Sustainable materials as covers for the closure of tailings storage facilities

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ABSTRACT

Closure of mining waste (tailings and waste rock) storage facilities requires that the wastes must be physically and chemically stabilised, particularly those mine wastes with acid generation potential, to protect the environment and public health. To this aim, the reactive wastes are properly isolated from water and oxygen infiltration using engineered covers and bottom liners, commonly constructed with natural soils and clays. This massive use of such limited resources has revealed unsustainable and costly. In this article, a review of the diverse alternative, waste-based products, proposed in the scientific literature as materials for cover construction on mine waste storage facilities, is presented. Targeted waste products were addressed attending to their technical and environmental performance, among other aspects, while their advantages and drawbacks are outlined. Among the waste products, alkaline industrial wastes, which confer the cover an acid neutralizing and metal immobilization capacity, arise as particularly promising candidates for the proposed use. It is concluded that the use of some waste materials to constructs covers for containment of mine wastes is technically feasible, providing the environmental health and safe use are ensured.

INTRODUCTION

Mining plays an essential role in the economy of natural resources rich countries given that it constitutes a source of raw materials and incomes (Shengo, 2021). However, the mining industry also generates high amounts of wastes (waste rocks and tailings, among other) that can seriously impact the environment, wildlife and human health when inadequately managed. Noteworthy, tailings represent one of the most significant mining wastes associated with copper production. According to SERNAGEOMIN (Servicio Nacional de Geología y Minería de Chile), Chilean mining operations produce more than half-billion tonnes of tailings per year, which are mostly disposed in tailings surface facilities (TSF), generally near the mine. TSFs can pose a serious threat to humans and the environment in case of their improper design, handling or management (United Nations Economic Commission for Europe, 2014). By these reasons, the TSF needs to be engineered for closure, so that stability and environmental performance criteria can be achieved (Mylona et al. 2007). The closure and reclamation of TSFs commonly involves the placement of dry or water covers over the tailings. The operator shall control the physical and chemical stability of the facility and minimize any detrimental environmental impacts, in particular those exerted on surface and groundwater bodies.

For these purposes, containment of reactive mine wastes inside the soil is a commonly applied worldwide strategy for isolating wastes from the surrounding environment. In this approach, the waste impoundment is sealed by installing impermeable engineered layer barriers: top cover and bottom liner systems, both of which are composed of sealing, protective and drainage layers (Meggyes, 2007). Different types of low permeability covers have been proposed; among them, dry covers are aimed to avoid water infiltration and/or inhibit oxygen diffusion to the mining waste with the following objectives: (i) chemically stabilize tailings and control acid mine drainage (AMD) production, (ii) control metal(loid)s release and migration, and (iii) reduce the erosion and dust emissions due to wind (Mylona et al. 2007). Besides, these systems can be designed for achieving the revegetation of the site and landscape restoration (Álvarez et al. 2023). Dry covers are usually applied in the closure stage of mining operations, even though are also used for closure of abandoned TSFs.

Dry cover design is site-specific, depending on the climatic conditions, material availability and the sensitivity of the environment, and it can vary on its complexity. The low-hydraulic conductivity (K) barrier is considered the most critical engineered component of this type of covers, and generally it consists of a layer having a K $<10^{-9}$ m/s, while for hazardous wastes, the incorporation of an artificial liner is required. Traditionally, a compacted clay liner has been the most used hydraulic barrier layer, and clays and clayey materials (e.g., geosynthetic liners) have been traditionally used. However, clays are a valuable and limited resource, while artificial liner systems are rather expensive. Besides costs, use of clays materials to cap huge TSF supposes an enormous consumption of natural resources, exerting a considerable impact on environment (Rubinos and Spagnoli, 2019).

Consequently, a broad variety of alternative materials, either with natural or waste origin, have attracted growing interest as substitutes of natural clays for hydraulic barriers, if they fulfil some key technical properties: low K ($<10^{-9}$ m/s), very low potential to leach contaminants, sufficient compressive and flexural strength, and good environmental and chemical compatibility with the leachates and drainages (Hettiaratchi et al., 1999).

