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Incorporation of water treatment plant sludge into geosynthetic-reinforced soil: influence on mechanical and hydraulic properties

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Article

Keywords
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Waterproofing layer
WTP sludge

Abstract

The disposal of water treatment sludge (WTS) remains a major environmental challenge, especially in developing countries. This study evaluates the incorporation of WTS into silty clayey soils, with and without nonwoven geotextile reinforcement, to assess the mechanical and hydraulic behavior of mixtures for sanitary landfill applications. Laboratory tests—including compaction, confined compression, hydraulic conductivity, and direct shear—were performed on mixtures with 0–10% WTS and pure sludge. Results showed that increasing WTS content raised void ratios, reduced maximum dry unit weights, and lowered hydraulic conductivity, suggesting potential as a low-permeability barrier. However, higher WTS contents also increased compressibility and reduced shear strength, which may compromise stability. The 7.5% mixture maintained shear strength comparable to natural soil, representing an optimal balance between performance and sustainability. Geotextile reinforcement further improved shear strength in all mixtures, particularly under higher confining stresses, expanding applicability in engineered barriers. Overall, the findings confirm the viability of reusing untreated WTS as a partial soil substitute in landfill construction, contributing to resource conservation and sustainable waste management.

1. Introduction

Human activity has historically exerted significant, often irreversible, pressures on the environment. As settlements expanded, ecosystems were altered and natural resources strained, with potable water among the most affected. Population growth, urbanization, and industrialization intensified global demand for freshwater, increasing exploitation of natural sources and treatment infrastructure.

To meet this demand, large-scale treatment technologies became essential but generated by-products requiring management, notably sludge from settling tanks and filter backwashing at conventional water treatment plants (WTPs). This water treatment sludge (WTS) is a direct outcome of processes ensuring potability (Silva, 2021).

WTS is a non-biodegradable waste composed mainly of water and suspended solids, with characteristics dependent on raw water quality, treatment procedures, and chemical additives (Roque et al., 2021). In Brazil, NBR 10004 (ABNT, 2004) classifies WTS as solid waste to be disposed of in sanitary landfills. In practice, however, irregular discharges into water bodies remain common, violating Law No. 9605/1998 (Brasil, 1998) and causing sediment accumulation, reduced capacity, and water quality deterioration (Boscov et al., 2021).

Even regulated landfill disposal poses challenges: high moisture content and low shear strength may compromise integrity and long-term stability (Boscov et al., 2021). To mitigate these issues, research has explored alternative uses of WTS in geotechnical applications, particularly soil incorporation (Castilhos Junior et al., 2012; Scapin, 2021; Mazzutti et al., 2023; Knierim et al., 2023).

This study extends Fiedler et al. (2025) by investigating soil-sludge mixtures with an additional variable: geosynthetics, widely used in geotechnical engineering. These polymer-based materials perform reinforcement, stabilization, drainage, filtration, and barrier functions, depending on fiber arrangement and properties (Palmeira, 2018). For example, geotextiles in landfill systems may facilitate drainage, provide reinforcement, or protect geomembranes (Costa, 1999).

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Here, a nonwoven geotextile was employed for its versatility. Typically manufactured from polymers such as polyethylene, polypropylene, polyester, polyamide, polyvinyl alcohol, and polyaramid (Vertematti, 2022), its fibrous, porous structure enables multiple simultaneous functions, making it suitable for complex geotechnical applications.

Thus, combining soil-sludge mixtures with geosynthetic reinforcement emerges as a promising strategy to reduce the environmental impact of WTS disposal while improving landfill performance. This research advances sustainable solutions in landfill engineering by integrating waste reuse with geosynthetic applications.

2. Materials and methods

As previously mentioned, this research extends the experimental study of Fiedler et al. (2025) by incorporating two additional sludge percentages into the soil matrix, evaluating shear strength of the mixtures, and integrating geotextiles to assess their effect on shear performance. These modifications aim to deepen understanding of mechanical behavior and explore the reinforcing role of geosynthetics under complex loading.

As shown in Figure 1, the initial stages — including sample preparation, basic characterization, compaction (stage 3), hydraulic conductivity (stage 3), and confined compression (stage 4) — were conducted by Fiedler et al. (2025) for sludge incorporation levels of 0% (pure soil), 2.5%, and 5%.

The proportions were defined on a dry-mass basis, with sludge incorporated without pretreatment to preserve its characteristics, reduce processing, and valorize a by-product, in line with sustainable engineering practices. Fiedler et al. (2025) focused on low sludge contents, contrasting with studies reporting 15 – 100% incorporation (Montalvan, 2016; Gonçalves et al., 2017). To expand the database, additional levels of 7.5% and 10% were introduced (92.5% and 90% soil, respectively). Pure sludge (100%) was also tested in confined compression and direct shear to identify intrinsic mechanical properties and provide reference values for comparison.

The sludge samples were the same used by Fiedler et al. (2025), collected at the Iraí Water Treatment Plant in Pinhais, Paraná, operated by SANEPAR. This plant uses a flotation-filtration process including flotation, coagulation, flocculation, filtration, disinfection, pH adjustment, and chlorination, generating chemically conditioned sludge with stable properties for laboratory use. Soil samples came from the Ponta Grossa Geotechnical Experimental Field (Campos Gerais, Paraná), a recognized site for geotechnical research. According to Anibele et al. (2020), Pereira & Vargas (2019), and Tonus et al. (2022), this soil is mainly silty clayey, with intermediate plasticity and moderate permeability, serving as the basis for mixture design.

Compaction followed NBR 7182 (ABNT, 2016) using the standard Proctor method to determine maximum dry unit weight and optimum moisture content. Hydraulic conductivity was measured by NBR 14545 (ABNT, 2021) with a rigid-wall permeameter. Pure sludge could not be compacted due to its semi-solid consistency, which prevented standardized molding. For confined compression and direct shear, smaller specimens were prepared by progressively inserting sludge into molds and tamping until refusal (no further material could be added).

