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Study of the hydro-mechanical behavior of a stabilized soil with water treatment plant sludge for application in sanitary landfills

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Article

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Abstract

The improper disposal of water treatment plant sludge (WTPS) into the environment can cause irreparable damage. One way to minimize this negative impact is to mix the sludge with the soil, applying the materials 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 of a stabilized clay soil with different sludge percentages for application in waterproofing layers of bottom and final coverage of landfills. Formulations were prepared with additions of 0, 15, 30 and 50% of WTPS. Characterization, compaction, permeability and simple compression resistance tests were carried out. All mixtures met the Brazilian requirements for use in landfill layers, but the mixture composed of 70% soil + 30% WTPS was defined as the best for application in bottom layers and final coverage for the following reasons: it meets the coefficient of permeability and has the highest simple compression resistance of all blends. Furthermore, it is noteworthy that the use of the mixtures, especially 50% soil + 50% WTPS, in daily (intermediate) layers would be an environmentally beneficial alternative that would contribute to the circular economy and to achieving sustainable development goals 11, 12 and 15 by 2030. These applications would bring advantages in the destination of WTPS and reduced consumption of natural resources (soil).

1. Introduction

Water coming from underground or surface springs is extremely important to supply the population. However, fresh water needs to be treated so that it can be consumed by humans, passing through Water Treatment Stations (WTS) and through various physical, biological and chemical processes.

At the beginning of the water treatment, chemical products are added in order to separate the existing impurities, and in this separation the particles are dispersed in a liquid medium, where, later, they agglomerate and form flakes, which sediment by the action of gravity. The residue that accumulates in the sedimentation process is called Water Treatment Plant Sludge (WTPS), being obtained from the washing of the decanters. Initially, after removing the sludge from the decanters, it has a liquid consistency and large volume, requiring adequate treatment and disposal (Montalvan, 2016; Guimarães & Urashima, 2013).

The sludge consists of solid residues of organic and inorganic nature, therefore, depending on the characteristics, the residues of the WTPs increase the degree of pollution and contamination of the water bodies, contributing to the loss of the quality of life of the populations existing downstream of the sludge releases (Roque et al., 2022).

The WTPS was initially deposited in water bodies, without any adequate treatment, providing negative aspects to water quality and causing silting of rivers. However, this practice was abolished by CONAMA (Brazilian National Environmental Council) resolution n° 357 (Brasil, 2005), which classifies this material as a pollutant of these bodies, requiring adequate disposal. In addition, the Brazilian Standard ABNT NBR 10004 (ABNT, 2004) brings WTPS as a solid waste, so it cannot be disposed of in bodies of water. However, according to a study carried out by Achon & Cordeiro (2015), in the Water Treatment Stations of São Paulo, only 9% of them sent the sludge to Waste Treatment

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Units and had the same dewatered in industrial landfills, 86% of the WTS disposed of the untreated sludge in bodies of water and 5% sent it to one of the available Sewage Treatment Stations.

The final destination of WTPS is a very important and complex activity, as the capacity of treatment plants and landfills is usually extrapolated. Therefore, there is a need for alternatives to the final destination of the waste, which is the responsibility of the producers of the tailings. In this way, some environmental agencies have demanded details of the final disposal in the WTPs licensing process, representing an advance in environmental management in the country (Montalvan, 2016).

The great production of WTPS and the environmental concern of the final destination of this residue has instigated researchers to seek appropriate forms of management, one of them being the use in civil construction. Due to the high consumption of aggregates by this branch, materials from the deposits are increasingly scarce, requiring the use of materials that often do not meet the specifications of use (Santos et al., 2018).

In Brazil, the construction of sanitary landfill covers depends on the exploitation of clay deposits, extracted from the place of execution itself or from the deposit closest to the landfill. In several situations, due to the large volume of transport, or even the distance from the deposits, the cost of transporting these soils is higher than the extraction itself, when considering the frequent increases in fuel prices, not showing economic viability to use nobler soils in landfills. In addition, the soils available in the locality often do not achieve an efficient waterproofing for landfill layers, resulting in the need to use less noble soils, stabilizing them with binders and residues that improve their properties (Knierim, 2020).

The use of sludge is one of the ways out for the use of the residue, which has already been used in some research at the national level that justify this trend: the dosage of lime and sludge from the WTP for use as a supplementary material to Portland cement by Ferreira et al. (2022); as raw material for precast concrete floors by Castro (2014); use as ceramic material for the manufacture of tiles by Cremades et al. (2018); as a material incorporated into the asphalt binder by Martinez (2014); in road paving for its incorporation into the base layer and sub-base of road pavement by Medaoud et al. (2022). The cited works resume the importance of a study of this residue so that it can be used as a raw material or final product, contributing even more to a sustainable organizational growth.

This research aimed to use 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 sanitary landfills.

