

Hydraulic conductivity of waste-based liners: Valorization of industrial by-products for sustainable systems

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ABSTRACT: Environmental challenges are an increased issue regarding waste generation and landfilling management, due to soil and water contamination. Traditional compacted clay liners (CCL), geosynthetic clay liners (GCL), and geomembranes, often face limitations related to availability, cost, and long-term performance. The valorization of industrial by-products as geomaterials offers a promising alternative for waste containment applications, especially in addressing the permeability results and waste disposal mitigation. This study investigates the incorporation of industrial by-products, water treatment sludge (WTS), vegetal biomass ash (VBA), granitic mining waste (GMW), and blast furnace slag (BFS), into sandy soil to develop sustainable liner materials. By mixing WTS and VBA at ratios up to 20%, and GMW and BFS at ratios up to 50%, laboratory tests evaluated the particle size, physical, chemical, and hydraulic properties of the mixtures. Tests included chemical and mineralogical characterization through x-ray fluorescence and diffraction, respectively; specific gravity, consistency limits, compaction and falling head permeability following ISO 17892 standard. Results indicate that these waste-based materials can achieve low hydraulic conductivity (10^{-9} m/s) attached to compaction effort and moisture content, making them suitable for waste containment applications. Optimal performance was observed with 15% introduction of WTS, 10% of VBA, 50% of GMW, and 25% of BFS, based on dry mass incorporation into the soil. These mixtures also demonstrated favorable swelling and consolidation ensuring stability and chemical compatibility. The findings contribute to resilient infrastructure development through the rational design of eco-friendly, waste-based geomaterials for containment systems, emphasizing permeability control as a key factor in sustainable waste management.

KEYWORDS: Liner, permeability, waste management, geomaterials, geotechnical engineering.

1 INTRODUCTION

Global industrialization and rapid urbanization have led to exponential increases in waste generation, posing major environmental challenges, particularly concerning landfilling practices (Booker et al., 2004; Rowe, 2005; Voukkali et al., 2024). The World Bank estimates global municipal solid waste production will exceed 3.4 billion tons by 2050 (Kaza, Shrikanth and Chaudhary, 2021), making the development of effective and sustainable waste management strategies a top geoenvironmental priority (Roque et al., 2021).

To mitigate these risks, modern landfill designs integrate containment barriers, particularly CCL, GCL and geomembranes low-permeability systems, which prevent leaching infiltration (Cossu and Stegmann, 2018). While effective, these systems are associated with notable limitations, including cost, material availability, durability under physical and chemical stresses, and vulnerability to mechanical or thermal damage over time (Allen, 2001; Rowe, 2005).

Recent studies have reviewed the feasibility of reusing industrial waste materials for geotechnical and geoenvironmental purposes (Liu and Hung, 2023; Marchiori et al., 2025b). Water treatment sludge (WTS), a water purification by-product, has been indicated as a partial replacement for traditional clay liners given their low permeability and plastic characteristics when appropriately compacted (Takao et al., 2024; Al-Soudany, Fattah and Rahil, 2025). Besides, vegetal biomass ash (VBA), a residue from burning biomass, can offer pozzolanic activity and reduce permeability in soil-ash mixtures by promoting particle bonding and pore water reduction (Spreadbury et al., 2021; Bressan Junior et al., 2022). Also, granitic mining waste (GMW), largely composed of crushed stone fines, could provide mineralogical and chemical compatibility, stability and good structural support for liners (Rubinos, Spagnoli and Barral, 2016; Marchiori, Albuquerque and Cavaleiro, 2022). In addition, blast furnace slag (BFS), a by-product from steel manufacturing, has latent hydraulic and cementitious properties, improving cohesion, reducing void

ratios, leading to enhanced impermeability and stiffness (Devarangadi and Masilamani, 2023; Studart et al., 2023).

The valorization of waste into useful geomaterials contributes to a circular economy and aligns with global sustainability goals, such as those outlined in the United Nations Sustainable Development Goals (SDGs), particularly SDG 9 (industry, innovation, and infrastructure), 11 (sustainable cities and communities), and 12 (responsible consumption and production). Given the legal and sustainability imperatives, evaluating waste materials is essential, these materials potentially offer multiple environmental, economic, and engineering benefits (Marchiori et al., 2025a).

