Water Treatment Sludge as Geotechnical Liner Material: State-of-Art

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Water Treatment Sludge as Geotechnical Liner Material: State-of-Art

Leonardo Marchiori, António Albuquerque, and Victor Cavaleiro

Abstract The periodical cleaning of the decanters at the plant generates solid wastes called water treatment sludges (WTS), a chemical compound similar to aluminum silicates. WTS's properties have been studied for geotechnical purpose and it seems to be suitable for producing liner materials for landfills, dams, ponds, and lagoons which store and prevent soil's infiltration of residues. Liners are usually shaped of soil and geosynthetics, their main properties required are compaction, compressibility and shear strength, chemical compatibility, and hydraulic conductivity. WTS to be considered as a soil substitute, it must be function like a soil, thus, for developing alternative materials, physical, chemical, mechanical, and hydraulic characterization laboratorial parameters are the first step to make viable its reuse. In this sense, the study aims to review the literature over the above-mentioned parameters in order to evaluate WTS as liner material. This review concluded that WTS have high heterogeneity in chemical and mechanical behavior due source of water and treatment processes. WTS' water affinity affects plasticity behavior, and its incorporation into soils seems to contribute for a composite with pozzolanic characteristics, low specific gravity, finer granulometry, and mechanical stabilization. Although need attention on its chemical compatibility, the influence on shear resistance—increasing internal effective friction angle and decreasing cohesion—and the optimum ratio of introduction within soils for an alternative liner material. Nonetheless, there are lacks in literature over hydraulic conductivity, and long-term behavior, the use of the material in practice must be preceded by pilot tests or experimental landfills.

Keywords Water treatment sludge · Liner · Geotechnical material · Waterproofing · Review

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1 Introduction

Water treatment plants (WTP) operations basically consisting of capture, chemical coagulation, flocculation, decantation, filtration, and disinfection of the water, natural or residual, several minerals are used on that process, as Ca, Mg, Na, K, Fe, chlorides, nitrates, and nitrites. Cornwell [1] developed WTS estimative for WTP that use alum or ferric coagulant for the removal of suspended solids, the sludge production (S) can be estimated along plant flow (Q) in ML/d and quantities in mg/L of alum (Al) or iron (Fe) coagulant, suspended solids (SS) and additional chemicals (A) as polymer, clay, lime and activated carbon, by (1) and (2), respectively:

$$S = Q \times (0.44\mathrm{Al} + \mathrm{SS} + \mathrm{A}) \tag{1}$$

$$S = Q \times (0.29\mathrm{Fe} + \mathrm{SS} + \mathrm{A}) \tag{2}$$

Its chemical and mineralogy are basically compound for silica around 20%, aluminum 60%, and iron 5%, looking similar to aluminum silicates [2–4]. These chemical compounds are derived from the coagulants, principally aluminum sulphate ($Al_2(SO_4)_3$) and ferric chloride ($FeCl_3$), and also from alkalizing or acidifying agents to control the water pH. WTS is characterized by a black slurry due activated carbon in water treatment processes. According to Kyncl [4], WTS sludge can be divided in several types: caught in trash-racks; saline water from ion exchange recovery; wastewater produced in preparation of chemicals; polymeric flocculant clarification sludge; decarbonization sludge; sludge from removal of iron and manganese from groundwater; filter washing slurry; and the most common from floc suspensions of iron and alumina oxides from settlement tanks and clarifiers, the last one contains much water and it is called alumina sludge. The water industry produces daily tones WTS, in which a single water treatment plant WTP produces approximately 100,000 ton/year [5], its disposal costs are around US$100/ton [6]. Their disposal methods are in sanitary landfills, discharging into steams and ocean barging and being reutilized in sewage treatment plants.

WTS's properties seem to be suitable for producing liner materials [7] and for reinforcing weakened clay soils [8, 9], other studies evaluated lime sludge and concluded as possible fill material for road construction, moreover the sludge is used for phosphorus removal in wastewater treatment and for cement production as admixtures [4]. Dehydrated and treated, chemically or incinerated, sludges and muds from WTP also have the potential to be alternative materials for liners instead of clays [10] with a severe attention for its hazardousness especially for residual water and mainly because of its permeability, compaction, durability, and workability in constructions [2], so, a more sustainable destination for WTS is its use in earthworks and as landfill lining. However, due to its high-water content and plasticity, the investigation of WTS's workability in construction procedures is mandatory. United Nations (UN) directive [11] established sustainable objectives for the future, thus, the valorization of WTS within soils for reinforcement and liner application minimize the waste disposal problem, while at the same time moving the society towards a more sustainable future. In addition to an environmentally friendly approach, following the circular economy principles, it seems to be cheaper than current solutions that extract natural materials and generate more waste in synthetics industry.

