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Beneficial Use of Water Treatment Sludge with Stabilizers for Application in Road Pavements

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Abstract: Water treatment sludge (WTS) is the residue produced during water treatment processes for public use. Exploring the reintroduction of these wastes into the production chain to generate new, value-added materials presents a current challenge. This could promote their reuse and reduce the negative environmental impacts associated with their disposal. This study assessed the technical feasibility of using aluminum-based WTS to partially replace silty sand soil in mixtures that include two stabilizers (hydrated lime and Portland cement), potentially for use in road pavements. After conducting a thorough physical, chemical, and geotechnical characterization of both the soil and the sludge, bench-scale experiments were carried out to test the mixtures' resistance, with WTS proportions of 5%, 8%, 10%, 15%, and 20%, stabilized with either lime or cement. The findings confirm that WTS does not contain potentially toxic elements, according to Brazilian standards, and all tested composites appear suitable for paving. However, the mechanical resistance of the soil–sludge–cement mixtures decreases as the WTS content increases, with an optimum California bearing ratio (CBR) of 41.50% achieved at a 5% WTS addition. Meanwhile, incorporating 15% WTS into soil–sludge–lime mixtures resulted in the highest CBR value of 21.25% for this type of mixture. It is concluded that incorporating stabilizers into soil–WTPS mixtures for road construction allows for an increased percentage of WTPS in silty-sandy soils. Further studies are recommended with different soil types and the addition of fibers to the mixes, to assess the long-term performance of the structure, along with economic and environmental analyses.

Keywords: water treatment sludge; cement; lime; stabilizing materials; geotechnical characterization

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1. Introduction

The global demand for drinking water is increasing daily due to continuous population growth [1]. Water intended for potabilization and public supply carries impurities such as sand, mud, clay, nutrients, humic substances, and other contaminants resulting from surface runoff and the discharge of effluents from urban and industrial sources [2]. The treatment of raw water produces residual by-products during the decantation and filtration stages, known as water treatment sludge (WTS). This residue contains impurities removed from the raw water, along with chemicals used in the water treatment processes [3], and polymers utilized in dewatering [4]. Undried WTS consists of over 97% water and primarily includes soil particles (sand, silt, and clay), organic material, nutrients, algae, bacteria, and viruses [5]. Heavy metals such as arsenic and chromium have exhibited increased concentrations in WTS in recent years [6]. Iron- and aluminum-based salts, which are normally used as coagulants for water purification because they help in the effective precipitation of water impurities, are colored inorganic elements of the outflowing WTS. Therefore, in general, these residues are called iron sludge and aluminum sludge [4].

In Brazil, WTS is classified as a non-toxic waste [7]. However, there is growing global environmental concern that calls for more detailed studies to accurately characterize WTS. This will ensure that management practices are conducted in an environmentally safe and sustainable manner [8]. The challenge of reintroducing materials into the production chain of new waste-based materials lies in finding ways to utilize previously discarded materials at the lowest possible cost, without harming the environment, specifically through the contamination of soil and water [9].

The beneficial use of WTS has already been discussed in the literature [1,3,8]. WTS application has been studied as an adsorbent for the removal of pollutants such as cadmium [10], nitrogen [11], hydrogen sulfide [12], organic matter [13], phosphorus [14], molybdenum [15], turbidity and color [16], and heavy metals [17]. WTS has been efficiently used for the removal of color from textile wastewaters [18] and to treat oil industry wastewaters [19]. Studies have reported the feasibility of recovering coagulants present in WTS [16,20], their potential for application in agricultural land [6], potential soil amendment for native plants [21], increasing methanogenic activity in the digestion of primary domestic wastewater sludge [13], and in the remediation of impacted ecosystems [22]. In civil and geotechnical engineering, several studies have been carried out on the partial replacement of natural materials by WTS, to produce bricks [23–26], additional cementitious material [27], tiles [28], earthworks [5], and concrete [29–32]. Table 1 summarizes WTS for geotechnical applications.

Table 1. Main studies on the use of WTS in geotechnical applications.