2. Materials and methods

This chapter describes the procedures during the experimental phase of the research. This was developed in 3 stages: in the first stage, we sought to develop a bibliographic review on the subject, in order to deepen our knowledge on the subject and to better understand the behaviors found by other researchers in relation to WTPS and soil + WTPS mixtures.

Subsequently, in the second phase, soil and WTPS characterization tests were developed, in addition to the development of Compaction, Permeability and Simple Compressive Strength tests of all mixtures, in order to know the characteristics and properties of soil and soil + WTPS.

In the third and final phase, the results found were analyzed and compared to those found in the literature under study, in order to give greater veracity to them and also to verify the possibility of using soil and mixtures within the standards established as mandatory by the Brazilian Standard ABNT NBR 13896 (ABNT, 1997), which defines criteria for non-hazardous waste landfills, by the United States Environmental Protection Agency (USEPA, 1998, 2003), by German Standard (1993) and also desirable requirements found in the study literature for bottom layers and final cover of landfills, thus increasing the spectrum of analysis for the implementation of the technique in other countries.

The research was developed with the joint work of bibliographic research and laboratory tests, mainly in the Materials and Civil Construction Laboratory (MCCL) and in the Soil Laboratory of the Integrated Regional University of Alto Uruguai and Missões - Frederico Westphalen Campus (URI -FW).

2.1 Materials

2.1.1 Soil

The soil used in the research was obtained from a deposit in the city of Frederico Westphalen (FW), State of Rio Grande do Sul (RS), Brazil. The deposit is located in Volta Grande, on the banks of BR-386 highway, km 38, with coordinates of latitude 27°24’9.35” South and longitude 53°24’28.93” West, being this soil used in the works carried out by the city government.

The soil of the place has a clayey characteristic, due to the previous tactile-visual analysis and the characteristics of the soils found in the North and Northwest of the State of Rio Grande do Sul.

2.1.2 Water Treatment Plant Sludge

The WTPS used in the research was collected at the water treatment plant, located in the north of the state of Rio Grande do Sul, at CORSAN/FW (Riograndense sanitation company). The station collects water by pumping from the Pardo River dam, located in the interior of the same city, and takes it through pipes to the treatment site, located at the highest point within the urban environment.

The station works with full cycle treatment. Basically, the treatment consists of the following phases: coagulation/

flocculation, decantation, filtration, chlorination and fluoridation. It is known that in WTPs of this classification the largest amount of sludge (in terms of mass) is generated in the decanters. At the WTP where the sludge was collected, there are two decanters with a capacity of 800 m^3 each, however the company did not inform the amount of sludge generated there.

2.2 Description of processes

2.2.1 Soil collection and preparation

The soil was collected in accordance with the specifications of the Brazilian Standard ABNT NBR 9604 (ABNT, 2016c). Previously, before excavation, a surface cleaning of the land was carried out, removing any trace of vegetation present, as specified in the regulations. The soil was collected at a depth of 2 m and packed in clean bags for transport and laboratory storage. In the laboratory, the sample was broken up for use in the tests.

2.2.2 Soil characterization

For the characterization of the soil, the granulometric analysis test was carried out according to Brazilian Standard ABNT NBR 7181 (ABNT, 2018). The determination of the Liquid Limit of the soil was carried out according to ABNT NBR 6459 (ABNT, 2017) and the Plasticity Limit was carried out in accordance with ABNT NBR 7180 (ABNT, 2016b). The density of soil particles was determined by the ABNT NBR 6458 (ABNT, 2016a).

In addition to the tests already mentioned, to complement the characterization, a chemical analysis test was carried out for the soil. It should be noted that for all the above-mentioned soil characterization tests, tests were carried out on 3 samples, in order to obtain greater reliability in the results.

2.2.3 Collection and preparation of WTPS

At the time of collection, WTPS had a gravimetric moisture content of about 2385%, which characterized it as a thixotropic material, that is, it is in the form of a gel, with a gravimetric moisture value - ratio of water mass per mass of particles solid – which exceeds 900%. Thus, it would be necessary to perform drying in drainage beds to improve workability. However, it was not possible to perform this drainage due to lack of adequate equipment. Thus, the sludge was obtained directly from the conditioning tanks and placed in plastic drums for storage in the laboratory.

In the laboratory, the sludge was dried in an oven at a temperature of 60 °C. This temperature was defined in order to avoid the possibility of burning the organic matter present in the material.

The dry sludge sample was obtained when the moisture reached a value below 15%, which was evidenced after the seventh day in the oven. The material was characterized at that time as granular, the size of a pebble with about 99.4% retained in the sieve with an opening of 0.075 mm.

2.2.4 Characterization of WTPS

For the sludge, in order to know its properties, the chemical analysis test was performed. In the same way as for the characterization of the soil, for the characterization of the WTPS, tests were carried out on 3 samples, giving greater credibility to the results.

2.2.5 Dosage and mixing

As the WTPS and the soil were previously dried, they were mixed and homogenized and then water was added to the mixture. The mixtures to be studied are presented in Table 1, which were defined from the researched literature.

