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Sustainable materials as covers for the closure of tailings storage facilities

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Mining waste and its management

- 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).
- The mining industry also generates high amounts of waste rocks and tailings that can seriously impact the environment, wildlife and human health when inadequately managed.

Tailings management practices

- The most common tailings management method remains the disposal as slurry deposited behind containment dams.
- Containment of reactive tailings inside the soil is also worldwide practiced.

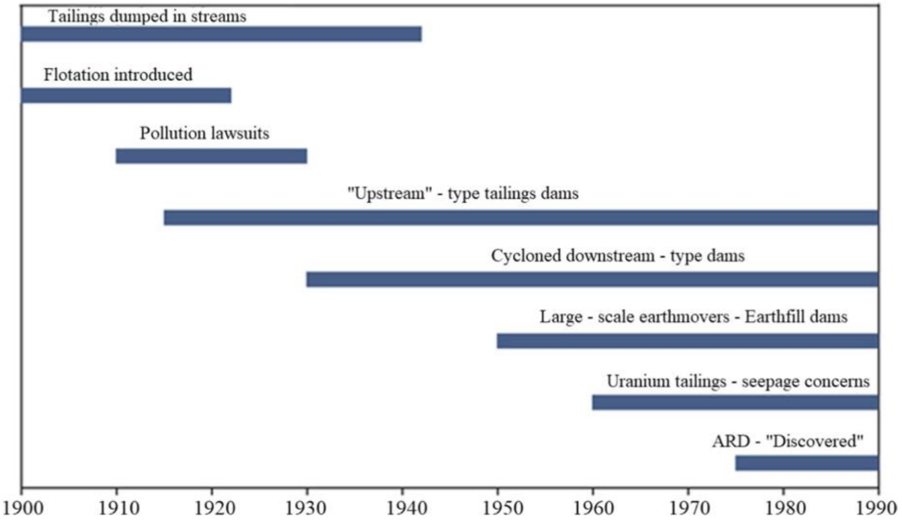


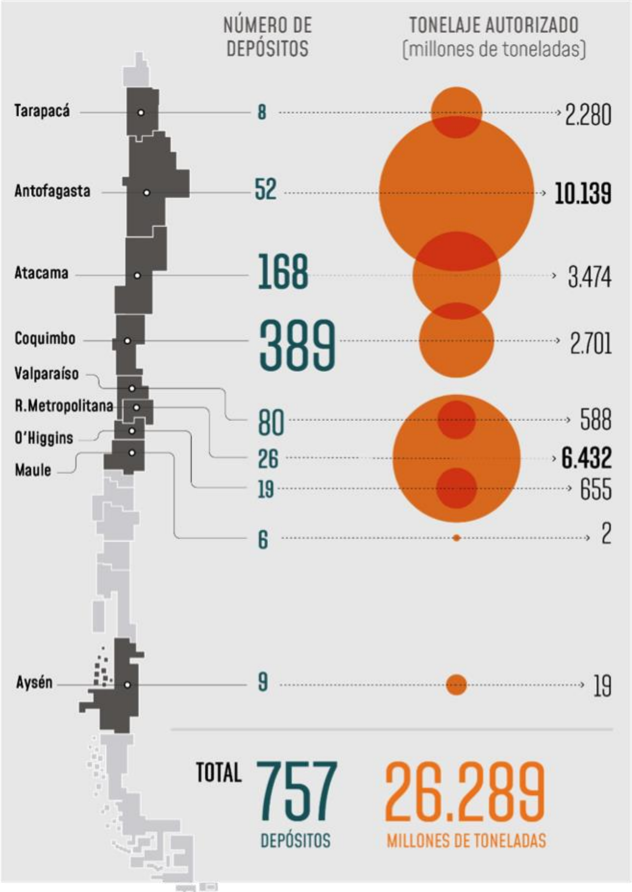
Figure - Evolution over time of tailing management practices (after Bruce et al.,1997). [Shengo Review of Practices in the Managements of Mineral Wastes: The Case of Waste Rocks and Mine Tailings. *Water Air Soil Pollut* (2021) 232: 273

Tailings disposal

- Surface disposal is the most widely used technology in the world in the management of mineral wastes such as flotation's tailings (Coal, 2001; EPA, 1994).
- The surface disposal of tailings in TSFs results in severe environmental impacts, occupation of large surface-footprint and excessive water inventory.

