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# SM soils and biochar in landfill cover layers: Sustainable potential for containment works

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ABSTRACT: The search for sustainable practices in geotechnical engineering has encouraged the use of residual materials in environmental containment works. In sanitary landfills, slope stability and the performance of cover layers are essential to ensure waste containment, control infiltration, and mitigate gas emissions, especially under critical climatic conditions. With the increasing occurrence of extreme events, the response of these layers must also be evaluated under more severe scenarios, which may compromise their long-term efficiency. This study evaluated soils from two areas of the Campina Grande Sanitary Landfill (ASCG), classified as silty sand (SM), regarding their suitability as barrier materials in surface layers and slopes. Biochar, obtained from the gasification of wood waste, was characterized by BET, XRD, and SEM/EDS, aiming at its incorporation into the soil. The results indicated a material with high porosity, amorphous carbon, and a microstructure favorable to water retention and gas adsorption, contributing to the reorganization of the pore structure, increased tortuosity, and control of fluid flow. Geotechnical tests showed soils with good compaction and permeability on the order of $10^{-7}$ m/s, consistent with barrier function. The addition of biochar increased the liquid limit, indicating improvement in hydraulic behavior. The results suggest that the controlled incorporation of biochar contributes to infiltration control, gas retention, and slope stability under wetting–drying cycles, with technical and environmental benefits.

**KEYWORDS:** biochar, environmental geotechnics, infiltration, stability, barriers

## 1 INTRODUCTION

The final cover layer of sanitary landfills plays an important role in controlling infiltration, gas emissions, odors, erosion, and in supporting vegetation cover, maintaining the environmental and structural integrity of the system (Kamaruddin et al., 2021). However, factors such as biogas generation, waste decomposition, and moisture variations may compromise stability, causing settlements and consolidation (Bonaparte et al., 2020).

The use of biochar in cover soils has been investigated to improve geotechnical properties. This carbonaceous material, produced by the pyrolysis of organic residues under limited oxygen conditions, presents high porosity, large specific surface area, thermal stability, and water retention capacity, enhancing soil performance (Zhang et al., 2020).

From a geotechnical perspective, biochar addition can increase apparent cohesion, reduce maximum dry density, and improve water retention, contributing to erosion control and to mechanical and hydraulic behavior under climatic variations (Li et al., 2020; Ng et al., 2022). In addition, it can act as an adsorbent, retaining toxic compounds and reducing gas emissions such as methane (Nanda et al., 2016). Its effects vary according to soil type, feedstock, pyrolysis conditions, and applied proportion, requiring further full-scale studies (Sikiru et al., 2024).

This scenario becomes more critical with the increasing frequency of extreme climatic events, which impose severe wetting–drying conditions. In semi-arid regions, cover soils often exhibit low water retention and high susceptibility to cracking, compromising long-term performance (Boscov, 2008; Catapreta et al., 2016).

In this context, the incorporation of materials with high porosity and water retention capacity has been investigated. The use of biochar has gained attention due to its ability to improve the physical, chemical, and environmental properties of soils (Downie et al., 2009; Gonzaga et al., 2019). From a physical standpoint, its porous structure allows void filling, modifying density, porosity, and infiltration (Abrishamkesh et al., 2015). Chemically, it influences soil pH, provides nutrients, enhances contaminant adsorption, and improves cation exchange capacity (Glaser et al., 2002).

In soil–biochar mixtures, changes in dry density, optimum moisture content, shear strength, and permeability are observed, depending on soil characteristics and applied proportion (Kong et al., 2021). Biochar promotes aggregate formation, increases interparticle friction, and improves shear strength, reducing erosion. It can also reduce permeability, favoring soil stabilization and its application in hydraulic barriers and slopes (Zhang et al., 2019).

Beyond mechanical and hydraulic effects, soil–biochar mixtures can reduce gas emissions and promote methane oxidation. Its porous structure creates a favorable environment for methanotrophic bacteria, contributing to $CH_4$ degradation (Yaghoubi, 2011). Biochar derived from lignocellulosic residues, such as wood, presents higher fixed carbon content, thermal stability, and structural rigidity, providing advantageous structural and adsorptive properties (Lehmann and Joseph, 2015; Zhang et al., 2019). It is recognized for improving soil properties, adsorbing pollutants, and reinforcing soil–biochar mixtures (Inda and Bayer, 2018).

