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Geotechnical Characterization Methodology of Water Treatment Sludge for Production of Liner Material



Leonardo Marchiori , Maria Vitoria Morais , António Albuquerque ,
and Victor Cavaleiro 

Abstract Clayey soils and geosynthetic materials are used as low hydraulic conductivity layers and environmental protection barriers in civil engineering works for storing wastes as covering and bottom impermeabilization layer structures, known as liners. Future shortage of clay materials and geosynthetic's high costs are usual problems, aligned with the need of prevention of environmental impacts associated to wastes by industry infiltrating into groundwater, sustainable solutions are needed. The reuse of industrial waste materials follows directives of the circular economy when this application is expected to reduce construction costs, help preserve natural resources, reduce the use of synthetic materials, reuse industrial waste materials, and contribute to sustainability. Water treatment sludges (WTS) are generated by water treatment plants mainly from periodic washing of the sedimentation tanks and filters and seems to be suitable for a geomaterial replacement. To make it feasible, the most significant factors that need more investigations are index properties, physical and mechanical behavior, chemical compaction and resistance, hydraulic conductivity, and leaching potential. A methodology for different ratios of WTS, soil, and with or without additive needing, along with a laboratorial analysis of water treatment sludge sample were proposed to ensure the expected results and parameters for liner alternative material.

Keywords Industrial waste(s) valorization · Hydraulic barrier(s) · Waterproofing · Earthwork(s) · Water treatment sludge(s)

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1 Introduction

1.1 Waste Valorization

Waste is any substance discarded or which had the intention or obligation to discard and the called industrial waste is that produced by industrial activity such as mining operations, water treatment plants, thermal processes, and factories' waste generation. Solid and semi-solid waste from water and effluent treatment facilities are water treatment sludges (WTS), or water treatment residuals, or waterwork wastes, mainly any waste from water treatment plant (WTP) [1]. Since United Nations (UN) Conference on the Human Environment in 1972, known as the Stockholm Conference, UN has been designing and planning initiatives around the preservation of the environment, other worldwide events as ECO-92, also known as Rio-92, which used the first report as a basis, has become more frequent and treated as national and global problems, indicating its importance. Direct reuse, remanufacturing, and reprocessing to produce biological and chemical conversion products, fuel source and land reclamation are the main strategies, emerging a change in society's attitudes, resulting in investments for development of beneficial reuse of industrial by-products [2]. Other industrial wastes, such as blast furnace and boiler slag, fly and bottom coal ash wastes and other materials have been used as road construction materials and continues to grow due to its great performance and financial numbers. In view of this possible and viable application, started to investigate the rejected products for other applications in civil engineering.

A potential for the valorization of industrial waste is the application of some of them as barrier materials for waterproofing earthworks for the storage of solid waste (SW) and wastewater. However, for this application, it is needed investigation over different areas in geotechnical engineering, chemical compatibility and long-term behavior, laboratorial tests can achieve mechanical properties, chemical and mineralogical composition, in addition to conducting geotechnical characterization, hydraulic and leaching experiments, proving several parameters. Important physical characteristics include specific weight, moisture content, particle size distribution, compacted porosity of residues, oxides composition, and biological and chemical resistance properties [1]. The identification of appropriate geo-applications for an industrial waste is the most crucial step, requiring consideration of its properties and a comprehensive knowledge and understanding of geotechnical construction, in addition to economic and environmental regulations [3].

1.2 Hydraulic Barriers

The process to qualify a waste material as a sustainable barrier for waste disposal is divided in many aspects and complex phases, their role in a liner is to prevent some behaviors of clays that, because of its plasticity, usually cause differential settlement,

volume changes and possibly cracking allowing leaching through the barrier. These phases can be condensed by 2 bigger ones: (1) selection, characterization, physical and chemical, and testing of solid industrial wastes that are non-hazardous and with dispositive, always making comparisons with clays and/or clayey soils, after analysis (2) should be evaluated the performance, mechanical and hydraulic, of several clay-waste mixtures to define optimum moisture.

Clays and geosynthetic layers like compacted clay liner (CCL) or geosynthetic-clay liner (GCL) have low hydraulic conductivity and are used as environmental protection barriers in geotechnical engineering works like solid waste landfill, wastewater ponds and mining ponds, being cover and bottom liners [2–14]. Basal liners are generally built with natural clay soils, due to their characteristics of high strength and low hydraulic conductivity, however, it is increasingly difficult to find locally available clay soils that satisfy the necessary engineering properties [11]. In addition, several solid industrial wastes appear to have physical and chemical characteristics similar to clays and continue to be discarded in soils, water or landfills, contributing to significant negative environmental impacts and not being recycled or recovered [8].