This research aims to address the above gaps by investigating the feasibility of using WTS, VBA, GMW, and BFS, individually mixed with different formulations, for liner applications. The goal is to evaluate hydraulic conductivity under compaction conditions, assess physical and chemical compatibility, analyze mechanical impact. Ultimately, the study contributes to sustainable waste management by proposing resilient, cost-effective, and environmentally sound geomaterials for containment systems.

2 MATERIALS AND METHODS

2.1 Materials

Four industrial by-products were collected in bulk: WTS was collected from a municipal water treatment plant at Guarda (Portugal); VBA sourced from biomass energy plants from Castelo Branco (Portugal); GMW was obtained from quarry crushing operations in Santana de Azinha (Portugal); and BFS from local steel industry in Lisbon (Portugal). The reference soil was collected from a construction site at Castelo Branco (Portugal).

All materials were stored in sealed containers to prevent contamination, and at the lab, they were dried at 105°C for 24 hours, and sieved to <2 mm, and homogenized prior to mixing.

2.2 Mix Design and Testing Methodology

All mixtures were prepared by dry-weight ratio. The geocomposites sets of blends created are presented to exemplify the nomenclatures used for the samples in Table 1. According to the specific gravity of each waste, the WTS and VBA content has been increased from 5% to 20% by 5% steps, differing from GMW and BFS, which were adjusted between 25% and 50%. The first two are due to low values of density and the last two with higher values of density, below and above 2.5, respectively.

Table 1. Waste-based geocomposite design.

Sample	Soil (%)	Waste (%)	Waste Source
Soil	100	0	-
WTS15%	85	15	WTS
VBA10%	90	10	VBA
GMW50%	50	50	GMW
BFS25%	75	25	BFS

Chemical analysis was performed using energy dispersive X-ray fluorescence (EDXRF) combined with scanning electron microscopy (SEM), employing a Tescan Vega SEM-EDS system. Prior to imaging and elemental mapping, the samples were homogenized and compacted to obtain a flat surface, allowing for detailed investigation of potential localized contamination and elemental distribution. Mineralogical composition was determined via X-ray diffraction (XRD) using a Phillips Analytical X-Ray B.V. instrument, with subsequent data interpretation carried out through the X'Pert-Pro MPD Data Viewer software by Malvern Panalytical.

Particle size distribution was obtained by sieving, specific gravity was determined by pycnometer with distilled water, consistency limits were found through Casagrande and plasticity apparatus, following the (BS 1377-2, 1990; ISO 17892-2, 2014, ISO 17892-12, 2018), respectively.

Compaction tests were done using Normal Proctor procedure with low energy compaction in the standard mold to obtain maximum dry density (MDD) and optimum moisture content (OMC), through (BS 1377-4, 1990).

Hydraulic conductivity tests were determined using a falling-head permeameter, in accordance with (ISO 17892-11, 2019), for specimens compacted at different moisture contents and dry densities. The performance criteria considered hydraulic conductivity (k) equal or less than 10^{-9} m/s, in accordance with recommended practices for liners (Booker et al., 2004).

3 RESULTS

3.1 Geocomposites Identification

Chemical composition, and mineralogical and microscopical images of the raw materials are exposed in Table 2 and Figure 2, respectively. Besides, the geotechnical characteristics and compaction curves of the tested and raw materials are exposed in Table 3 and Figure 1, respectively.

SEM-EDS samples were homogenized and pressed to create a smooth surface for the mapping evaluation of the elements looking to investigate possible punctual contamination and elemental heterogeneity. The images were done only to identify the distribution and to confirm the elemental composition of the raw materials. All samples look chemically homogeneous and do not seem to have any contamination.