The mixture 5 was used only in the characterization tests to know the properties of WTPS. Furthermore, in order to characterize the mixtures highlighted in Table 1, granulometry tests, Atterberg limits test, soil particles density analysis and chemical analysis were performed.

2.2.6 Compaction test

In this study, the use of intermediate energy prevailed, since this energy is commonly used in sanitary landfill compaction. The test procedure followed the methodology described in the Brazilian Standard ABNT NBR 7182 (ABNT, 2020) with 3 samples for each mixture.

2.2.7 Simple compression strength test

The preparation of the specimens was carried out in cylindrical molds measuring 10 cm in diameter and 20 cm in height, at the optimum moisture and maximum specific weight for each mixture, determined from the Proctor compaction test, at the intermediate energy.

The molding took place dynamically, using a manual compactor. Three specimens were molded for each dosage in order to obtain the average of the Simple Compressive Strength (SCS). After molding, the specimens were packed in plastic film and proceeded to cure, in a temperature-controlled environment, for 7 and 28 days. The test followed the precepts of the Brazilian Standard ABNT NBR 12025 (ABNT, 2012).

Table 1. Mixtures.

Nomenclature	Soil (%)	WTPS (%)
M1	100	0
M2	85	15
M3	70	30
M4	50	50
M5	0	100

2.2.8 Permeability test

The permeability test of soil and soil + WTPS mixtures was carried out with variable load, due to the possible low permeability of the mixtures. For this, the Brazilian Standard ABNT NBR 14545 was used (ABNT, 2000). For each mixture, tests were carried out on 3 specimens, molded in cylindrical molds of 10 cm in diameter by 20 cm in height. Soon after molding, the specimens were prepared for the start of the test.

2.2.9 Data analysis

After obtaining the results of the characterization, hydrous and mechanical tests, the data was compiled. Subsequently, these were compared to other studies and standards and the possibility of use in bottom layers and final cover of sanitary landfills was verified.

3. Analysis and results

3.1 Mixture characterization tests

Initially, the physical characterization of the mixtures under study was performed. The granulometric analysis consists of coarse sieving together with the sedimentation test with and without a deflocculant agent, for subsequent performance of the fine sieving. With these results, together with the unit weight of soil particles and Atterberg limits, it is possible to classify the materials according to the Transportation Research Board (TRB) and Unified Soil Classification System (USCS) systems, thus being able to predict the behavior of the same. In the Table 2 is possible to visualize the results of the physical characteristics of the mixtures, the Atterberg limits and the respective classifications according to the USCS and TRB.

Regarding the granulometry test (sieving + sedimentation), more specifically for mixtures without deflocculant, from Table 2, it is possible to observe that:

- With the addition of sludge in the mixtures, there was a tendency to increase the percentage of gravel and decrease the percentage of coarse sand, which stabilized from M2. Furthermore, mixtures 1, 2, 3 and 4 had more than 50% of their fractions composed of fine material (silt and clay); and mixture 5 showed a predominance of stony, with more than 80% of material in this fraction;
- Changes in granulometric characteristics of soil + WTPS mixtures are evident when compared to natural soil. The average sand percentage was doubled from M1 to M2, M3 and M4, and for M2, M3 and M4 the value found was the same for all. Another important perception is that, with the increase in the percentages of soil replacement by sludge, there was a tendency to decrease in the percentages of fine sand and silt, in addition to a small tendency to increase in the clay fraction;
- Also, in relation to the amount of sand, the soil presented an average of 27% (being this material with the highest sandy fraction), the mixture 85%

Table 2. 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 from the no deflocculant test	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
	γ_s (g/cm^3)	3.009	2.945	2.694	2.590	2.559
Physical characteristics from the deflocculant test	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
Atterberg Limits	LL (%)	55	56	58	58	NP
	PL (%)	35	35	37	37	NP
	PI (%)	20	21	21	21	NP
Classification 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
Classification 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

γ_s: unit weight of soil particles; LL: liquid limit; PL: plasticity limit; PI: plasticity index; NP: not plastic.

Soil + 15% WTPS presented 25%, the mixture of 70% Soil + 30% WTPS presented 22% and in the 50% Soil + 50% WTPS there was only 18%, that is, there was a tendency to decrease the amount of sand with the increase of WTPS in the mixture. Finally, the mixture of 100% WTPS had 11% of sand in its composition;

- The non-linearity of growth or decrease in the variations in the percentages of the soil + WTPS mixtures can be attributed mainly to the variability of the sludge granulometry, which is affected depending on the place of water collection, the time of year and what happens around the sludge collection place;
- Analyzing all samples using the Unified Soil Classification System (USCS), mixtures 1, 2, 3 and 4 were classified as medium to high plasticity silt (MH); mixture 5 was classified as poorly graded silty gravel (GP-GM);
- Evaluating the materials by the TRB classification system, it fits mixtures 1, 2, 3 and 4 as A-7-5, typical classification of silty clay materials with moderate plasticity index in relation to the liquid limit, being subject to high changes volume and may be excessively elastic. WTPS was classified as A-2-7 (high plasticity silty stony soil).