Confined compression tests followed NBR 16853 (ABNT, 2020) using incremental loading. Two preload,

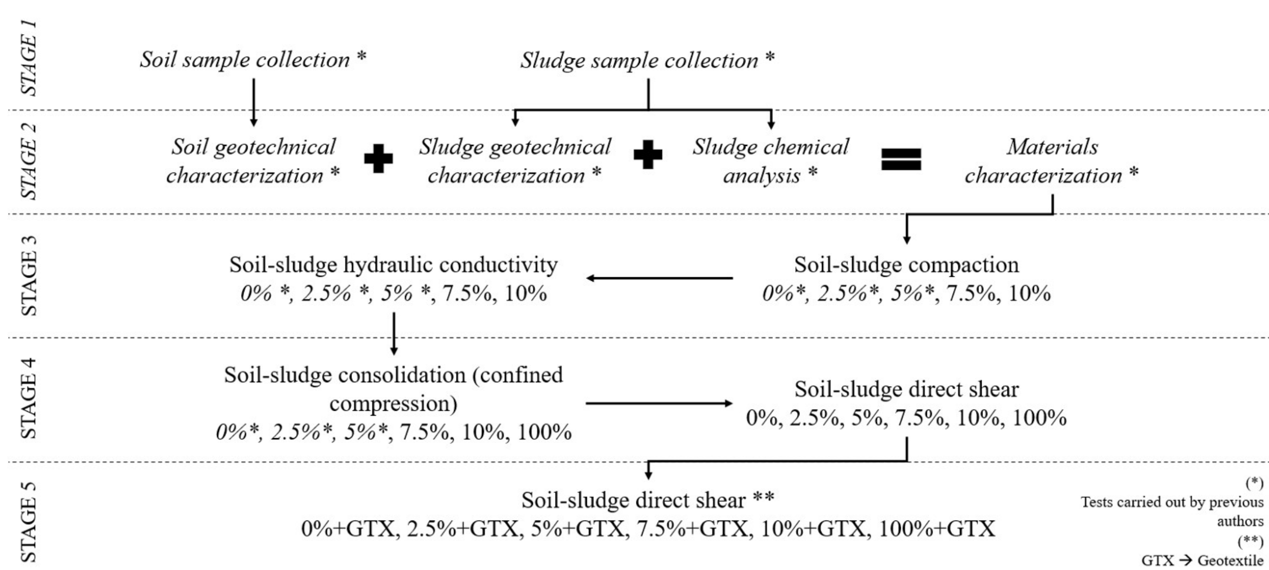

Figure 1. Research flowchart.

six load, and three unload stages were applied, with stress values summarized in Table 1. The maximum stress matched that of Fiedler et al. (2025), justified by expected surcharge conditions in sanitary landfills.

The direct shear tests followed the procedures outlined in ASTM D3080M (ASTM, 2023), employing three levels of normal stress (50 kPa, 250 kPa, and 300 kPa) and displacement-controlled shearing to evaluate the peak and residual shear strength of the specimens, both with and without geotextile reinforcement, using a square shear box with dimensions of 60 mm × 60 mm and a height of 20 mm.

Regarding the geosynthetic component of the study, a nonwoven geotextile made of polyester fibers was selected. This geotextile featured an apparent opening size (O95) of 0.102 mm, a property that plays a crucial role in the filtration and drainage performance of the material. Each geotextile specimen was cut to precisely match the internal dimensions of the compaction molds and shear boxes, thereby ensuring adequate contact with the surrounding soil and proper alignment along the anticipated failure plane. This careful placement was essential to assess the geotextile's effectiveness in modifying the shear resistance of the composite specimens and minimizing variability during testing.

Table 1. Loads applied in the consolidation test stages.

Step	Stage	Applied load (kPa)
Preload	1º	2
	2º	5
Load	1º	12
	2º	25
	3º	50
	4º	100
	5º	200
	6º	400
Unloading	1º	200
	2º	50
	3º	12

3. Analysis and results

As stated in the methodology, the initial characterization of soil and sludge is summarized in Table 2. These data, obtained from Anibele et al. (2020) and Fiedler et al. (2025), derive from geotechnical, chemical, and mineralogical analyses of samples collected from the same sites used in this study. This baseline information establishes the physical and compositional properties of the materials, serving as a reference for interpreting their behavior in composite mixtures.

Compaction tests were performed for mixtures with 7.5% and 10% sludge by dry mass to determine maximum dry unit weight and optimum moisture content using the Proctor method (NBR 7182, ABNT, 2016). Table 3 compiles these results together with those previously published by Fiedler et al. (2025) for natural soil and sludge. For clarity and consistency, the data were reorganized and presented in Figure 2 (Almeida et al., 2024a), allowing direct comparison among all compositions.

The compaction curve for pure sludge is absent from Figure 2 due to its semi-solid consistency. As explained in the methodology, its high-water content and cohesive nature prevented molding and compaction under standardized procedures. Consequently, reliable compaction parameters for sludge alone could not be obtained using conventional methods.

As noted by Fiedler et al. (2025), progressively adding untreated sludge to the soil matrix significantly affected the position and shape of the compaction curves. This trend, evident in Figure 2 and Figure 3, shows a systematic shift with increasing sludge content: optimum moisture content

Table 2. Material characterization results.

Variable	Test	Result	Reference
Soil	Specific gravity values of the grains (kN/m³)	26.3 – 28.5	Anibele et al. (2020)
	Liquid limit (%)	32 – 43	
	Plasticity index	Non plastic	
Sludge	Moisture content (%)	342.87	Fiedler et al. (2025)
	Specific gravity values of the grains (kN/m³)	20.51 – 21.10	
	Organic matter content (%)	51.72	
	Liquid limit (raw samples) (%)	487	
	Plasticity index (raw samples) (%)	95	
	Unified Soil Classification System (SUCS)	OH – Organic clay	

Table 3. Results of compaction and hydraulic conductivity tests on soil and soil-sludge mixtures.