Overview of Chile

- Tailings represent one of the most significant mining wastes associated with copper production in Chile.
- Chilean mining operations produce >0.5 billion t of tailings per year (SERNAGEOMIN).
- 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.



Fuente: Sernageomin, Catastro de Depósitos de Relaves en Chile, Agosto 2020.

Closure of TSFs

- TSFs need to be engineered for closure, so that stability and environmental performance criteria can be achieved.
- The closure and reclamation of TSFs commonly involves the placement of **covers** over the tailings for assuring their physical and chemical stability and minimize environmental impacts.
- The mining industry will require enormous amounts of materials for covering huge TSF as a part of their closure planning.

Mine waste containment

- The waste impoundment is sealed by installing impermeable engineered layer barriers: top cover and bottom liner systems.
- **Covers** are designed to limit the ingress of water and oxygen into the underlying waste.
- **Liner systems** are designed to act as a barrier for contaminant flow from the overlying waste into the environment.
- Both systems comprise sealing, protective and drainage layers.

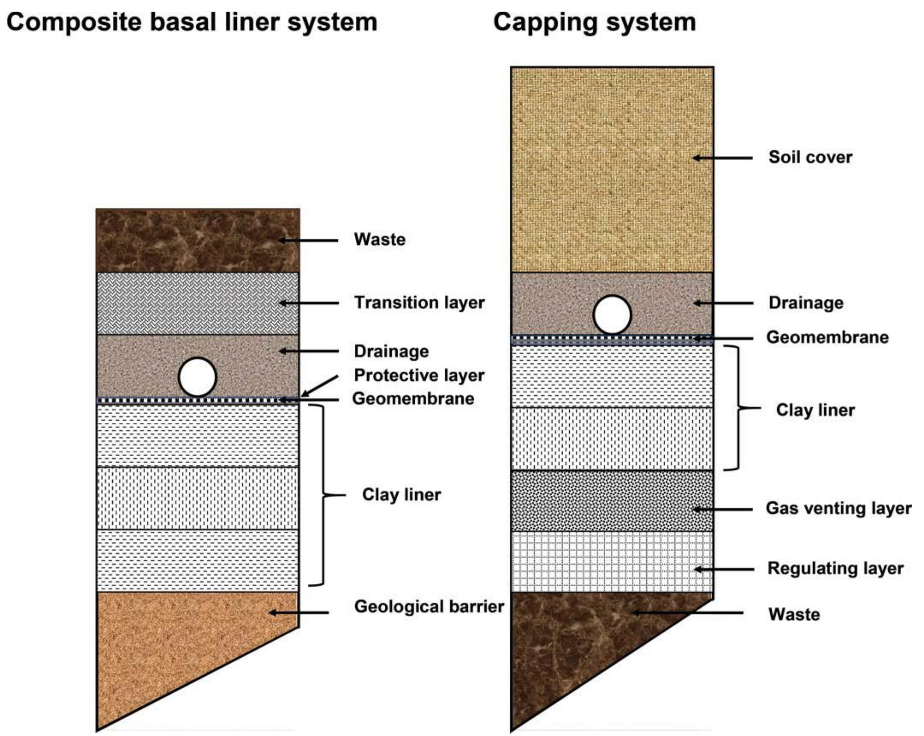


Figure - Liner and capping systems for landfills according to TA Siedlungsabfall (1993) modified after Roehl and Czurda (2007) and Meggyes (2007b)) (Rubinos and Spagnoli, 2019).

Dry cover systems

Dry covers are typically earthen, organic, or synthetic materials placed over mine wastes, with the purpose of:

- Chemically stabilize tailings and control AMD production;
- Control metal(loid)s release and migration;
- Reduce the erosion and dust emissions due to wind;
- Provision of a growth medium for establishment of sustainable vegetation and landscape restoration.