For the granulometry test with deflocculant, in Table 2, it is possible to observe that:

- With the increase of sludge in the mixtures there was a tendency of growth in the percentage of clay, if compared to the natural soil. Furthermore, the percentage of 33% of silt was maintained for mixtures 1, 2 and 3, and for mixture 4 it decreased to 27%. Furthermore, mixtures 1, 2, 3 had more than 70% of their fractions composed of fine materials and M4 more than 50%. M5, on the other hand, showed a predominance of silty stony;
- There was a tendency to increase the percentages of fine sand and gravel. The percentage of coarse sand remained the same for mixtures 1, 2, 3 and 4. In addition, coarse sand remained the same for M1, M2, M3 and M4;
- Analyzing the materials by the TRB classification system, it fits mixtures 1, 2, 3 and 4 as A-7-5. The WTPS was classified as A-4 (low compressibility silty soil). In the Unified Soil Classification System, mixtures 1, 2, 3 and 4 were classified as high compressibility clays (CH). Mixture 5, which is composed only of WTPS, was classified as GP-GM.

In general, comparing the mixtures tested without deflocculant and with deflocculant, it is noted that the classes of gravel and medium sand remained similar. In relation to the fractions of coarse sand, fine sand and silt, there was a decrease in these percentages and, consequently, an increase in the clay fraction, showing the efficiency of the deflocculant.

Regarding the unit weight of soil particles, Pinto (2006) points out that this parameter is around 2.7 g/cm^3 for clayey soils. In the case of sandy soils this value may be lower, around 2.65 g/cm^3. In lateritic clays, the unit weight of soil particles can reach values of up to 3 g/cm^3. Therefore, by Table 2, the average value of 3.009 g/cm^3 for unit weight of soil particles, found in Mixture 1, is a plausible value for lateritic clayey soils, therefore, being consistent with the local soil.

The increase in sludge in the mixtures caused the unit weight to decrease, with values of 2.945 g/cm^3, 2.694 g/cm^3, 2.590 g/cm^3 and 2.559 g/cm^3 for mixtures 2, 3, 4 and 5, respectively. This decrease with the addition of sludge occurred because the sludge has a lower unit weight than the soil under study. This situation was also verified in the study by Knierim (2020), which in mixtures 100% soil, 85% soil + 15% WTPS, 70% soil + 30% WTPS and 50% soil + 50% WTPS, a reduction of 2.702 g/cm^3 of the 100% soil mixture to 2.297 g/cm^3 of the 50% soil + 50% WTPS mixture.

The Plasticity Index determines the plasticity of the soil and the amount of water that must be added to the mixture to change it from the plastic to the liquid state. Observing the Atterberg limit tests, according to Table 2, the PI value in Mixture 1 was 20%, considered of high plasticity (20% $\leq$ PI $\leq$ 40%). For Mixtures 2, 3 and 4, although with a small variation in the LL and PL values, the Plasticity Index was 21%, also considered to be of high plasticity. This high plasticity can be credited to the greater presence of clay in the samples. Also, from Table 2, it can be seen that there is a small variation in the values of LL and PL with the increase of WTPS. Although 50% of the soil was replaced by WTPS, there was practically no change in the parameters.

Comparing the results found in this chapter with those of Montalvan (2016) and Delgado (2016), it can be seen that both authors found higher proportions of fine materials in the sludge, while in this study more granular materials were found in the sludge. It was also found that Delgado (2016) found WTPS Atterberg limits to be non-plastic. Finally, it is noted that in the study by Montalvan (2016) there was a lack of linearity in the increases or decreases of the fractions in the mixtures according to the increment of sludge.

As previously mentioned, the WTPS have great variation in characteristics, which depend on the water potability system used in each station and on the water collection site, so the differences at this stage of the study are justified.

3.2 Chemical analysis tests

The chemical analysis test was performed for the four mixtures under study and also for a sample of 100% WTPS (M5), and the results are shown in Table 3 for Mixtures 1, 2, 3, 4 and 5.

From the correlation with values of Cation Exchange Capacity - CEC - it is possible to know the clay mineral present in the structure of the material under study, which helps in the perception of the behavior of the material.

According to the results achieved in the chemical analysis (Table 3) of Mixture 1, soil saturation by bases of 38% was verified, a characteristic value of dystrophic soils, with low fertility (Vasconcellos, 1986). The aluminum saturation is less than 50%, which means that the amount of aluminum present in the soil is not toxic to the plants present in the place. The CEC value was exactly 10 cmolc/L, which according to the usual values of Ronquim (2010) indicates that there is presence of kaolinite in the soil and, possibly, there is also illite, which is a clay mineral with a tendency to have medium expandability. In relation to the values of OM and pH of the soil, they indicate little presence of organic matter and that the acidity of the soil is high (Vasconcellos, 1986).