Variable	Sample evaluated				
	Pure Soil	**Soil-Sludge 2.5%**	**Soil-Sludge 5%**	**Soil-Sludge 7.5%**	**Soil-Sludge 10%**
Optimum moisture (%)	24.6	28.2	34.2	39.80	46.30
Maximum apparent dry unit weight (kN/m³)	14.98	14.28	13.05	12.21	10.79
Hydraulic conductivity (m/s)	8.5×10^{-8}	2.8×10^{-8}	4.9×10^{-9}	3.7×10^{-9}	8.6×10^{-9}
Void ratio	0.78	0.86	1.04	1.18	1.46
Porosity (%)	44	46	51	54	59

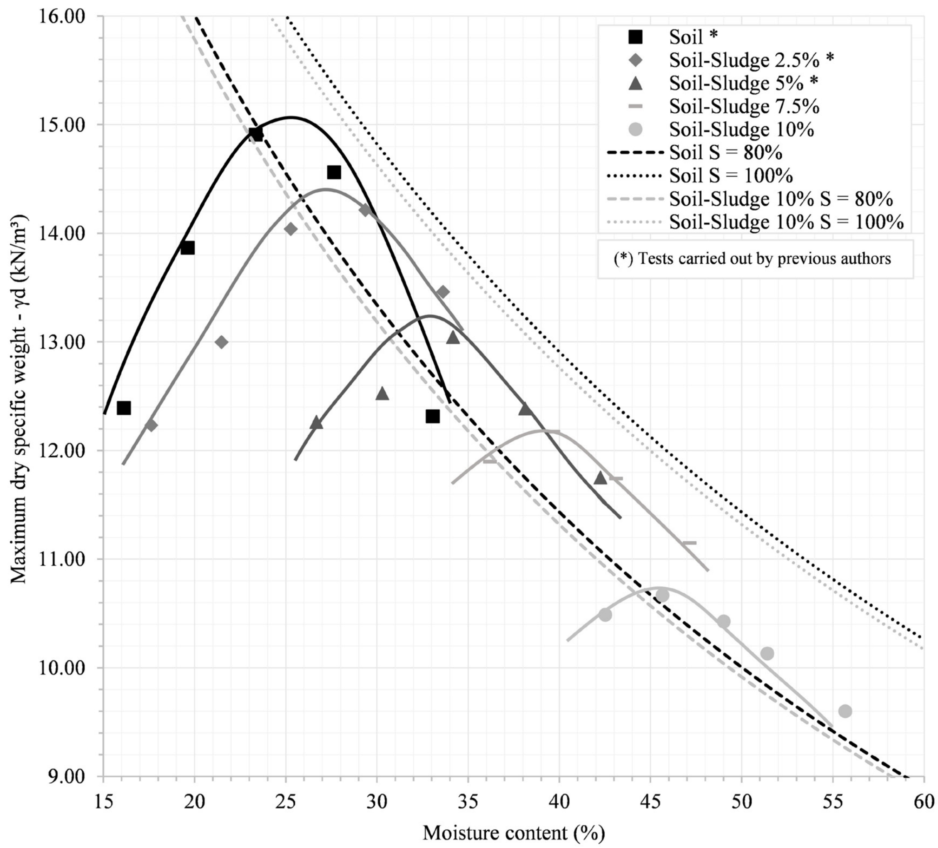

Figure 2. Moisture–density curves of the specimens.

rises while maximum dry unit weight decreases. This behavior is consistent with Montalvan (2016) and other studies.

The higher moisture content results from the sludge's natural water, which adds free water before compaction. The reduction in dry unit weight reflects both the lower specific gravity of the sludge and its fine-grained particle size, which limits particle rearrangement during compaction (Fiedler et al., 2025). These findings underscore the importance of accounting for the intrinsic characteristics of WTS when designing soil-sludge mixtures for geotechnical use.

In the hydraulic conductivity test, specimen preparation followed the maximum dry unit weight and optimum moisture content obtained from compaction tests. These parameters provided reference conditions for molding and ensured consistency among mixtures.

The results of Fiedler et al. (2025) for 0%, 2.5%, and 5% sludge incorporation were combined with the new data for 7.5% and 10%. The consolidated dataset, presented in Table 3, offers an overview of hydraulic conductivity behavior across sludge contents.

The experiments revealed a clear trend: hydraulic conductivity decreased progressively with higher sludge content. This behavior reflects the intrinsic properties of untreated sludge, which contains abundant fine particles.

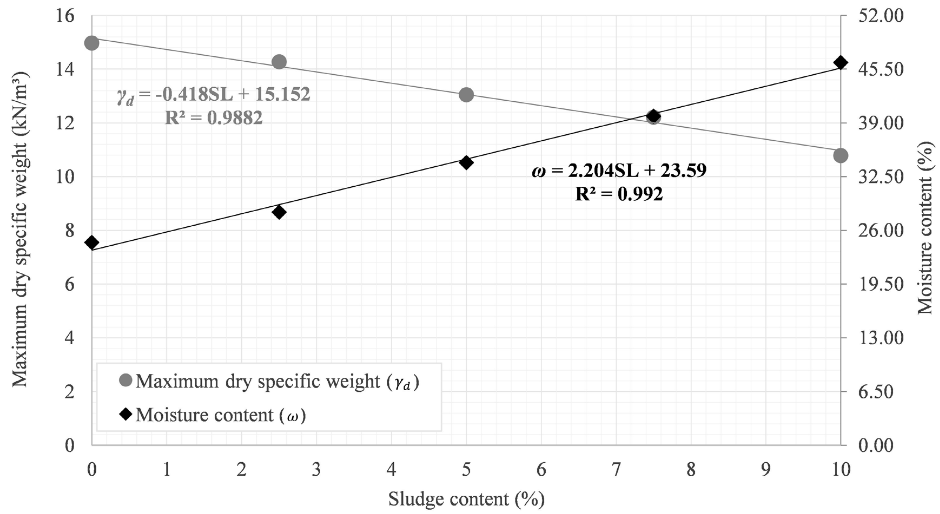

Figure 3. Values of maximum dry specific weight and optimum moisture content as a function of WTP sludge incorporation.