WTS geotechnical properties have been studied for the past decades and summarized by Roque da Silva [12] as cover and bottom for industrial and sanitary landfills and road pavement sub-bases and bases, containment structures, embankments, and trench filling; in construction industry as ceramic material and as aggregates for mortars and cementitious elements; and in sanitation as coagulant and pollutant control in sewage treatment. Ahmad et al. [13] encouraged recovery, recycling and reuse of sludge called 3 R's conception, reviewing the abovementioned applications, for coagulant recovery; despite having a lower cost and reducing disposal, it requires complex and limited laboratory recovery.

It also shows to be efficient in removing heavy metals and turbidity, but it has high costs, the use as adsorbent is efficient for P removal, but it needs studies for other elements. For substrate in wetlands, it improves the removal of P and N, however it still needs investigation, and as sewage dewatering has improved its consolidation and dewatering, but it still has high costs and logistics problems. In addition, for cement production, its chemical composition and cementitious properties are similar to cement but implicate a retardation of settling and add deleterious components affecting mechanical properties, therefore it can generate lightweight aggregates or even suiting for non-structural concrete as sand, although requiring high temperatures which can pollute, reduce compressive strength and increase water retention. And, at last, for agriculture purpose, it improves soil aggregation, water permeability, but it is a risk of metal accumulation.

For these applications, the main properties required are compaction, compressibility and shear strength, chemical compatibility, and hydraulic conductivity, Dayton and Basta [14] concluded that for a WTS to be considered as a soil substitute, it must be function like a soil, thus, for developing alternative materials, physical, chemical, mechanical, and hydraulic characterization and knowledge about geotechnical parameters are the first step to make viable the reuse of WTS. Besides, for an adequate environmental characterization, solubilization and leaching tests are methods used for classification and diagnosis for quantification of the transferred material to environment, solubilization is a dissolution mechanism of a given material in water, and leaching is the potential transference of organic and inorganic substances through the material.

1.1 Bibliometric Analysis

This research was done in 3 of the main databases for bibliometric and data analysis, Google Scholar, Scopus and Web of Science, for title, abstract and keyworks, the search was performed using Boolean OR, keywords truncated as it follows: "water treatment sludge*" OR "water treatment residu*" OR "alum sludge*" OR "waterwork sludge*" OR "waterwork residu*" was searched and resulted in 7310, 1769 and 1512 scientific works, for Google Scholar, Scopus and Web of Science, respectively. Publications started since 1970 and showed a growing relevance of the subject in recent years, this research was carried out with the aim of designating and characterizing the studied residue. The main subjects are from Environmental Science and Engineering with more than half of the works, corroborating the relevance for the studied area.

When combining the above-mentioned with other keywords, using Boolean AND, separately, for "characteristic*, "production", "quantities", looking to evaluate the main parameters when analyzing WTS. However, to search deeper into the area of research, again with Boolean AND, separately, for "landfill*", "wetland*", "liner*", "earthwork*", and "pond*". For landfilling and constructed wetlands, there are more works comparing to liners and earthworks, and even more for stabilization and mining ponds.

The most frequent keywords of the downloaded data in Scopus around WTS were performed with a bibliometric analysis software "VOSviewer" (https://www.vosviewer.com accessed January 2022) while version 1.6.17 was used in this study. VOSviewer is a software tool specifically developed for building and viewing bibliometric networks, built based on keyword co-occurrence, sources, bibliometric coupling, co-citation, or co-authorship relationships. Items are presented in Fig. 1 as circles for viewing, while their sizes depend on the importance of each term.

2 Geotechnical Characteristics

WTS physical characteristics are directly involved with understanding of the material state, liquid or solid, because of its high moisture content and its use when dehydrated. The WTS liquid phase is composed by free water, not associated with solid particles and which surrounds the solid residue; interstitial water, between molecular structure voids; capillary water, maintained by surface tension; and the hydration water when the positive pole of the water molecules approaches the negative charges of the WTS colloids [15]. The relationship with water has an important factor in WTS properties, [15] observed WTS subjected to dry–wet (D–W) and freeze–thaw (F–T) cycles and its plasticity decrease, grain size increase and greater undrained shear strength along cycles. Due moisture content and compaction method affects hydraulic conductivity and shear strength, WTS sample water content and interaction must be very carried analyzed.

The granulometry difference between WTS samples is determined by the nature of particles in the water, and coagulation, flocculation, and sedimentation efficiency, in addition to removal techniques [16], the weather station at the time of sampling, and the initial moisture of the sample [17]. The specific gravity depends mainly on the mineralogical composition, generally the WTS present values lower than 2.70–2.85 [17], typical values for clay minerals.