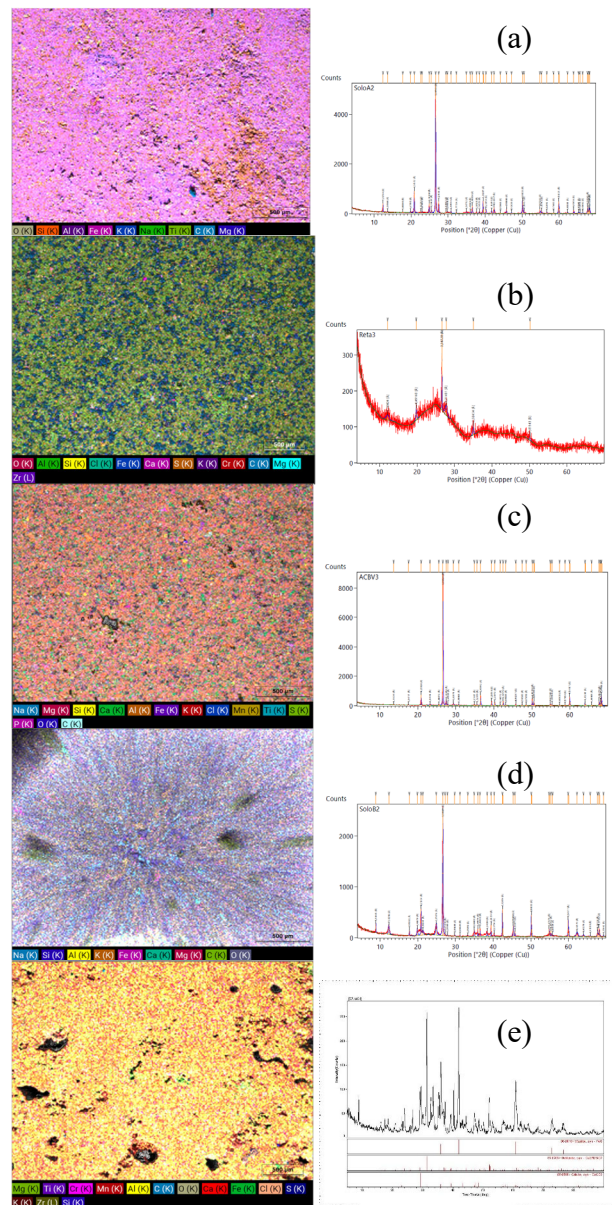


Figure 1. SEM-EDS and XRD results of the soil (a), WTS (b), VBA (c), GMW (d), and BFS (e).

Table 2. Concentration of major elements present as oxides (%) in the studied geocomposites.

Oxides	Soil	WTS	VBA	GMW	BFS
Na ₂ O	0.34	0.06	10.86	12.00	21.17
MgO	1.71	0.35	0.20	0.30	0.90
Al ₂ O ₃	21.01	19.88	9.20	5.65	9.05
SiO ₂	57.15	13.02	9.30	6.95	9.80
P ₂ O ₅	0.10	0.27	5.52	0.23	0.32
K ₂ O	3.33	0.35	2.98	2.40	5.98
TiO ₂	0.78	0.00	15.59	20.82	9.42
CaO	0.09	0.72	38.87	54.76	18.28
Fe ₂ O ₃	8.24	2.73	2.99	0.52	0.30
Mineralogy	Quartz, Muscovite, Kaolinite	Amorpha	Quartz, Calcite	Quartz, Muscovite, Kaolinite	Wurtzite, Goethite, Calcite

WTS is a fine, black slurry rich in Al, Si, and Fe, with low density and silty sand behavior. When mixed with the soil, it forms SW-SM materials, classified between A-2-4 and A-2-5

under BS 1377-2 (1990). WTS is non-plastic when dry but has a high liquid limit, with strong moisture sensitivity which could influence mechanical performance. Mixing increases the liquid limit and slightly raises the PI (up to 7%), while compaction tests show decreased MDD and increased OMC as WTS content rises, producing finer, clay-like composites. VBA is generally a well-graded sand (sometimes poorly graded in literature), and its inclusion in soil results in SW mixtures classified as A-2-5 and A-3. It has no plasticity, low density, and fine particle filling effects that can increase internal friction while reducing voids. VBA raises the liquid limit slightly (up to 3% for 5% addition) and lowers MDD while increasing OMC, mainly due to its low specific gravity and filler properties. Like WTS, it generates finer mixtures, but its calcite content may trigger pozzolanic activity, enhancing potential for use as a soil amendment or liner material.