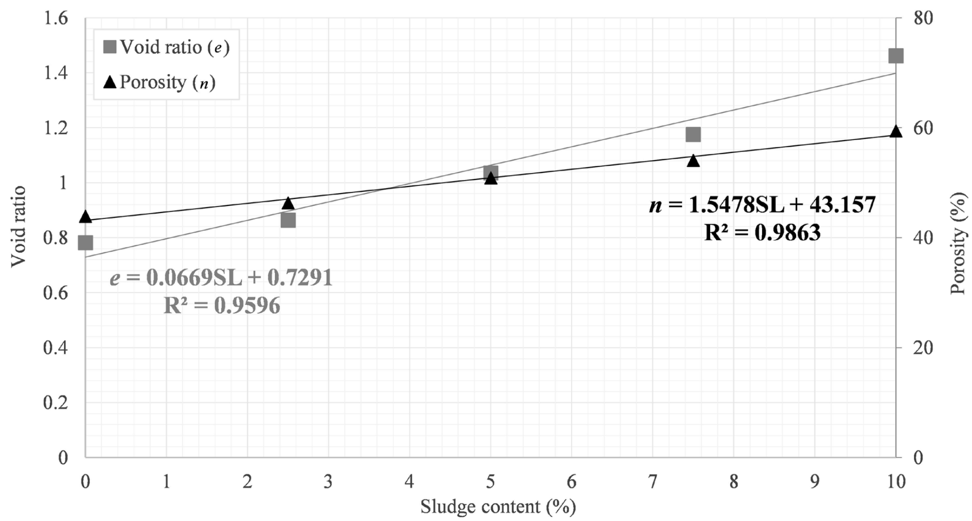

Figure 4. Void ratio and porosity values as a function of WTP sludge incorporation.

These fines fill soil voids, reducing interconnected porosity and impeding water flow. Sludge is also classified as an organic clay (Fiedler et al., 2025), a material known for low permeability due to fine granulometry, high plasticity, and organic matter.

The reduction in conductivity indicates that soil-sludge mixtures can be less permeable than pure soil. This characteristic is advantageous in geotechnical and geoenvironmental applications such as landfill liners, where low permeability minimizes leachate migration. The results reinforce the potential of soil-sludge mixtures in engineered barriers.

Figure 4 shows that increasing sludge content in the mixtures produced proportional rises in void ratio and porosity. This trend reflects the reduction in maximum dry unit weight of sludge-containing mixtures, consistently lower than pure soil. The lower specific gravity and fine texture of untreated sludge led to looser particle packing during compaction, increasing the void volume of the compacted mass.

The linear increase in void ratio and porosity is technically coherent and consistent with the material composition and compaction behavior. A similar trend was found for optimum moisture content, which also rose with sludge addition due to the higher water retention capacity of sludge, related to its organic matter and finer granulometry. Together, these factors reduce dry density and enlarge void volume.

This behavior underscores the influence of sludge properties on compaction. The increase in porosity and void ratio reflects soil-sludge particle interactions and may affect both hydraulic and mechanical performance. These findings are particularly relevant to landfill liners or other low-permeability layers, where controlling porosity is essential for barrier effectiveness and long-term stability.

The confined compression test was conducted on compacted specimens of pure soil, soil-sludge mixtures with varying sludge contents, and pure sludge. All specimens were compacted directly within the 50.5 mm × 20 mm consolidation ring to ensure proper fit and minimize disturbance. Each was prepared under controlled mass conditions to achieve its maximum dry unit weight, except for pure sludge, which was tested untreated. This approach standardized boundary conditions across tests, enhancing result comparability.

Consolidation curves were generated for the 7.5% and 10% mixtures and the 100% sludge sample. These were integrated with curves from Fiedler et al. (2025) for pure soil, 2.5%, and 5% mixtures, enabling comparative analysis across a broader range of sludge contents and clearer identification of compressibility trends.

Compiled by Almeida et al. (2024b) from the present and previous results, Figure 5 compares consolidation curves for pure soil and mixtures with 2.5%, 5%, 7.5%, and 10% sludge, as well as pure sludge. The figure highlights increasing void ratios with higher sludge content, reflecting greater compressibility. Notably, the curve for pure sludge provides insight into the intrinsic compressibility of untreated waste, serving as a reference for understanding its mechanical influence when incorporated into soil mixtures.

Following the methodology of Fiedler et al. (2025), the compression (Cc) and recompression (Cr) indexes were determined for the studied materials. The results are presented in Table 4 and illustrated in Figure 6. This consistency ensures comparability between datasets and reinforces the reliability of the parameters, which are essential for evaluating the compressibility of soil-sludge mixtures under geotechnical loading conditions.