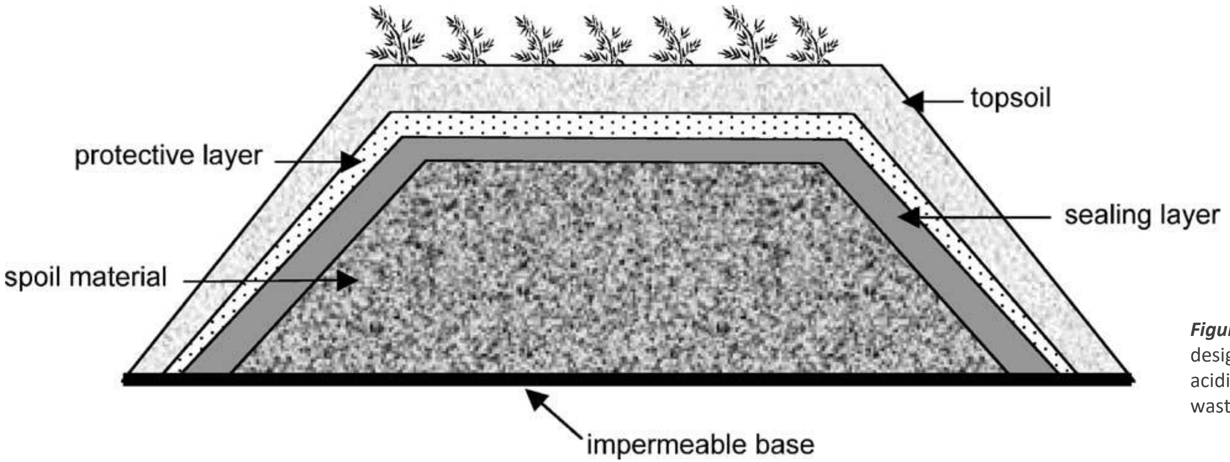


Figure - Diagram of a typical dry cover designed to minimize the production of acidic effluents from sulfide-bearing wastes (Jonhson and Hallberg, 2005)

The “Sealing” layer

- The low-permeability layer is the most critical component of dry covers.
- A compacted clay liner (CCL) has been the most used barrier layer.
- Clays are a limited resource, while artificial liner systems (geosynthetics) are expensive.
- Alternative materials emerge as substitutes of clays for barriers:

  (i) Low K (< 10^{-9} m/s)

  (ii) Low leaching of contaminants.

  (iii) Sufficient compressive and strength.

  (iv) Compatibility with the drainages.

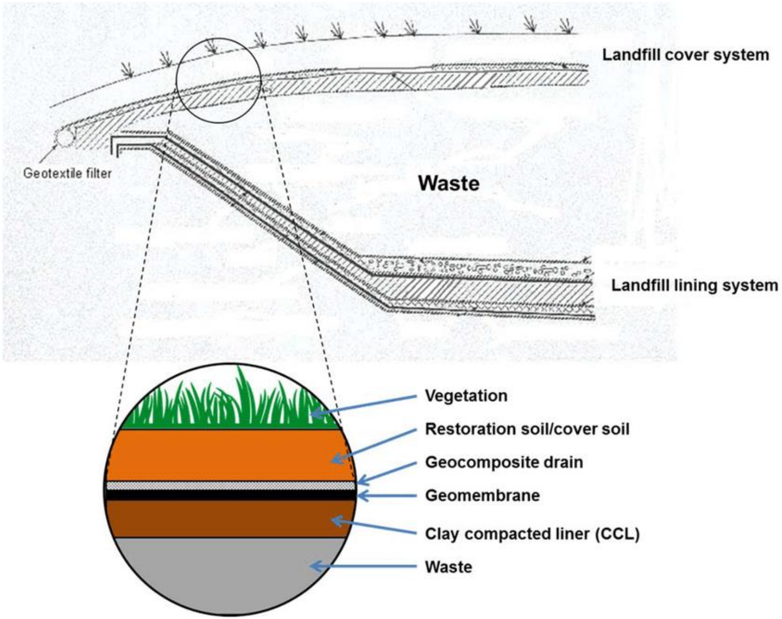


Figure - Landfill cover system (after Zornberg and Christopher 2007) (Othman, 2016).

Objectives

- Explore unconventional waste-based materials as covers on mine wastes, with special attention to by-products from other industrial processes.
- Addressing the most promising products to be used in TSF covers based on their technical performance and environmental safety, availability and costs.

Methodology

- Comprehensive review of the scientific literature (Scopus, ISI-Web of Science and Google Scholar databases): indexed Journal peer-reviewed articles on-line published before February 1st, 2024.
- Case-study: Bauxite residue (“*red mud*”).

Results

Waste materials for covers on mining residues

1. Wastes from mining and mineral processing.
2. Wastes from water and effluents treatment (biosolids).
3. Wastes from thermal processes (coal combustion, MSWI).
4. Wastes from metallurgy.
5. Agro-industrial wastes.
6. Other (miscellaneous).

