Civil Engineering

Soil stabilization with water treatment plant sludge for road paving

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Abstract

One of the methods to minimize the negative impact caused by inadequate disposal of Water Treatment Plant Sludge (WTPS) is to mix it with the soil, applying the material in engineering works. In this research, the objective was the use of WTPS for soil stabilization purposes, verifying the improvement of the characteristics and properties with 0%, 15%, 30% and 50% of sludge, for application in the base and sub-base layers of road pavements. Characterization, compaction, permeability, Resistance to Simple Compression (RCS), and California Bearing Ratio (CBR) tests were carried out. However, none of the mixes met all the necessary requirements for use in the pavement layers, but it is concluded that there was an increase in the RCS, CBR and impermeability of the mixtures compared to the reference mixture (100% soil). The RCS increased 142.75% of the soil for a blend with 30% sludge, CBR increased 76.52% of the soil for mixture with 50% WTPS, and the permeability of blends with 15%, 30% and 50% sludge was lower than then with only the soil. These results show that these mixtures can be useful for other types of applications in Geotechnics, being able to contribute to the sustainable destination of WTPS.

Keywords: soil stabilization, water treatment plant sludge, road pavement, sustainability.

List of notations

γs	real specific weight of the grains
CBR	california bearing ratio
CONAMA	national environmental council
CSI	california support index
DNIT	national department of infrastructure of transport
GI	group index
LL	liquidity limit
MDSW	maximum dry specific weight
NP	not plastic
PL	plasticity limit
PI	plasticity index
SCS	simple compressive strength
TRB	transportation research board
USCS	unified soil classification system
WTPS	water treatment plant sludge
WTP	water treatment plant

1. Introduction

During the initial stages of water treatment, chemicals are introduced to facilitate the separation of existing impurities. In this process, the particles are dispersed within a liquid medium, and subsequently, they come together to form flakes that settle under the influence of gravity. The residue that accumulates during this sedimentation process is referred to as Water Treatment Plant Sludge (WTPS), which is obtained from decanter cleaning. Initially, when removed from the decanters, this sludge has a liquid consistency and occupies a significant volume, necessitating proper treatment and disposal methods (Guimarães & Urashima, 2013; Montalvan, 2016).

Initially, Water Treatment Plant Sludge (WTPS) used to be deposited in water bodies without undergoing proper treatment, which had adverse effects on water quality and led to the siltation of rivers. However, this practice was discontinued following CONAMA (National Environmental Council) Resolution No. 357 (2005), which categorizes this material as a pollutant of aquatic environments and mandates its appropriate disposal. Furthermore, NBR 10004 (2004) classifies WTPS as solid waste, prohibiting its disposal in water bodies. Nevertheless, a study conducted by Achon & Cordeiro (2015) revealed that in São Paulo's Water Treatment Stations (WTPs), only 9% of them sent the sludge to Waste Treatment Units, where it was dewatered in industrial landfills, while 86% of the WTP was disposed of as untreated sludge in water bodies, and 5% was sent to available Sewage Treatment Stations.

The ultimate disposal of Water Treatment Plant Sludge represents a highly significant and intricate task, primarily because treatment facilities and landfills frequently exceed their capacities. The substantial production of sludge, coupled with environmental apprehensions regarding its final disposal, has prompted researchers to explore suitable management methods, one of which involves its utilization in civil construction. Given the considerable demand for aggregates within this sector, resources from traditional deposits are becoming increasingly scarce, necessitating the use of materials that often do not meet standard specifications (Santos *et al*., 2018).

This use of sludge is one of the ways existing for the use of the residue, which has already been used in some research, justifying this trend: the dosage of rice husk and sludge from the WTP incorporated into soil–cement brick (Barbosa *et al*., 2019); for manufacturing concrete paving blocks (Sajitthan *et al*., 2023), geopolymer masonry units (Suksiripattanapong *et al*., 2015), cement (Ruviaro *et al*., 2023) and repair mortars (Hemkemeier, 2023); in the improvement of sandy soils (Güner, 2022; Roque *et al*., 2022); as raw material for precast concrete floors (Castro, 2014); use as ceramic coating (Medeiros *et al*., 2014); and as a material incorporated into the asphalt binder (Bastidas-Martínez, 2020). The mentioned studies underscore the significance of investigating this residue, with the aim of harnessing it as either a raw material or a finished product. Such an endeavor further bolsters sustainable organizational development.

In this research, the focus was on the use of sludge for soil stabilization purposes, verifying the improvement of the characteristics and properties of clayey soil stabilized with different percentages of WTPS for application in road paving. This article is the first to analyze the characteristics of WTPS in the northwestern region of the state of Rio Grande do Sul / Brazil and to try to apply it in road paving. The objective is to contribute to a more sustainable alternative for disposing this waste, in addition to reducing the use of natural resources in civil construction in the southern region of Brazil, contributing to the circular economy and the United Nations Sustainable Development Goals, bearing in mind that, today, in the country, much of this material still does not have an adequate destination.

2. Materials and methods

2.1 Soil

The soil utilized in the research was sourced from a deposit situated in Frederico Westphalen (FW), Rio Grande do Sul (location shown in Figure 1). This deposit is located in Volta Grande, adjacent to BR-386 at kilometer 38, with geographic coordinates of approximately 27°24'9.35" South latitude and 53°24'28.93" West longitude. This soil is commonly employed in municipal construction projects by the City Hall.

Figure 1 - Region where Frederico Westphalen is located in Rio Grande do Sul (Emater-RS – Ascar, 2009).

This soil exhibits clayey characteristics, a determination based on both tactile-visual analysis and the prevalent soil characteristics found in the northwestern region of the state of Rio Grande do Sul.

