivity of fine ground material can be more easily and economically enhanced by e.g. a thermal process step, since an additional grinding might not be necessary.

When thinking of an active mining operation, the resulting alkali-activated materials are best used directly at the mine site, since further valorisation as e.g. construction material might be uneconomic due to the distance of most mining operations to potential end-consumers. Primary possible applications of such materials are backfill for underground cavities and surface covers for tailings or waste rock storage facilities. However, when economically and technically feasible, the principle of alkali-activated tailings can also be applied for construction purposes at the mine site or elsewhere potentially generating additional value from the tailings. From the perspective of the mine operator, the best-case scenario is a complete valorisation of the tailings, preferably with no deposition at the surface level. If a deposition at the surface cannot be avoided (as for example for open pit mines), shielding the potentially problematic sulphidic tailings from environmental conditions by using covers made of alkali-activated materials, seems to be a very promising and sustainable solution. As a result, current and future mining operations will be more ecologically friendly and sustainable. Considering future regulations regarding mining, this will most likely also lead to economically more feasible solutions for many mining operations.

5.3. Pre-treatment of mining tailings and alkali-activation

When evaluating the valorisation potential of a specific mineral waste material as a precursor for alkali-activated materials or geopolymers, the following key parameters can be considered crucial: the amount of reactive aluminium and silicon when in contact with an alkaline activator solution, the amount of other elements such as Ca, Mg or Fe, the amount of glassy phase, as well as the particle size distribution of the material. For the formation of geopolymer precipitates, the molar ratio of silicon to aluminium that can be dissolved is of great importance and should preferably be between 2.5 and 4 (Davidovits, 1994). However, certain applications at the mine site do not require a high compressive strength and therefore a wider range regarding chemical composition can be tolerated. Furthermore, the presence of calcium in the tailings might be favourable, since calcium can contribute to the polymerisation of aluminosilicates by linking individual chains to form more complex aluminosilicate structures or alternatively lead to the formation of calcium-silicate hydrate gels as for OPC, especially

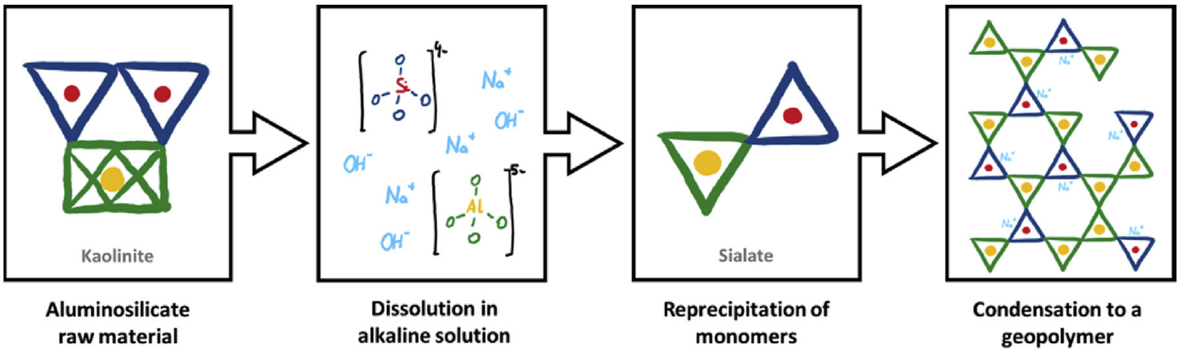

Fig. 2. Geopolymerisation of an aluminosilicate raw material. An alkaline solution dissolves aluminium and silicon ions that have a tetrahedral coordination in the solution. When the solubility limit is reached, aluminosilicate monomers precipitate the condense into more complex structure to form a solid network structure in the end. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

when the amount of reactive aluminium is low. As a consequence, the ratio of reactive silicon to aluminium can also be higher for mine tailings, when calcium is available in a reactive form in the tailings (Rao and Liu, 2015). Mine tailings that only have very little amount of reactive aluminium can still be used for alkali-activated materials or even geopolymers, when an appropriate amount of reactive silicon is present and aluminium is introduced into the alkali-activated material by the addition of external sources, especially alkali aluminate solutions.