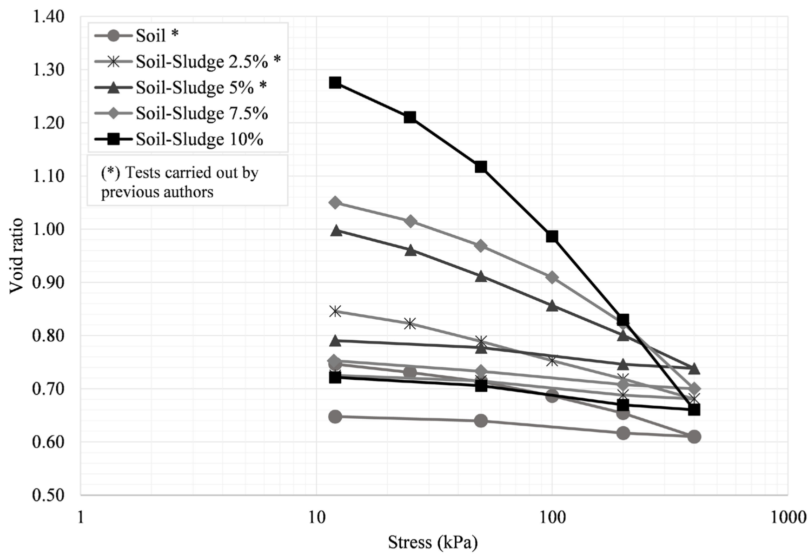

Figure 5. Consolidation curves - Soil and soil-sludge mixtures.

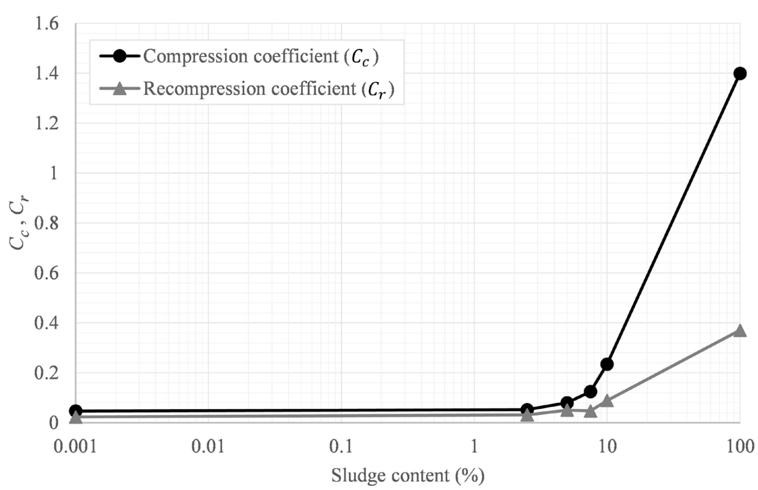

Figure 6. Comparison of compression and recompression indices for soil and soil-sludge mixtures.

Table 4. Evolution and recompression index of soil, sludge, and soil-sludge sample.

Sample	Compression coefficient (C_c)	Recompression coefficient (C_r)
Soil	0.05	0.02
Soil-Sludge 2,5%	0.05	0.03
Soil-Sludge 5%	0.08	0.05
Soil-Sludge 7,5%	0.12	0.05
Soil-Sludge 10%	0.23	0.09
Raw Sludge	1.40	0.37

In Figure 6, the C_c and C_r values for pure soil were plotted at 0.001% sludge content only to make them visible, not to indicate actual incorporation. As pure soil results closely matched the 2.5% mixture, this positioning does not affect interpretation.

Compression and recompression indexes were consistently higher in mixtures containing sludge than in pure soil, confirming the high compressibility of raw sludge (Boscov et al., 2021). Its inclusion reduces soil matrix stiffness, producing greater deformation under load. Such compressibility is a drawback for landfill layers, where long-term integrity and geometry must be preserved. Excessive settlement can compromise barrier functions such as impermeability and stability (Fiedler et al., 2025). Thus, controlling compressibility is essential when considering sludge in geotechnical projects.

Direct shear tests were performed on soil, mixtures, and pure sludge, with and without geotextile reinforcement, under normal stresses of 50, 200, and 350 kPa, to evaluate shear strength under increasing confinement and the geotextile's reinforcing effect. Shear stress–displacement curves were obtained for each specimen, and Mohr–Coulomb envelopes constructed under drained conditions. To assess strain influence, envelopes were built for displacement thresholds of 5, 10, and 15 mm (8.33%, 16.67%, and 25% horizontal strain; Figure 7). This multi-criterion approach identified the most representative failure condition for each material, with and without geosynthetics.

The soil matrix showed distinct envelopes depending on the adopted criterion. With higher sludge contents, however, envelopes converged, particularly at 50 kPa confinement. For individual samples, this convergence produced lower friction angles as the criterion shifted to higher strains, indicating that at low confinement shear strength depends more on sludge content than on the criterion itself. As summarized in Table 5, both cohesion intercept and friction angle vary accordingly. It is important to note that the high strength parameters reported correspond to compacted specimens under controlled laboratory conditions and should not be extrapolated to undisturbed samples.

Under the 25% horizontal deformation criterion, the cohesion intercept decreased once sludge content exceeded 2.5%, though the trend was non-linear, as the 7.5% mixture showed higher cohesion than the 5% mixture.

Friction angle results were more consistent across deformation thresholds. The largest standard deviation (4.5°) occurred for the 5% mixture, with values of 29° at 8.33% deformation, 34° at 16.67%, and 38° at 25%. This dispersion highlights the greater sensitivity of this composition to the deformation limit. In general, friction angle increased slightly with deformation, consistent with Mohr–Coulomb envelopes fitted at higher strains.

With respect to sludge content, mixtures presented a range of friction angles, some exceeding that of pure soil, a favorable outcome for landfill barriers or structural fills, provided deformation criteria are carefully defined.

Accordingly, the 25% horizontal deformation threshold was adopted as the failure criterion for all specimens (pure soil, pure sludge, and soil-sludge mixtures without reinforcement), as this displacement limit encompasses all samples and isolates the influence of sludge in the interpretation of results. The resulting envelopes were compared with those reported by Boscov et al. (2021) (Figure 8), which compile a broader database of Brazilian soils and soil-sludge mixtures from the Taiçupeba and Cubatão plants (São Paulo), enabling direct contextualization of the present results.