2.2 Soil collection and preparation

The soil collection process adhered to the guidelines outlined in NBR 9604 (2016), which pertains to the excavation of wells and soil inspection trenches. Prior to excavation, the land's surface underwent cleaning to eliminate any existing vegetation, as mandated by regulations. The soil was collected from a depth of 2 meters and placed into clean bags for transportation and subsequent storage within the laboratory. In the laboratory setting, the sample was further prepared for use in the tests.

2.3 Soil characterization

The soil characterization encompassed various tests, including the granulometric analysis test, which adhered to NBR 7181 (2018) guidelines, while the determination of the Liquidity Limit and Plasticity Limit of the soil followed NBR 6459 (2017) and NBR 7180 (2016) standards, respectively, and the real density of soil grains was assessed through the NBR 6458 test (2016). It is noteworthy that all these characterization tests were conducted on three separate samples to ensure heightened result reliability.

2.4 Water treatment plant sludge

The WTPS utilized in the research was sourced from the water treatment plant situated in the northwestern region of Rio Grande do Sul, operated by CORSAN/FW. This facility acquires water from the Pardo River dam, located within the same city, by means of pumping, and conveys it through pipelines to the treatment facility situated at the highest point within the urban area.

The treatment station employs a treatment process encompassing several phases: coagulation/flocculation, decantation, filtration, chlorination, and fluoridation. Within this classification of WTPs, the decanters are known to generate the largest volume of sludge in terms of mass. At the specific WTP from which the sludge was obtained, there are two decanters, each with an 800 m³ capacity; however, the exact quantity of sludge generated by the plant was not disclosed by the company. It is important to emphasize that a sludge passing through a 4.75 mm sieve was used, since this represents the granulometry of the sludge after drying and breaking up.

2.5 Collection and preparation of WTPS

During the collection phase, the Water Treatment Plant Sludge had a gravimetric moisture content of approximately 2.385%, classifying it as a thixotropic substance, essentially a gel-like state, with a gravimetric moisture level - the ratio of water mass to solid particle mass - exceeding 900%. Consequently, the need arose for a drying process in drainage beds to enhance its workability. However, due to the absence of suitable equipment, this drainage procedure could not be carried out. As a result, the sludge was directly obtained from the conditioning tanks and placed in plastic drums for subsequent storage in the laboratory.

Within the laboratory setting, the sludge underwent a drying process in an oven set at a temperature of 60°C. This temperature was chosen to prevent the risk of organic matter combustion within the material. The dry sludge sample was obtained when the moisture content dropped below 15%, a condition achieved after seven days in the oven. At this stage, the material exhibited a granular texture, with approximately 99.4% of it retained in the sieve with an opening of 0.075 mm.

2.6 Characterization of WTPS

To assess the properties of the sludge, the same characterization tests that were conducted for the soil were employed. Each test was performed on three separate samples, thereby enhancing the credibility and reliability of the obtained results.

2.7 Dosage and mixing

After drying both the sludge and the soil in advance, they were combined, homogenized and then water was added to the mixture. The mixtures studied were defined based on the researched literature, such as Knierim (2023); Güner (2022); Coelho *et al.* (2015); Montalvan (2016) and Lucena et al. (2014), and are: M1: 100% Soil + 0% WTPS; M2: 85% Soil + 15% WTPS; M3: 70% Soil + 30% WTPS; M4: 50% Soil + 50% WTPS; and M5: 0% Soil + 100% WTPS.

Mixture 5 (M5) was exclusively employed for the characterization tests to assess the properties of the sludge. Moreover, granulometry tests, Atterberg limits, and real grain density tests were conducted to characterize all the mixtures.

2.8 Compaction test

In this research, the predominant energy level used was intermediate, as it aligns with the standard practice for compacting base and sub-base layers. The testing protocol adhered to the methodology outlined in NBR 7182 (2020), with three samples considered for each mixture.

2.9 Simple compression strength test

The specimens were prepared in cylindrical molds with dimensions of 10 cm in diameter and 20 cm in height. This was done at the optimal moisture content and maximum specific weight, determined for each mixture through the Proctor compaction test at intermediate energy levels. The dynamic molding process employed a manual compactor, resulting in the creation of three specimens for each mix, aiming to obtain the average Simple Compressive Strength (SCS). Following molding, the specimens were enveloped in plastic film and subjected to a curing period in a temperature-controlled environment for 7 and 28 days, a time defined based on research that supported the study. The testing procedures adhered to the guidelines outlined in NBR 12025 (2012).

2.10 Permeability test

The permeability test for both the soil and the soil + WTPS mixtures was conducted with a variable load, considering the potential low permeability of these mixtures. To perform this, the NBR 14545 (2000) standard was followed. Each mixture underwent testing using three specimens, which were molded in cylindrical molds measuring 10 cm in diameter and 20 cm in height. Following the molding process, the specimens were prepared for the commencement of the test.

2.11 California support index assay

The California Support Index (CSI), also called California Bearing Ratio (CBR), is obtained in percentage through the relationship between pressure and penetration of the piston in the specimen. The soil expansion index can also be obtained during saturation by immersion of the specimen. This parameter serves to analyze the behavior of this material in the pavement layers when saturated.

In this part of the research, the samples were molded and tested following the recommendations of the NBR 9895 standard (2017). All samples were compacted under intermediate compaction energies, the test being performed 3 times for each sample, to obtain the average of the results.

2.12 Data analysis

Once the results of the characterization, hydration and mechanical tests were obtained, the data was compiled. Following this, a comparative analysis was conducted, involving reference to other studies and established standards, in order to assess the feasibility for utilization in the base and sub-base layers of road pavements.