Mixing Components with WTS	Type of Sludge Aluminum/ Iron (A/I)	Pre-Treatment of Sludge	Evaluated WTS Incorporation Percentages (%)	Percentage of Most Suitable WTS (%)	Use for Geotechnical Applications	Reference
Clayey sand soil and sandy soil	A and I	Drying in thermal equipment (150 to 180 °C)	25; 50	25 e 50	Embankment	[4]
Sandy soil	I	N.S.	2; 4; 6; 8; 10; 12; 14; 16; 18; 20; 22	18	N.S.	[33]
Clayey soil	A	N.S.	2; 4; 6; 8; 10	8	Road infrastructure	[34]
Clayey sand soil, clayey soil, hydrated lime and granite–gneiss rock powder	A and I	N.S.	3.4; 4.2; 4.5; 5.6; 5.7; 7.0; 7.4; 7.5; 8.5; 9.3; 10.0; 11.3; 13.9; 14.3; 20.0; 22.2; 25.0; 28.6	7.4	Daily and intermediate covers of waste landfills, and other applications with low soliciting stresses	[35]
Collapsing soil	N.S.	Oven drying at 105 °C	4; 8; 12; 16	10	Road construction	[36]
Sandy silt	Al	N.S:	5; 10; 15; 20	15	Liner material	[37]
Clayey soil	I	Oven drying at 105 °C	2; 4; 6; 8; 10; 12	10	Construction of roads, particularly with lower-traffic loads, lowered airfields, and non-structural applications, such as subfloors, blocks, non-load bearing walls, sidewalks, and residential floors	[38]

A: aluminum; I: iron; N.S: not specified.

Studies conducted to date indicate significant scientific gaps in research on the use of WTS) for geotechnical applications. Specifically:

- Few studies have evaluated the replacement of soil with sludge in combination with stabilizing materials;
- Most research is limited to a single material, restricting analysis to comparisons between mixtures;
- Many studies lack standardization or specifications for the pre-treatment of incorporated WTS;
- There is no specific legislation governing the use of sludge.

The highest incorporation percentages were reported by Fiore et al. [4], who used post-thermal-treated WTS without stabilizers, with their evaluation confined to clayey sand and clayey soil. This highlights the need for new assessments of WTS utilization under similar conditions across different soil types and with the inclusion of stabilizers.

Soil stabilization involves enhancing its performance by adding binders, typically cement or lime, to improve granulometry, density, and resistance aspects [39]. The selection of a stabilizing method depends on various factors, including the types and gradations of soil and aggregates, the specific geotechnical layer requiring stabilization, the extent of soil property enhancement desired, prevailing climatic conditions, and soil conditions [40]. Portland cement may play an important role in binding soil particles together, effectively improving compaction, cohesion, strength, compressibility, workability, and swell potential [41], especially for granular and sandy soils [40]. Lime is a low-cost soil stabilizer and is more affordable compared to cement, also bringing the benefit of chemically transforming expansive and unhealthy soils into structurally stable materials for foundations [42].

This study aimed to evaluate the technical feasibility of using mixtures of aluminum-based WTS, hydrated lime, and Portland cement as a partial replacement for silty-sandy soil for the construction of road pavements. The association of the three materials with silty-sandy soil for use as road bases has not previously been studied, thus constituting the novelty of the work.

2. Materials and Methods

The experimental method employed a mixed methods approach [43], following the scheme illustrated in Figure 1.

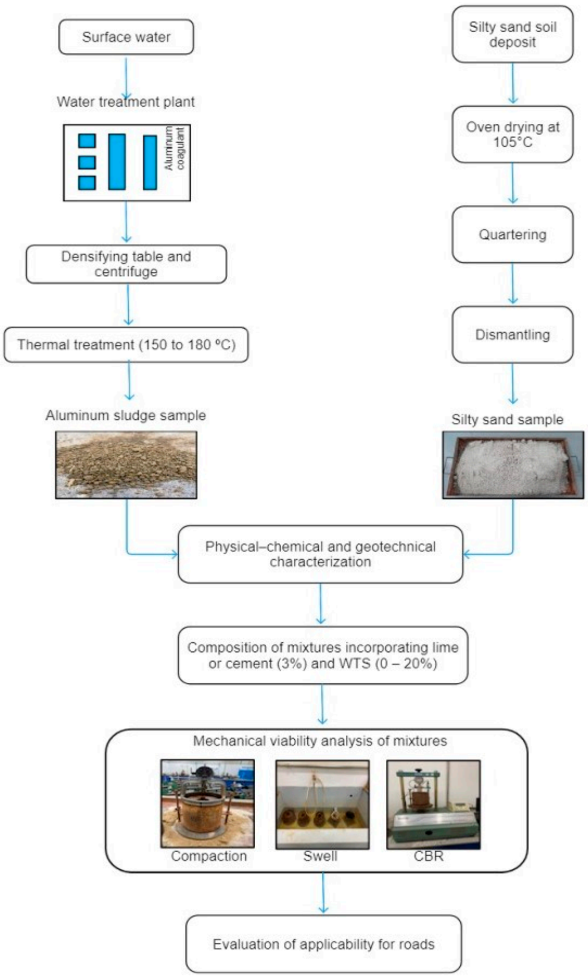


Figure 1. Scheme of the experimental research.