In general, mine tailings contain a high variety of minerals, of which not all might be able to contribute to the formation of appropriate precipitates, when alkali-activated in their original form. However, pre-treatment of the tailings could increase the reactivity and thus contribute to the formation of precipitates and strength. The dissolution of relevant species not only depends on its mineralogical heritage, but additionally on the reactive surface area of these minerals. Therefore, the particle size distribution of individual minerals, as well as their liberation degree need to be studied to facilitate the selection and application of additional mineral processing steps (e.g. grinding, classification, additional flotation steps) to further increase the reactivity of the tailings, if necessary. Other options to increase the reactivity are thermal or thermo-chemical process routes. However, such additional operations will most likely require further capital investment at the mine site and are only considered, if other methods do not have a crucial impact on the use of the mine tailings as precursors for alkali-activated materials. Due to the complex host rock composition of many mines, it is likely that different methods for increasing the reactivity of different particle size fractions might be advantageous – e.g. coarser fraction will most likely show a drastically higher reactivity after grinding.

In addition, the nature of the alkali activator plays an important role with respect to the dissolution of relevant species from the solid precursor material. The most common alkali activators can be grouped as follows: (1) activators of the M_2CO_3- and MOH-type, (2) alkali-silicates of the $xM_2O{*}SiO_2$-type and (3) alkali-aluminates of the $xM_2O{*}Al_2O_3$-type, where M represents an element of the alkali group. In order to adjust the chemical composition of the solution, when in contact with the solid material, these activators are either used independently or in combinations (Rao and Liu, 2015; Duxson et al., 2007a, 2007b; Fernández-Jiménez et al., 2005). Since a liquid component is needed to adjust the viscosity of the resulting alkali-activated material according to the needs of the installation method, the alkali activator is dissolved in water prior to the addition. The selection of activator type and concentration is one of the most crucial factors influencing the dissolution behaviour of relevant species from the solid material as well as the formation of precipitates, which in return govern the properties of the resulting alkali-activated material.

5.4. Target applications

At the first glance, alkali-activated materials from mine tailings will in most cases not be able to compete with current construction materials, such as OPC. Even if a material with a high compressive strength can be manufactured using the mine tailings, the location for a possible application might be too far away in order to compete with locally available construction materials, or the overall mix including the activator might be economically unfavourable. Only if a material with outstanding properties can be manufactured or under certain favourable circumstances (e.g. tailings composition, location of the mine, local regulations), an application of alkali-activated mine tailings in areas competing with currently available construction materials seems to be feasible.

However, alkali-activated materials from tailings can potentially be used for applications directly at the mine site. For underground mines, these materials could replace traditional backfill systems that normally rely on OPC and therefore offer a more sustainable alternative. Application of backfill to fill open cavities in underground mining activities is one of the major factors contributing to occupational safety and, depending on the mining method, helps to facilitate a higher ore recovery. Additionally, the amount of tailings that needs to be deposited in tailings storage facilities at the surface can be reduced. For open pit mines, or in cases where not all of the available tailings can be stored in underground cavities, some of the tailings might still have to be stored at the surface in tailings storage facilities. Whenever tailings that containing sulphides are stored subaerial (i.e. without a covering layer of water on top of the solids), the presence of oxygen and moisture will ultimately lead to the formation of sulphuric acid leading to acidic mine drainage. In order to safely store these tailings and prevent acid mine drainage, these tailings have to be shielded from external water flows and oxidizing conditions. For both applications, also a combination of tailings with waste rock as a coarser fraction might be feasible, if the waste rock material cannot be valorised for other applications (e.g. construction of dykes for surface tailings storage facilities).

In order to use the tailings as precursor materials for alkali-activated backfill solutions, the setting time, the mechanical properties as well as the pumpability of the backfill slurry have to be adjusted for the individual application of a given mine site. Furthermore, the strength development of the installed backfill is crucial for further mining activities in areas close to the place of installation – a minimum strength is required to guarantee a safe environment for machines and miners to work close to these areas.

For the application as a cover material for tailings storage facilities at the surface, the permeability of water and oxygen through an installed layer of alkali-activated tailings are crucial parameters to guarantee the cover's functionality and to prevent acid mine drainage. Furthermore, the mechanical properties of such covers have to be fitted to the local environment and installation method. Wherever there are cold winters with freezing conditions, the covers need to have high freeze-thaw resistance with no degradation over time. If further layers are installed on top of the layer, a certain flexural strength might be of advantage, especially for the case where heavy machines have to drive on previously installed cover layers.

