Industrial solid wastes acting as barrier material for storing solid wastes (SW) and wastewaters – A critical review

Déchets solides industriels agissant comme matériau barrière pour le stockage des déchets solides et des eaux usées - Un examen critique

Leonardo Marchiori, António Albuquerque & Victor Cavaleiro
GeoBioTec and FibEnTech, Universidade da Beira Interior, Civil Engineering and Architecture Depto., Portugal

ABSTRACT: Clays and geosynthetic materials are commonly applied as low hydraulic conductivity layers and environmental protection barriers for storing solid wastes and wastewaters for both cover and bottom impermeabilization of geotechnical structures. However, due to a future shortage of clay materials and their high transport costs, in addition to geosynthetics generating more waste and presenting high costs, two needs emerge: reducing the amount of waste generated and developing strategies for preventing this waste from infiltrating the soil and ground water. One of the possible solutions consists in the use of some geotechnically applicable residues to prevent soil infiltration. Many by-products have been extensively studied as to their suitability as a geomaterial (Kumar et al., 2019) and showed promising results for use in liners. The most significant factors that depend on hydraulic conductivity are index, compaction, and compressive properties, so, in this aspect, hydraulic, mechanical, physic-chemical, and mineralogical properties determine the valorization, or not, of the waste as liner material (Marchiori & Albuquerque, 2020). Industrial wastes and geocomposite acting as hydraulic barriers material and its geotechnical properties were reviewed and analyzed lack of research and future investigations suggestions.

RÉSUMÉ : Les argiles et les matériaux géosynthétiques sont couramment appliqués en tant que couches à faible conductivité hydraulique et barrières de protection de l'environnement pour le stockage des déchets solides et des eaux usées pour l'imperméabilisation de la couverture et du fond des structures géotechniques. Cependant, en raison d'une future pénurie de matériaux argileux et de leurs coûts de transport élevés, en plus des géosynthétiques générant plus de déchets et présentant des coûts élevés, deux besoins se font jour: réduire la quantité de déchets générés et développer des stratégies pour empêcher ces déchets de s'infiltrer dans le sol et eaux souterraines. L'une des solutions possibles consiste à utiliser certains résidus géotechniquement applicables pour empêcher l'infiltration du sol. De nombreux sous-produits ont été largement étudiés quant à leur aptitude en tant que géomatériau et ont montré des résultats prometteurs pour une utilisation dans les revêtements. Les facteurs les plus importants qui dépendent de la conductivité hydraulique sont les propriétés d'indice, de compactage et de compression, de sorte que, sous cet aspect, les propriétés hydrauliques, mécaniques, physico-chimiques et minéralogiques déterminent la valorisation ou non des déchets en tant que matériau de revêtement. Les déchets industriels et le géocomposite agissant comme matériau de barrière hydraulique et ses propriétés géotechniques ont été examinés et analysés en l'absence de recherches et de suggestions d'enquêtes futures.

KEYWORDS: Industrial waste valorization; hydraulic barrier(s); liner material(s); geotechnical earthwork(s)

1 INTRODUCTION.

Natural materials, clays, and synthetic materials, geosynthetics, are commonly applied as layers of low hydraulic conductivity and environmental protection barriers in civil engineering works to store solid waste and wastewater (landfill, wastewater ponds and mining ponds) for both cover and waterproofing the bottom of soil structures. Many industrial wastes, such as mining wastes (MW), biomass incineration ashes (BA), blast furnace slag (BFS) and water treatment sludge (WTS) have been studied as incorporation material for geotechnical barriers, they appear to have physical and chemical characteristics similar to clays and continue to be discarded in soils, water or landfills, contributing to significant negative environmental impacts and not being recycled or recovered (Agamuthu, 2013).

Valorization of industrial waste as applicable barrier materials for waterproofing earthworks for the storage of solid waste (SW) and wastewater have great potential and this research continue to grow due to its great performance and financial numbers. Although they its physical, chemical, and mineralogical properties, in addition to conducting characterization, mechanical and leaching experiments, proving the low hydraulic conductivity, compaction and chemical resistance, must be studied. Important physical characteristics include specific weight (ρ), density (G_S), water content (w), particle size distribution and specific surface (SS), compaction characteristics as optimal water content (w_{opt}) and optimal dry density ($\rho_{d,opt}$), chemical properties are main elements and oxides analysis, mineralogy, and cation exchange capacity (CEC), compressive strength (CS) with parameters as friction angle (φ') and cohesion (c') and the main property hydraulic conductivity (k). The identification of appropriate geo-applications for an industrial waste is the most crucial step, requiring consideration of its properties and a comprehensive knowledge and understanding of geotechnical construction, in addition to economic and environmental regulations (Abichou, Edil, et al., 1998).