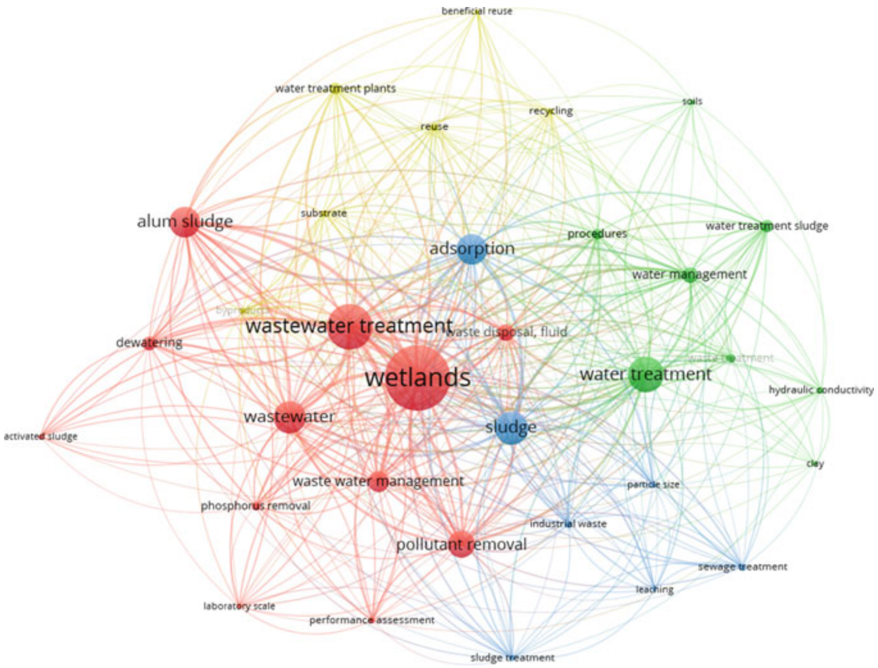

Fig. 1 Keyword co-occurrence net by VOSviewer

WTS have high water content and usually plasticity due affinity of alum for water and sometimes very low specific gravity comparing to soils, value below 2.0 [18], but some studies found WTS' plasticity varying abusively with IP values around NP-670 [15], mostly in natural samples show plastic behavior, like fine-grained soils, and dehydrated present granular and non-plastic characteristics. According to Basim [15], water content variation is the greatest cause in geotechnical properties impacts, altering its floc structure, particle size and ion concentration and complex formation. Besides, [15] concluded an influence of age and weather in WTS samples, fresh and new ones have high plasticity comparable to montmorillonite, however when subjected to weathering, they lost plasticity and water affinity, also showed differences in several parameters such as density, shear strength and consolidation parameters. Another factor that impacts plasticity is F–T cycles, Basim [15] found plastic samples becoming non-plastic when imposed to one or more cycles and referred this change of plasticity and granulometry due dehydration because of cementitious action of the colloids and binding properties due calcium, iron, and aluminum oxide presence and [18] attached this significant plasticity decrease due alum is a precipitating agent. If needed, plasticity can be altered by anti-plasticizer as micas, sands, or coal fly ashes [16].

Table 1 was design by the author reviewing literature's index properties to illustrate the difference between WTS explaining divergent processes of treatment and chemical composition of the water utilized, the data are ordered from the highest GS to the lowest, including their respective plasticity limit values, liquidity and consequently their plasticity index, the variance is explicit according to the material worked and the dewatering technique already portrayed, with very high plasticity indexes to non-plastic for samples with the same specific density range.

Table 1 Physical properties

References	G_S (−)	W_L (%)	W_P (%)	PI (%)
Montalvan and Boscov [21]	2.9	239	81	158
Silva and Hemsi [22]	2.8	228–156	85–75	154–71
Zekkos et al. [23]	2.7	38	32	6
Gonçalves et al. [24]	2.7	–	NP	NP
Basim [15]	2.7–1.7	690–53	228–NP	670–NP
Dąbska [25]	2.8–2.7	63–58	41–34	31–17
Shah et al. [26]	2.8	55	21	34
	2.7	54	27	27
	2.6	48	28	20
	2.6	42	29	13
	2.6	40	30	10
	2.5	43	NP	NP
Scapin et al. [27]	2.7	40	20	20
	2.6	42	30	12
	2.6	43	36	7
	2.4	–	NP	NP
	2.5	–	NP	NP
Montalvan [17]	2.4	536	236	300
Roque da Silva [12]	2.4	536	236	300
Dehydrated		–	NP	NP
O'Kelly and Quille [28]	2.0–1.8	550–430	325–240	290–105
O'Kelly [18]	1.9	490	240	250
Arulrajah et al. [29]	1.8	110	80	30
Aydilek et al. [30]	1.8	–	NP	NP
Wolff et al. [16]	–	79	57	22
Bağrıaçık and Güner [31]	–	98	45	53
Machado and Müller [32]	–	–	NP	NP