Figure 8 shows that raw sludge behaved similarly to soils from the referenced database under confining stresses above 150 kPa. The soil-sludge mixtures produced in this study, along with the pure soil sample, exhibited higher shear strength than those reported previously. Among them, the pure soil and the 10% mixture showed the closest friction angle to the clayey soil-sludge blends from Campinas with WTS from the Cubatão plant.

For the geotextile-reinforced samples, shear strength envelopes corresponding to the 25% horizontal strain failure criterion are presented in Figure 9, with the associated parameters summarized in Table 6.

Geotextile-reinforced specimens showed the same non-linear variation in cohesion intercept and friction angle as non-reinforced ones, preventing the establishment of a consistent trend between sludge content and shear parameters. Cohesion values for soil + GTX and sludge + GTX were similar, while friction angles diverged considerably, indicating distinct behavior. Although cohesion tended to decrease with higher sludge content, the similarity between mixtures suggests that refining the mixing methodology could improve sample uniformity and interaction.

Direct shear tests with reinforced specimens considered the practical role of nonwoven geotextiles in landfill protection layers. Accordingly, the filtration opening size (O95) of the geotextile was compared to the particle size distributions of soil and sludge (Figure 10). Soil contained only a small fraction finer than O95 (0.102 mm, green line), whereas most sludge particles were below this limit. Yet, due to its fine content and flocculated structure, sludge did not infiltrate the fabric, instead sliding over the surface during shearing. The combination with silty clayey soil from the Ponta Grossa Experimental Site may have favored better interaction with the GTX.

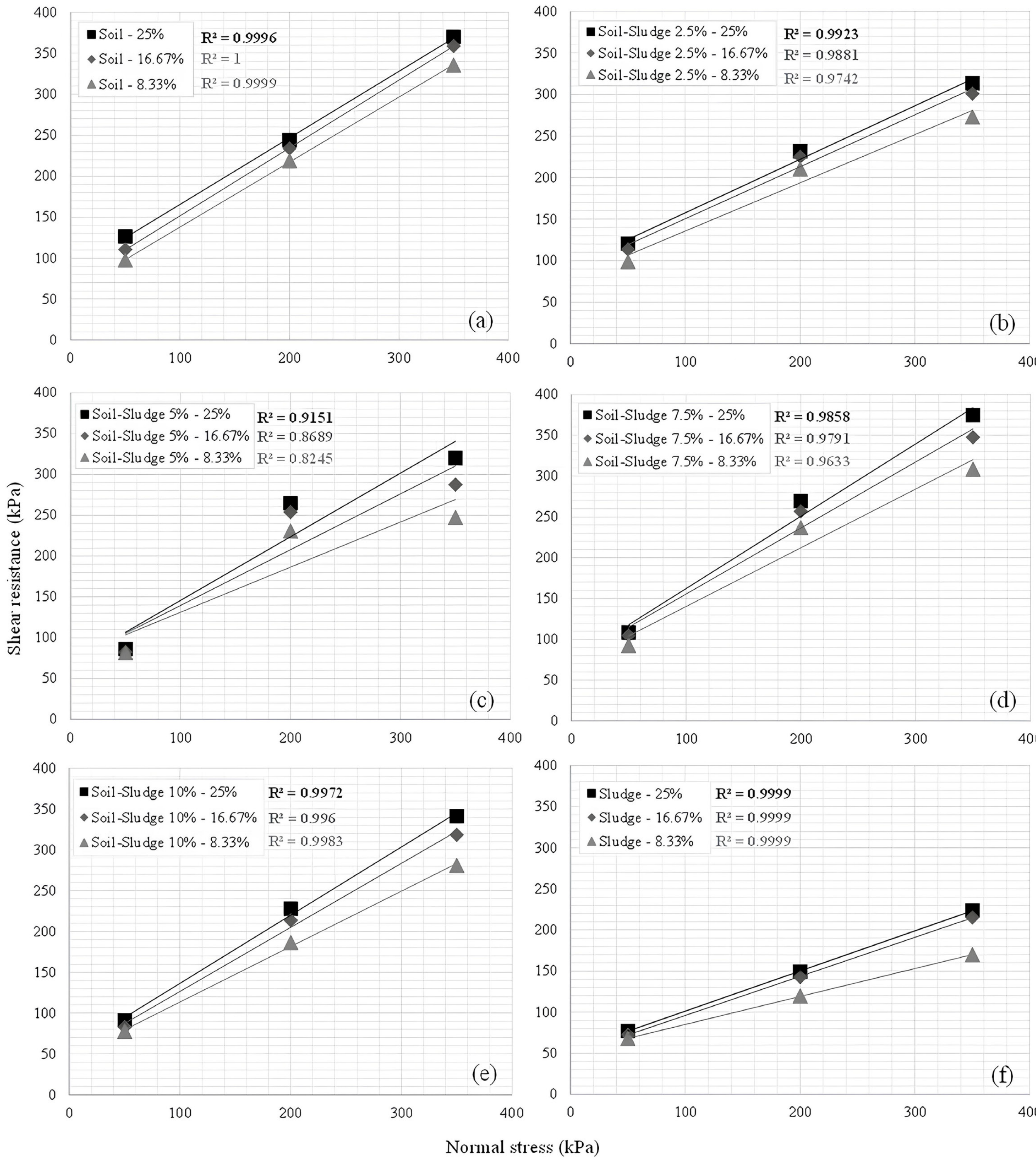

Figure 7. Comparison between failure criteria for different specimens: (a) Soil; (b) Soil-Sludge 2.5%; (c) Soil-Sludge 5%; (d) Soil-Sludge 7.5%; (e) Soil-Sludge 10%; (f) Sludge.