Clays are aluminum silicates, when well compacted have low hydraulic conductivity and relatively cheap for engineering earthworks and high-density polyethylene (HDPE) are widely used in liners, principally acting as an waterproofing membrane to prevent the migration of liquids and gases (Vertematti, 2015). Liners are usually made of compacted clay liner (CCL) or geosynthetic-clay liner (GCL), and it's value for compacted liner must be less than or equal to 10^{-7} cm/s (Khalid et al., 2019). The main properties of an ideal barrier system are summarized by (Ganjian et al., 2004):

(i) low hydraulic conductivity, less than 1 x 10^{-7} cm/s.
(ii) enough strength to support the weigh above it, at least 5 N/mm^2.
(iii) deformation during service without cracking or rupture and self-healing properties.
(iv) chemical compatibility and high cation exchange capacity.
(v) easy construction and with low-cost materials.

Although, before analysing the possible alternative materials for use in geotechnical barriers, it is extremely important to disqualify those that are harmful in such applications, due to a physical or chemical incompatibility (Marchiori & Albuquerque, 2020). Composites normally are divided by layers, the first one, from top to bottom, with the perspective of provide a hard surface, tensile strength, and an initial leachate migration; the middle one (can be 1 or more depending on the type of waste) reduces permeability and have high cation exchange capacity, usually a cheaper material with proper properties; the last one, contribute with a firm base for the other layers and a chemical and physical final barrier to prevent migration to the soil and groundwater (Ganjian et al., 2004).

The main geotechnical aspects of a landfill involve the control of its base and its top to minimize soil infiltrations and gas emissions, in addition, it is needed to secure the place utilization after its closure and having its capacity optimized. Its general constitution is summed up by a basal covering layer, insulating the soil, drainage layer, to remove the leachate, covering layer, isolating the material dumped from the outside and a superficial drainage layer, to avoid surface erosion. Its hydric balance is explicit in Figure 1:

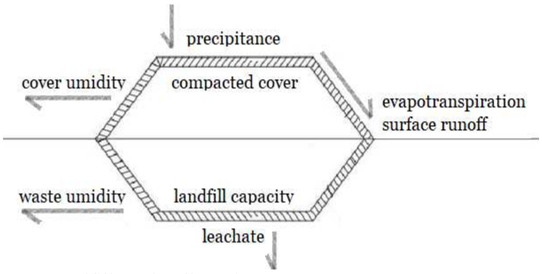

Figure 1. Landfill Hydraulic Balance.

The increased use of energy and fossil resources consumption, linked to the immense generation of waste and not having an appropriate place or logistic for responsible disposal, in addition to the most recent intention to save energy and effort, seeking greater efficiency and the lower costs for industries, justifies the use of alternative materials and energies. For this and other reasons already explained, countries and economic blocs are being obliged by programs such as the (United Nations) for research and use on an industrial scale of cleaner and cheaper energies, solving part of the great problem that is the excess of waste.

2 LINERS GEOTECHNICAL PROPERTIES

2.1 *Index Properties*

Index properties as specific gravity, essential for the final weight and can be determined by the method of the pycnometer, granulometry is important to obtain the fine particle size amount, along with plasticity are the most important index properties for liners. Plasticity or Atterberg limits are a very important characteristic of fine soils, it describes the capability of the soil to suffer irreversible deformation without break or crumble, as liners must have deformation without cracking or rupture. These characteristics directly influence the chemical, mechanical and hydraulic approaches of a soil.

2.2 *Chemical Analysis*

Chemical analysis as CEC, through a determinate cation saturation, is the quantity of ions that a mineral can exchange, important for clay minerals to quantify its ion adsorption and/or absorption, modifying physical and chemical properties. Oxide's analysis and principally the percentage of Al_2O_3, SiO_2 and Fe_2O_3 can affect plasticity, pozzolanic activity and specific weight. As liner application, the most important factor for chemical components and behavior is according to chemical compatibility with the disposal material and the leaching properties, principally for heavy metals.

2.3 *Mechanical Characteristics*

Optimal compaction parameters and compressive strength simulates field conditions, Standard Proctor was designed to increase soil density grouping the particles with reduction of air volume permissible until reaching an optimum value in this humidity-density relation, load capacity is limited for an adequate security coefficient against rupture by shear, triaxial consolidated undrained load permits to obtain the shear resistance, cohesion, and friction angle for liner application. The immediate settlement must take into account the permanent load plus the short-term load, the one immediately constructed, this one has alternate method to calculate the tensions and settlement depending on the form of the load, such as concentrated, linear, triangular load, uniformly distributed in a band, in circular or rectangular areas (Craig, 2007), oedometric test simulate those conditions in laboratory.

2.4 *Hydraulic Conductivity*

Hydraulic performance by constant head permeameters are laboratorial tests to evaluate hydraulic conductivity, it is is the most significant factor effecting soil liner performance. Liners are usually made of compacted soils, commonly clays, k normally for compacted liner must be less than or equal to 1 x 10^{-7} cm/s (Khalid et al., 2019).