Those liners' properties can be summarized in, mainly low hydraulic conductivity, less than 1×10^{-9} m/s; enough strength to support the weight above it, depending on the disposed material; deformation during service without cracking or rupture and self-healing properties; chemical compatibility with the disposed, and high cation exchange capacity; and an important issue for development countries and work owners with not many resources, easy construction with low-cost materials.

2 Properties Review

2.1 Water Treatment Sludge as Liners

WTS are mainly sludges from periodic washing of the sedimentation tanks and filters, called water treatment sludges (WTS) [15], its chemical and mineralogy are basically compound for silica, around 20%, and aluminum, 60%, and iron, 5%, looking similar to aluminum silicates as clays like kaolin [16]. According to Fourier transform infrared spectroscopy (FTIR) analysis, WTS has almost 70% of similarity with clay soils [16], because of the main presence of kaolinite, a common clay mineral [17, 18]. Dehydrated and treated, chemically or incinerated, sludges and muds from WTP also have the potential to be alternative materials for liners instead of clays [19], with a severe attention for its hazardousness especially for high organic matter content and mainly because of its permeability, compaction, durability and workability in constructions [20].

Gonçalves et al. [21] mixed dehydrated WTS with clayey soils with 1:0.5 and 1:1 ratio and with sand, 1:0.25 ratio, reaching at least 1×10^{-9} m/s after compaction showing viability for landfill liner material. Corroborating, [7] concluded that samples of WTS from Cubatão, São Paulo, 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. Other ratios have been tested, just like mixtures with other wastes and clays, [22] found optimum moisture of clay, WTS and calcium carbide residue of 40:40:20 ratio, WTS principally affected the hydraulic conductivity and compressive strength, reaching hydraulic conductivity of 6.6×10^{-9} m/s and a 56-day compressive strength of 2.95 MPa. Tests were conducted with a comprehensive investigation into the use of WTS in unconfined compressive strength and the retraction behavior of kaolinite clay, samples were added to kaolinite by the dry weight of clay and showed an increase in strength within WTS addition. An increase in the curing period resulted in an increase in the resistance to unconfined compression and a reduction in the shrinkage potential.

Research on the hydraulic conductivity of water treatment sludge is lacking, however, it has the potential to be used as a covering material in landfills, but it can also be studied as a bottom material if it presents hydraulic conductivity lower than 10^{-9} m/s.

3 Laboratorial Methodologies

3.1 Sampling

The sampling procedure was conducted as follows based on Theory of Sampling [23]:

1. samples of approximately 50 kg must be collected and stored in plastic boxes tagged with a composite code, the collection date, the donor company, and the site's coordinates.
2. transport from collection place to the Soil Mechanics, Geotechnics, Environmental, Sanitation, and/or Chemical Laboratories which will store the materials and performed the tests
3. approximately 50% of the total sample stored as replacement material, also used in mixtures, and the other 50% dehydrated and determined raw material water content
4. the dehydrated portion of the sample was divided for laboratory tests according to each standard and amounts

3.2 *Index Properties and Physical Characterization Methods*

The standard adopted for the separation of soil samples and residual materials can follow the guidelines of the [24]. Also, from that standard were determinate the water content (w) of the samples using the 105–110 °C oven for 24 h.

Granulometry is the measurement of the particle size distribution of the grains of soils, it is defined as the distribution by weight percentage of soil particles in accordance with their dimensions, summarizing the nomenclature according to size is clay (<0.005 mm), silt (0.005–0.075 mm), sand (0.075–4.5 mm), gravel (4.5–75 mm), rock (75–300 mm) and cobbles (>300 mm). For fine particles such as clays, characterized for those which pass for sifting process that pass through the #200 sieve (0.075 mm), the sedimentation method used is from [25], or even laser analysis. Classification for composites follows the one for soil like Unified Soil Classification System (USCS) [26].

For index properties determination, solid particles specific gravity (G_s), by pycnometer method [27] can be used. Besides, consistency, or Atterberg, limits were determined following standards [28, 29] for liquid and plastic limits respectively, only for the fraction of the soil that passes through the #40 sieve (0.425 mm). Casagrande shell method for liquidity index (w_L) and molded sample by hand on a glass plate for plasticity index (w_P), and the difference between those values is the plasticity index (PI). Plasticity is a very important characteristic of fine soils; it describes the capability of the soil to suffer irreversible deformation without break or crumble. In general, depending on the quantity of water, or humidity, the soil can be in one of the states of plasticity, liquid, plastic, semi-solid and solid. Decreasing the amount of a liquid state soil, it became a plastic, decreasing volume until the solid state be reached [30].