2.1. Sample Collection and Preparation

The sampling for collecting WTS followed Brazilian standard NBR 10007 [44]. WTS was generated during the decanting and filter-washing steps of a water treatment plant (WTP) located in the state of São Paulo (Brazil). The WTP produces approximately 15 m^3/s of drinking water [45], comprising the following processes: coagulation, flocculation, decantation, filtration, disinfection, fluoridation, and pH correction. During the sample collection period, the WTP used aluminum coagulants (aluminum sulfate or aluminum polychloride); therefore, the residue was named aluminum sludge. The solids content of the WTS was elevated through the utilization of dewatering tables and centrifuges, necessitating the supplementary use of cationic polymers (polyacrylamide). Following dewatering, the moisture content of the WTS was adjusted to meet the destination conditions using industrial thermal equipment, operating within the temperature range of 150 to 180 °C, as outlined by Silva et al. [46]. The Brazilian standard NBR 10007 [44] was employed for obtaining and collecting the sample.

Silty sand soil samples were obtained from a deposit located in the municipality of Cubatão, state of São Paulo (Brazil). In the laboratory, soil was dried in an oven at 105 °C, quartered, and crushed to achieve homogenization. Samples were then obtained, sieved (⌀ 4.76 mm), and stored until testing. The experimental procedure involved using CP-II Portland cement and CH-III hydrated lime as stabilizing materials for mechanical analysis of the mixtures.

2.2. Analysis Methods

The soil and the WTS underwent physical, chemical, and geotechnical characterization to prepare nine different mixtures. Both materials were characterized using methods established by Brazilian and international standards, as outlined below.

2.2.1. Physical and Chemical Characterization

The physical and chemical characteristics of the soil and WTS samples were assessed in terms of gross mass at a laboratory accredited by the National Institute of Metrology, Quality, and Technology (INMETRO). This evaluation followed preparation procedures outlined in the US EPA 3051A [47], with analysis conducted according to EPA 245.7 [48], standards method 2540 G [49], using an Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES) EPA 6010D [50].

The values obtained for the physical and chemical parameters of the WTS were compared against the quality reference values (QRVs) established in the standard NBR 10004 [51] to assess the potential toxicity of the sample. For the soil, these parameters were compared to the Guiding Values for Soil and Groundwater in the State of São Paulo, Brazil [52], which are derived from the guidelines outlined in Resolution No. 420 (CONAMA, 2009) [53].

2.2.2. Geotechnical Characterization

Geotechnical characterization and the determination of soil and WTS properties were carried out in accordance with Brazilian NBR standards. Particle size distribution was assessed following NBR 7181 standard [54], albeit without the use of a deflocculant. Liquid and plasticity limits were determined according to standards NBR 6459 [55] and NBR 7180 [56], respectively. The former sets the moisture content limit between semi-liquid and plastic states, while the latter helps identify the boundary between plastic states and semi-solid, as outlined in ASTM standard D4318 [57].

2.2.3. Mechanical Viability Analysis of Mixtures

Nine mixtures (CP) were prepared containing different percentages of silty sand soil (S), aluminum sludge (WTS) and stabilizing materials, hydrated lime (LIM), and Portland cement (CEM), as presented in Table 2.

Table 2. Composition of samples for analysis.

Nomenclature	Composition	Description
CP1	S	Soil (100%)
CP2	S + 3%CEM	Soil (97%) + cement (3%)
CP3	S + 3%LIME	Soil (97%) + lime (3%)
CP4	S + 10%WTS	Soil (90%) + WTS (10%)
CP5	S + 5%WTS + 3%CEM	Soil (92%) + WTS (5%) + cement (3%)
CP6	S + 8%WTS + 3%CEM	Soil (89%) + WTS (8%) + cement (3%)
CP7	S + 10%WTS + 3%CEM	Soil (87%) + WTS (10%) + cement (3%)
CP8	S + 10%WTS + 3%LIM	Soil (87%) + WTS (10%) + lime (3%)
CP9	S + 15%WTS + 3%LIM	Soil (82%) + WTS (15%) + lime (3%)
CP10	S + 20%WTS + 3%LIM	Soil (77%) + WTS (20%) + lime (3%)

The mechanical characteristics of the ten samples were evaluated using the same tests employed to assess the viability of conventional materials in Brazilian road construction. Each mechanical test was conducted on a minimum of three specimens. Cement and lime were used as stabilizing agents in the mixtures, each at a proportion of 3%.