3 RESIDUES AS LINERS

3.1 *Mining Wastes*

Mine waste lagoons are described as dangerous structures and responsible for many environmental disasters, thus it is an almost unlimited source, on account that mining activities continue to generate more waste. Through extraction of ores and minerals in mining industry, extremely fine particles are rejected by crushing, sorting or processing the raw material, mainly as sludge (Almeida et al., 2020) called MW, or mining tailing, generated from crushed rocks. Physical, chemical, and mechanical properties over mining residues are in accordance with the extracted ore, but they can undergo changes due to chemical processes applied, also are interest for reuse, mainly low to moderate hydraulic conductivity, plasticity, and shear strength. The hydraulic conductivity of mine tailings has been studied by itself or mixed with other components to improve performance utilizing alternative barrier materials from different ores industries. From aluminum industry, bauxite refining process results in a residue called red mud (RM), industrial by-product composed of solid and metallic oxides (Rubinos et al., 2015), due to its large and global aluminum appliance (Gangadhara Reddy & Hanumantha Rao, 2016) estimated around 120 million tons per year of RM and tested biotreated RM and found compaction characteristics improvement thought lower optimum water content and higher unconfined compressive strength (USC), and its potential valorization was extended by (Rubinos et al., 2015) when it found hydraulic conductivity around liner limit of 10^{-7} cm/s, concluding its feasibility. Additionally, (Aswathy et al., 2016) improved compaction and compressive properties for soil-RM mixtures with 2% of lime. Residues from ores extraction of iron, copper and gold were also studied and concluded that the feasibility for liner is mandatory mixtures with clayey soils due to its high permeability and leaching properties. Other studies analyzed spitilic MW from exploitation of nickeliferous laterites (Maritsa et al., 2016) and found k less than 10^{-7} cm/s when adding 3% of bentonite, drawing attention for incorporation possibilities. (Bareither & Gorakhki, 2016) developed a geocomposite by intrusion of waste rock particles in tailing's matrix called

GeoWaste, pure tailing and GeoWaste hydraulic performance are similar achieving 10^{-7} cm/s and an improve of mechanical resistance. Drilling processes generates drilling fluids and piles as waste, they can be water, synthetic or natural material as bentonite or even a mixture of them, this type of waste has the potential to impact the environment, when it is not contaminated with heavy metals, it has the potential to be a liner alternative material due its high bentonite content. (Marchiori & Albuquerque, 2020) summarized for MW, the main advantages are low cost, potential compost incorporation, mechanical, shear resistance, and chemical resistance, but need to incorporation in clayey mixtures for hydraulic conductivity and can present contaminants, they are already used as dams and landfill covers and slope stability, although lack long-term behaviour and chemical compatibility.

3.2 *Biomass Wastes*

BA from agro-industrial wastes are mostly prevenient through thermochemical processes as combustion, pyrolysis and incineration, varying from 5-15 % of biomass processed of ash production from those systems (James et al., 2012) and the recycle of this residue is growing, BA has received attention due to its combustion due its pozzolanic properties can be used as cementitious material after alkali content reduction (Salvo et al., 2015), can substitute gravel in road construction and possibly can replace fine-grained clays and soils in the construction of landfill liners on account of its latent hydraulic properties (Obernberger I & Supancic K, 2009), thus low costs, plasticity and chemical compatibility are the advantages, but need incorporation for mechanical resistance, BA are used as soil additive and landfill cover, but need investigation over mechanical properties and durability (Marchiori & Albuquerque, 2020). Main examples of agriculture wastes as liner studies are bagasse ash (BHA), rice husk (RHA), palm oil fuel ash (POFA) and wool ash (WA), its potential utilization was evaluated and concluded the main advantages are recovery of valuable components (SiO_2, Al_2O_3, CaO), providing essential elements and liming effects when incorporating clayey soils (Vassilev et al., 2013). Other BA types are cellulose and paper mill sludge (PMS) consist mainly of fibers, fillers, clays, and several other minor impurities that can have low hydraulic conductivity when properly compacted, also have been used to build hydraulic barrier layers in landfill cover (Kraus et al., 1997a). It is important to notice that BA geotechnical properties can vary when dealing with different paper-producing plants and agriculture. According to overload studies, PMS hydraulic conductivity varies around 10^{-7}-10^{-9} cm/s (Kuokkanen et al., 2008). (Osinubi & Eberemu, 2013) tested on residual granite soil mixture with 0-15% of POFA to assess its hydraulic conductivity and improve soil plasticity, while $\rho_{d,max}$ decreased and water content increased with the POFA content, also k decreased to a 10% POFA content achieving k around 10^{-9} cm/s suitable for liners. Also, tests were conducted on a reddish-brown lateritic soil treated with up to 12% bagasse ash were also suitable for use in barrier applications of waste containment.