3. Results and discussion

3.1 Mixture characterization tests

Initially, the physical characterization of the studied mixtures was carried out. This included a granulometric analysis involving coarse sieving and sedimentation tests with and without a deflocculant agent, followed by fine sieving. These results, combined with the real specific weight of the grains and Atterberg limits, enabled the classification of the materials using both the Transportation Research Board (TRB) and Unified Soil Classification System (USCS) systems, offering insights into their anticipated behavior. Additionally, as the National Department of Infrastructure of Transport (DNIT, 2006) incorporates the Group Index (GI) for assessing material suitability in road pavement layers, this analysis was also included in Table 1.

Table 1 – Characterization of mixtures.

Parameters		**M1 (100% Soil)**	**M2 (85% Soil + 15% WTPS)**	**M3 (70% Soil + 30% WTPS)**	**M4 (50% Soil + 50% WTPS)**	**M5 (100% WTPS)**
Physical characteristics of the no deflocculant assay	**Gravel (%)**	3	8	14	29	81
	Coarse Sand (%)	5	4	3	3	4
	Medium Sand (%)	1	2	2	2	2
	Fine Sand (%)	21	19	17	13	5
	Silt (%)	53	49	45	31	6
	Clay (%)	17	18	19	22	2
	γs (g/cm³)	3.009	2.945	2.694	2.590	2.559
	GI	15	16	16	14	3
Physical characteristics of the deflocculant assay	**Gravel (%)**	2	10	14	29	44
	Coarse Sand (%)	1	1	1	1	2
	Medium Sand (%)	1	2	2	2	1
	Fine Sand (%)	6	7	7	8	4
	Silt (%)	33	33	33	27	37
	Clay (%)	57	47	43	33	12
	GI	15	16	16	13	0
***Atterberg* limits**	**LL (%)**	55	56	58	58	NP
	PL (%)	35	35	37	37	NP
	PI (%)	20	21	21	21	NP
Assay ratings without deflocculant	**USCS Classification**	MH	MH	MH	MH	GP-GM
	TRB Classification	A-7-5	A-7-5	A-7-5	A-7-5	A-2-7
Test classifications with deflocculant	**USCS Classification**	CH	CH	CH	CH	GP-GM
	TRB Classification	A-7-5	A-7-5	A-7-5	A-7-5	A-4

γs: real specific weight of the grains; GI: Group Index; LL: liquidity limit; PL: plasticity limit; PI: plasticity index; NP: not plastic.

In the context of the granulometry test, particularly for mixtures without the use of a deflocculant, the data presented in Table 1 reveals some significant observations:

- The introduction of sludge into the mixtures exhibited a pattern of elevating the gravel content while reducing the proportion of coarse sand, being that this trend reached stability from M2 onwards. Additionally, it is noteworthy that Mixtures 1, 2, 3, and 4 predominantly consisted of fine materials, specifically silt and clay, accounting for over 50% of their composition. Conversely, Mixture 5 displayed a clear dominance of stony materials, with more than 80% of its composition falling within this fraction.

- Significant alterations in the granulometric characteristics of the soil + WTPS mixtures are discernible when contrasted with the natural soil. The average sand content doubled from M1 to M2, M3, and M4, with these three mixtures sharing identical sand percentages. Another notable observation is that, as the percentage of soil replacement by sludge increased, there was a decrease in the proportions of fine sand and silt, coupled with a slight tendency towards an increase in the clay fraction.

- Furthermore, concerning the sand content, the natural soil exhibited an average of 27%, constituting the material with the highest proportion of sandy fractions. In contrast, the mixture of 85% Soil + 15% WTPS contained 25% sand, the mixture of 70% Soil + 30% WTPS displayed 22%, and the 50% Soil + 50% WTPS mixture had only 18%. This trend demonstrates a consistent reduction in the sand content as the proportion of WTPS in the mixture increased. Lastly, the 100% WTPS mixture contained 11% sand within its composition.

- The non-linear patterns observed in the fluctuations of percentages within the soil + WTPS mixtures can predominantly be attributed to the inherent variability in the granulometry of the sludge. This variability is influenced by factors, such as the location of water collection, the seasonal variations, and the environmental conditions surrounding the collection site for the sludge.

- Upon comprehensive analysis utilizing the Unified Soil Classification System (USCS), it was determined that mixtures 1, 2, 3, and 4 fell under the classification of medium to high plasticity silt (MH). In contrast, mixture 5 was categorized as poorly graded silty gravel (GP-GM).

- When evaluated using the TRB classification system, mixtures 1, 2, 3, and 4 were categorized as A-7-5, representing a typical classification of silty clay materials with a moderate plasticity index concerning the liquidity limit. These materials are characterized by their susceptibility to significant volume changes and can exhibit excessive elasticity. In contrast, WTPS received a classification of A-2-7, denoting high plasticity silty stony soil.

In the context of the granulometry test conducted with a deflocculant, the data presented in Table 1 provides the following insights:

- As the proportion of sludge in the mixtures increased, there was a discernible trend towards an augmentation in the clay percentage when compared to the natural soil. Additionally, the percentage of silt remained consistent at 33% for mixtures 1, 2, and 3, but decreased to 27% for mixture 4. Furthermore, mixtures 1, 2, and 3 comprised over 70% of fine materials in their composition, while mixture 4 exceeded 50% in this regard. In contrast, Mixture 5 predominantly featured silty stony material.

- An observable trend indicated an increase in the percentages of fine sand and gravel within the mixtures. The percentage of coarse sand remained consistent for mixtures 1, 2, 3 and 4. Furthermore, the proportion of coarse sand remained unchanged for M1, M2, M3 and M4.

- Upon examination using the TRB classification system, mixtures 1, 2, 3, and 4 were classified as A-7-5, indicating their alignment with typical high compressibility clays. Conversely, WTPS received a classification of A-4, denoting low compressibility silty soil within this system. In the Unified Soil Classification System, mixtures 1, 2, 3, and 4 were categorized as high compressibility clays (CH), and Mixture 5, composed exclusively of WTPS, was classified as GP-GM.