Currently, there are only niche applications of mine tailings as precursors for alkali-activated materials or geopolymers for eco-friendly construction products or materials. Some tailings from copper mines have been valorised by using them as an additive for construction materials (Duxson et al., 2007b). In the future, a sustainable mining operation will have to find solutions to utilize mine tailings to a high extent and develop technologies to safely store remaining mine tailings and other residuals for centuries. Alkali-activation offers a variety of possible applications to reach this crucial goal for future mining activities.

6. Sustainability of closing the water loops

United Nations have set 17 Sustainable Development Goals for 2015–2030 to ensure global economic development, environmental sustainability and social inclusion. Closing the water loops in mining minimizes the amount of water and thus contributes especially to the Sustainable Development Goal 6 “Clean Water and Sanitation” (World Economic Forum, 2016). The reduction in the water use and the increase in the energy efficiency are the main drivers for sustainable mining industry (Nguyen et al., 2014). In the studies of Nguyen et al. (2014), a certain water management option could simultaneously result in reduced energy efficiency in one mine and in increased energy usage in another mine. Therefore, the solutions are always case-specific.

The paradigm of sustainable mining has been debated for years or decades. In a review of the literature on sustainability in mining, Laurence (2011) found that there is rather limited guidance for mine operators that they could use sustainability frameworks and theory in action. The implementation of leading practices can improve the sustainability of mine sites, when environment, economics, community, safety and resource efficiency are taken into account. It is also evident that impacts over the entire life cycle of a mine operation need to be considered, including e.g. supply chains for additives and energy used in the mine (Mancini et al., 2018). Further, it is clear that risks need to be assessed as well, to not exclude potential impacts from the mine linked to accidents and unplanned events, e.g. for releases of heavy metal emissions from tailings ponds. Especially when comparing a mine with closed water cycles to a mine with open water cycles, inclusion of risks is important since closing the water cycles changes and typically reduces the risks from the mine. For example, it promises to reduce the risks of large tailing ponds (Di Noi and Ciroth, 2018).

The overall sustainability assessment for a mine site with the idea to close the water cycle thus includes a data collection for current and future status with life cycle modelling; a qualitative, causal loop diagram modelling that serves to provide a detailed understanding of the situation at the mine site, including stressors and screening and hot spot analysis, which both feed the sustainability assessment. The sustainability assessment should be prepared to include various scenarios to “play around” with e.g. different weather conditions, different detailed technical solutions for closing the water cycle, and different scales and water recycling rates. Further, risk assessment and detailed geochemical modelling of the mine site are important to understand and reflect potential emissions and impacts from tailings stacks and from the mining location.

For the social acceptance, Prno (2013) pointed out the increased demand of communities worldwide to be involved in the decision making processes for local mining projects, to have a greater share of benefits and to obtain assurances of safe and responsible mineral development. At the same time, legal compliance with state environmental regulations is not considered completely sufficient in satisfying the expectations of societies with regards to mining. In addition, the mining operations need to recover ‘social licence to operate’ (SLO) to avoid potential conflicts and related business risks. However, there is limited amount of research to determine factors leading to the issuance or non-issuance of a SLO in the complex environment often characterising the mineral development projects. Prno (2013) indicated that to obtain a SLO, it is important to consider the following five points: (1) the context; (2) to build the SLO based on relationships; (3) to respect the sustainability concept for the communities, since it is a dominant concern; (4) to include public participation in the decision making process to some extent; and (5) to be flexible and adaptable to confront complexity.

Closing the water loop fits into the requirements of the SLO, since one major concern of the communities in front of the mine operation or project is the impacts on their water resources, during and after the life of the project. Therefore, it is crucial to demonstrate that the project invests in real solutions that are not only beneficial for the mineral beneficiation, but also for local communities in terms of no-impact on the water cycle.