Wastes from mining and mineral processing

- Low-sulfide tailings and waste rock
- Paste tailings mixtures
- Coal gangue
- Bauxite “Red mud”

Low-sulphide tailings and waste rock

- Cover systems with capillary barrier effects (CCBE)

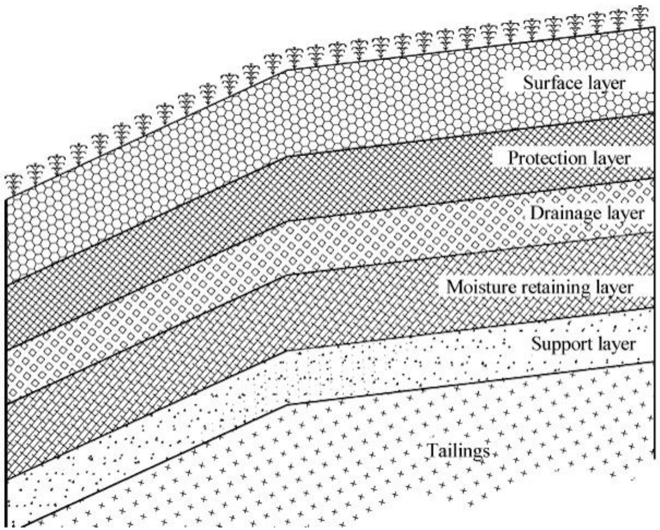
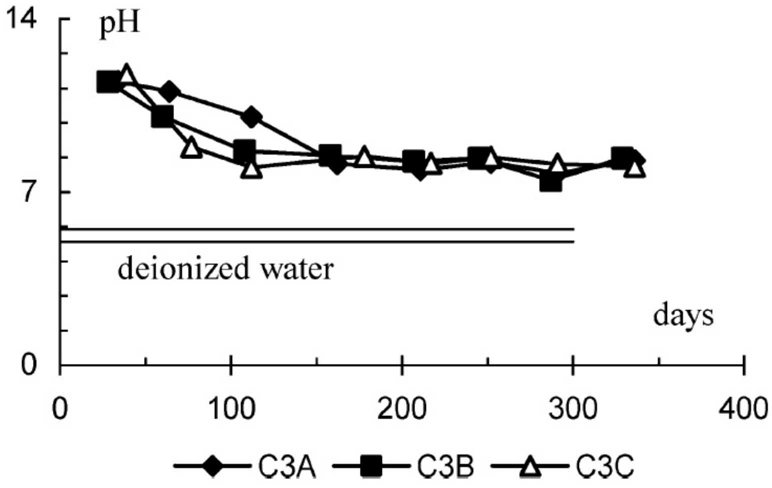


Figure - Typical configuration of a CCBE used to limit the production of AMD (Aubertin et al 1995)

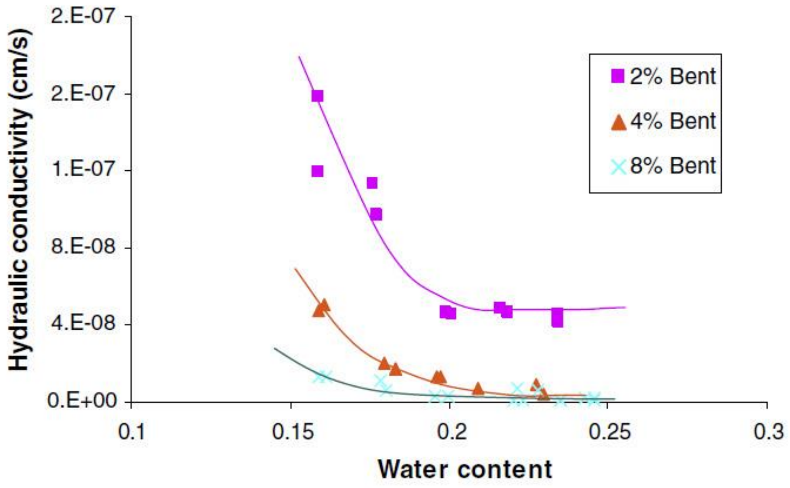


Brussière, B., et al. "A laboratory study of covers made of low-sulphide tailings to prevent acid mine drainage." Environmental Geology 45.5 (2004): 609-622.