Friction angle trends mirrored those of non-reinforced specimens, with values both above and below pure soil. Most reinforced samples, however, showed higher friction angles than their non-reinforced counterparts at the same sludge contents. This improvement reflects the reinforcing role of the geotextile, whose fibrous structure enhanced matrix integration. Soil-sludge grains appeared to bond with the nonwoven fabric, producing a fiber-like interaction that increased shear resistance, consistent with the O95 analysis.

Table 5. Cohesion intercept and friction angle results – samples without geosynthetic.

Sample	Cohesion intercept (kPa)	Friction angle (º)	R^2
Horizontal deformation – 8.33%			
Soil	58	38	0.9999
Soil-Sludge 2.5%	78	30	0.9742
Soil-Sludge 5%	76	29	0.8245
Soil-Sludge 7.5%	68	36	0.9633
Soil-Sludge 10%	46	34	0.9983
Sludge	51	19	0.9999
Horizontal deformation – 16.67%			
Soil	69	40	1.000
Soil-Sludge 2.5%	88	32	0.9881
Soil-Sludge 5%	71	34	0.8689
Soil-Sludge 7.5%	74	39	0.9791
Soil-Sludge 10%	48	38	0.9960
Sludge	49	26	0.9999
Horizontal deformation – 25%			
Soil	84	39	0.9996
Soil-Sludge 2.5%	93	33	0.9923
Soil-Sludge 5%	68	38	0.9151
Soil-Sludge 7.5%	73	42	0.9858
Soil-Sludge 10%	53	40	0.9972
Sludge	52	26	0.9999

Table 6. Cohesion intercept and friction angle results – samples with geosynthetic.

Sample	Cohesion intercept (kPa)	Friction angle (º)	R^2
Horizontal deformation – 25%			
Soil + GTX	33	42	0.9895
Soil-Sludge 2.5% + GTX	30	37	0.9679
Soil-Sludge 5% + GTX	12	46	0.9979
Soil-Sludge 7.5% + GTX	26	42	0.9801
Soil-Sludge 10% + GTX	7	45	0.9984
Sludge + GTX	32	37	0.9699

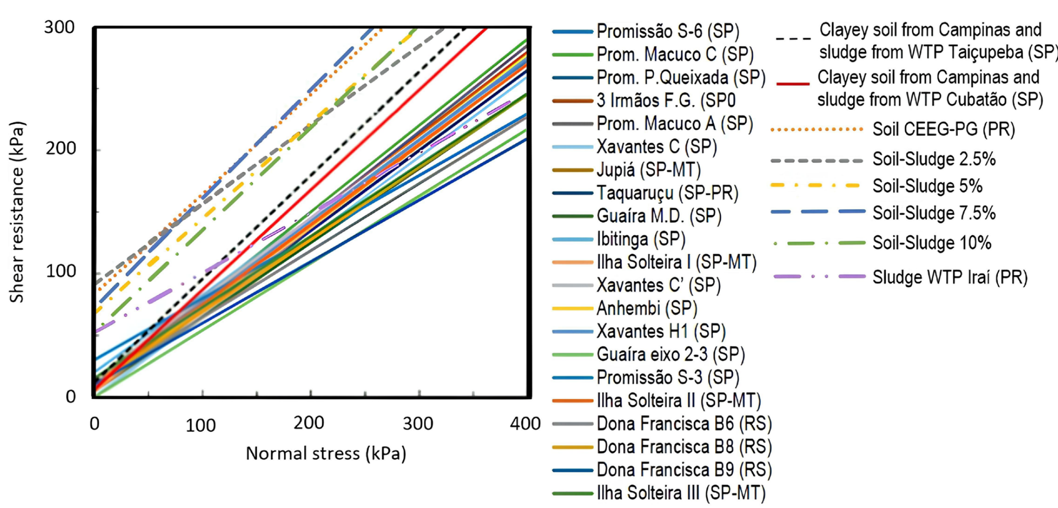

Figure 8. Comparison of shear strength of soil-sludge samples under drained conditions.

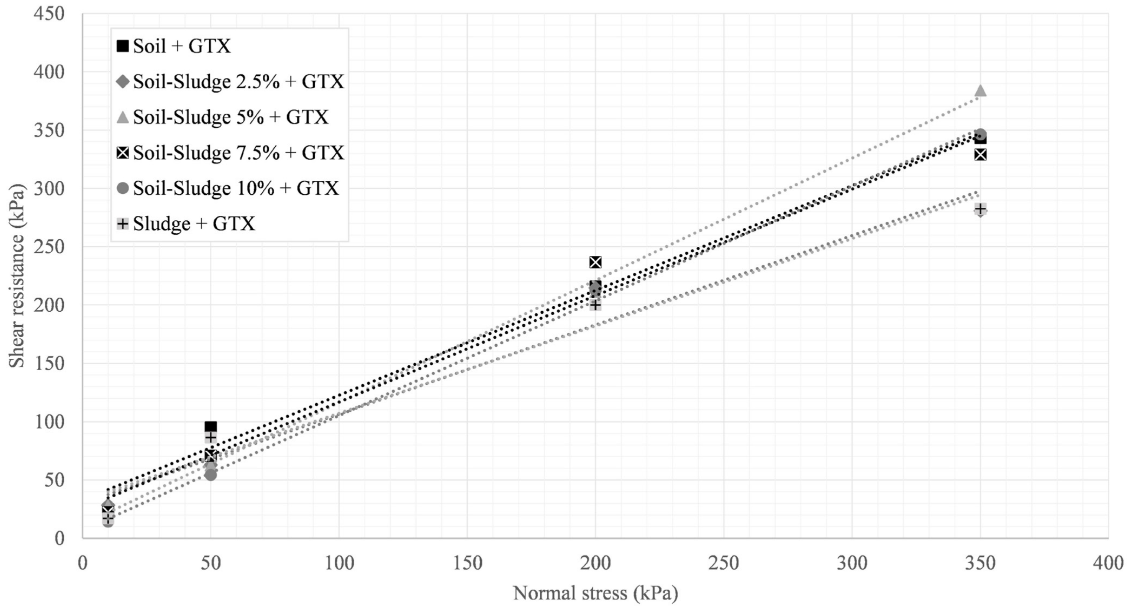

Figure 9. Geotextile – Failure envelope at 25% horizontal strain.