A sustainable alternative is the use of wood waste from discarded school furniture for biochar production. Pyrolysis produces a porous material capable of improving soil properties, increasing water retention, and contributing to carbon sequestration (Li et al., 2021), while promoting circular economy and waste management (Zhang et al., 2020).

Studies highlight the potential of biochar in modifying geotechnical parameters (Rajakaruna et al., 2020; Zhang et al., 2022). Sadasivam and Reddy (2015) correlated mechanical properties with physicochemical characteristics, while Kinney et al. (2012) analyzed hydrological properties such as water retention.

In this study, the biochar was produced from wood residues, presenting high surface area, porous structure, and adsorption capacity (Guo et al., 2016; Hussain and Ravi, 2022). Its incorporation can modify soil pore structure, influencing water retention, permeability, and shear strength (Reddy et al., 2015; Chorbani et al., 2024). The characterization of these mixtures involves granulometry, Atterberg limits, compaction, permeability, and shear strength tests, allowing the assessment of their suitability for different applications.

Therefore, this study evaluates the geotechnical behavior of soils used in cover layers and slopes of a sanitary landfill in the semi-arid region of Paraíba, as well as the potential incorporation of biochar, focusing on fluid flow control and slope stability.

## 2 MATERIALS AND METHODS

### Study Area – Campina Grande Landfill, State of Paraíba, Brazil

The study area corresponds to the Campina Grande Sanitary Landfill (ASCG), located in a semi-arid climate region, characterized by alternating periods of drought and intense rainfall events. These conditions impose additional challenges on the performance of cover layers, particularly regarding the maintenance of surface integrity and flow control.

### 2.1 MATERIALS

Two soils were analyzed: Both were classified as silty sand (SM), according to the Unified Soil Classification System (USCS).

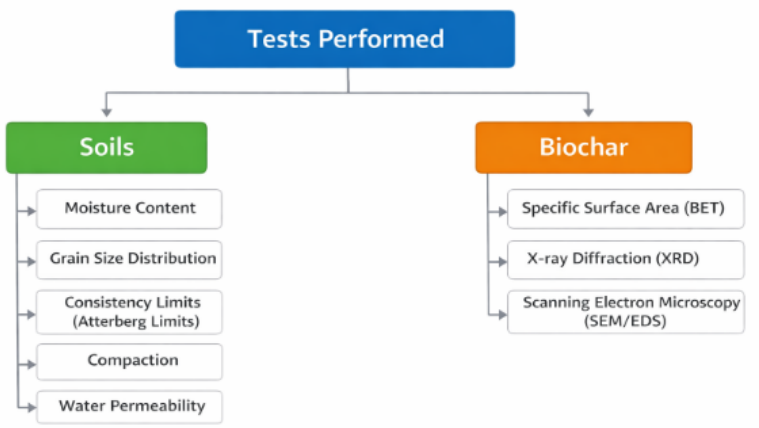
• **Soil A:** collected from the final cover layer, in an area defined by Souza (2021) with higher gas emission rates;

• **Soil B:** collected from an intermediate slope layer.

• **Biochar:** produced from the gasification of wood waste from discarded school furniture. The thermal process resulted in a carbonaceous material with typical biochar characteristics, including high porosity and the presence of amorphous carbon.

• **Mixture Preparation:** A soil–biochar mixture was prepared, containing 3% biochar by mass incorporated into Soil A, based on previous studies indicating this proportion as intermediate for evaluating initial effects (Marques et al., 2020; Yu et al., 2021).

### 2.2 METHODOLOGY




## 3 RESULTS AND DISCUSSION

The material shows a predominance of amorphous structure, with the presence of secondary crystalline phases such as quartz ($SiO_2$) and carbon domains with partial graphitic organization (Georgin et al., 2020; Salomon et al., 2022). The carbonaceous matrix is characterized by a disordered structure, typical of biochars derived from lignocellulosic biomass, with contributions associated with lignin and cellulose (Meili et al., 2019a, 2019b). This structural configuration, with the absence of long crystalline domains, is common in materials subjected to high-temperature carbonization processes (Li et al., 2022).