The solutions thus provided must in turn be energy-effective and represent a low carbon and overall sustainability footprint. For instance, much has been debated on the green energy solutions such as solar energy sources into the mine operations. Chile is running into this process due to the fact, that most of the mines are located in or close to the Atacama Desert. However, this may not be applicable to all operations especially those in the Northern Hemisphere or even in the upper Artic Circle. Renewable energy technologies have gained increased interest in mining one of the principles of sustainable mining industry (Zharan and Bongaerts, 2017). These authors studied this process in various pilot projects in major mining countries worldwide. Switching from fossil fuel to renewable energy technologies depends on decision making processes. According to the authors, research on decision making to use renewable energy in mining is underdeveloped. They present a practical decision rule, which is based on a principle of indifference between renewable energy and fossil fuel technologies and on suitable time management to come to the conclusion that essentially the decisions are based on capital and operational costs. Carbon emissions are of course only one aspect of mining impacts; heavy metal emissions, landscape changes, and access to local resources like water are others. It is recommended, with solutions now available e.g. from recent research projects such as ITERAMS (www.iterams.eu), to provide a full sustainability assessment of the mine operation, in order to increase the trust and confidence of the public.

7. Importance of industry examples

Industrial examples of closing the water loops in mining operations and valorizing tailings can be crucial for the acceleration of sustainable thinking within the whole mining sector. According to Campbell (2006), institutional conditions clearly affect the responsible behaviour of corporations. Even though the preassumptions generally assume a reluctance to regulations in the mining sector, global standard setting and stricter policies are preferred over regulatory uncertainties by large mining companies (Dashwood, 2014). The companies tend to follow the examples of big profitable mining companies. At some point, the way of thinking and same kinds of rules are shared between the professionals in the field (de Villiers et al., 2014; Stål and Corvellec, 2018). According to Nikolaou and Evangelinos (2010), similar environmental management practices in the mining sector are based on mimicking the successful mining companies. The conformance is further increased by regulations and stakeholder demands (de Villers et al., 2014). There can be also changes in the institutional environment, when for example new technologies are developed (Tao, 2016). When good examples of closing the water loops and valorizing the tailings in the mining sector exist, their potential will be explored at some point also by other mining companies.

8. Conclusion

Conservation and management of freshwater resources belong to major challenges of this century. Despite the fact that the net consumption of water is low compared to other economic activities such as agriculture, in mining one should be able to control the quantity of water intake, as well as the volume and quality of effluents. Conventionally, water, ore and tailings are considered separately from each other, even though they are strongly interconnected.

When closing the water loops, the plant is technically isolated from the surrounding water systems. All water will be recycled within the plant and tailings are deposited filter dry. Closing the water loops in mining requires the development of new methods to control and optimize water qualities for all process steps. The closure of water cycles will inevitably result in the process disturbance and instability. This complete water recycling requires new holistic water management in mining.

Tailings and mine water issues should be considered simultaneously, not separately. Ore sorting affects the ore quality, which further affects the water quality in flotation and tailings quality in further applications or disposal. The closed water loops are possible only then, when the tailings are filtered and stacked dry. Geopolymerisation of the remaining tailings can be used in water and oxygen tight covers on the deposited tailings or for backfilling. The traditional end-of-pipe solution thinking targets to cleaning the effluents and storing the waste and considers the effluents and wastes valueless. However, the water and waste streams contain value, which needs to be utilized.

There has been very limited research on such complex dynamic systems, where the interactions are accounted from a systematic and holistic perspective. Furthermore, there is very scarce understanding of the final balance of a fully recycled water system. In the future, the mining industry is expected to considerably increase the water recycling rates, which results in increased complexity in water management. New knowledge and technologies enable the path towards recycling of water and valorizing tailings to improve environmental and economic performance. In the ITERAMS project, new holistic water and waste concepts and a procedure to assess the overall sustainability of mine operations are developed. These solutions are jointly validated by industrial and research partners at the mine sites in Finland, Portugal and South Africa. The results are then combined for the development of the water recycling testing protocol for the mining industry. It has been shown, that the mining companies tend to follow the examples of big profitable mining companies. Therefore, it is important to create success stories in the industry for closing the water loops, which other companies can follow.

From the social standpoint, one could contend that one of the main origins of conflicts between mine projects and communities is the perception of the competition for water, both in terms of quantity and quality. Such situation worsens in periods of severe drought like the one experienced in the Andean region from 2010 to 2020. Results from the ITERAMS project help at communicating with communities and integrating them into the development of the mining regions thus promoting the education and wealth of their inhabitants. Future direction of research should include new on-line and remote sensing and control of operations. Educating communities in this respect would facilitate their engagement in the mining projects and cover the gap that one perceives today in a sustainable integration of the mine operations.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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