Compaction tests were carried out on soil samples and material mixtures (soil, sludge, cement, or lime) to determine the relationship between moisture content and dry unit weight when compacted, according to the specified procedures in standard NBR 7182 [58]. The Normal Proctor cylinder (101.4 mm in diameter) was used, with a compaction energy of 570 kJ/m^3, under three layers of compaction, as shown in Figure 2. This enabled determination of the optimal moisture content (OMC) and maximum dry unit weight (DUWmax) for each sample. In constructing all pavement layers, the compaction operation aimed to achieve maximum stability and reduce settlement due to traffic [4].

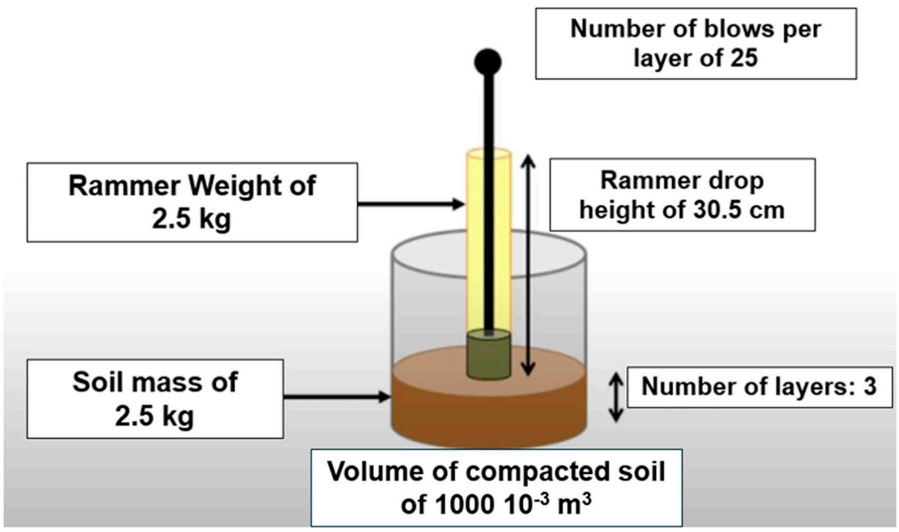


Figure 2. Experimental compaction process diagram.

To evaluate the strength of the materials, California bearing ratio (CBR) tests were carried out in accordance with the NBR 9895 standard [59]. The mixtures were moistened to their optimal moisture content, determined by compaction tests, and then compacted in five layers using a 4536 g hammer in a CBR cylinder (152 mm in diameter) with consistent energy. To assess the swelling potential of the specimens, an expansion meter was used while the samples were submerged in water for 96 h, following the Brazilian standard. During the penetration test, a constant penetration rate of 1.27 mm/min was maintained. The CBR value is expressed as the ratio of the unit load on the piston required to penetrate 2.54 mm and 5.08 mm of the test material compared to a well-calibrated crushed stone standard material.

The results of the material resistance analysis were compared with the Brazilian highway standards, as specified by the Department of Infrastructure and Transport (DNIT), which outline the minimum requirements for use in pavement layers [60]:

- Subgrade materials must exhibit a swell of 2% or less, as measured in the CBR test, and have a CBR of at least 2%.
- Materials for subgrade reinforcement must have a CBR greater than that of the subgrade and a swell of 1% or less.
- Sub-base materials must have a CBR of at least 20% and a swell of 1% or less.
- Base materials must have a CBR of at least 80% and a swell of 0.5% or less.

3. Results and Discussion

3.1. Soil and WTPS Characteristics

The results of the physical and chemical characterization of the WTS and soil samples are presented in Table 3.

Table 3. Physical and chemical characterization of WTS and soil.