Based on the results of the Mixture 85% Soil + 15% WTPS, according to Table 3, they showed that the mixture under analysis presents a saturation of the material by bases of 52.1%, which characterizes the material as being eutrophic (with high fertility). The aluminum saturation is 1.8%, which means that M2 is not toxic to plants. Still, the mixture presented 10.2 cmolc/kg of CEC, which characterizes a material constituted by kaolinite and illite. Moreover, the mixture showed little presence of organic matter (OM) and low pH, indicating a material of high acidity.

From Table 3, it is noted that the material present in M3, due to aluminum saturation, is not toxic, as it has zero saturation. Analyzing the base saturation (63%) the mixture can be characterized as eutrophic, with high fertility. In the CEC value, the value of 10.6 cmol/L was obtained, which means that there is presence of kaolinite and illite in the mixture. The mixture also showed low values of OM (1.7%) and pH (5.2) indicating little presence of organic matter and that the acidity of the material is medium.

According to the results achieved in the chemical analysis of Mixture 4 (Table 3), there was a saturation of the material by bases of 73.5%, a characteristic value of eutrophic soils, with high fertility. Again, the aluminum saturation is null, which means that the mixture is not toxic to the plants present in the place. The CEC value was exactly 11.7 cmolc/L, which means that kaolinite is present in addition to illite. In relation to the values of OM and pH of the material, they indicate little presence of organic matter and a low acidity.

The results of Table 3, for Mixture 100% WTPS, showed that the mixture under analysis presents a saturation of the mixture by bases of 81.8%, which characterizes the material as being eutrophic (with high fertility). The aluminum saturation is zero, which means that M5 is not toxic to plants. Still, the material presented 13.8 cmolc/kg of CEC, which characterizes a mixture constituted by illite and kaolinite. In relation to OM, the mixture showed little presence of organic matter and pH indicating a material with very low acidity. The result of the chemical analysis also indicates that Mixture 5 has a low amount of clay compared to the other mixtures, about 22%.

Analyzing the results found for the sludge with those of Montalvan (2016) and Knierim (2020) there are some results close to those of this study, but for the most part they differ, once again confirming the heterogeneity of the sludge in each WTP.

3.3 Compaction tests

With the compaction curves, the optimal moisture content and maximum dry density (MDD) were obtained, and the Table 4 illustrates the optimal compaction parameters of mixtures 1, 2, 3 and 4.

Table 3. Chemical analysis of the mixtures under study (LASTV, 2020a, b, c, d, e).

Mixtures	Clay (%)	pH/ H_2O	SMP Index	P (mg/L)	K (mg/L)	OM (%)	Al (cmolc/L)	Ca (cmolc/L)
M1 (100% Soil)	79	4.7	5.7	2.1	36.5	0.9	0.6	2.8
M2 (85% Soil + 15% WTPS)	65	4.9	5.9	3.2	49.5	1.4	0.1	4
M3 (70% Soil + 30% WTPS)	51	5.2	6.1	4.8	61	1.7	0	5.1
M4 (50% Soil + 50% WTPS)	40	5.7	6.3	7.1	80	2.4	0	6.7
M5 (100% WTPS)	22	6.2	6.5	7.1	107.5	3.5	0	9
	Mg (cmolc/L)	CEC (cmolc/L)	H + L (cmolc/L)	% Sat. of CEC		Relations		
				Bases	Al	Ca/Mg	Ca/K	Mg/K
M1 (100% Soil)	0.9	10	6.2	38	13.7	3.1	30	9.6
M2 (85% Soil + 15% WTPS)	1.2	10.2	4.9	52.1	1.8	3.3	31.6	9.5
M3 (70% Soil + 30% WTPS)	1.4	10.6	3.9	63	0	3.6	32.7	9
M4 (50% Soil + 50% WTPS)	1.7	11.7	3.1	73.5	0	3.9	32.7	8.3
M5 (100% WTPS)	2	13.8	2.5	81.8	0	4.5	32.7	7.3

Analyzing the Table 4, In general, there was an increase in optimal moisture content and decreased the MDD in the mixes. This can be explained because the sludge is lighter than the soil, causing the MDD to decrease in mixtures 2, 3 and 4. Still, it was identified that with the increase of WTPS there is a tendency that there is an increase of the optimal moisture content, since it has a higher natural moisture content, as well as a greater power of absorption of water compared to the soil.

From the results presented in Table 4, it was possible to observe that with the addition of 15% of WTP sludge to the soil there was a small decrease in MDD, this reduction being about 2.7% in relation to the soil. With the addition of 30% and 50% of sludge, the decrease was 3.16% and 6.11%, respectively, in relation to M1. It was also identified an increase in optimal moisture of about 7.7% and 15.62%, in the proper order of M2 and M4 in relation to the soil. That is, in the maximum dry apparent specific weight there was a tendency to decrease and in the optimal moisture content there was a tendency to increase, with an exception in this last criterion in M3 which was slightly lower than M2, but even so they were close values.