3 Chemical, Mineralogical and Morphological Composition

According to Bashar [2], WTS has almost 70% similarity in chemical composition with clayey soils. Caniani et al. [19] noticed the presence of hydroxides, originated from coagulating agents, colloids, organic matter, and inorganic precipitates, meanwhile does not show substances that could be dangerous for the environment. The main oxides of WTS are alumina (Al_2O_3), silica (SiO_2) and iron (Fe_2O_3), varying its percentage due methodologies and coagulant utilized in water treatment processes, the one with higher alumina, indicates aluminum coagulant, and others which used ferric coagulant have higher iron content, high silica (SiO_2) content can create the possibility for pozzolanic activity, and Wang et al. [20] stated that in consolidation tests, pozzolanic reaction may depress the diffuse double layer and causing dispersion flocculating as result of free water drainage. The amorphous and porous nature of Al and Fe hydroxides makes the sludge a possible adsorption site for majority of anions [13].

In general, studied WTS that have neutral or acid pH due mostly to very low organic matter in its composition, and slightly alkaline when have addition of chemicals and conditioning during treatment processes [28]. pH is important because it affects the leaching of metals and the biodegradation of organic matter [17]. Gonçalves et al. [24] considered higher organic carbon and organic matter content in WTS than in clayey soils, as the material contains a concentration of elements found in the soil and, eventually, algae and bacteria from the water. Basim [15] concluded that W–D or F–T cycle have no impact in organic matter content, and chemical analysis, elemental or in oxides. Usually, it has high loss on ignition (LOI), between 40 and 60% [28], that is related to clayey mineral, hydroxides, and organic matter [16]. Rodríguez et al. [33] referenced heavy metals presence habitually observed in concentrations much lower than the minimum values allowed but need a rigid analysis both from the sludge and the treated water, as they may have been contaminated with precipitates or pollutants.

Mineralogy and chemical compositions differences among calcium, aluminum and iron sludges are expected to influence the physical, chemical, and geotechnical characteristics of the sludge [23]. Clayey minerals presence can impact several WTS's properties as plasticity, shrinkage or swelling, cohesion and cation exchange capacity, consequently compaction and consolidation characteristics. Presence of organic matter and heavy metals in WTS composition consequently decrease and increase specific gravity, respectively [15], thus, leaching is not a concern for groundwater and soil contamination [23], such as heavy metals that are below international limits [34].

Ahmad et al. [5] found through x-ray diffraction (XRD) tests an absent well-crystalline phase and thus considering WTS having amorphous structure. Diffractogram studies indicate mainly quartz (SiO_2), large amounts for alum sludge [34], and others clayey mineral such as kaolinite, calcite, muscovite, chlorite, gibbsite, goethite, and micas, explained by the water source bedrock. For the crystalline phase, the Al_2O_3 content was associated with kaolinite ($Al_2Si_2O_5(OH)_4$) and gibbsite ($Al(OH)_3$), Fe_2O_3 with hematite (Fe_2O_3), magnetite (Fe_3O_4) and goethite (FeO(OH)), and SiO_2, to quartz, present among the suspended solids in raw water [12]. Ahmad et al. [13] found that aged sludge exhibited similar XRD characteristics to fresh sludge indicating that the crystallization did not occur during the ageing process. WTS presented metakaolin, a highly reactive pozzolan material, obligatory when calcinated in its crystallography, [34] classified alum sludge as Class N (natural) pozzolan material due viable replacement in concrete. Lime (CaO), when present or added, leads to three types of chemical reactions, first cation exchange with an immediate reduction in plasticity, second, carbonation, a reaction that originates calcite ($CaCO_3$), and pozzolanic reactions [35]. Calcite and graphite (C) explain lime as coagulant and high LOI [16], related to the decomposition of organic matter. Amorphous material is usually related to humid compounds and aluminum/iron oxides and hydroxides.

Table 2 synthesize chemical characteristics of WTS, it demonstrates the difference in the percentages of aluminum, silica, and iron oxides, respectively, ordered by the largest amount of Al_2O_3 as it is an important component for liner production, these discrepancies show the coagulants used in the process of water treatment, these sludges are differentiated between alum or ferric sludge, and according to [22] both can contribute to geotechnical properties. Furthermore, it shows the difference between cation exchange capacity (CEC), pH and organic matter percentages for studied sludges, properties of importance regarding chemical compatibility due ability to hold positively charged ions when acting as liner. Also, [3] concluded that CEC is proportionally inversed to mineral grain size particles, the more clayey the soil, the lower its CEC, high CEC denote potentially high holding capacity of contaminants.

Table 3 summarized that typical mineralogy when all studied WTS presented quartz, most kaolinite, some muscovite and other in lower quantities gibbsite, goethite, and calcite, among others uncommon minerals.

Along with crystallography, elemental and oxides composition, the morphology of the composites can help distinguish elements distribution through the sample, scanning electron microscope (SEM) is the normally used methodology, SEM analysis for WTS identify it as a filling material into soil incorporation, providing a finer granulometry and more homogeneous mixture, which corroborate the particle size distribution [36]. An example of SEM image is showed in Fig. 2.