Parameter	WTS	Silty Sand Soil	QRV
Dry solids content (% *w*/*w*)	78.1	95.7	NE
Organic matter (% *w*/*w*)	36.8	0.05	NE
Iron (mg/kg)	36,500	12,400	NE
Aluminum (mg/kg)	93,300	44,400	NE
Cadmium (mg/kg)	<0.1	<0.1	<0.5
Barium (mg/kg)	57.2	62.0	75
Lead (mg/kg)	4.45	6.45	17
Chromium (mg/kg)	11.4	5.22	40
Mercury (mg/kg)	<0.05	<0.05	0.05
Manganese (mg/kg)	1330	1	NE
Copper (mg/kg)	366	1	35

WTS: water treatment sludge; QRV: quality reference value; NE: non-existent.

The elements identified in the WTS correspond to the total composition of the material, as the sample preparation adhered to the standard EPA 3051A [47]. The digestion of the raw sample enabled analysis of its elemental composition. The dry solids content of the sample was notably high, reaching 78.1% and 95.7%. This can be attributed to the prior thermal treatment of the samples, although the lower value in the WTS indicates that some water remained even after the treatment. The result of organic matter is consistent with previous studies. Ackah et al. [22] obtained 34.19% of organic matter in the WTS used in their research, while Boscov et al. [35] also obtained high results for organic matter in WTS, with 26.7%. Typically, higher organic content is found in surface water sources [61].

The results indicate a high concentration of aluminum, likely due to the use of aluminum coagulants in the water treatment plant (WTP). Iron was found to be the second most concentrated element in the sample, a finding that aligns with observations by Gadekar and Ahammed [18] in a similar aluminum-based water treatment system (WTS). Iron is typically associated with minerals such as hematite (Fe_2O_3), magnetite (Fe_3O_4), and goethite (FeO(OH)), as reported by Marchiori et al. [62].

The Brazilian standard NBR 10004 [51] establishes reference concentrations (QRVs) for chemical elements for leachates and solubilized residues. These extracts generally have lower concentrations than those identified in a sample of gross mass, as evidenced in the studies by Ackah et al. [22] and Boscov et al. [35]. As described in Annex C of standard NBR 10004 [51], the presence of barium, lead, and chromium in the WTS sample suggests potential toxicity. However, to confirm this risk, specific toxicity tests, such as leaching experiments, are required. The high concentration of these elements can be explained by the sludge drying process, which reduces the moisture content and consequently increases the solids concentration, as observed by Silva et al. [46]. The same metals were found in WTS used by Ackah et al. [22], Bağriaçik and Güner [38], and Cremades et al. [28]. Nevertheless, the experimental results demonstrated that incorporating WTS as an additive to enhance soil quality was both cost-effective and environmentally sound. In the studies conducted by Siswoyo et al. [10] and Trang et al. [61], although lead and chromium were detected in the gross mass analyses of the residue, their presence did not negate the beneficial potential of using WTS.

The concentrations of soil parameters, when compared with the standards set by CETESB [51], do not indicate soil contamination. It is worth noting that the soil under evaluation exhibited higher concentrations of barium and lead compared to WTS. This suggests that the partial replacement of silty sand with WTS, as proposed in this research, does not exacerbate the risk of environmental toxicity.

3.2. Geotechnical Characterization of Soil and WTPS

In Figure 3, the particle size distribution curves of both the WTS and the soil are depicted. Both materials were classified as silty sands.