In an overall comparison between the mixtures tested without deflocculant and those tested with deflocculant, it becomes apparent that the classifications within the gravel and medium sand categories remained similar. However, changes were observed in the proportions of coarse sand, fine sand, and silt, with a decrease in these percentages. Consequently, there was an increase in the clay fraction, indicating the effectiveness of the deflocculant in altering the granulometric composition of the mixtures.

In reference to the actual specific weight of grains, as mentioned by Pinto (2006), it is approximately 2.700 g/cm³ for clayey soils, potentially lower at approximately 2.650 g/cm³ for sandy soils and can even reach values of up to 3.000 g/cm³ in lateritic clays. Consequently, the average of 3.009 g/cm³, as presented in Table 1, for the real specific weight of grains in Mixture 1 aligns with the characteristics of lateritic clayey soils, thus maintaining consistency with the soil of northwestern RS.

The incorporation of sludge into the mixtures led to a reduction in specific weight, resulting in values of 2.945 g/cm³, 2.694 g/cm³, 2.590 g/cm³, and 2.559 g/cm³ for mixtures 2, 3, 4, and 5, respectively. This decline in specific weight can be attributed to the lower specific weight of the sludge compared to the soil being studied, a phenomenon also observed in Knierim's (2023) research. In Knierim's study, specific weight decreased from 2.702 g/cm³ in the 100% soil mixture to 2.297 g/cm³ in the 50% soil + 50% WTPS mixture.

The Plasticity Index (PI) serves as an indicator of soil plasticity and quantifies the water content required to shift the soil from a plastic to a liquid state. Examining the Atterberg limit tests based on Table 1, it was found that in Mixture 1, the PI value stood at 20%, signifying a high plasticity (20% ≤ PI ≤ 40%). Mixtures 2, 3, and 4 exhibited a consistent PI of 21%, indicating high plasticity, despite minor fluctuations in the Liquid Limit (LL) and Plastic Limit (PL) values. This elevated plasticity can be attributed to the increased presence of clay in the samples. Furthermore, as shown in Table 1, there is minimal variation in LL and PL values as the proportion of WTPS increases. Even when 50% of the soil is substituted with WTPS, these parameters remain virtually unchanged.

When comparing the findings in this section to those reported by Montalvan (2016) and Delgado (2016), noteworthy differences emerge. Both Montalvan and Delgado observed higher proportions of fine materials within the sludge, whereas in this search, it revealed a prevalence of more coarse materials in the sludge. Additionally, Delgado's research indicated that the Atterberg limits of WTPS were non-plastic, which contrasts with the present findings. Finally, it is worth mentioning that Montalvan's study lacked a clear linear pattern in the variations of the fractions within the mixtures in relation to the incremental addition of sludge.

As mentioned before, the wide-ranging characteristics of WTPS are contingent on the specific water potability systems employed at each station and the location of water collection. Therefore, the disparities observed in this phase of the study are entirely justified.

Regarding the group index of both analyses (with and without deflocculant), it is noted that there was an increase in M2 and M3 in relation to M1 and that it decreased in M4 and M5. Values closer to zero indicate soils with greater carrying capacity, with M5 showing better performance in this criterion. M4 presented intermediate values, and M1, M2 and M3 presented values considered high for use in paving; that is, not being indicated for this purpose.

3.2 Compaction tests

With the compaction curves of Mixtures 1, 2, 3 and 4 shown in Figure 2, the optimum humidity content was obtained: 28.30%, 30.48%, 29.98% and 32.72%; and the maximum dry specific weight (MDSW): 1.521 g/cm³, 1.480 g/cm³, 1.473 g/cm³ and 1.428 g/cm³, respectively.

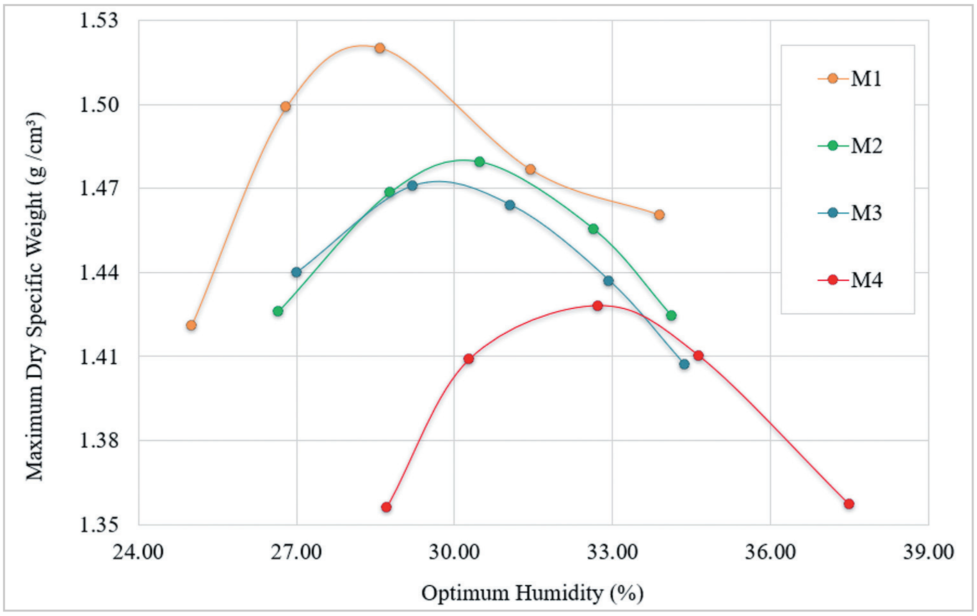

Figure 2 - Compaction curves.