3.3 *Blast Furnace Slags*

Combustion of materials generates waste, a process that is classified as a thermal process, the tailings are usually found in the form of ash, fly or inert, slag or sand. Due to a granulometry like that of clays and sands, natural usually used in civil construction. Coal ashes are divided by Class F fly ash, produced from the burning of anthracite and bituminous coal, and Class C fly ash, produced from lignite and sub-bituminous coal and can contain significant amounts of calcium hydroxide (Bhatt et al., 2019) and, as a result, can be self-cementing, were extensively studied as liner material (Palmer et al., 2000) its future disuse as a raw material for energy generation makes long term studies unfeasible due to a future lack of material on a large scale. Sands are usually from foundries, that use sand in two ways: for molds that form the external part and in cores that form the internal shapes and cavities of the foundry, the excess of foundry sands (FS) from metal generally contains a significant amount of bentonite, up to 15%, and therefore can have low hydraulic conductivity, also shows low sensitivity to moisture and compaction effort and environmental impact, making FS excellent hydraulic barrier materials (Abichou et al., 2000; Abichou, Benson, et al., 1998; Yaghoubi et al., 2020). The investigated thermal residue is BFS, a product of iron production, which has been widely investigated and used, particularly as a supplementary cementitious material due to its alkali activation reactivity, improving mechanical properties, workability and chemical resistance, and also high compressive strength. The compaction behavior of the material is like granular soils, a study of BFS properties was carried out with the conventional filling material, and it is considered for filling applications (Kumar et al., 2019), making BFS be considered as landfill alternative material, but lack research in long-term behavior and chemical compatibility, such as leaching potential.

3.4 *Water Treatment Sludge*

Water treatment plants (WTP) operations basically consists of capture, chemical coagulation, flocculation, decantation, filtration, and disinfection of the water, natural or residual, several minerals are used on that process, as Ca, Mg, Na, K, Fe, chlorides, nitrates, and nitrites. The periodical cleaning of the decanters at the plant generates solid wastes called water treatment sludges (WTS). Its chemical and mineralogy are basically silica, around 20%, aluminum, 60%, and iron, 5%, looking similar to aluminum silicates as clays (Bashar et al., 2016; Coelho, 2016; Kyncl, 2008). WTS's properties seem to be suitable for producing liner materials and for reinforcing weakened clay soils. Dehydrated and treated, chemically or incinerated, sludges and muds from WTP also have the aforementioned potential to be alternative materials for liners instead of clays (Okoli et al., 1999), with a severe attention for its hazardousness especially for residual water and mainly because of its permeability, compaction, durability and workability in constructions (Bashar et al., 2016), so, a more sustainable destination for WTS is its use in earthworks and as landfill lining. (Tsugawa et al., 2017b) observed thixotropy, increase in resistance over time when the system is left at rest, in WTS, and high plasticity from São Paulo's WTS, and with a optimal mixture 3:1 ratio soil:WTS qualifying as feasible for liner application (E L T Montalvan, 2021; E L T Montalvan & Boscov, 2016). Such as BA, notice that WTS geotechnical properties can vary when dealing with different WTP and water origin, they seems feasible to landfill cover for its low k, but need research around incorporation possibilities, chemical and mechanical resistance, and long-term behavior.

Table 1 summarized geotechnical parameters range obtained in laboratorial tests, index properties as G_S and SS, chemical oxide analysis with silica, aluminum and iron oxides content, optimal compaction parameter of water content and specific weight, compressive strength properties as cohesion and friction angle, and hydraulic conductivity. For valorization, composite material as referred should take advantage of the best properties a residue can provide to achieve liners design characteristics abovementioned by (Ganjian et al., 2004) in topic 1.

Table 1. Residues Geotechnical Properties

Geotechnical Properties	MW[1]	BA[2]	BFS[3]	WTS[4]
G_S (g/cm³)	2.5-3.5	1.5-2.5	2.0-3.0	1.5-2.5
SS (cm²/g)	>2000	>5000	>2000	>15000
LL (%)	35-65	30-40	35-45	30-50
LP (%)	NP-35	NP-25	25-30	NP-30
IP (%)	NP-30	NP-15	10-15	NP-25
CEC (meq/100g)	5-10	-	5-10	-
Al_2O_3 (%)	10-30	0-10	5-20	40-80
SiO_2 (%)	0-20	20-60	10-30	15-25
Fe_2O_3 (%)	10-50	0-15	0-5	0-10
w_{opt} (%)	25-35	15-40	5-10	20-200
$\rho_{d,opt}$ (g/cm³)	1.5-2.0	1.0-2.0	2.0-2.5	1.0-2.0
c' (KPa)	0-100	20-25	30-80	10-20
φ'(°)	30-40	30-45	40-50	35-40
k (cm/s)	10^{-6}-10^{-8}	10^{-4}-10^{-8}	10^{-8}-10^{-9}	10^{-4}-10^{-6}

[1](Aswathy et al., 2016; Bareither et al., 2018; Gangadhara Reddy & Hanumantha Rao, 2016; Hu et al., 2017; Maritsa et al., 2016; Patiño et al., 2018; Rubinos et al., 2015; Schnaid et al., 2014)
[2](Aziz et al., 2016; Benson & Wang, 1999; Kraus et al., 1997b; Kuokkanen et al., 2008; Osinubi & Eberemu, 2013; Soltani et al., 2015; Vassilev et al., 2010)
[3](Devarangadi & M, 2020; Devarangadi & Shankar, 2019; Herrmann et al., 2010; Smolar et al., 2016; Yildirim & Prezzi, 2015)
[4](Ahmad et al., 2016; Bağrıaçık & Güner, 2020; Bashar et al., 2016; Basim, 1999; Marchiori, Studart, Alburquerque, et al., 2021; Marchiori, Studart, Morais, et al., 2021; Edy L T Montalvan & Boscov, 2016, 2017; Pleysler et al., 2009; Rodríguez et al., 2010; Tsugawa et al., 2017a, 2019; Wolff et al., 2007)