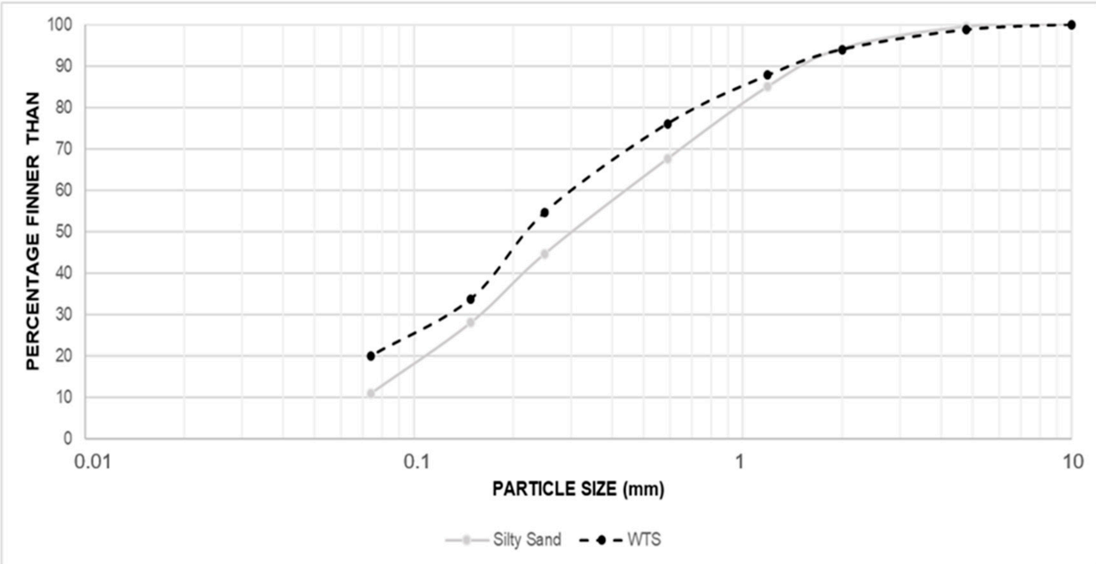


Figure 3. Particle size distributions of soil and WTS.

The granulometric distribution of WTS exhibited similarities to the aluminum WTS examined by Fiore et al. [4]. This similarity can be attributed to both WTSs undergoing thermal pre-treatment ranging between 150 and 180 °C. The silty sand displayed a liquid limit of 26.42% and a plasticity index of 2.68%. However, liquid and plasticity limits could not be ascertained for WTS. Hence, the plasticity index is deemed non-plastic, consistent with observations in the study by Marchiori et al. [37].

3.3. Mechanical Analysis of Mixtures

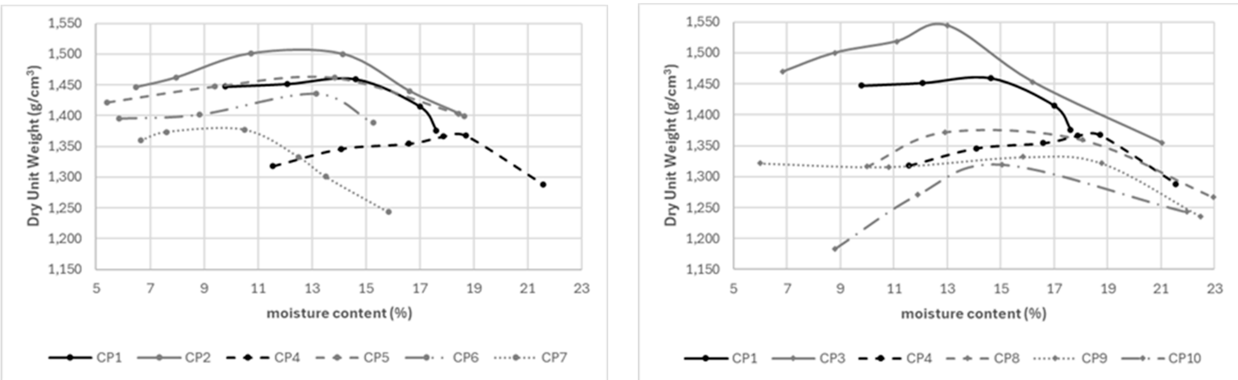
The results for the mechanical parameters of the soil and the nine mixtures are presented in Table 4. Additionally, the table includes recommendations for their suitability in paving structures, according to DNIT [60] classification.

The curves obtained for the Normal Proctor are present in Figure 4.

The silty sand presented a DUWmax of 1.68 g/cm^3 and optimum humidity of 14.4%. Comparison of the results for optimum moisture and DUWmax between the pure soil and soil mixed with stabilizing materials revealed that the addition of lime decreases the optimum moisture to 13% and the addition of cement to 14.20%. The DUWmax increased significantly with the addition of lime, reaching 1.74 g/cm^3, while with cement, it reached 1.72 g/cm^3. Introducing sludge into the soil at a 10% ratio reduces the sample's DUWmax by up to 15%, owing to the lower density of the sludge (1.42 g/cm^3). Adding stabilizing materials at 3% to the same proportion of the soil–sludge mixture increased the DUWmax to 1.51 g/cm^3 and 1.60 g/cm^3 for cement and lime, respectively. Notably, increasing the proportion of sludge in soil–sludge mixtures with cement incorporation led to a decrease in DUWmax, ranging between 1.51 and 1.66 g/cm^3, with the maximum value occurring at a 5% replacement of soil with sludge.

Table 4. Results obtained in the mechanical analysis of soil and mixtures and applicability in paving.