The presented results reveal that the addition of 15% of WTP sludge to the soil resulted in a slight decrease in the Maximum Dry Specific Weight (MDSW), representing approximately a 2.70% reduction compared to the soil. When 30% and 50% of sludge were added, this reduction increased to 3.16% and 6.11%, respectively, in relation to M1. Additionally, there was an increase in the optimal moisture content by approximately 7.70% and 15.62%, in that order for M2 and M4 compared to the soil. In summary, there was a tendency for MDSW to decrease and optimal moisture content to increase, except for M3, where the latter was slightly lower than M2, albeit still relatively close in value.

The outcomes of this investigation align with the findings from Delgado (2016). In Delgado's study, he examined a clayey soil combined with 5% WTPS, demonstrating a behavior akin to that observed in this research: following the addition of 5% sludge, there was an approximately 8% decline in Maximum Dry Apparent Specific Weight and a substantial increase in moisture content, roughly 32.4%, when compared to values solely from the clayey soil. Delgado also explored mixtures containing 5%, 10%, and 15% sludge blended with stone dust, despite the dissimilarity in the soil types, the author also found a reduction in MDSW with the increment of sludge in the mixtures. Specifically, for the 5% and 10% mixtures, identical optimal moisture values were identified, while the 15% mixture exhibited a higher moisture content compared to the other two samples. The minor variation in optimal moisture for M2 and M3 in the present research, as well as the absence of variation for the 5% and 10% mixtures in Delgado's (2016) study, can be attributed to the inherent heterogeneity of the WTPS.

As per Lucena et al. (2014), the reduction in Maximum Dry Apparent Specific Weight and the heightened water absorption observed following the introduction of sludge into the mixture can be attributed to the mineralogical composition of the particles. This phenomenon arises from the substantial surface area, significant void spaces, and inherent porosity characterizing sludge particles.

3.3 Simple compression strength tests

The results of Simple Compression Strength (SCS) were detailed in Figure 3.

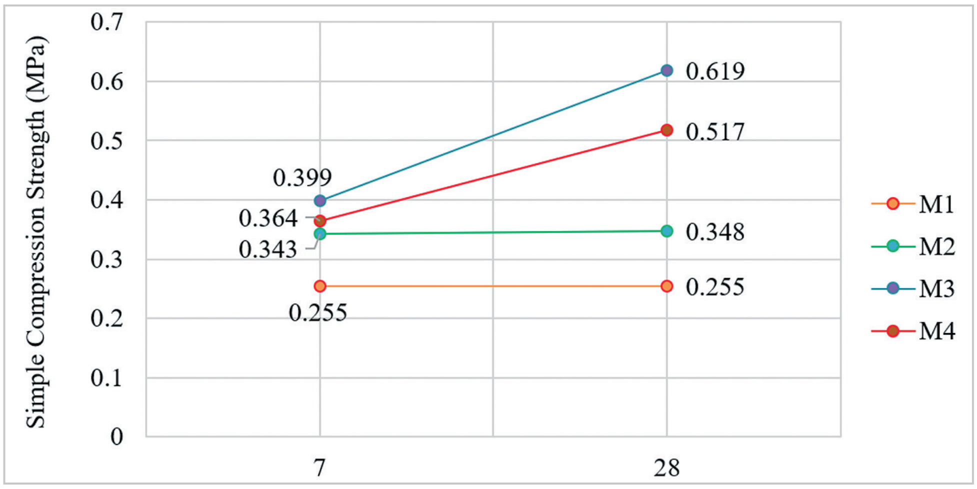

Figure 3 - Average simple compression strength results for mixtures.

Figure 3 illustrates that the soil exhibited an average Simple Compression Strength (SCS) of 0.255 MPa for both 7 and 28 days of curing, a typical SCS value for clayey soils. The substitution of soil with WTPS across all mixtures resulted in an enhancement of SCS in comparison to pure soil, with the most remarkable performance observed in the 70% Soil + 30% WTPS mixture, boasting an SCS of 0.619 MPa. This signifies 142.75% increase in average strength over the unaltered soil. It is worth noting that Knierim (2023) also arrived at a similar conclusion in her research, identifying the same mixture as having the highest strength when compared to pure soil.

In Mixture 2, there was an increase in average SCS of 34.51% and 36.47% above that of the soil for the curing periods of 7 and 28 days, respectively. Mixture 3 exhibited even more significant results, with an average strength surpassing that of the soil by 56.47% in the 7 days. Lastly, the 50% Soil + 50% WTPS mixture demonstrated average strengths of 42.75% and 102.75% for the 7 and 28 days, respectively.

As evident from Figure 3, there is a discernible trend where the resistance in M2, M3, and M4 increases with the extension of curing time. This phenomenon is likely attributed to the presence of certain chemical components within the WTPS.

The replacement of soil with WTPS resulted in an SCS increase in the samples, is evident up to a 30% replacement, whereas at 50%, a decrease was observed compared to M3. This variation likely stems from the distinct behavior of WTPS, which tends to enhance inter-particle friction, consequently elevating the compressive strength of the specimens. This aligns with the findings in Knierim's (2023) study, where the addition of WTP sludge in mixtures exhibited a propensity to elevate SCS in contrast to pure soil, in the highest WTPS proportion, there was a reduction in the parameter, yet it remained superior to natural soil, mirroring the results observed in this study.

3.4 Permeability tests

The permeability coefficient (k) values for Mixtures 1, 2, 3, and 4 were 1.66E-08, 1.71E-09, 2.44E-09, and 2.03E-09, respectively. Notably, the studied soil exhibited an average permeability coefficient that, in accordance with Terzaghi & Peck's classification (1967), falls within the range indicative of soils with very low permeability (k ranging from 10-07 to 10-09 m/s).

In the case of the 85% Soil + 15% WTPS mixture, there was a reduction in the k value compared to that of the pure soil. Specifically, the average permeability coefficient measured was 1.71E-09 m/s. Meanwhile, for the 70% Soil + 30% WTPS mixture, the average permeability coefficient stood at 2.44E-09 m/s, and the 50% Soil + 50% WTPS mixture reached 2.03E-09 m/s. These findings indicate that all mixtures, regardless of the WTPS content, possess characteristics typical of materials with very low permeability.