GMW reflects the mineralogy of the source ore (mainly quartz and kaolinite), is a silty sand that, when mixed with soil, produces SW-SM mixtures classified as A-2-4. It increases the fine fraction slightly but has minimal impact on plasticity. Like other residues, GMW lowers specific gravity. Compaction results show only minor changes, OMC increasing 2% and MDD decreasing by 10%, making it attractive for use in liners without requiring changes to standard compaction procedures. Reduced hydraulic conductivity can be achieved by adjusting compaction methods. BFS is rich in Fe, Ca, and Mg, a well-graded sand with high specific gravity. Mixed with soil, it produces SW mixtures (A-2-4) while pure BFS can classify as A-3. Its coarse texture reduces fine content in mixtures and increases MDD while lowering OMC, contrasting with the other by-products. BFS is non-plastic and does not alter soil plasticity significantly, although it can slightly increase liquid limit due to calcite-driven pozzolanic reactions. The coarse granulometry stabilizes soils, reduces plasticity, and offers less sensitivity to water content during compaction compared to clayey soils.

Table 3. Geotechnical parameters of the geocomposites.

Sample	Fines (%) <75µm	Coarse (%) >75µm	Gs (-)	PI (%)	OMC (%)	MDD (g/cm ³)
Soil	9	91	2.73	6.0	18.0	1.73
WTS	25	75	1.90	NP	80.1	0.70
WTS20%	18	82	2.46	1.0	25.8	1.44
WTS15%	15	85	2.48	3.0	24.0	1.48
WTS10%	12	88	2.56	4.0	21.3	1.58
WTS05%	10	90	2.69	7.0	17.6	1.68
VBA	10	90	1.88	NP	25.4	0.90
VBA20%	8	92	2.42	NP	24.0	1.48
VBA15%	8	92	2.49	NP	21.5	1.55
VBA10%	9	91	2.54	NP	18.1	1.62
VBA05%	9	91	2.63	3.0	17.3	1.65
GMW	26	74	2.50	5.8	21.5	1.51
GMW50%	22	78	2.60	5.0	20.0	1.57
GMW25%	18	82	2.70	9.0	19.2	1.69
BFS	10	90	3.70	NP	-	-
BFS50%	9	91	3.07	NP	9.4	2.15
BFS25%	9	91	2.96	12.0	12.8	1.96

Gs. Specific gravity; PI. Plastic index; OMC. Optimal moisture content; MDD. Maximum dry density.

Although chemical reactivity plays a varying role, for WTS, predominantly physical blockage by fines, moisture-sensitive, high water retention; VBA also with physical blockage plus chemical binding via pozzolanic activity; GMW too with physical blockage via improved gradation, low shrink-swell, robust compaction response; and BFS in which coarse skeleton with cementitious hydration products filling pores.

3.2 Hydraulic conductivity

Hydraulic conductivity results are shown in Figure 3. As stated, hydraulic conductivity is the most critical parameters in assessing the suitability of materials for use in landfill liners and other containment systems, targeting $k \leq 1 \times 10^{-9}$ m/s (red dashed line) criterion for effective liners. However, the mechanisms by which each by-product reduces permeability differ significantly due to their physical properties, mineralogy, particle size distribution, and specific gravity.

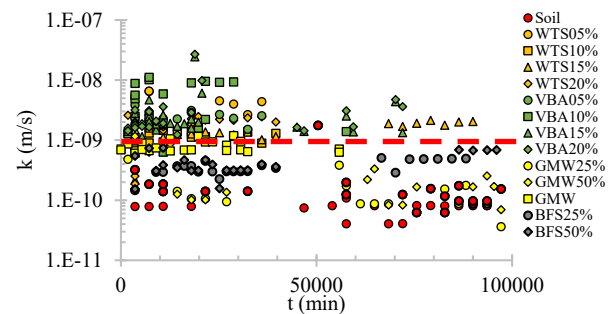


Figure 2. Hydraulic conductivity results.