In this article, diverse alternative, waste-based materials proposed in the scientific literature as components of covers on mine wastes are reviewed, with special attention to by-products arising from other industrial processes, with the objective of addressing the most promising candidate products to be used in TSF covers based on their technical performance and environmental safety, as well as attending to their availability, costs, and proximity to the TSF as criteria. Benefits and drawbacks of the products are also outlined.

METHODOLOGY

The literature search used Scopus, ISI-Web of Science and Google Scholar databases. The search was restricted to indexed Journal peer-reviewed articles published before February 1st, 2024 (or as In press/Online first status). The keywords used were cover(s), dry covers, hydraulic barrier(s), mine waste, tailings, acid mine drainage, acid rock drainage, residue(s), byproduct(s), containment, storage, sealing, alternative materials.

RESULTS AND DISCUSSION

Waste materials for cover construction on mining wastes

The review of the literature yielded a number of waste-based product with properties to be potentially used as alternative covers of TSF, mostly belonging to the following class-types: (1) Wastes from mining and mineral processing, (2) Wastes from water and effluents treatment (biosolids), (3) Wastes from thermal processes (coal combustion, municipal solid waste incineration, etc.), (4) Wastes from metallurgy, (5) Agro-industrial wastes, and (6) Other.

Wastes from mining and mineral processing

Most promising identified waste products in this category are low-sulfide tailings and waste rock, coal gangue, and alkaline wastes such as bauxite residue (red mud, RM). A series of studies in Canada (Boulanger-Martel et al, 2021) evaluated the possibility of using mine wastes (low-sulfide tailings and waste rocks) as cover components to prevent acid mine drainage (AMD) generation from highly reactive tailings and cover materials, showing that these mine waste materials have suitable hydrogeological and geochemical properties to be used in covers with capillary barrier effects (CCBE). More recently, tested cover systems constructed with such waste-type successfully performed to control oxygen migration, sulphide oxidation and to reduce the generation of contaminants from the LaRonde mine site tailings (Quebec, Canada) (Kalonji-Kabambi et al. 2020a, b). Barriers of desulphurised paste tailings mixed with bentonite (BPT) (4-8% w/w) exhibit low K values (10^{-11}-10^{-12} m/s) and acceptable performance upon freeze-thaw and desiccation, while the costs of the barrier are much cheaper (33–86%) than conventional compacted clay liners, indicating the suitability of BPT to seal mine waste dumps (Fall et al., 2009). The drawbacks of such material are the necessity of additives (bentonite or polymers), pretreatment (desulphurization), and from uncertainty on leaching of metals and long-term performance. Abreu et al. (2012) studied the effectiveness of alkaline covers, consisting of waste rock and alkaline materials (limestone/lime/red mud) as neutralizing agents, to control acid generation from uranium (U) rock mining waste from the Osamu Utsumi mine, in Caldas, Minas Gerais (Brazil). The parameters evaluated indicate the use of a mixture of red mud with disposal waste rock in cover systems is a viable alternative to restrict AMD generation; however, it has the disadvantage of introducing soluble material into the leachate (Table 1).

Wu et al. (2017) tested coal gangue (CG) as barrier material in terms of K, metal sorption and leaching behaviour. Their results indicated that CG could achieve adequate K < 10^{-9} m/s, high metal (Pb and Zn) sorption capacity, and low metal leaching; all these supporting CG as a good candidate to be used as a barrier material (Table 1).