Despite the distinct behavior exhibited by WTPS, it is suggested that its incorporation into the soil facilitated improved particle interlocking. This, in turn, resulted in a reduction in the permeability coefficient value and rendered the mixtures more impermeable when contrasted with the natural soil. This phenomenon likely transpired because, even as the clay content diminished, the silt content remained relatively constant with the increasing presence of sludge in the tests with a deflocculant. Consequently, the silt component compensated for the scarcity of clay material, thereby diminishing the void index and contributing to the observed decrease in permeability.

Knierim (2023) encountered permeability values that did not exhibit a linear trend; for the 85% Soil + 15% WTPS mixture, the coefficient decreased compared to the soil, whereas it increased for the other mixtures. These findings align with the outcomes of the current research, and the disparities in results between the two studies can be attributed to the contrasting granulometry of the sludge employed in each investigation.

3.5 California support index tests

The California Support Index (SCI) test seeks to verify the bearing capacity of a compacted soil. The expansion test determines the expansion of the submerged soil for a period of 96 hours. The average values for Mixtures 1, 2, 3 and 4 of SCI were 11.5%, 18.1%, 20.0%, 20.3%, and expansion of the tests were 0.0175%, 0.0525%, 0.4374% and 0.6037%.

According to the results presented, there was an increase in the percentage of SCI of 57.27% for M2, 73.91% for M3 and 76.52% for M4, all of which were increases in relation to M1. There was also an increase in expansion, where the greatest expansion occurred for mixture 4, which has a higher percentage of sludge, already expected considering that the sludge has a high capacity of water absorption, causing expansion. Regarding expansion, there was an increase of 200% for M2, 2399.42% for M3 and 3349.71% for M4, all of them in relation to M1.

Coelho *et al.* (2015) studied clayey soil (100%), clayey soil - sludge (50% of each), sandy soil (100%) and sandy soil - sludge (1:0.25), and in both mixtures with sludge, there occurred a decrease in the SCI percentage and an increase in expansion, both in relation to 100% soil mixtures. The increase in expansion was also verified in the present research, since the difference in the percentages of SCI is justifiable considering that there was an increase in SCS with the addition of WTPS, and consequently, the penetration resistance also increased.

3.6 Analysis of the technical viability of using the mixtures in base and sub-base layers of road pavements

In this section, the goal was to assess the utilization of the materials under investigation for their application in the base and sub-base layers of road pavements. For this, a compilation of the mandatory requirements of standards already presented in the literature review was made. In Table 2, a checklist was conducted under the specified conditions to evaluate the suitability of each of the materials for potential applications.

Table 2 – Verification of the mixtures under study for use in layers of road pavements.

	Parameter	Condition for application	Material / Application Verification			
			M1	M2	M3	M4
Base Layer	DNIT 141/2022 – ES (2022)	Liquidity Limit ≤ 25% for material passing through sieve nº. 40	NO	NO	NO	NO
		Plasticity Index ≤ 6% for material passing through sieve nº. 40	NO	NO	NO	NO
		Sand Equivalent > 30%	NO	NO	NO	NO
		Material passing through sieve no. 200 does not exceed 2/3 of the percentage passing through sieve nº. 40	NO	NO	NO	NO
	DNIT (2006)	CSI ≥ 80%	NO	NO	NO	NO
		Expansion ≤ 0,5%	YES	NO	NO	NO
	DER/PR ES - P 11/18 (2018)	1.5 MPa ≤ SCS ≤ 2.1 MPa (for 7 days of curing)	NO	NO	NO	NO
Sub-base Layer	DNIT (2006)	CSI ≥ 20%	NO	NO	YES	YES
		Expansion ≤ 1%	YES	YES	YES	YES
		Group Index = 0	NO	NO	NO	NO
	DER/PR ES - P 11/18 (2018)	1.5 MPa ≤ SCS ≤ 2.1 MPa (for 7 days of curing)	NO	NO	NO	NO

In relation to Table 2, the following analyzes can be made:

- In relation to the sub-base, of the group indexes found, no mixture presented a value equal to zero.

- For the base layer, all mixtures have an LL and PI higher than the necessary conditions (25% and 6%, respectively). Also, neither mixture presented a percentage of sand above 30%, and material that passed through sieve number 200 exceeded 2/3 of the percentage that passed through sieve number 40.

- For Simple Compressive Strength tests, DER/PR ES-P 11/18 (2018) specifies that the material is only acceptable for base or subbase use if its Simple Compressive Strength is greater than or equal to 1.5 MPa and less than or equal to 2.1 MPa, so no sample reached the minimum necessary established for use in the layers under study.

- Regarding the California Support Index, only M3 met the minimum requirement for using the material as a base (SCI equal to or greater than 80%), and M3 and M4 met the requirement for use in a sub-base layer (SCI being equal to or greater than 20%). Regarding the expansion to the base, it must be less than or equal to 0.5%, however, only M1 fulfilled the requirement. The expansion of the sub-base layer must be less than or equal to 1%, where all mixtures met this item.

- For the compaction and permeability steps, there are no specific criteria for using the mixtures as a base or sub-base.

Finally, through Table 2, it is possible to see that no mixture met all the criteria established for base or sub-base, so none of the mixtures could be used for these purposes.

4. Conclusions

The soil mechanics have classified the soil as predominantly clayey. However, as WTPS was introduced into the soil, a noticeable trend emerged: a reduction in the fractions of silt and sand alongside an augmentation in clay and gravel content. Additionally, the incorporation of WTPS led to an increased plasticity in the mixtures. The actual specific weight of the soil particles adhered to the typical characteristics of lateritic clayey soil and as the WTPS percentage in the soil increased, there was a decrease in this parameter. This decline can be attributed to the relatively low actual specific weight of the sludge particles.