Table 2. Residues Contribution for Liner Design

Liner Design (Ganjian et al., 2004)	MW	BA	BFS	WTS
(i) $k < 10^{-7}$ cm/s	+	-	+	-
(ii) Strength > 5 MPa	+	o	+	-
(iii) Deform without Rupture	+	-	o	+
(iv) Chemical Compatibility	-	+	o	+
(v) Low-cost Material	+	+	+	+

+ Positive Contribution
- Negative Contribution
o Neutral Contribution

Different ratios should be explored according to main characteristics for each residue. MW, BFS and some BA, such as PMS allow to achieve the limit (i) hydraulic conductivity less than 10^{-7} cm/s BFS and MW increase a composite strength during load, mainly for its mechanical resistance parameter similar to clays, providing (ii) enough strength to support the weigh above it. MW and WTS due to it higher plasticity indexes than other waste types, reaching IP around 25-30%, contribute for (iii) deformation during service without cracking or rupture and self-healing properties, in addition BFS can guarantee that the compaction remain good enough. WTS and BA allow better (iv) chemical compatibility and high cation exchange capacity should due its elemental and oxides analysis. For (v) low-cost raw material, all the residues fulfill by definition, industries can decrease their disposal costs and the landfill constructing cost, that range from US$300,000-US$800,000 per acre and the main difference is clay availability, US$30,000-US$160,000 (Duffy, 2015, 2016). This evaluation are summarized in Table 2.

4 CONCLUSIONS

According to overload studies, hydraulic conductivity is a potential feature of many materials, such as waste and residues, which should be further explored by researchers and not only as individual materials, but as mixtures that can obtain better performance, solving part of the problems explained in this article, such as excess waste in landfills, the future lack of raw clayey materials, high costs and waste generation of geosynthetic production (Marchiori & Albuquerque, 2020). Each one of the industrial by-products studied has geotechnical properties that are necessary for a liner material, with the ideal arrangement balancing these main properties, these wastes have the potential for an alternative liner. The main findings of this study include:

- Mining wastes (MW) allow to at least maintain hydraulic performance while improving mechanical characteristics; also, can perform as filler improving compaction characteristics, with due attention to tracking heavy metals and their leached potential.
- Biomass ashes (BA) low specific weight and silica content can contribute with pozzolanic activity, due to their inherent high amount of silica minerals, creating a silica-gel that connects grains and structural layers while minimizing porosity within the soil, increasing its bearing capacity.
- Blast furnace slag (BFS) can improve considerably mechanical resistance, also tracking heavy metals and their leached potential; and can decrease hydraulic conductivity.
- Water treatment sludge (WTS) can provide filling properties when using fine particle and decrease of specific weight; its large specific surface area will require more liquid to wet the surface and, thus, affects geotechnical characteristics results as specific weight, plasticity indexes and optimum compaction values; Al and Si high content approximates the clay behaviour high plasticity and volumetric variation; and CaO and high silica content can improve pozzolanic activity and bearing capacity.

These residues can be valorized with mixtures among them and along with clayey soils, lime and/or bentonite with different ratios, the investigation must be based on the principles of geotechnical properties described above, its physical, chemical, mechanical, and hydraulic characterization, and for application in field scale liners, it is necessary to investigate chemical compatibility, long-term performance, and leaching potential.

5 ACKNOWLEDGMENT

This work is supported by the UIDB / 00195/2020 (FibEnTech) and UIDB / 04035/2020 (GeoBioTec) projects, both funded by the Foundation for Science and Technology (FCT) from Portugal.

6 REFERENCES

Abichou, T., Benson, C. H., & Edil, T. B. (1998). Beneficial Reuse of Foundry Sands in Construction of Hydraulic Barrire Layers. *Environmental Geotechnics Report*, *98*(2).

Abichou, T., Benson, C. H., & Edil, T. B. (2000). Foundry Green Sands as Hydraulic Barriers: Laboratory Study. *Journal of Geotechnical and Geoenvironmental Engineering*, *126*(12), 1174–1183. https://doi.org/10.1061/(asce)1090-0241(2000)126:12(1174)

Abichou, T., Edil, T. B., Benson, C. H., & Tawfiq, K. (1998). Beneficial Reuse of Foundry Sands in Construction of Hydraulic Barrier Layers. *Geotechnical Special Publication*, *127*, 186–200. https://doi.org/https://doi.org/10.1061/40756(149)13

Agamuthu, P. (2013). Landfilling in developing countries. *Waste Management and Research*, *31*(1), 1–2.