Some alkaline mine wastes seem particularly interesting for their use as TSF covers, because besides they have suitable geotechnical and hydraulic properties, provide the cover with the ability for neutralizing generated acidity and reduce metals leaching from the reactive tailings. In this regard, red mud, the alkaline, oxide-rich, fine solid residue from bauxite refining to extract alumina, was firstly investigated as reactive cover/liner for the inhibition and neutralization of AMD and bacteria. The RM barrier successfully reduced Fe, SO_4, and metal leaching, as well as and the number of viable bacteria (Duchesne and Doye, 2005). Afterwards, a series of articles by Rubinos and collaborators assessed RM from Spain (Figure 1) as reactive low-permeability barrier material for sealing waste landfills (Rubinos et al., 2015, 2016; Rubinos and Spagnoli, 2019), indicating that RM is technically suitable when compacted to perform as technical barrier in liner or cover systems of waste landfills, based on its appropriate hydraulic and geotechnical characteristics, AMD neutralization and metal(loid)s (As, Hg, Cd, Pb) sorption capacity. Nevertheless, desiccation adversely affected the permeability of RM through development of cracks, which brings into question its direct use in top covers of landfills. Field-scale performance of installed RM covers and liners on site still requires verification. The possibility of leaching of some present metal(loid)s and radionuclides from RM is also an issue (Table 1). At view of these aspects, the use of RM sealing barriers should be restricted to industrial or mine waste impoundments.

Wastes from water and effluents treatment

Sludges from (waste)water depuration (sewage sludges, SS) have been explored primarily to be used in landfill cover systems since early 90's. Direct reuse of dewatered SS without any soil or solidifying agents is barely reported due to the high-water content and low strength of the material. However, a recent study by Yang et al (2017) showed the feasibility of direct reuse without any solidifying agents of deep-dewatered sludge cakes as landfill cover materials, based on their appropriate geotechnical and K properties. In general, sludge covers are effective to reduce the infiltration of O_2 and water, reduce dissolution of metals, and are available at low-cost. In opposition, main drawbacks relate with the need of pre-treatment, susceptibility to biodegradation, odour problems and risks of metallic and biological contamination (Table 1).

Figure 1 Red mud dump in ALCOA-San Cibrao bauxite refinery (Spain)

Wastes from thermal processes

Two main types of wastes were identified in this category: (i) coal fly and bottom ashes, and (ii) ashes from urban waste and sewage sludge incineration. Coal fly ash is probably the most studied waste as alternative material for construction of landfill liners and covers. In general, it has been reported that fly ash and mixtures containing fly ash pose adequate K and geotechnical properties to perform as sealing liners and covers (Rubinos and Spagnoli, 2019). An interesting approach is to take advantage of the alkaline characteristics of fly ashes and use it as barrier material for covers on acid-generating mine wastes (e.g., Mudd et al., 2007, Yeheyis et al., 2010). However, it must be stated that fly and bottom ash can contain considerable amounts of toxic metal(loid)s whose potential release into the environment can be dangerous to the environment and human health, and it could restrict the use of these wastes (Table 1). Similarly, the utilisation of urban waste fly ash in landfill top covers has been reviewed by Brännvall and Kumpiene (2016). Considering the chemical and mineralogical composition, geotechnical and hydraulic properties, the review concluded that this waste could be considered as a suitable alternative material to be used in top covers on waste impoundments, but its use as a soil amendment in the vegetation layer is not advisable due to the potential enhancement in leaching of toxic metal(loid)s (e.g., As, Cd and Pb) (Table 1).

Wastes from metallurgy

Among these, in particular, electric furnace arc and blast furnace steel slags have been explored as promising candidates to be used in landfill barrier applications. Mixtures of electric arc furnace slag

(EAFS) and ladle slag (LS) have been assessed in deep as waste cover materials at both laboratory (Herrmann et al., 2010; Diener et al., 2010) and in a full-scale field study on the Hagfors landfill (Sweden). This study showed that a 50% EAFS:50% LS cover achieved infiltration rates lower than the Swedish infiltration criteria for final covers for landfills for non-hazardous waste. Globally, these studies suggest that LS-EAFS covers similarly perform as those with a clay liner layer, although long-term performance studies need to be developed to validate this (Table 1).

Agro-industrial wastes

Ashes arising from combustion of agro-wastes (eg., bagasse ash (BGA), rice husk ash (RHA) and palm oil fuel ash (POFA)) have received attention as substitutes of clays in landfill liners and covers. Commonly, their utilization involves mixing locally available soils with the wastes to produce a suitable material for engineered landfilling (Nik Daud et al., 2017) (Table 1). Also, some recent studies (e.g., Chen et al., 2016; Wong et al., 2017) show that peanut shell biochar-amended clay can be a potential and advantageous landfill final cover material in terms of gas emission and soil-water retention properties, and reduced contaminant leaching and odour mitigation.