Regarding the outcomes from the compaction test, a clear pattern emerged: as the quantity of WTPS added to the soil increased, there was a corresponding reduction in the maximum dry apparent specific weight. Additionally, there was an elevation in the optimal moisture content observed in tandem with the growing presence of sludge within the soil. This phenomenon can be attributed to the inherently low actual specific weight of the grains within these mixtures.

The permeability test revealed a heightened impermeability in the mixtures, which is advantageous for their potential use in engineering projects. The permeability coefficient of both the soil and mixtures fell within the range of 10-09, signifying that these materials possess a high level of impermeability.

Concerning the results from the Simple Compression Strength tests, these indicated a consistent rise in strength with the progressive inclusion of sludge in the mixtures. Notably, the mixture displaying the highest SCS was the 70% soil + 30% WTPS combination after 28 days, showcasing a strength that surpassed the pure soil by 142.75%.

Through the California Support Index test, it was possible to identify an increase in penetration resistance and in the expansion of the mixtures with the increase in the percentage of sludge in the soil, and the best performance in terms of CSI was mixture 4, with CSI 76.52% higher than the soil.

The following aspects are suggested for all mixtures, given the importance for future research: obtaining the shear resistance parameters through the triaxial compression test; analyze the resilience module; study the mixtures in this research at different compaction energies: normal and modified; use different soils and different percentages of WTPS in order to evaluate the behavior of different mixtures; and study different applications of residue.

This article is the first to analyze the characteristics of WTPS in the northwest region of the state of Rio Grande do Sul / Brazil and to try to apply it in road paving. Even though none of the mixtures meet all the requirements for application, the improvement in soil performance makes it clear that the application can occur in other areas of Civil Engineering, thus contributing to a more sustainable alternative for disposal of this waste, in addition to reducing the use of natural resources in civil construction in the southern region of Brazil, contributing to the circular economy and the United Nations Sustainable Development Goals.

References

ACHON, C. L.; CORDEIRO, J. S. Destinação e disposição final de lodo gerado em ETA - Lei 12.305/2010. *In*: EXPOSIÇÃO DE EXPERIÊNCIAS MUNICIPAIS EM SANEAMENTO, 19, 2015. Poços de Caldas. ***Anais*[...].** Poços de Caldas: ASSEMAE, 2015, p. 1-8.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. ***ABNT NBR 6458***: grãos de pedregulho retidos na peneira de abertura 4,8 mm - determinação da massa específica, da massa específica aparente e da absorção de água. Rio de Janeiro: ABNT, 2016.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. ***ABNT NBR 6459***: solo – determinação do Limite de Liquidez. Rio de Janeiro: ABNT, 2017.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. ***ABNT NBR 7180***: solo – determinação do Limite de Plasticidade. Rio de Janeiro: ABNT, 2016.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. ***ABNT NBR 7181***: solo – análise granulométrica. Rio de Janeiro: ABNT, 2018.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. ***ABNT NBR 7182***: solo – ensaio de compactação. Rio de Janeiro: ABNT, 2020.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. ***ABNT NBR 9604***: abertura de poço e trincheira de inspeção em solo, com retirada de amostras deformadas e indeformadas. Rio de Janeiro: ABNT, 2016.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. ***ABNT NBR 9895***: solo – determinação de suporte Califórnia (ISC) – método de ensaio. Rio de Janeiro: ABNT, 2017.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. ***ABNT NBR 10004***: resíduos sólidos – classificação. Rio de Janeiro: ABNT, 2004.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. ***ABNT NBR 12025***: solo-cimento - ensaio de compressão simples de corpos de prova cilíndricos - método de ensaio. Rio de Janeiro: ABNT, 2012.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. ***ABNT NBR 14545***: solo – determinação do coeficiente de permeabilidade de solos argilosos a carga variável. Rio de Janeiro: ABNT, 2000.

BARBOSA, M. F. L.; PIRONCELLI A. B. S.; SILVA, C.A.; JUNIOR A. C.; CEREDA M. P.;MAGALHÃES FILHO, F. J. C. Rice husk and water treatment plant sludge incorporated into soil – cement brick. ***Asian Journal of Civil Engineering,*** v. 20, p. 563-570, 2019. Available in: https://doi.org/10.1007/s42107-019-00124-2

BASTIDAS-MARTÍNEZ, J. G.; CAMAPUM DE CARVALHO, J.; LUCENA, L. C.; FARIAS M. M.; RONDÓN--QUINTANA, H. A. Preliminary study of hot mix asphalt containing water treatment and sewage sludge. ***Archives of Civil Engineering,*** v. 66, n. 1, p. 225-240, 2020. Available in: https://doi.org/10.24425/ace.2020.131785

BRASIL. Ministério do Meio Ambiente. ***Resolução CONAMA n° 357, de 17 de março de 2005.*** Conselho Nacional do Meio Ambiente - CONAMA, 2005. 36 p.

CASTRO, C. E. ***Uso de lodo de estação de tratamento de água (LETA) para fabricação de pavimentos pré-moldados de concreto.*** 2014. Dissertação (Mestrado em Engenharia de Materiais) - Universidade Federal de Itajubá, 2014.

COELHO, R.; TAHIRA, F.; FERNANDES, F.; FONTENELE, H.; TEIXEIRA, R. Uso de lodo de estação de tratamento de água na pavimentação rodoviária. ***Revista Eletrônica de Engenharia Civil - REEC ,*** v. 10, n. 2, p. 11-22, 2015. https://doi.org/10.5216/reec.V10i2.33134

DELGADO, J. V. C. ***Avaliação da aplicação do lodo da ETA Guandu na pavimentação como disposição final ambientalmente adequada.*** 2016. Dissertação (Mestrado em Engenharia Civil) - Universidade Federal do

Rio de Janeiro, Rio de Janeiro, 2016.