The structural organization, composed of amorphous regions interspersed with graphitic domains, is associated with high porosity and a heterogeneous distribution of micropores and mesopores (Crini et al., 2008; Tomassoni et al., 2020). These characteristics favor adsorption processes due to the increased surface area and the presence of active sites (Salomon, 2021), contributing to the retention of gases such as $CO_2$ and $CH_4$ (Peres et al., 2020; Liu et al., 2021).

BET analysis indicated that the biochar has a specific surface area of 330.3 $m^2/g$ and a total pore volume of 0.1934 $cm^3/g$, with an average diameter of approximately 1.847 nm, characterizing a predominantly microporous structure with contribution from mesopores (Mohammadnezhad et al., 2019). These results are consistent with materials of high adsorption capacity, in which microporosity favors gas molecule retention by diffusion (Abuelnoor et al., 2021; Li and Lan, 2024). Although the obtained surface area is lower than maximum values reported for activated carbons under controlled conditions, it falls within the typical range of biochars produced by physical activation (Nazem et al., 2020).

Morphological analysis reveals a heterogeneous and interconnected structure, with cavities and discontinuities associated with the carbonization process, consistent with the development of micropores and mesopores indicated by BET analysis (Kelm et al., 2019). Complementary EDS analysis confirmed a high carbon content (94.1%), reinforcing the carbonaceous nature of the material. This combination of composition, morphology, and pore distribution indicates that the thermal process was sufficient to produce a material with relevant adsorption potential.

From a geotechnical perspective, this structure tends to influence properties such as moisture retention, permeability, and shear strength in soil–biochar mixtures, in addition to contributing to gas retention in landfill cover layers (Huang and Xu, 2024; Chorbani et al., 2024). The results indicated that the analyzed soils exhibit typical behavior of silty sand materials, with a predominance of sandy fractions and fine content close to the recommended limit for cover applications (CETESB, 1993; USEPA, 2004). The addition of biochar increased the fine fraction content, allowing the material to meet normative limits. Soil A presented approximately 28.36% fines, while the mixture with 3% biochar reached 30.1%.

Soils A and B showed liquid limits (LL) of 22% and 19%, respectively, below the minimum of 30% recommended by CETESB (1993), reflecting the silty sand nature and low water retention capacity of the materials. Although the natural soil fine content is slightly below the recommended minimum, studies indicate that soils with fine fractions between 15% and 30% can perform satisfactorily in cover layers when properly compacted (Benson et al., 2001; Kameyama, 2012). The Figure 1 illustrates the consistency limits of the natural soils and the soil–biochar mixture.

In this context, the incorporation of biochar promoted an increase in the liquid limit from 22% to 26%, associated with its high specific surface area, porous structure, and water retention capacity (Yang et al., 2014;

Zanutel et al., 2024; Lee et al., 2021), reducing liquid percolation and the potential for leachate generation, as well as contributing to surface erosion control.

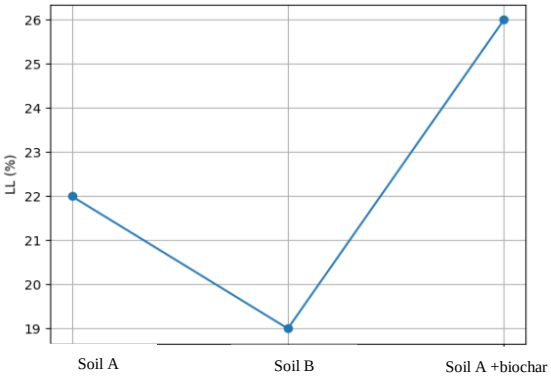



Figure 1 – Liquid limits of soils A and B and of the mixture Soil A + biochar

Although the materials remain non-plastic (NP), this variation indicates a change in hydraulic behavior, influencing suction, response to wetting and drying cycles, volumetric behavior, and shear strength. The increase in the liquid limit suggests improved hydraulic behavior, potentially reducing susceptibility to cracking, especially in semi-arid environments (Mirmongereh et al., 2023).