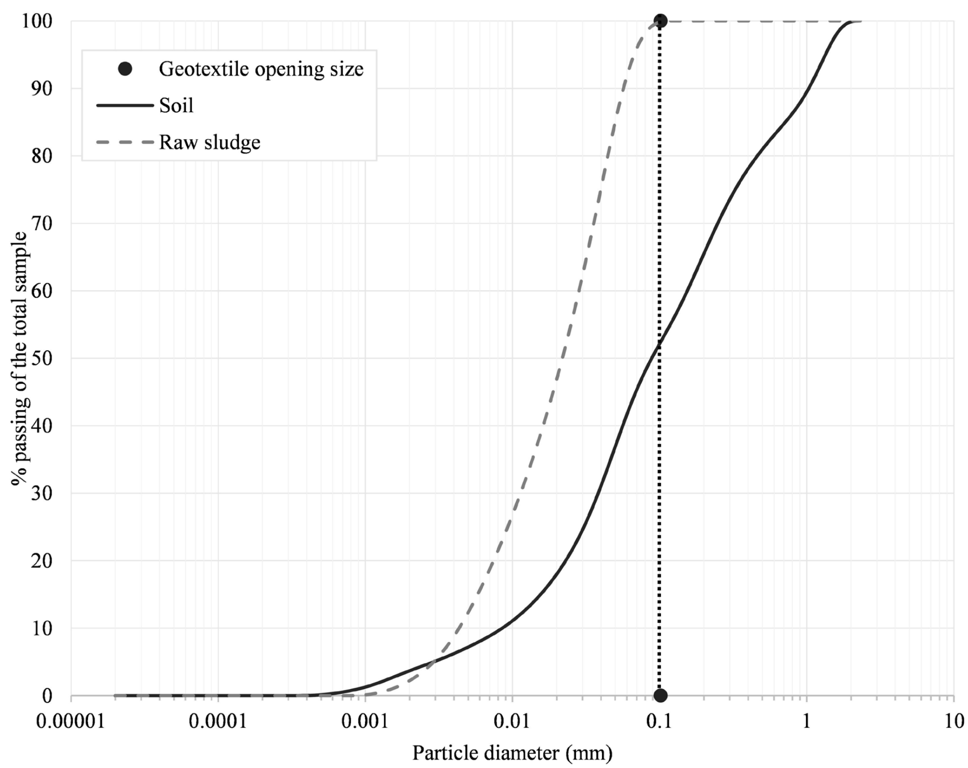

Figure 10. Comparison between the geotextile's filtration opening size and the particle size distribution of the samples.

4. Conclusion

Based on the findings, water treatment sludge (WTS) shows significant potential for incorporation into soil mixtures for sanitary landfill applications, particularly when combined with geosynthetics.

Its semi-solid nature hindered compaction and, consequently, specimen preparation for hydraulic conductivity tests. It also affected confined compression and direct shear. Nonetheless, when incorporated in moderate amounts (up to 10%), WTS contributes to sustainability by reusing a material often improperly discarded. Even when disposed of in landfills, untreated WTS may present cohesion intercept and friction angle values less favorable than those of municipal solid waste (MSW), potentially affecting stability.

Although WTS alone exhibits higher compressibility and lower shear strength, its use in combination with soil for base layers, intermediate covers, and daily cover systems conserves natural resources, reduces landfill volume, and does not degrade average strength parameters of the waste mass. This benefit was most evident at 7.5% incorporation, the highest rate at which strength remained close to that of pure soil.

Despite limitations of sludge properties, geosynthetics can mitigate some drawbacks. Geotextiles improved shear strength under higher stress levels, expanding potential applications of WTS in landfill engineering.

Finally, the variability of WTS properties, influenced by raw water origin and quality, underscores the need for site-specific characterization to ensure performance. Overall, soil-sludge mixtures reinforced with geosynthetics represent a practical, viable solution for WTS valorization, enabling reuse without prior treatment and promoting environmental sustainability in infrastructure development.

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Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the contents of the paper and there is no financial interest to report.

Authors' contributions

Maitê Milléo Almeida: conceptualization, data curation, visualization, investigation, writing – original draft. Daiana Tatiele Fiedler: conceptualization, data curation, visualization, investigation, writing – original draft. Ingrid Leticia Andrusczak: data curation, visualization, investigation. Bianca Penteado de Almeida Tonus: formal analysis, funding acquisition, investigation, methodology, project administration, resources, software, supervision, validation, writing – review & editing. Carlos Emmanuel Ribeiro Lautenschläger: formal analysis, funding acquisition, investigation, methodology, project administration, resources, software, supervision, validation, writing – review & editing.

Data availability

The datasets generated and analyzed in the course of the current study are available from the corresponding author upon request.

Declaration of use of generative artificial intelligence

This work was prepared with the assistance of generative artificial intelligence (GenAI), specifically OpenAI's ChatGPT, with the aim of enhancing the clarity, fluency, and cohesion of the English writing. GenAI was used primarily to support the translation of technical content from Portuguese to academic English, as well as to refine grammar and terminology in accordance with scientific writing standards. The entire process of using this tool was supervised, reviewed, and when necessary, edited by the authors. The authors assume full responsibility for the content of the publication that involved the aid of GenAI.

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