Paste tailings mixtures

- Paste tailings + bentonite (2-8% w/w)

Benefits	Drawbacks
Low permeability	Aditives required (Bentonite, polymers)
Freezing resistance	Pretreatment (desulfurization)
Resistance to dessication	Metals presence
Costs reduction	Unknown long-term performance



Fall, M., Célestin, J. C., & Han, F. S. (2009). Suitability of bentonite-paste tailings mixtures as engineering barrier material for mine waste containment facilities. Minerals Engineering, 22(9-10), 840-848.

Wastes from thermal processes

- Coal fly and bottom ashes
- Ashes from urban waste and sewage sludge incineration

Fly ash

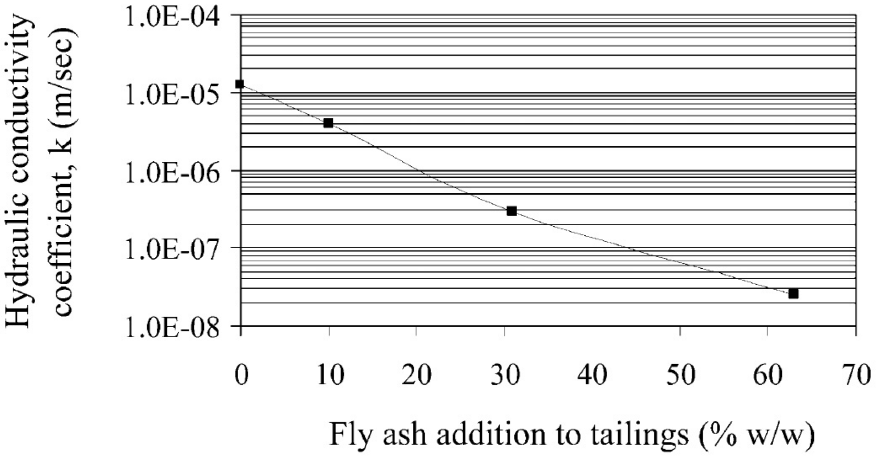


Figure - Hydraulic conductivity (k) vs Fly ash dosage (% w/w)

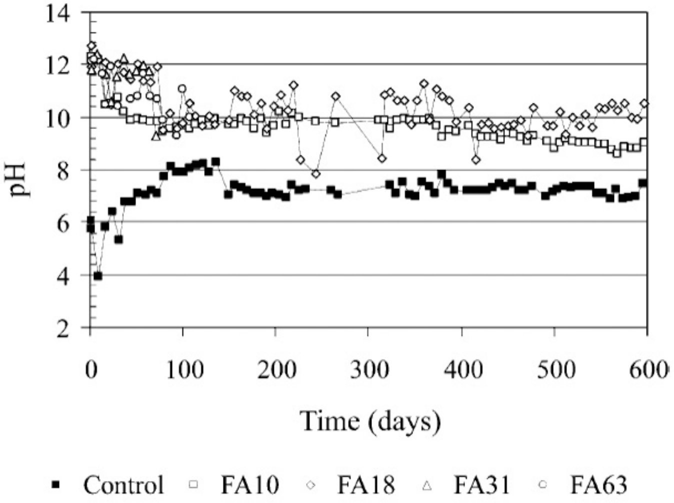


Figure - pH of the leachates of Lavrion tailings-fly ash mixtures vs time as compared with the control.

Xenidis, A., Mylona, E., & Paspaliaris, I. (2002). Potential use of lignite fly ash for the control of acid generation from sulphidic wastes. Waste management, 22(6), 631-641.

Fly ash

Benefits	Drawbacks
Low permeability. High shear strength	Aditives required
Inhibition of AMD and metals dissolution	Presence of potentially toxic metal(loid)s
Resistance to environmental effects (dessication, freezing)	Excessive FA doses may promote metals leaching
Low cost and widely available	Surveillance and monitoring implementation

Wastes from metallurgy industry

- Electric arc furnace slags (EAFS)
- Blast furnace steel slags

Steel slags

Full-scale field study on the Hagfors landfill (Sweden)