This modification has implications for slope stability, as increased water retention favors continuity of the medium and reduces crack formation, helping to control preferential flow paths and maintain surface integrity (Mirmongereh, Pakbaz, and Sasani, 2023). Furthermore, biochar tends to alter void distribution and permeability, influencing pore pressure dissipation and the balance between strength and deformation (Huang and Xu, 2024). However, these effects tend to be more pronounced at contents above 5%, indicating that the addition of 3% promotes moderate changes, with potential intensification at higher dosages (Wong et al., 2016).

The grain size distribution results indicate soils classified as silty sand (SM), with a predominance of sandy particles and the presence of fines that influence hydraulic and mechanical behavior. This composition presents limitations, such as low water retention and a higher tendency to crack during drying periods (Boscov, 2008; Catapreta et al., 2016). Pinto (2006) highlights that soils with good grain size distribution exhibit better compaction performance, forming denser and more stable structures.

Grain size heterogeneity is desirable in cover layers, as it influences water retention, shear strength, crack formation, permeability, and response to moisture variations (Araújo, 2016; Lima et al., 2019; Oliveira et al., 2011).

The analysis of the grain size curves indicates that the addition of biochar does not significantly alter particle distribution, demonstrating compatibility between the materials and contributing to better void distribution and fluid flow control. In terms of compaction, Soil A presented a maximum dry density of 1,925 kg/m³ and an optimum moisture content of 12%, values that indicate good compaction capacity and ease of field execution. These results are consistent with silty sandy soils, which tend to exhibit a relatively stable structure under compaction, with a balance between coarse particles (responsible for strength) and fine particles (responsible for cohesion and water retention) (Mitchell and Soga, 2005).

The achieved dry density can be considered high for this type of material, indicating a compacted structure with low compressibility and good mechanical strength. This behavior is particularly important in landfill cover layers, where surface stability and resistance to deformation are essential to prevent differential settlement and erosive processes. The literature indicates that compaction directly influences hydraulic conductivity and the overall performance of the cover layer, as increasing the degree of compaction reduces void volume and limits the formation of preferential flow paths (Daniel and Benson, 1990; Benson et al., 2001).

In this context, the obtained values indicate that the soil presents suitable conditions to act simultaneously as a structural support and a hydraulic barrier. Furthermore, the relationship between dry density and the estimated void ratio (ranging approximately from 0.27 to 0.34) shows that the compacted soil has a relatively dense structure, yet still with sufficient porosity to allow gas diffusion processes. This balance is particularly desirable in cover layers, as it enables the reduction of water infiltration while promoting gas oxidation (Thurner et al., 2024; Trinh et al., 2023).