Nomenclature	OMC (%)	DUW$_{max}$ (g/cm^3)	Swell (%)	CBR (%)	Applicability in Paving [60]
CP1	14.40	1.68	0.88	14.44	Subgrade reinforcement
CP2	14.20	1.72	0.36	92.33	Base
CP3	13.00	1.74	0.39	8.11	Subgrade reinforcement
CP4	18.60	1.42	0.24	14.87	Subgrade reinforcement
CP5	11.00	1.66	0.22	41.50	Subbase
CP6	13.20	1.62	0.64	26.65	Sub-base
CP7	15.00	1.51	0.35	28.68	Sub-base
CP8	18.10	1.60	0.40	12.89	Subgrade reinforcement
CP9	19.30	1.58	0.22	21.25	Sub-base
CP10	21.00	1.52	0.37	20.13	Sub-base



(**a**) (**b**)

Figure 4. Proctor curves for (**a**) soil–sludge mixtures with cement incorporation and (**b**) soil–sludge mixtures with lime incorporation.

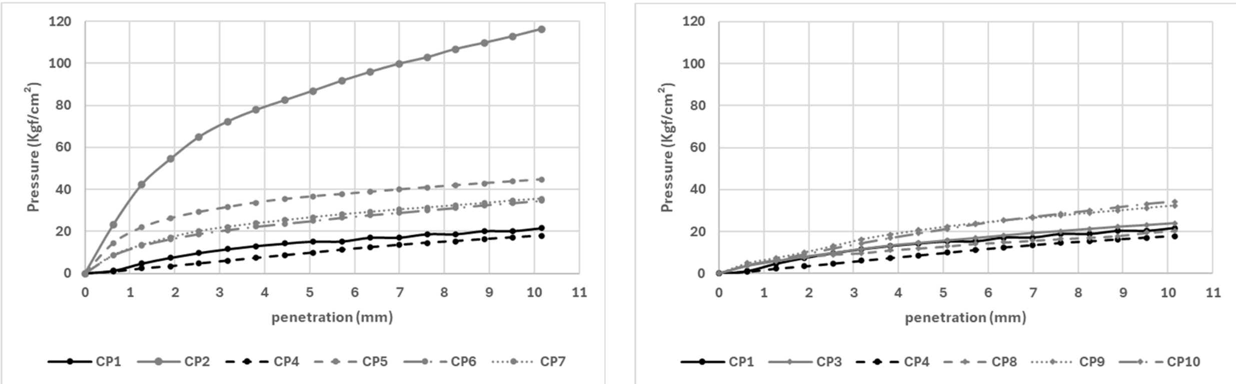
In soil–sludge mixtures with lime incorporation, it was observed that as the proportion of sludge increased, the DUWmax decreased, ranging from 1.52 to 1.60 g/cm^3. The maximum value was recorded when the soil was replaced by sludge at a rate of 10%. Consequently, both stabilizing materials exhibited similar behavior when integrated into the mixtures, necessitating increased water content to achieve optimal moisture levels. This phenomenon arises due to the finer sludge particles augmenting the specific surface area within the mixtures, thereby demanding more water to facilitate particle lubrication during the compaction process [4].

The interaction between lime and soil results in a modification of the soil's moisture-density relationship, which varies depending on the soil type. With the addition of lime, the density curve peaks at a higher moisture content and at a lower density value compared to without lime [63]. Introducing lime to the soil–WTS mixture could elevate the OMC due to the substitution of soil particles by lime particles possessing a larger specific surface area, and their chemical interaction with water.

The findings closely resemble those documented by Fadanelli and Wiecheteck [64], who investigated the substitution of 3%, 5%, and 7% of silty sand with WTS, along with a 7% cement addition. They also observed an increase in the optimum moisture content, coupled with a decrease in DUWmax.

The silty sand showed a swell of 0.88%. This swelling was mitigated by the addition of stabilizing materials in the study, resulting in reductions to 0.36% and 0.39% with cement and lime, respectively. Introducing 10% sludge into the mixture reduced expansion further to 0.24%. When the stabilizing materials were added in the same proportions to the soil–sludge mixture, swell values of 0.35% for cement and 0.40% for lime were achieved. When cement was used in the soil–sludge mixtures, the minimum swell value was observed with 5% soil replacement by sludge, ranging between 0.22% and 0.64%. Conversely, when lime was utilized in the mixtures, swelling varied from 0.22% to 0.40%, reaching its lowest point with a 15% soil replacement by sludge.

The CBR curves are present in Figure 5.



(**a**) (**b**)

Figure 5. CBR curves for (**a**) soil–sludge mixtures with cement incorporation and (**b**) soil–sludge mixtures with lime incorporation.