The results obtained in this research are in line with the results found by Delgado (2016). In his study, the author analyzed a clayey soil + 5% WTPS, presenting a behavior similar to that of this study: after the addition of 5% of sludge, there was a decrease of about 8% in the maximum dry apparent specific weight and an increase in the moisture content of about 32.4%, when compared to values obtained only from clayey soil. The same author also studied the percentages of 5%, 10% and 15% of sludge mixed with stone dust, even though they were not equivalent soils, the author also found a decrease in MDASW with increasing sludge in the mixtures. For the mixtures of 5% and 10%, he found equal optimum moisture content values and for the mixture of 15%, a higher moisture content than that found for the other two samples. This small variation of the optimum moisture content for M2 and M3 of the present research and the non-variation for 5% and 10% of the research by Delgado (2016) are justified by the heterogeneity of the WTPS.

According to Lucena (2012), the decrease in the maximum dry density and the increase in water absorption caused after the addition of sludge in the mixture is due to the mineralogical composition of the particles, because the sludge has a considerable surface area, its high void and for its porosity.

3.4 Simple compression strength tests

The unconfined compressive strength (UCS) tests followed the instructions described in the methodology, and the results are presented in Table 5. The soil presented an average UCS of 0.255 MPa for both 7 and 28 days of curing, which is consistent with the UCS of clayey soils. The replacement of soil by WTPS, in all mixtures, showed an increase in UCS compared to soil, and the best performance was presented by the mixture of 70% Soil + 30% WTPS, with UCS of 0.619 MPa, with an increase of 142.75% of average resistance superior to the soil. It is noteworthy that Knierim (2020) also found in her studies the same mixture presenting the highest resistance when compared to soil.

Mixture 2 presented 34.51% and 36.47% of average UCS above the soil for the ages of 7 and 28 days, respectively. M3 showed an average resistance of 56.47% above the soil for the 7 days. Finally, the mixture 50% Soil + 50% WTPS showed average strengths of 42.75% and 102.75% for 7 and 28 days, respectively.

It is noticeable, through Table 5, that with the increase in the curing time, there was also an increase in resistance for M2, M3 and M4. It is believed that this occurred due to the presence of some chemical material present in the WTPS.

Soil replacements by WTPS made it possible to increase SCS in the samples up to 30% replacement, while at 50% there was a decrease in relation to M3. This situation possibly occurred due to the different behavior of the WTPS, which tends to increase the friction between the particles and, consequently, increase the compressive strength of the samples. This fact is in line with the study by Knierim (2020), where the author found that the addition of WTP sludge in the mixtures tended to increase SCS compared to soil. And, in the highest proportion of WTPS, there was a small reduction in the parameter, but still remaining superior to the natural soil, as also occurred in this work.

3.5 Permeability tests

The permeability tests followed the instructions presented in the methodology, in order to determine the permeability coefficient of soil and soil + WTPS mixtures, for samples compacted at intermediate energy. The permeability coefficient values are presented in Table 6.

It is observed that the soil under study presented an average permeability coefficient (*k*) of $1.66E^{-8}$ m/s, which

Table 4. Chemical analysis of the mixtures under study.

Mixtures	Mixture 1	Mixture 2	Mixture 3	Mixture 4
Maximum dry density (g/cm^3)	1.521	1.480	1.473	1.428
Optimum moisture content (%)	28.3	30.48	29.98	32.72

according to Terzaghi & Peck (1967) represent soils with very low permeability (*k* from $1E^{-7}$ to $1E^{-9}$ m/s).

In the mixture 85% Soil + 15% WTPS, when substituting 15% of the soil for WTPS, there was a reduction in the permeability coefficient value of the mixture when compared to the soil. The average permeability coefficient was $1.71E^{-9}$ m/s; the mixture 70% Soil + 30% WTPS showed an average permeability coefficient of $2.44E^{-9}$ m/s; the mixture 50% Soil + 50% WTPS presented an average coefficient of $2.03E^{-9}$ m/s. All results found, for all mixtures, are characteristic of materials with very low permeability.

Although the WTPS presents a different behavior, it is believed that, in this case, the inclusion of the material in the soil caused a better intermeshing of the particles, reducing the permeability coefficient value and making the mixtures more impermeable compared to the natural soil. This occurred, possibly, because even with the decrease of the clay percentage, the silt percentage remained practically stable with the increase of sludge in the tests with deflocculant and this silt filled the lack of clay material, reducing the void index.

Knierim (2020) found permeability values that did not follow a linearity, where for 85% Soil + 15% WTPS the coefficient decreased in relation to the soil and increased for the other mixtures. These results are in agreement with the present research, and the difference in the results between the two studies was generated by the different granulometry of the sludge in each study.