4 Mechanical Resistance

Compaction standards using Normal or Modified Proctor proved to be very difficult due a very dense block of material is formed when WTS is by itself, having no workability [12, 39] that explains mixtures with soils. Shah et al. [26] concluded that by incorporating WTS in soil as stabilizer can reduce field compaction effort and costs. Wang et al. [20] found unusual shape of compaction curves for WTS by itself, showing no optimum values, the dry density increased along with higher water

Table 2 Chemical properties

References	Al_2O_3 (%)	SiO_2 (%)	Fe_2O_3 (%)
Coelho [3]	60	25	5
Shah et al. [26]	38	29	15
Montalvan [17]	37	4	17
Gomes Ramirez et al. [37]	35	42	5
Thermally treated [37]	42		
Roque da Silva [12]	30	5	12
Wolff et al. [16]	30	38	1
de Godoy et al. [38]	27	52	12
Gomes Ramirez et al. [37]	25	27	18
Rodríguez et al. [33]	18	30	5
Ahmad et al. [5]	14	53	5
Montalvan and Boscov [21]	9	18	46
Basim [15]	8–28	7–11	3–14
Bağrıaçık and Güner [31]	2	16	48
References	CEC (meq/100 g)	pH (–)	OM (%)
Dayton and Basta [14]	56.5–13.6	5–8	1–15
Montalvan [17]	32.5	7	2
Montalvan and Boscov [21]	25.5	7	3
Gonçalves et al. [24]	8.9	5	3
Roque da Silva [12]	7.3	6	27

contents, although when mixed with sandy soils or lime the one-hump compaction was obtained, concluding that when upon drying, particles attract strongly together forming flocs and when dried and rewetted, it loses its cohesion behaving like granular material. This one-hump compaction curve was also obtained by [15] utilizing wet to dry method, diverging from the usual dry to wet method, logically explained due WTS's high water content and difficult workability. [12, 17, 18, 40] tested mixtures with different ratios of WTS incorporating sandy and clayey soils and presented maximum dry unit weight decreasing and optimum water content

Table 3 Mineralogical properties

References	Quartz	Kaolinite	Muscovite	Gibsite	Calcite	Goethite
Gonçalves et al. [24]	✓	✓	✓	✓		✓
Montalvan and Boscov [21]	✓	✓	✓			✓
Montalvan [17]	✓	✓	✓	✓		✓
de Godoy et al. [38]	✓	✓	✓			
Bashar et al. [2]	✓	✓				
Roque da Silva [12]	✓	✓		✓		
Gomes Ramirez et al. [37]	✓	✓				✓
Basim [15]	✓				✓	✓
O'Kelly [18]	✓				✓	
Wolff et al. [16]	✓			✓		
Rodríguez et al. [33]	✓				✓	
Machado and Müller [32]	✓					

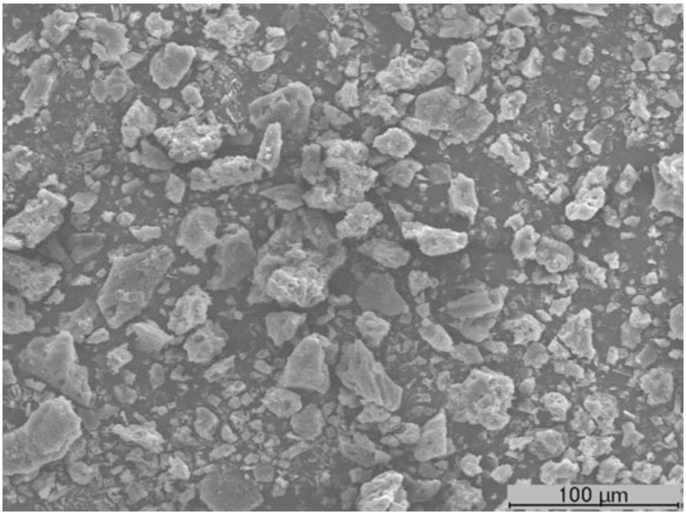

Fig. 2 SEM of WTS

increasing with increasing WTS content, explained by the increment in fines due WTS' fine granulometry.

Mixtures can be an effective way to valorize WTS for soil amendment, [24] tried 35% and 50% amount of WTS with clayey soil, and 20% with sandy soil, for waterproofing barriers layers reaching acceptable compaction characteristics, other authors [17, 26, 27, 32] mixed clays and sands in ratios between 2 and 50% and tested compaction searching for incorporation as liners materials, bottom and top layers, soft soils reinforcements or just to improve geotechnical properties of soils.