https://doi.org/10.1177/0734242X12469169
Ahmad, T., Ahmad, K., & Alam, M. (2016). Characterization of Water Treatment Plant's Sludge and its Safe Disposal Options. *Procedia Environmental Sciences*, *35*, 950–955. https://doi.org/10.1016/j.proenv.2016.07.088
Almeida, J., Ribeiro, A. B., Silva, A. S., & Faria, P. (2020). Overview of mining residues incorporation in construction materials and barriers for full-scale application. In *Journal of Building Engineering* (Vol. 29). https://doi.org/10.1016/j.jobe.2020.101215
Aswathy, M., Salini U, & Gayathri, V. G. (2016). Utility of Lime and Red Mud in Clay Soil Stabilization. *Geotechnical Characterisation and Geoenvironmental Engineering*, *16*, 19–26.
Aziz, H. A., Yik, W. C., Ramli, H., & Amr, S. S. A. (2016). Investigations on the Hydraulic Conductivity and Physical Properties of Silt and Sludge as Potential Landfill Capping Material. *International Journal of GEOMATE*, *10*(22), 1989–1993.
Bağrıaçık, B., & Güner, E. D. (2020). An Experimental Investigation of Reinforcement Thickness of Improved Clay Soil with Drinking Water Treatment Sludge as an Additive. *KSCE Journal of Civil Engineering*, *24*(12), 3619–3627. https://doi.org/10.1007/s12205-020-0111-5
Bareither, C., & Gorakhki, M. (2016). Compression Behavior of Filtered Tailings and Waste Rock Mixtures : GeoWaste Mixed Waste Rock & Tailings. *Journal of Geotechnical and Geoenvironmental Engineering.*, *October*.
Bareither, C., Gorakhki, M., Scalia, J., & Jacobs, M. (2018). *Compression Behavior of Filtered Tailings and Waste Rock Mixtures: GeoWaste*.
Bashar, N. A. M., Zubir, Z. H., Ayob, A., & Alias, S. (2016). Water treatment sludge as an alternative liner for landfill site: FTIR and XRD analysis. *AIP Conference Proceedings*, *1774*. https://doi.org/10.1063/1.4965082
Basim, S. C. (1999). *Physical and geotechnical characterization of water treatment plant residuals* [New Jersey INstitute of Technology]. https://digitalcommons.njit.edu/dissertations
Benson, C. H., & Wang, X. (1999). Hydraulic conductivity assessment of hydraulic barriers constructed with paper sludge. *Geotechnics of High Water Content Materials*, *ASTM STP*(1374).
Bhatt, A., Priyadarshini, S., Acharath Mohanakrishnan, A., Abri, A., Sattler, M., & Techapaphawit, S. (2019). Physical, chemical, and geotechnical properties of coal fly ash: A global review. *Case Studies in Construction Materials*, *11*. https://doi.org/10.1016/j.cscm.2019.e00263
Coelho, G. M. R. (2016). *Avaliação da Capacidade Reativa de uma Lama de ETA para Remoção de Metais Pesados de Escorrências Rodoviárias*. Universidade da Beira Interior.
Craig, R. F. (2007). *Craig, mecânica dos solos*. LTC Editora. https://books.google.pt/books?id=zw8oOgAACAAJ
Devarangadi, M., & M, U. S. (2020, July 10). Correlation studies on geotechnical properties of various industrial byproducts generated from thermal power plants, iron and steel industries as liners in a landfill- a detailed review. *Journal of Cleaner Production*, *261*. https://doi.org/10.1016/j.jclepro.2020.121207
Devarangadi, M., & Shankar, M. U. (2019). Use of ground granulated blast furnace slag blended with bentonite and cement mixtures as a liner in a landfill to retain diesel oil contaminants. *Journal of Environmental Chemical Engineering*, *7*(5). https://doi.org/10.1016/j.jece.2019.103360
Duffy, D. P. (2015, April 6). *Landfill Economics - Part 1 - Getting Down to Business*. MSW Management.
Duffy, D. P. (2016, June 2). *Landfill Economics - Getting Down to Business - Part 2*. MSW Management.
Gangadhara Reddy, N., & Hanumantha Rao, B. (2016). Evaluation of the Compaction Characteristics of Untreated and Treated Red Mud. *Geo-Chicago*, 23–32. https://doi.org/10.1061/9780784480151.003
Ganjian, E., Claisse, P., Tyrer, M., & Atkinson, A. (2004). Preliminary investigations into the use of secondary waste minerals as a novel cementitious landfill liner. *Construction and Building Materials*, *18*(9), 689–699. https://doi.org/10.1016/j.conbuildmat.2004.04.020
Herrmann, I., Andreas, L., Diener, S., & Lind, L. (2010). Steel slag used in landfill cover liners: Laboratory and field tests. *Waste Management and Research*, *28*(12), 1114–1121. https://doi.org/10.1177/0734242X10365095
Hu, L., Wu, H., Zhang, L., Zhang, P., & Wen, Q. (2017). Geotechnical Properties of Mine Tailings. *Journal of Materials in Civil Engineering*, *29*(2), 04016220. https://doi.org/10.1061/(asce)mt.1943-5533.0001736