WTS (orange markers) content from 5% to 20% progressively reduced the hydraulic conductivity, with the most favorable performance at 15% of WTS. This optimal proportion is linked to a balance between sufficient fine particle filling of soil voids and maintenance of adequate workability for compaction. The permeability reduction in WTS-soil blends is due to pore space obstruction and increased tortuosity of flow paths. As WTS particles are much smaller than the host sand grains, they lodge within the intergranular spaces, effectively reducing the size and continuity of water-conducting pores. Additionally, WTS has a high water retention capacity, which can help maintain low k-values even under fluctuating moisture conditions. However, excessive WTS, higher than 15%) can lead to compaction difficulties and heterogeneous density distribution, which may create localized zones of higher permeability.

VBA (green markers) incorporation from 5% to 20% showed a progressive reduction in k, with 10% VBA providing the most favorable results. The permeability reduction mechanism for VBA differs from WTS: in addition to fine particle filling, VBA's reactive mineral phases promote particle bonding and microstructural densification over time. Calcite content and potential pozzolanic reactions (with Si and Al sources in the soil) can produce secondary cementitious compounds such as calcium silicate hydrate, which further occlude pore spaces. This suggests that VBA-based liners could experience continued permeability reduction post-compaction, which is an advantage for long-term performance. One consideration for VBA is leaching potential, as some ash sources may contain soluble salts or trace metals. The results of this study, however, suggest that VBA's chemical composition is compatible with liner applications, aligning with previous findings (Bressan Junior et al., 2022).

GMW's hydraulic conductivity (yellow markers) is near the regulatory limit due to its finer content, however, when mixed with the reference soil at 50% proportion, GMW demonstrated k-values within the acceptable range, if

compaction moisture and density were optimized. The permeability reduction in GMW-based mixtures is primarily due to fines content from filling voids in the base sand, reducing the size of effective pore channels. The mineralogical compatibility of GMW with the host soil ensures low shrink-swell potential, which is beneficial for maintaining hydraulic performance under seasonal moisture variations. The results indicate that GMW mixtures are less sensitive to water content variation during compaction compared to WTS and VBA. Moreover, the fact that GMW-based mixtures achieve the desired permeability without major alterations to standard compaction procedures further enhances their practicality.

BFS (grey markers) has a coarser particle size distribution, which tends to increase permeability when introduced in large proportions. However, at 25% BFS content, mixtures with the reference soil achieved the target hydraulic conductivity, largely due to the cementitious and void-reducing effects of BFS hydration products. When compacted at OMC, BFS-based mixtures displayed improved packing density to WTS and VBA blends. The higher density, combined with hydration-induced pore filling, contributed to k-values in the order of 10^{-9} m/s. The Ca-rich nature of BFS could promote the formation of binding phases such as calcium silicate and calcium aluminate hydrates, which reduce pore connectivity over time.

The incorporation of WTS, VBA, GMW, and BFS into a sandy soil matrix demonstrated that all four industrial by-products, under specific proportions and compaction conditions, can achieve value within this regulatory threshold. Across all four materials, the dominant mechanism for permeability reduction involves pore size reduction through fine particle filling. In terms of optimal incorporation ratios, the study determined WTS15%, VBA10%, GMW50%, and BFS25% as the best-performing blends.

Beyond permeability, these materials offer economic and environmental benefits by diverting waste from landfills and reducing the demand for virgin clay resources.

4 CONCLUSIONS

This study validates the feasibility of using industrial by-products (WTS, VBA, GMW, BFS) as sustainable materials in landfill liner systems. The optimal soil-waste mix design achieved hydraulic conductivity below 1×10^{-9} m/s, satisfying regulatory standards. Compaction moisture content strongly influences liner effectiveness, nonetheless, optimal formulations were determined via permeability testing, and best design was centered on four samples: WTS15%, VBA10%, GMW50%, and BFS25%. The study limitations are around long-term and large-scale performance; thus, future investigation should analyze leachate compatibility and percolation under real conditions, scalability from, and variation of the raw soil and percentages within more than one by-product.

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