Wang et al. [20] found similar consolidation behavior to treated and untreated, but initial void ratio lower for treated ones, attributable to the decreased water content within additives, although both resulting high compression indexes and recompression very low due its dispersive structure, most WTS's Cc values are between 0.20 and 0.50 and Cs among 0.01–0.07. Hydraulic conductivity from oedometer tests decrease along with void ratio, according to [30] when comparing to natural clays, WTS have higher consolidation rate and permeability due high-water content, explaining the k-void relationship.

The WTS are highly compressible, [28] consolidation test program concluded for WTS, that primary consolidation occurs due to dissipation of excess pore pressure and it was dominant during the early load stages, and the secondary compression due to the realignment of the solids became increasingly dominant at higher stresses as consequence to the significant reduction in the hydraulic conductivity, several authors noticed that WTS generated a certain amount of gas, which interfered and sometimes prevented the consolidation process due to test long duration. Anisotropic consolidation aims to reproduce more realistic field conditions, as it is known that the stress state in the field is generally anisotropic, although triaxial tests with isotropic densification are more widespread [17].

Studies [31] resulted in an optimum mixing ratio of 10% of WTS increasing the bearing capacity of clay soil by 1.69 times along with an optimum reinforcement thickness of height/diameter (H/D) = 2.25, furthermore found consolidation settlements decreased by up to 62%, probably due high amount of silica minerals that becoming a gel which connect the soils' grains blocking voids and consequently increase the bearing capacity.

For liner simulation, consolidated undrained (CU) triaxial tests are performed and according to [18], WTS' shear resistance is enhanced firstly by the aggregation of the clay particles into larger flocs and the deactivation of water by the alum, and secondly by the binding together of these flocs into clusters by the long-chained polyelectrolyte molecules. Wang et al. [20] tested untreated WTS in CU triaxial compression and it behave as a consolidated soil with high sensitivity explained for its high plasticity, and high friction angle, literature φ' values are mostly 35–45°, low shear strength and cohesion, [41] reported φ' values for alum WTS are high compared with the values generally associated with high-plasticity organic clays as montmorillonite. Basim [15] determined an increase relationship between compressive strength and solids content, characteristic of normally consolidated clay [18]. Also, [18] attached the failure line that best-fit WTS was through the origin ($c' = 0$). For practical analysis, undrained shear strength (Su) is taken as half the maximum deviator stress in triaxial cells. For waste landfills, undrained shear strength must be more than 40 kPa [17].

Additionally, [20, 42] concluded that samples of WTS are thixotropic, a phenomenon of reversible time-dependent decrease of viscosity, namely when it is sheared for some time, the viscosity decreases, however, when the shear is stopped, the viscosity of the system is restored, the undrained shear increased five times since the immediate measure, although remain needs treatment to achieve adequate shear strength. There is a significant variation in the undrained shear strength according to water content, alum WTS tends to have marginally higher shear strength values than iron WTS [41].

Tests on WTS were conducted with a comprehensive investigation into the use of lime sludge, which use lime as coagulant, in unconfined compressive strength (UCS) and the retraction behavior of commercially available kaolinite clay, different ratios were added to kaolinite by the dry weight of the clay and showed that, with the increase of WTS content, the UCS value increased initially, followed by a slight decrease, an increase in the curing period resulted in an increase in the resistance to UCS, in addition, an increase of WTS led to a reduction in the shrinkage potential. Basim [15] found a relevant difference in sampled drying conditions, for dry to wet condition, Su and dry density decreased when moisture content increased, and for wet to dry, the opposite relation, Su increased with w until certain value, then Su decreased. Furthermore, [22] found an exponential relationship between Su and solid contents (s) for WTS through (3):

$$S_u = 0.018 \times \left(e^{13.5s}\right) \tag{3}$$

Table 4 presents mechanical parameters like optimal values of compaction, moisture, and dry specific weight, for WTS and WTS-soil mixtures within the mixture's percentages, either with clays or sands, for laboratory tests using standard or modified compaction. Data are ordered to evaluate the sludge in its purest state, thus WTS ratio decrease. Optimum moisture content are mainly around 15–35%, although according to dehydration method of samples, it can rise to 160%, when WTS compaction parameters are analyzed from dry to wet, it behave like a soil within one-hump compaction curve reaching 15–35% values, besides that when treated the opposite way, wet to dry like usually it's done for soils, compaction curve are more like a linear progression linked with higher values for moisture content [18, 20]. Also summarized consolidation and compressibility parameters as compression and swell coefficients (Cc and Cs, respectively), in order of least compressive samples, lower to higher Cc values, and the conclusion is when adding WTS compacted mixtures were more compressible than the soils. More WTS content results in higher compressibility of the mixtures, such behavior was expected since WTS addition causes reduction of dry unit weight and increases plasticity [17]. Additionally, it gathered the values of cohesion and friction angle organized by decreasing WTS percentages, reducing the amount of sludge in the mixtures, thus, it was possible to observe that increasing WTS in the soils' mixtures, the cohesion decreased, and the friction angle increased, corroborating with other studies justified by WTS' loss of plasticity, decreasing cohesion, and increasing strength by filling voids due to its fine portion. Furthermore, Wang et al. [20] concluded that this strength can be achieved by enhancing density by consolidation and/or compaction.