James, A. K., Thring, R. W., Helle, S., & Ghuman, H. S. (2012). Ash Management Review -Applications of Biomass Bottom Ash. *Energies*, *5*, 3856–3873. https://doi.org/10.3390/en5103856
Khalid, N., Mukri, M., Fadzil Arshad, M., Sidek, N., & Kamarudin, F. (2019). Effect on Salak Tinggi residual soil mixed Bentonite as compacted clay liner. *IOP Conference Series: Materials Science and Engineering*, *513*(1). https://doi.org/10.1088/1757-899X/513/1/012024
Kraus, J. F., Benson, C. H., Maltby, C. Van, & Wang, X. (1997a). Laboratory and Field Hydraulic Conductivity of Three Compacted Paper Mill Sludges. *Journal of Geotechnical and Geoenvironmental Engineering*, *123*(7), 654–662. https://doi.org/10.1061/(asce)1090-0241(1997)123:7(654)
Kraus, J. F., Benson, C. H., Maltby, C. Van, & Wang, X. (1997b). Laboratory and Field Hydraulic Conductivity of Three Compacted Paper Mill Sludges. *Journal of Geotechnical and Geoenvironmental Engineering*, *123*(7), 654–662. https://doi.org/10.1061/(asce)1090-0241(1997)123:7(654)
Kumar, K. P. B., Krishna, G., & Umashankar, B. (2019). Evaluation of Waste Foundry Sand and Blast Furnace Steel Slag as Geomaterials. In *Geo-Congress 2019* (pp. 304–313). https://doi.org/10.1061/9780784482148.031
Kuokkanen, T., Nurmesniemi, H., Pöykiö, R., Kujala, K., Kaakinen, J., & Kuokkanen, M. (2008). Chemical and leaching properties of paper mill sludge. *Chemical Speciation and Bioavailability*, *20*(2), 111–122. https://doi.org/10.3184/095422908X324480
Kyncl, M. (2008). Opportunities for water treatment sludge re-use. *GeoScience Engineering*, *LIV*(N°1), 11–22. http://gse.vsb.cz
Marchiori, L., & Albuquerque, A. (2020). CRITICAL REVIEW OF INDUSTRIAL SOLID WASTES AS BARRIER MATERIAL FOR IMPERMEABILIZATION OF STORAGE WASTE. *SUM2020 - 5th Symposium on Urban Mining and Circular Economy*, *November*.
Marchiori, L., Studart, A., Alburquerque, A., Cavaleiro, V., & Silva, A. (2021). Geotechnical characterization of water treatment sludge for liner material production and soft soil reinforcement. *Advanced Engineering Materials*.
Marchiori, L., Studart, A., Morais, M. V., Albuquerque, A., & Cavaleiro, V. (2021). AVALIAÇÃO DO POTENCIAL DE UTILIZAÇÃO DE RESÍDUO DE ETA COMO IMPERMEABILIZANTE DE OBRAS DE TERRA PARA A CONTENÇÃO DE RESÍDUOS. *1° Encontro Nacional de Lodo de Estação de Tratamento de Água*.
Maritsa, L., Tsakiridis, P. E., Katsiotis, N. S., Tsiavos, H., Velissariou, D., Xenidis, A., & Beazi-Katsioti, M. (2016). Utilization of spilitic mining wastes in the construction of landfill bottom liners. *Journal of Environmental Chemical Engineering*, *4*(2), 1818–1825. https://doi.org/10.1016/j.jece.2016.03.011
Montalvan, E L T. (2021). *Geotechnical properties of mixtures of water treatment sludge and residual lateritic soils from the State of São Paulo Geotechnical properties of mixtures of water treatment sludge and residual lateritic soils from the State of São Paulo*.
Montalvan, Edy L T, & Boscov, M. E. G. (2016). Geotechnical Characterization of a Soil-Water Treatment Sludge Mixture. *Geo-Chicago*, *GSP*(271), 418–427.
Montalvan, Edy L T, & Boscov, M. E. G. (2017). *Geotechnical Parameters of Mixtures of a Tropical Soil with Water Treatment Sludge*.
Obernberger I, & Supancic K. (2009). Possibilities of ash utilisation from biomass combustion plants. *17th European Biomass Conference & Exhibition*. https://www.bioenergy2020.at/files/publications/pdf/Obernberger-Supancic-Hamburg-2009-ash-utilisation.pdf
Okoli, R. E., Balafoutas, G., & Okoli, R. E. (1999). Bottom ash from sludge cake as a barrier material to pollutant migration in landfills. *Waste Management & Research*, *17*, 288–295.
Osinubi, K. J., & Eberemu, A. O. (2013). Hydraulic conductivity of compacted lateritic soil treated with bagasse ash. *International Journal of Environment and Waste Management*, *11*(1), 38–58. https://doi.org/10.1504/IJEWM.2013.050522
Palmer, B. G., Edil, T. B., & Benson, C. H. (2000). Liners for waste containment constructed with class F and C fly ashes. *Journal of Hazardous Materials*, *76*(2–3), 193–216. https://doi.org/10.1016/S0304-3894(00)00199-0
Patiño, H., Martínez, E., González, J., & Soriano, A. (2018). Permeability of mine tailings measured in a triaxial cell. *Canadian Geotechnical Journal*, 1–41. www.nrcresearchpress.com
Pleysler, R., Douglas, G., Trefry, M. G., & Wendling, L. A. (2009,