3.6 Analysis of the technical viability of using the mixtures in bottom layers and final cover of sanitary landfills

In this item, we sought to analyze the application of the materials under study in bottom layers and in the final cover of sanitary landfills. For this, it was made a compilation of mandatory requirements, standards, and desirable, found in research. Requirements specified with "NBR" are from Brazilian Standards, from "USEPA" are from the United States Environmental Protection Agency and with "German" are from German standards. Then, due to the imposed conditions, a checklist was carried out to verify the possibility of application of each of the materials. To facilitate this analysis, the requirements were compiled in Table 7.

Regarding Table 7, the following analyzes can be made:

- Regarding the final covering layer, all mixtures complied with the permeability coefficient requirements of NBR and USEPA, however, none of the mixtures met the criteria of the German standard. In addition, all other requirements for percentage passing through sieve #200, liquid limit, plasticity index and USCS classifications were met.
- Regarding the bottom layer, all mixtures complied with the permeability coefficient requirements of the Brazilian standard, however, M1 did not respect the same requirement of the US standard and no mixture met the criterion of the German standard. In addition, all other requirements for percentage passing through sieve #200, liquid limit, plasticity index and USCS classifications were met.

Still, together with the results discussed, as well as the others obtained in the research, the following considerations can be made:

- The chemical analyzes carried out in this research showed that all materials tend to have kaolinite in their composition, causing no material to be prevented from being applied in layers of sanitary landfills due to possible expansion problems;
- The simple compressive strength of soil + WTPS mixtures showed improvement compared to soil. The best performance in this regard occurred in the mixture 70% Soil + 30% WTPS and, together with the requirements presented in Table 7, it is the most favorable for application in bottom layers and final cover of sanitary landfills;

It is important to highlight that, analyzing only the requirements of the Brazilian standard, the soil and all mixtures meet the minimum requirements of the same, therefore, being subject to use in the bottom layer and final cover of sanitary landfills. In this specific analysis, the material with the best performance is the mixture 70% Soil + 30% WTPS, for the following reasons: it meets the permeability coefficient and presents the highest resistance to simple compression among all mixtures.

It is also indicated the use of the materials under study as intermediate layers (daily), since there are no requirements and recommendations for these. Authors cited in the theoretical framework indicate the use of organic compounds, WTPS and Sewage Treatment Sludge for these layers, therefore, the use of mixtures (mainly the mixture 50% Soil + 50% WTPS)

Table 5. Average unconfined compressive strength test results for the mixtures.

Mixture	Time of curing	UCS (MPa)
M1 (100% Soil)	7 days	0.255
	28 days	0.255
M2 (85% Soil + 15% WTPS)	7 days	0.343
	28 days	0.348
M3 (70% Soil + 30% WTPS)	7 days	0.399
	28 days	0.619
M4 (50% Soil + 50% WTPS)	7 days	0.364
	28 days	0.517

Table 6. Permeability coefficient of the mixtures under study.

Mixture	*k* (m/s)
M1 (100% Soil)	$1.66E^{-8}$
M2 (85% Soil + 15% WTPS)	$1.71E^{-9}$
M3 (70% Soil + 30% WTPS)	$2.44E^{-9}$
M4 (50% Soil + 50% WTPS)	$2.03E^{-9}$

Table 7. Verification of the mixtures under study for use in layers of sanitary landfills.

	Parameter	Condition for application	Requirements		Material / Application Verification			
			M	D	M1	M2	M3	M4
Final cover layer	*k* (NBR) [m/s]	≤ 5×10^{-7}	X		YES	YES	YES	YES
	k (USEPA) [m/s]	≤ 10^{-7}	X		YES	YES	YES	YES
	k (German) [m/s]	≤ 5×10^{-10}	X		NO	NO	NO	NO
	SP#200 (USEPA) [%]	≥ 30	X		YES	YES	YES	YES
	SP#200 [%]	≥ 40		X	YES	YES	YES	YES
	LL (USEPA) [%]	≥ 30	X		YES	YES	YES	YES
	LL [%]	≥ 30		X	YES	YES	YES	YES
	PI [%]	10 a 50		X	YES	YES	YES	YES
	USCS	CL/CH/SC/OH		X	YES	YES	YES	YES
Background layer	*k* (NBR) [m/s]	≤ 10^{-8}		X	YES	YES	YES	YES
	k (USEPA) [m/s]	≤ 10^{-9}	X		NO	YES	YES	YES
	k (German) [m/s]	≤ 10^{-10}	X		NO	NO	NO	NO
	SP#200 [%]	≥ 30		X	YES	YES	YES	YES
	LL [%]	≥ 30		X	YES	YES	YES	YES
	PI [%]	≥ 15		X	YES	YES	YES	YES
	USCS	CL/CH/SC/OH		X	YES	YES	YES	YES

k: permeability; SP: sieve pass; LL: liquid limit; PI: plasticity index; M: mandatory; D: desirable.

would be beneficial, due to the reduction the exploitation of natural resources (soil) and the reduction of environmental liabilities with the use of WTPS.