Layer	Area 1 2005	Area 2+3 2007, 2008	Area 4+5 2010, 2011	Thickness
Vegetation layer	compost	compost	compost	≥ 0.25 m
Protection layer	80% borrow soil 10% bio ash 10% treated sludge 9.1 E-09 m/s	100% borrow soil 2.5 E-08 m/s	80% borrow soil 10% bio ash 10% treated sludge 3.1 E-09 m/s	≈ 1.5 m
Geotextile Drainage layer Geotextile	EAFS 1+2 (8-60 mm)	EAFS 1+2 (35-60 mm)	EAFS 1+2 (20-60 mm)	≥ 0.3 m
Liner	>50% EAFS 1+2 (<8 mm) <50% LS (<20 mm) < 2.2 E-11 m/s	>65% EAFS1+2 (<35 mm) <35% EAFS4+LS (<20mm) < 1.2 E-10 m/s	50% EAFS 3 (< 20 mm) 50% EAFS 4+LS (<20 mm) < 2.2 E-11 m/s	≈ 0.7 m
Foundation layer	Sweepings	Sweepings	EAFS 1+2 (0-150 mm)	≥ 0.3 m
	Waste	Waste	Waste	

50% EAFS:50% Ladle Slags cover achieved infiltration rates lower than the Swedish infiltration criteria for final covers of non-hazardous waste landfills

Andreas, L., Diener, S., & Lagerkvist, A. (2014). Steel slags in a landfill top cover–Experiences from a full-scale experiment. Waste management, 34(3), 692-701.

Study-case: Red Mud

- Alkaline covers for the inhibition and neutralization of AMD and bacteria
- Reactive alkaline barriers for hazardous waste containment and leachate attenuation

Reactive red mud barriers

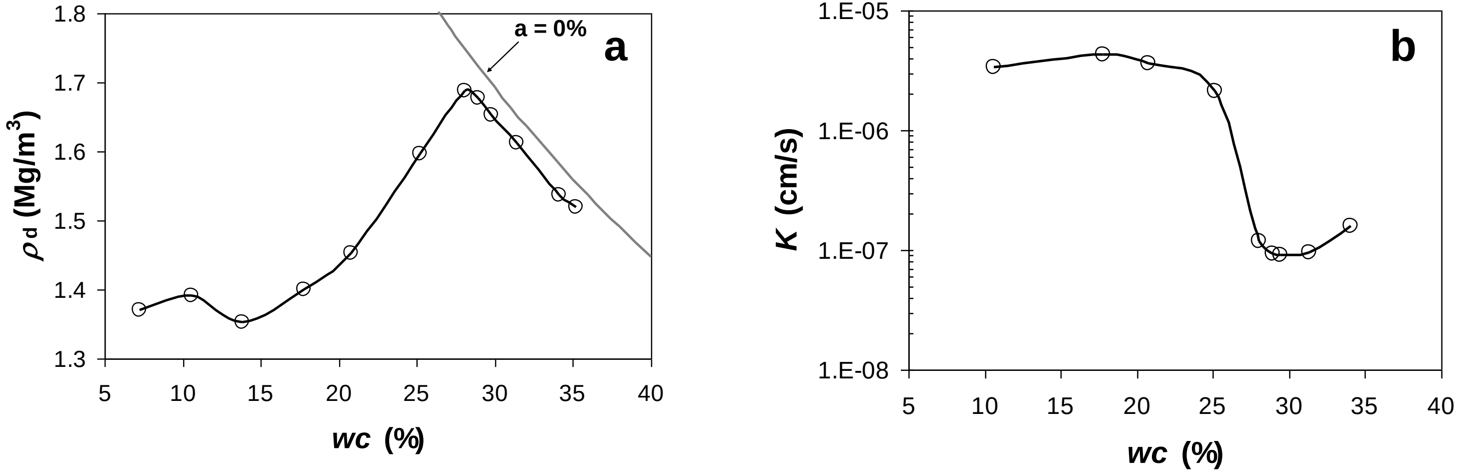


Figure - Compaction curve (a) and hydraulic conductivity – water content (b) for compacted (standard proctor) RM. Zero air void line (a = 0%) is also showed. ρd = dry density; K = hydraulic conductivity

Rubinos, D., Spagnoli, G., & Barral, M. T. (2015). Assessment of bauxite refining residue (red mud) as a liner for waste disposal facilities. International Journal of Mining, Reclamation and Environment, 29(6), 433-452.