October 19). Characterisation of water treatment sludge. *International Mine Water Conference*.
Rodríguez, N. H., Ramírez, S. M., Varela, M. T. B., Guillem, M., Puig, J., Larrotcha, E., & Flores, J. (2010). Re-use of drinking water treatment plant (DWTP) sludge: Characterization and technological behaviour of cement mortars with atomized sludge additions. *Cement and Concrete Research*, *40*(5), 778–786. https://doi.org/10.1016/j.cemconres.2009.11.012
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. https://doi.org/10.1080/17480930.2013.830906
Salvo, M., Rizzo, S., Caldirola, M., Novajra, G., Canonico, F., Bianchi, S., & Ferraris, S. (2015). Biomass ash as supplementary cementitious material (SCM). *Advances in Applied Ceramics*. https://doi.org/10.1179/1743676115Y.0000000043
Schnaid, F., Nierwinski, H. P., Bedin, J., & Odebrecht, E. (2014). On the Characterization and Classification of Bauxite Tailings. *Soils and Rocks*, *37*(3), 277–284.
Smolar, J., Maček, M., & Petkovšek, A. (2016). Geotechnical and Environmental Characterization of Boiler Slag as Fill Material. *Journal of Geotechnical and Geoenvironmental Engineering*, *142*(8), 06016005. https://doi.org/10.1061/(asce)gt.1943-5606.0001489
Soltani, N., Bahrami, A., Pech-Canul, M. I., & González, L. A. (2015). Review on the physicochemical treatments of rice husk for production of advanced materials. *Chemical Engineering Journal*, *264*, 899–935. https://doi.org/10.1016/j.cej.2014.11.056
Tsugawa, J. K., Monte, R., Eugênia, M., Boscov, G., Tsugawa, J. K., Fernandes, E., Sabino, D. S., & Gimenez Boscov, M. E. (2019). Importance of Composing Representative Samples According to the Theory of Sampling (TOS) for the Reuse of Water Treatment Sludge . *Geotechnical Engineering in the XXI Century: Lessons Learned*, 2450–2457. https://doi.org/10.3233/STAL190314
Tsugawa, J. K., Pereira, K. F. S., & Boscov, M. E. G. (2017a). Thixotropy of Sludge from the Cubatão Water Treatment Plant, Brazil. *Geotechnical Frontiers*, *GSP*(280), 842–851. https://doi.org/10.1061/9780784480472.090
Tsugawa, J. K., Pereira, K. F. S., & Boscov, M. E. G. (2017b). Thixotropy of Sludge from the Cubatão Water Treatment Plant, Brazil. *Geotechnical Frontiers*, 842–851. https://doi.org/10.1061/9780784480472.090
United Nations. (n.d.). *The 2030 Agenda for Sustainable Development*. https://doi.org/10.1201/b20466-7
Vassilev, S. V., Baxter, D., Andersen, L. K., & Vassileva, C. G. (2010, May 1). An overview of the chemical composition of biomass. *Fuel*, *89*(5), 913–933. https://doi.org/10.1016/j.fuel.2009.10.022
Vassilev, S. V., Baxter, D., Andersen, L. K., & Vassileva, C. G. (2013). An overview of the composition and application of biomass ash.: Part 2. Potential utilisation, technological and ecological advantages and challenges. In *Fuel* (Vol. 105, pp. 19–39). Elsevier. https://doi.org/10.1016/j.fuel.2012.10.001
Vertematti, J. C. (2015). *Manual Brasileiro de Geossintéticos*. https://books.google.pt/books?hl=pt-BR&lr=&id=moewDwAAQBAJ&oi=fnd&pg=PA17&dq=vertematti&ots=hCjR8clKW3&sig=_CVu7WZNet0Rho1XT37LUtbg4JY&redir_esc=y#v=onepage&q=vertematti&f=false
Wolff, E., Schwabe, W. K., Landim, A. B., Vitorino, M. D., & dos Santos, W. L. (2007). A Substituição de Argila por Lodo de ETA na Produção de cerâmica Vermelha. *51° Congresso Brasileiro de Cerâmica*. http://marefateadyan.nashriyat.ir/node/150
Yaghoubi, E., Arulrajah, A., Yaghoubi, M., & Horpibulsuk, S. (2020). Shear strength properties and stress–strain behavior of waste foundry sand. *Construction and Building Materials*, *249*. https://doi.org/10.1016/j.conbuildmat.2020.118761
Yildirim, I. Z., & Prezzi, M. (2015). Geotechnical Properties of Fresh and Aged Basic Oxygen Furnace Steel Slag. *Journal of Materials in Civil Engineering*, *27*(12), 04015046. https://doi.org/10.1061/(asce)mt.1943-5533.0001310