Table 4 Mechanical properties

References	wopt (%)	ρd, opt (g/cm^3)	WTS ratio (%)	Mixture
Dąbska [25]	29–38	1.3–1.4	100%	–
Fei et al. [23]	30	1.4	100%	–
Silva and Hemsi [22]	38	1.4	100%	–
Arulrajah et al. [29]	50	0.9	100%	–
O'Kelly [18]	160	3.6	100%	–
Gonçalves et al. [24]	33	1.4	35%	Clay
	32	1.5	50%	
	15	1.8	20%	
				Sand
Scapin et al. [27]	27	1.4	15%	Clay
	34	1.3	25%	Clay
	36	1.3	35%	Clay
	48	1.1	50%	Clay
Montalvan and Boscov [21]	12–17	1.7–1.9	20%	Sand
Machado and Müller [32]	16	1.8	5%	Clay
	20	1.7	20%	Clay
Shah et al. [26]	18	1.7	2%	Clay
	18	1.8	4%	Clay
	17	1.8	6%	Clay
	18	1.8	8%	Clay
	18	1.8	10%	Clay
	17	1.7	12%	Clay
References	Cc (–)	Cs (–)	WTS ratio (%)	Mixture
Montalvan [17]	0.1	0.02	5%	Sand
	0.2	0.03	6%	
	0.3	0.04	7%	
	0.4	0.05	8%	
	0.5	0.07	11%	
O'Kelly and Quille [28]	0.10–0.80	0.01	100%	–
Montalvan and Boscov [21]	0.13	0.02	20%	Sand
Roque da Silva [12]	0.21	0.06	15%	Sand
	0.16	0.03	20%	
	0.22	0.04	25%	
O'Kelly [18]	0.20–0.28	0.04–0.06	100%	–
Aydilek et al. [30]	0.20	0.06	100%	–
Fei et al. [23]	0.54	0.03	100%	–

(continued)

Table 4 (continued)

References	wopt (%)	ρd, opt (g/cm^3)	WTS ratio (%)	Mixture
Arulrajah et al. [29]	0.56–0.64	0.04	100%	
References	c′ (kPa)	φ′ (°)	WTS ratio (%)	Mixture
O'Kelly [18]	0	39	100%	–
O'Kelly and Quille [41]	0	39–44	100%	–
Arulrajah et al. [29]	1–23	33–40	100%	–
Basim [15]	0–36	16–35	100%	–
Roque da Silva [12]	6	38	15%	Sand
	13	35	20%	
	6	38	25%	
Montalvan [17]	12	38	15%	Sand
	6	39	20%	
	10	38	25%	
	14	36	35%	

5 Hydraulic Performance

Gonçalves et al. [24] mixed dehydrated WTS with clayey and sandy soils reaching satisfactory k after compaction showing viability for landfill liner material. Low permeability is due to the $Al(OH)_3$ present in the WTS [20] and also associated with the microstructure of the sludge flocs [18]. Gonçalves et al. [24] observed that mixtures with soil: WTS ratios of 1:0.25, 1:0.5 and 1:1 presented k in between 10^{-8} and 10^{-7} cm/s, suitable for use in landfill works as low permeability materials, furthermore, highlighted that the WTS' gravel granulometry did not significantly change the permeability of the soils in the mixtures, since this was noticeably reduced during the compaction process, the clods of the WTS were broken when compacted.

Bentonite is a clay mineral from the group of montmorillonites widely used in geotechnical works due to its low permeability, [32] tested the permeability of bentonite-WTS mixtures and found a reduction up to 10^{-2} cm/s, finding minimum values for barriers (10^{-7} cm/s) when increasing the sludge ratio by 20%, in short, the replacement of bentonite by WTS can be seen as a benefit due to the reduction of mineral extraction and production impacts without loss in hydraulic performance. A study over influences of WTS' hydraulic conductivity [25] measured long-term performances and showed k values increasing when with NaOH and HCl solutions and decreasing with tap and distilled water, and an important and practical reduction when measured with waste leachate, reaching 10^{-7} cm/s of permeability while water content around 25–35% and compaction degree between 95 and 105% as requirement.

Triaxial permeability tests are another effective way to obtain the hydraulic conductivity, but attention is needed during procedure, [17] indicated that lack of initial saturation would cause permeability to increase rather than to decrease over time, caused by a possible migration of colloids inside the sample, eventually causing partial clogging, consequently reducing flow rate, other possibility stated was clay's particle dispersion while internal swelling. Thus, the main cause of permeability and flow rate changes when under stress are particles migration, void ratio redistributions and clogging, physical, biological, and chemical.