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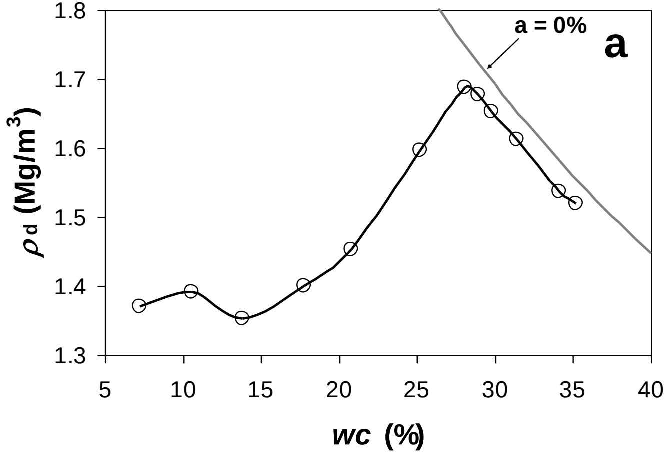

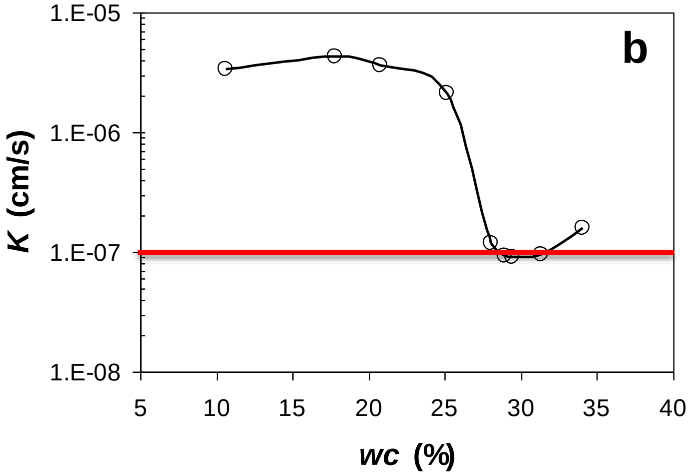

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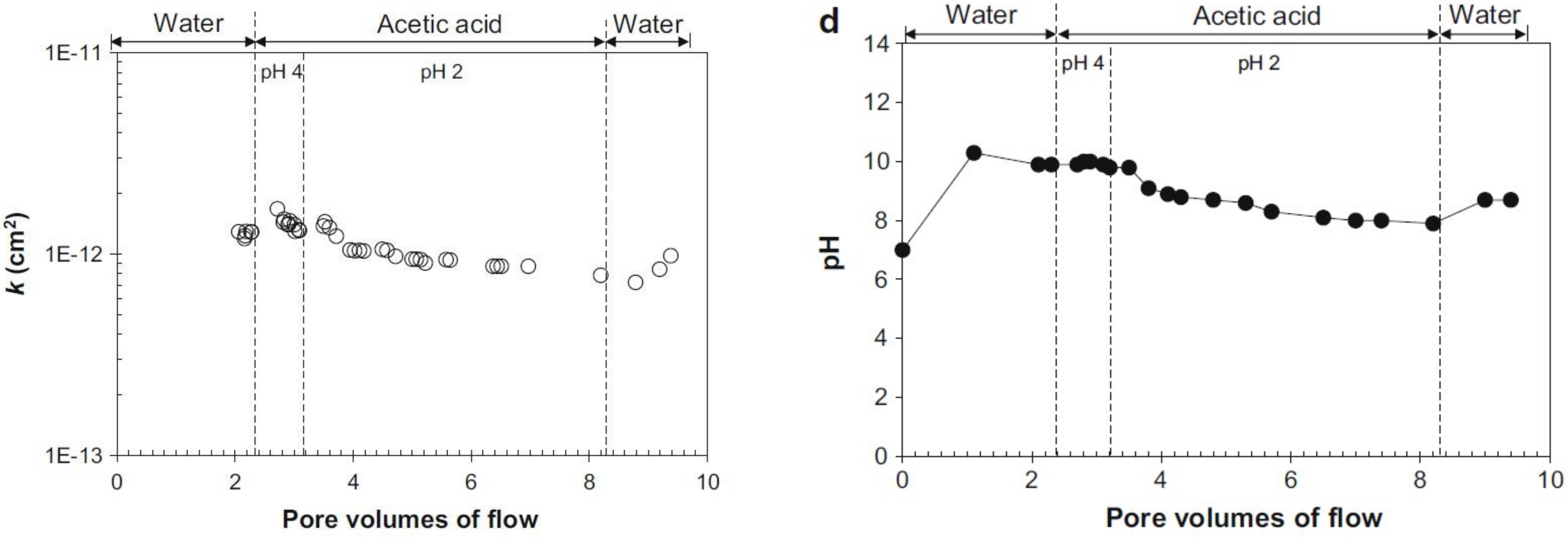