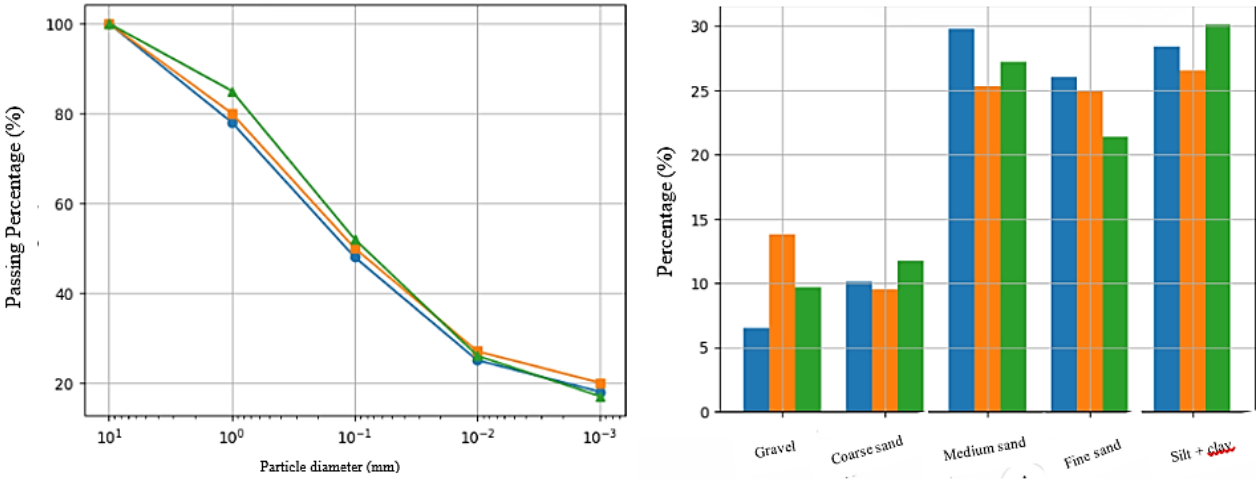



Figure 2 – Grain size distribution curves of the analyzed materials (a), highlighting Soil A (●), Soil B (■), and Soil A with 3% biochar (▲); Bar chart (b): orange → Soil A | blue → Soil B | green → Soil A + 3% biochar

Compaction of the cover layer in landfills is a key factor in soil permeability, controlling the movement of water and air within the pores (Gondim, 2020). Excessive compaction may limit the transport of moisture and nutrients, compromising methane oxidation, while adequate levels act as a barrier to gas emissions (Lima and Pinto Júnior, 2020). Typical dry density values between 1780 and 1950 kg/m³ indicate good geotechnical performance, associated with cover stability, infiltration control, and emission reduction (Mariano, 2008). The specific gravity of the particles also contributes to shear strength when combined with proper compaction, whereas lighter materials tend to form more porous structures (Pham et al., 2020; Santos, 2019).

The addition of biochar reduces the maximum dry density and increases the optimum moisture content due to its low density and high porosity (Zanutel et al., 2024; Reddy et al., 2015), favoring water retention but requiring control, as excessive reductions in density may compromise strength (Abichou et al., 2020). Consistent results have been reported by Lamprinakos (2019), Ganesan et al. (2024), and Mirmongereh et al. (2023), with variations depending on fines content and dosage. Studies also indicate that biochar particle size and porosity alter pore structure and compaction efficiency (Verheijen et al., 2019; Edeh and Mašek, 2021; Alghamdi et al., 2020).

Overall, biochar incorporation follows a consistent pattern of reducing dry density and increasing optimum moisture content, requiring a balance between functional benefits and mechanical performance maintenance. Regarding permeability, the tests indicated values on the order of $10^{-7}$ m/s, placing the soils within the recommended range for final cover layers, according to NBR 13896 (ABNT, 1997) and USEPA (2004). This order of magnitude is characteristic of materials with moderate hydraulic barrier behavior, capable of restricting water percolation without completely eliminating the presence of interconnected pores.

This behavior is consistent with studies such as Roessler et al. (2022), which observed similar values for compacted silty soils used in landfill covers. Furthermore, Thurner et al. (2024) highlight that materials with hydraulic conductivity in this range exhibit stable long-term performance, even under wetting and drying cycles. The interaction between grain size distribution, compaction, and permeability indicates that the analyzed soil presents a structure favorable for field performance. The presence of fine fractions contributes to filling voids between sandy particles, reducing permeability, while the sandy fraction ensures mechanical stability and shear strength.

The incorporation of biochar, even at low content (3%), tends to modify the internal soil structure, mainly through partial void filling and the introduction of an additional porous network. Studies indicate that, even in small proportions, biochar can influence soil matrix organization, increasing pore tortuosity and reducing hydraulic connectivity (Barnes et al., 2017; Mesbahnia et al., 2023). This effect, associated with the high specific surface area of biochar, can contribute to moisture redistribution in the soil and increased water retention, without significantly compromising compaction capacity. However, as observed by Marques et al. (2020) and Yu et al. (2021), low contents tend to produce subtler effects, acting mainly as local structural modifiers without significantly altering the overall soil parameters.

Therefore, the obtained results indicate that the analyzed soils exhibit geotechnical behavior compatible with their application in landfill cover layers, with adequate performance in terms of compaction and

permeability. The addition of biochar contributes to adjustments in soil structure, with potential for improved fluid flow control and behavior under variable environmental conditions.

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