The hydraulic conductivity (k) is usually determined using standard or modified Proctor compaction energy and measured in rigid wall permeameters using falling head testing. Although, [18, 20] established in consolidation tests through oedometer a relation valid for void ratio (e) values between 7 and 17 for hydraulic conductivity through (4):

$$k = \left(2.13 \times 10^{-15}\right) \times e^{6.15} \tag{4}$$

Table 5 summarizes WTS samples incorporated or not in soils and ordinated by decreasing their hydraulic conductivity, in addition an evaluation of their applicability in earth works using liners was made. The minimum and most adopted value for hydraulic barriers is $k < 10^{-7}$ cm/s, these collected data verifies the heterogeneity of the sludge, which can be waste material valorized in different proportions, from 5 to 100%, always depending on its physical, chemical, and geotechnical, however, as mentioned, these characteristics change significantly according to the sludge sample, its chemical processes in the WTP and the raw water composition. Dąbska [25] found for WTS by itself k around 10^{-9} cm/s over [29] only 10^{-5} cm/s, a difference in the order of 4 significant figures, identifying divergent materials. Roque da Silva [12], Montalvan [17], Ferreira [40], Tsugawa et al. [42] studies were analyzed, and a possible pattern was found, it conclude that WTS can be used as landfill bottom or cover liners when mixed with soils with lower hydraulic conductivity in ratios between 5 and 20% of dry mass.

6 Conclusions

Low hydraulic conductivity plays an important role in the applicability of water treatment sludge to landfill covers [42, 43], however, it has the potential to be used as a covering material in landfills, but it can also be studied as incorporation as bottom material if it presents low hydraulic conductivity, $< 10^{-7}$ cm/s. For liner application, WTS must have enough strength to support the disposal and construction loads induced. Thus, WTS has shown a possible strand within soils and landfill liners, enhancing specific geotechnical characteristics while valorizing disposable material.

The literature's review concluded:

- Water affinity of WTS is a very important factor, if the sample is treated with dry–wet procedure, it behaves in an opposite way to wet-dry treatment, influencing parameters as its liquidity, plasticity, shrinkage, and CEC.

Table 5 Hydraulical properties

References	k (cm/s)	WTS ratio (%)	Mixture	Liner
Arulrajah et al. [29]	1×10^{-5}	100%	–	
Fei et al. [23]	3×10^{-6}	100%	–	
Machado and Müller [32]	8×10^{-7}	5%	Clay	
	6×10^{-7}	20%	Clay	
O'Kelly [18]	2×10^{-7}	100%	–	
O'Kelly and Quille [28]	1×10^{-7}	100%	–	✔
Roque da Silva [12]	8×10^{-8}	15%	Sand	✔
	3×10^{-7}	20%	Sand	
Gonçalves et al. [24]	6×10^{-8}	35%	Clay	✔
	3×10^{-8}	50%	Sand	✔
	5×10^{-7}	20%	Sand	
Scapin et al. [27]	5×10^{-8}	15%	Clay	✔
	8×10^{-8}	25%	Clay	✔
	3×10^{-7}	35%	Clay	
Montalvan [17]	6×10^{-8}	3%	Sand	✔
	4×10^{-7}	4%	Sand	
	3×10^{-8}	6%	Sand	✔
Dąbska [25]	6×10^{-9}	100%	–	✔

- WTS has also exposed their variability in granulometric and geotechnical characteristics according to the region, the source of the water to be treated, the water treatment plant processes, chemical added and dewatering method.
- It seems to contribute with pozzolanic characteristics, due to their inherent high amount of silica minerals, creating a silica-gel that connects grains and structural layers while minimizing porosity within the soil, increasing its bearing capacity.
- High aluminum content is the responsible for its low specific gravity makes it possible to reduce the final weight of the mixture, which can reduce potential costs and transport effort.
- WTS' mineralogy is mainly quartz and kaolinite, which are utilized in liners.
- WTS have high compressibility, needing attention for possible differential settlements.
- WTS influence shear resistance increasing friction angle and decreasing cohesion. Enough strength can be achieved by enhancing density with consolidation and/or compaction effort.
- Hydraulic conductivity is the most important factor for liners, apparently, mixing WTS between 5 and 20% of dry mass in soils with a lower hydraulic conductivity,

is an effective way for their valorization as waterproofing layers in earth works, liners.

Although, due to lack of research, it needs more investigation and attention on:

- Laboratory tests over mechanical stability, hydraulic conductivity, and long-term behavior.
- An individual analysis of WTS' permeability must be carried for each region, and its geotechnical performance is an obligatory evaluation, searching for characteristic patterns.
- The analysis of geotechnical properties attested to the potential use of the mixtures, however, the use of the material in practice must be preceded by pilot tests or experimental landfills.

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