Figure - Intrinsic permeability k (left) and effluent pH versus pore volumes of flow for compacted red mud permeated with pH 4 and pH 2 acetic acid solutions (Rubinos et al., 2016, Chemical and environmental compatibility of red mud liners for hazardous waste containment. Int J Environ Sci Technol, 13(3), 773-792)

Red mud: AMD and bacteria inhibitor

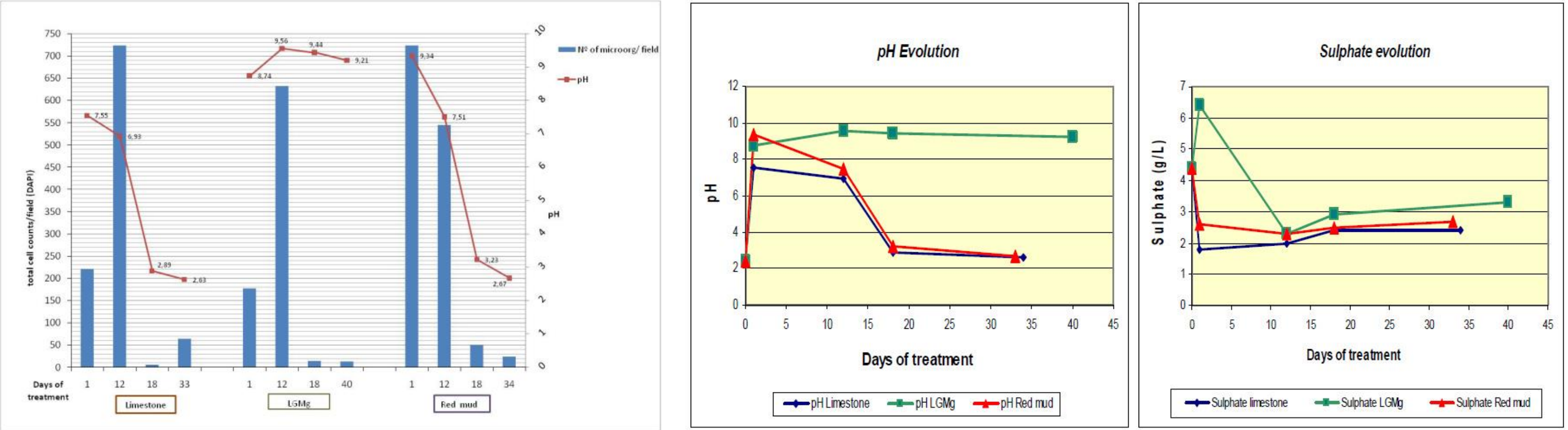

Figure - Number of total cells counts (left) and effluent pH and sulphate concentrations as a function of treatment days for red mud, limestone and limestone-Mg (Carnicero, D., Diaz, E., Escolano, O., Rubinos, D., Ballesteros, O., Barral, M. T., ... & García Frutos, F. J. (2009). Preliminary study of neutralization and inhibition of chemolitotrophic bacteria in an acid mine drainage from Rio Tinto site. In Advanced Materials Research, 71, 677-680).

Red mud barriers: benefits and concerns

Benefits	Drawbacks
High acid neutralization capacity (AMD/ARD)	• Strongly alkaline (pH > 10) (problematic handling) • Pretreatment required: Neutralization and drying
Mechanical strength (high density, shear strength and low consolidation)	• Narrow range of water content for $K < 10^{-9}$ m/s Field-control during construction
Resistance to chemical attack	• Presence of metal(loid)s and radionuclides. • Enhacement of As leaching due to excessive alkalinity.
High sorption capacity of pollutants	• Sensitive to dessication (cracks development)

Conclusions

- Opportunities for reusing a diversity of by-products for the construction of engineered covers on TSFs were identified.
- Alkaline industrial wastes (FA and RM) emerge as most promising products to be used in improved reactive covers on acid-generating mining wastes.
- The use of FA or RM sealing covers and liners should be restricted to industrial or mine waste impoundments.
- Barriers to use: distance between the waste source and the mine, uncertainty on long-term performance and leaching of contaminants.
- The use of diverse-type wastes in covers on TSF is a viable application, providing environmental safety, and wildlife and human health are guaranteed.

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Thank you!

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