Other

Examples of different-type wastes proposed as cover materials are end-of-life tyres and construction and demolition wastes. Some studies have addressed the use of shredded tyres (ST) and chips in engineered landfill barriers, commonly used as a mixture with clays and other wastes, and as drainage and adsorptive layers of final covers at abandoned landfills (Ng and Lo, 2007; Mukherjee and Mishra, 2017). Considered together, the findings of these studies suggest that ST are suitable as reinforcement additive of clay liners and covers, decreasing the damage by desiccation, frozen and organic chemicals. Conversely, potential contaminant leaching from the tyre is a relevant drawback of the product (Table 1).

CONCLUSION

The mining industry will require enormous amounts of materials for constructing covers on mine wastes stored in huge TSF as a part of their closure planning. This review study showed that there are opportunities for reusing different type by-products, otherwise considered waste, to be used as materials for the construction of engineered covers on mine waste impoundments, either as substitutes of conventional materials or mixed with them to improve their properties. Among the wastes addressed in the scientific literature, alkaline industrial wastes (such as fly ash and red mud) emerge as most suitable and promising candidates to be used in improved reactive covers on acid-generating mine wastes. Main barriers to use are the distance between the waste source and the mine site and the uncertainty on environmental safety of the wastes due to leaching of contaminants. It is concluded that the use of diverse-type wastes in covers on TSF is a viable and beneficial application, providing environmental safety, and wildlife and human health protection are guaranteed.

Table 1 Summary of advantages and drawbacks of the different wastes proposed as covers materials for mining wastes.

Material	**Advantages**	**Disadvantages**	**Environmental constraints**
Tailings and tailings mixtures	Resistance to desiccation and freeze-thaw, low cost	Desulphurization and additives required, uncertain long-term performance.	Potential AMD generation and trace metal leaching
Waste rock and alkaline wastes	Low cost, effectiveness to restrict AMD generation	Introducing soluble material into the leachate	Potential trace metal leaching
Coal gangue	Direct use, metal sorption ability, low metal leaching	Permeability close to regulatory limit, poor plasticity	Uncertainty on safety, and long-term performance.
Red mud	High neutralization and metal(loid)s sorption capacity, good mechanical and chemical resistance,	Narrow acceptable zone of K. Presence of metals and radionuclides, sensitivity to desiccation.	Caustic nature. Potential leaching of potentially toxic metal(loid)s.
(Waste)water treatment sludges	Inhibition of water and O_2 infiltration. Heavy metal attenuation capacity. Widely available	Pretreatment required. Odour problems. Biodegradation. Hazardous metals presence	Risks of biological and hazardous metals contamination
Coal fly ash	Inhibition of AMD. Resistance to environmental stresses. Improved shear strength. Heavy metals sorption.	Additives required. Presence and potential leaching of hazardous metal(loid)s.	Risks of contamination by metal(loid)s.
Urban waste incineration fly ash	Good hydraulic performance. Long-term stability and contaminant retention ability.	Amendments required. Presence of contaminants.	Risk of water contamination.
Steel slags	High compression strength and shear strength. Chemical stability. Acid neutralization capacity	Wet conditions are critical. Sensitivity to desiccation. Presence of metal(loid)s	Potential leaching of metal(loid)s and water pollution risks

Table 1 (continuation)

Material	Advantages	Disadvantages	Environmental constraints
Agro-wastes (BGA, RHA and POFA)	Improved shear strength and permeability. Contaminants attenuation ability.	Increased K at high-rate additions. Combined use (at low rates) with local soils.	Ash particles migration. Soil and groundwater contamination risks.
Shredded tyres	Decreased damage by desiccation, frozen and organic chemicals	Presence of contaminants. Limited use as additive	Risk of soil and water pollution.
Construction and demolition wastes	Minimized water infiltration. Restricted migration of chemicals	Pre-treatment required. Presence of contaminants. Variable composition.	Leaching of hazardous compounds

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