4. Conclusion

The classic results of Soil Mechanics characterized the soil as a clayey material. Still, in the WTPS additions to the soil, it was noticeable, with the increase of substitution, a reduction in the fractions of silt and sand, and an increase in clay and gravel. The inclusion of WTPS, in terms of consistency, made the mixtures even more plastic. The real specific weight of the soil grains is within the lateritic clayey soil standard, and as the percentage of WTPS in the soil increased, there was a reduction in the parameter, due to the low real specific weight of the sludge grains.

In specific to the chemical analysis of the soil and mixtures, it is highlighted that all presented kaolinite and illite, non-expandable and partially expandable clay minerals, respectively, so that no material was prevented from being applied in layers of sanitary landfills due to the low possibility of expansion problems.

In relation to the results obtained in the compaction test of the materials under study, it could be seen that the greater the addition of WTPS to the soil, the greater the decrease in the value of the maximum dry density. In addition, there was an increase in the optimal moisture content found with increasing sludge content in the soil. This situation can be credited to the low real specific weight of the grains of the mixtures.

The permeability test showed an increase in the impermeability of the mixtures, being beneficial in terms of application in engineering works. The permeability coefficient of the soil and mixtures was in the order of $1E^{-9}$, characterizing the materials as having high impermeability.

Regarding the mechanical tests, from the unconfined compressive strength tests, it was possible to conclude that there was an increase in resistance with the increase of sludge in the mixtures, and the mixture that presented the highest SCS was 70% soil + 30% WTPS at 28 days, with a resistance 142.75% superior to the soil.

In general terms, following ABNT NBR 13896 (ABNT, 1997), which defines the criteria for non-hazardous waste landfills, the mixture composed of 70% Soil + 30% WTPS was defined as the best for application in base layers and covering of landfills for meeting the permeability coefficient and presenting the highest Simple Compression Strength among all mixtures. However, the other mixtures (85% Soil + 15% WTPS and 50% Soil + 50% WTPS) could also be used, contributing to a circular economy and to Environmental, Social and Governance (ESG), a term used to refer to the what companies and entities are doing to be socially responsible, environmentally sustainable and managed correctly.

In addition, it is noteworthy that the use of mixtures, especially 50% Soil + 50% WTPS, in daily (intermediate) layers would be a sustainable alternative that cooperates to achieve Sustainable Development Goals 11, 12 and 15 of the United Nations United until 2030. The co-disposal of sludge is presented as a gain for the management of this waste, mainly for small WTPs, since, once its potential is observed, the stations can use this technique, minimizing the volume of waste that could be sent to the sanitary landfill, as well as avoiding the implementation of more costly technologies.

It is also noteworthy that the sludge showed excellent characteristics for other applications in specific quantities in geotechnics such as base layers, sub-base, subgrade reinforcement and landfills in general. There is the possibility of quantifying the sludge from the WTP, for tokenization (process by which an asset gains a digital representation) and generation of recycling credits in the Bitcoin Market, contributing to a better destination of this residue and to the generation of revenue for the Water Treatment Station. In addition, mixtures with sludge accelerate the decomposition of waste and increase the production of methane in landfills (Granato, 2010), thus, projects that perform the clean burning of methane can increase the tons burned, generating even more carbon credits and electricity, clean and renewable during firing, consequently also producing higher revenue.

These applications would bring advantages in the destination of WTPS and reduction of consumption of natural resources (soil). In this way, the benefits and importance of an adequate disposal of sludge in geotechnics are evident, in order to avoid environmental liabilities generated by this residue, in addition to acting in an innovative, technological and sustainable way, minimizing the use of natural resources with economically efficient solutions, profitable and environmentally advantageous in engineering works.

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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

Elisangela Aparecida Mazzutti: data curation, formal analysis, investigation, visualization, writing – original draft. Rodrigo André Klamt: conceptualization, data curation, funding acquisition, resources, methodology, supervision, validation, writing – original draft. Vítor Pereira Faro: methodology, project administration, supervision, validation, writing – review & editing.

Data availability

All data produced or examined in the course of the current study are included in this article.

List of symbols

k	Permeability
A-4	Low compressibility silty material
A-7-5	Silty clay material with moderate Plasticity Index
CEC	Cation Exchange Capacity
FW	Frederico Westphalen
LL	Liquidity Limit
MH	Medium to High Plasticity Silt
ML	Low Compressibility Silt
NP	Not Plastic
OH	Medium to high plasticity organic clay
PH	Hydrogen potential
PI	Plasticity Limit
PL	Plasticity Index
RS	Rio Grande do Sul
SC	Clayey Sand
SP	Sieve Pass;
TRB	Transportation Research Board
UCS	Unconfined compressive strength
USCS	Unified Soil Classification System
USEPA	United States Environmental Protection Agency
WTPS	Water Treatment Plant Sludge
WTS	Water Treatment Stations
γ_s	Unit weight of soil particles;

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