DEPARTAMENTO DE ESTRADAS DE RODAGEM (Paraná) - ES-P 11/18. ***Pavimentação***: solo-cimento e solo tratado com cimento. Curitiba, Brasil, 2018. 19 p.

DEPARTAMENTO NACIONAL DE INFRAESTRUTURA DE TRANSPORTES. ***Manual de pavimentação.*** Publicação IPR 719. Rio de Janeiro: DNIT, 2006. 277 p.

DEPARTAMENTO NACIONAL DE INFRAESTRUTURA DE TRANSPORTES - 141/2022 – ES. ***Pavimentação***: base estabilizada granulometricamente – especificação de serviço. Brasília: DNIT, 2010. 12 p.

EMPRESA DE ASSISTÊNCIA TÉCNICA E EXTENSÃO RURAL - EMATER - RS – ASCAR. Regional – Frederico Westphalen. 2009. Available in: <http://www.emater.tche.br/site/regionais/frederico-westphalen.php#.Xy7yP4pKipo> Access at: 17 jan. 2024.

GUIMARÃES, M. G. A.; URASHIMA, D. C. Dewatering sludge in geotextile closed systems: brazilian experiences. ***Soils and Rocks,*** v. 36, n. 3, p. 251-263, 2013. https://doi.org/10.28927/SR.363251.

GÜNER, E. D. Experimental investigation of the feasibility of using drinking water treatment plant sludge in the improvement of sandy soils. ***Journal of Material Cycles and Waste Management,*** v. 24, p. 1923-1933, 2022. Available in: https://doi.org/10.1007/s10163-022-01448-z

HEMKEMEIER, T. A.; ALMEIDA, F. C. R.; SALES, A., KLEMM, A. J. Repair mortars with water treatment plant sludge (WTPS) and sugarcane bagasse ash sand (SBAS) for more eco-efficient and durable constructions. ***Journal of Cleaner Production,*** v. 386, p. 135750, 2023. Available in: https://doi.org/10.1016/j.jclepro.2022.135750.

KNIERIM, L. D. S. Study of the mechanical and hydric behavior of the use of water treatment station sludge in mixtures with lateritic clay soil. ***Revista DAE***, v. 71, n. 240, p. 51-64, 2023. Available in: https://doi.org/10.36659/dae.2023.021.

LUCENA, L. C. F. L.; JUCA, J. F.; SOARES, J. B.; MARINHO FILHO, P. G. T. Use of wastewater sludge for base and subbase of road pavements. ***Transportation Research Part D: Transport and Environment,*** v. 33, p. 210-219, 2014. Available in: https://doi.org/10.1016/j.trd.2014.06.007.

MEDEIROS, E. N. M. D.; SPOSTO, R. M.; NEVES, G. D. A.; MENEZES, R. R. Technical feasibility of the incorporation of rice husk ash, sludge from water treatment plant and wood ash in clay for ceramic coating. ***REM - Revista Escola de Minas,*** v. 67, n. 3, p. 279-283, 2014. Available in: https://doi.org/10.1590/S0370-44672014000300006

MONTALVAN, E. L. T. ***Research on the geotechnical behavior of mixtures of sandy soil with sludge from Cubatão water treatment plant.*** 2016. Dissertação (Mestrado em Engenharia Geotécnica) - Universidade de São Paulo, São Paulo, 2016.

PINTO, C. S. ***Curso básico de mecânica dos solos.*** São Paulo: Oficina de Textos, 2006. 368 p.

RONQUIM, C. C. ***Conceitos de fertilidade do solo e manejo adequado para as regiões tropicais.*** Campinas: Embrapa Monitoramento por Satélite, 2010. 26 p.

ROQUE, A.; MONTALVAN, E. L. T.; BOSCOV, M. E. G. Reuse of water treatment plant sludge mixed with lateritic soil in geotechnical works. ***Environmental Challenges,*** v. 7, p. 100465, 2022. Available in: http://dx.doi.org/10.1016/j.envc.2022.100465

RUVIARO, A. S.; SILVESTRO, L.; ANDRADE NETO, J. D. S.; GLEIZE, P. J. P.; PELISSER, F. Eco-efficient cement production: investigating water treatment plant sludge and eggshell filler use in LC3 systems. ***Construction and Building Materials,*** v. 394, p. 132300, 2023. Available in: https://doi.org/10.1016/j.conbuildmat.2023.132300.

SAJITTHAN, S.; RAJAPAKSHE, E. P.; ILLANGASINGHE, I. M. W. K.; MANATUNGE, J. M. A. Reuse potential of drinking water treatment plant sludge for the manufacture of concrete paving blocks. ***ICSBE 2022*** - Lecture Notes in Civil Engineering, v. 362, p. 853-867, 2023. Available in: https://doi.org/10.1007/978-981-99-3471-3_58

SANTOS, G. Z. B. D.; MELO FILHO, J. D. A.; MANZATO, L. Prospects of technological applications of sludge from water treatment process of the Negro and Solimões rivers. ***Revista Matéria,*** v. 23, n. 3, p. 1-14, 2018. Available in: https://doi.org/10.1590/S1517-707620180003.0501

SUKSIRIPATTANAPONG, C.; HORPIBULSUK, S.; CHANPRASERT, P., SUKMAK, P.; ARULRAJAH, A. Compressive strength development in fly ash geopolymer masonry units manufactured from water treatment sludge. ***Construction and Building Materials,*** v. 82, p. 20-30, 2015. Available in: https://doi.org/10.1016/j.conbuildmat.2015.02.040

TERZAGHI, K.; PECK, R. B. ***Soil mechanics in engineering practice.*** New York: John Willey & Sons, 1967.

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