During the penetration test of the specimens, it was noted that the sandy soil exhibited a CBR value of 14.44%. Incorporating cement into mixtures of soil and stabilizing materials resulted in a significant increase in CBR, reaching 92.33%, demonstrating the effective interaction between cement and granular soils. However, the use of lime did not lead to substantial variation in CBR, with a recorded value of 14.87%, likely due to the challenge of lime interacting with granular particles. Introducing a 10% replacement of soil with sludge resulted in a decrease in CBR to 9.37%, aligning with findings from Shah et al. [34], who studied the replacement of soil with aluminum WTS.

Comparing the addition of stabilizing materials in the same proportion to the soil–sludge mixture, it is evident that CBR increased when cement was used, reaching 28.68%, while the addition of lime led to an increase to 12.89%. Therefore, it is apparent that the incorporation of stabilizing materials positively influenced the behavior of soil–WTS mixtures concerning CBR.

The CBR decreases as the sludge content in cement addition increases, ranging from 26.65% to 41.50%. The highest value was achieved with a 5% replacement of soil by sludge. Conversely, with lime addition, the CBR exhibits an opposite trend, increasing as the sludge content rises in the mixture, ranging from 12.89% to 21.25%. The peak value occurred at a 15% soil replacement by WTS.

Analysis of particle size distributions indicates that the WTS contains a higher proportion of fine particles compared to silty sand. Consequently, as the sludge content increases, the mixture's fine particle percentage rises, explaining the CBR reduction in cement mixtures due to enhanced interaction with granular particles. Lime demonstrates greater efficacy with finer particles, explaining the CBR increase when WTS content rises in the mixtures, given that WTS has 20% of particles passing through sieve #200 compared to 10% for soil. When cement is added, full stabilization does not occur, resulting in a CBR decrease.

Lime exhibits greater efficacy with finer particles, explaining the rise in the CBR value as the WTS content increases in the mixtures. The mineralogical characteristics of soils dictate their level of reactivity with lime. Typically, fine-grained clay soils (with at least 25% passing the #200 sieves) are deemed suitable for stabilization. Soils with notable levels of organic matter (exceeding 1%) or sulfates (over 0.3%) might necessitate extra lime and/or specialized construction methods [65].

According to Brazilian standards for paving works, all soil–sludge mixtures tested with cement incorporation are suitable for use in paving structures for the sub-base. Additionally, soil–sludge mixtures with lime incorporation can be utilized for both the sub-base (15% and 20% sludge) and to reinforce the subgrade (10% sludge). The results of incorporation obtained in this study indicate that silty sand soil shows less suitability for incorporating aluminum WTS compared to sandy soil, as utilized by Fiore [4].

This experimental research solely examined mixtures containing dried WTPS and silty sand soil to assess the effectiveness of stabilizers. It is recommended that further investigations include the addition of fibers to the mixes, as conducted by Jiang et al. [66], and the analysis of deformations under traffic loading, as performed by Jiang et al. [67].

4. Conclusions

This study examined the substitution of soil with WTS, incorporating either cement or lime, for potential application in road pavements. The conclusions drawn from the study are as follows:

- The physical and chemical analysis of the WTS and soil indicated that the resulting composites, when mixed for road construction, do not pose environmental risks.
- Geotechnical analysis revealed that WTS and silty sand soil share similar particle sizes. However, while the silty sand exhibited a liquid limit of 26.42% and a plasticity index of 2.68%, the WTS was classified as non-plastic.
- Mechanical testing demonstrated that soil–sludge mixtures, when augmented with stabilizing agents, meet Brazilian standards for various pavement layers. The optimal composition was determined to be CP5 (92% soil + 5% WTS + 3% cement), achieving a CBR of 41.50%. With the addition of lime, the most favorable results were obtained for CP9 (82% soil + 15% WTS + 3% lime), yielding a CBR of 21.25%.
- Increasing the WTS content in cement mixtures resulted in decreased CBR values due to the rise in fine particles, which hindered interaction with the cement.
- Conversely, augmenting WTS content in lime mixtures led to increased CBR values, as lime exhibited a more effective interaction with fine particles.
- This study solely assessed mixtures with dried WTPS, silty sand soil stabilizers, and stabilizers (cement and lime). Future research could explore the utilization of other soil types with stabilizers, incorporate fibers into the mixes, evaluate the long-term performance of the pavement structure, and examine the economic and environmental feasibility of this beneficial application.

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