3.3 *Mechanical Behavior Methods*

Compaction is the process of increase density of the soil grouping the particles with reduction of air volume, there is no significant decrease of water [30]. Compacted clay liners are used as basal and cover for landfills, the compaction act decreasing the void index consequently increasing the hydraulic conductivity. Compaction curves of soils are essential for practical and a trustworthy analysis for field compaction quality [31]. The Proctor test described on [32] provide compaction curve and saturation curve, index properties such as optimal water content (w_{opt}), maximum dry weight (γ_{max}) and, in addition can determine void index (e), porosity (n) and saturation index (S).

Terzaghi formulated an equation, for the one-dimensional consolidation case, that relates the change in pore pressure (Δu), time (t), and the depth (z) of a soil element subjected to a stress ($\Delta \sigma$) uniformly distributed over an infinite area of soil, and presents the solutions of the consolidation equation by two dimensionless quantities, the time factor (T_v) and the average degree of consolidation (U_v) within consolidation

coefficient (c_v), for practical terms, it is adopted for the end of the consolidation when T_v equals to 1 and the consolidation reaches 90%. Looking to determine the consolidation coefficient, two traditional methods are used, Taylor and Casagrande, to predict the speed at which the soil settles. Taylor method uses the square root of time on the x-axis to fit a tangent line, obtaining degrees of consolidation 0 and 90%. The Casagrande Method, on the other hand, plot time in logarithm scale, and uses an extension of the instantaneous consolidation part to obtain 0%, and two tangent lines, one in the primary consolidation and another in the secondary consolidation, where the intersection between them is the 100% point. Both methods seek to obtain the equivalent of 50% of the consolidation and its respective time.

Coulomb and Mohr strength theory express shear strength (τ_f) in terms of cohesion (c) and friction angle (φ) and utilizing Terzaghi concept of effective stress, parameters c' and φ' can be determined from triaxial tests. Triaxial tests consist in a cylindrical specimen enclosed in flexible membranes between a loading cap and a pedestal for drainage and axial load, this enclosed into a water pressure chamber. The load is applied in two stages, in the first, the water in the chamber confines the specimen and the second is applied axial load from a constant rate press. Theoretically, triaxial should apply three stresses, one for each axis, although in practice using cylindrical samples, there is a axial symmetrically resulting in $\sigma_1 \geq \sigma_2 = \sigma_3$, the major and axial stress being σ_1 and the fluid pressure from the cell being $\sigma_2 = \sigma_3$. Consolidated undrained assembly must not allow drainage during application of deviator stress.

For liner simulation, consolidated undrained (CU) triaxial tests were performed, the first stage is saturation and consolidation, where the specimen wets and consolidate at confining pressure (σ_c') and in the second stage, when drainage is not permitted but pore pressure may be measured. Different pressures are applied called deviator stress (σ_d), at least three, to generate a Mohr–Coulomb line or determine the effective stress path due parameterizations.

3.4 Chemical Composition Methods

Cation exchange capacity (CEC) is proportionally inversed to mineral grain size particles [18]. Clay Activity values higher than 27 meq/100 g correspond to high chemical activity [17]. CEC is determined by the ammonium acetate method buffered to pH = 7. X-Ray Diffractometry (XRD), X-Ray Fluorescence (XRF) and Scanning Electron Microscopy (SEM) are the main chemical and mineralogical characterization techniques used.

In XRD, each mineral species is characterized by a systematic arrangement atomic (or ion) specific, with characteristic crystalline planes that can diffract X-rays. The diffraction of X-rays by atoms in a crystalline plane produces characteristic patterns when recorded (angles and intensities). These diffraction patterns are used as a fingerprint in the identification of mineral species, producing a series of dots or lines, called bands. The XRF consists of the incidence of an X-ray beam on a sample, making with its electrons being ejected from the layers close to the nucleus, The vacancies

created are filled by electrons from the outermost layers, emitting X-rays (fluorescent or secondary), whose energies correspond to the difference between the energies of the levels and sublevels of the transitions. Each type of atom has a characteristic and unique X-ray spectrum that is used as a comparison for identification. The intensity of the FRX of a certain wavelength is related to the concentration of the element that emitted it. FRX analysis is semi-quantitative and provides the chemical composition expressed as the oxides of the elements. The Scanning Electron Microscope (SEM) is one of the most versatile instruments to obtain information on the morphology of minerals. When they have detectors that capture characteristic X-rays by energy dispersion (Energy Dispersive Spectroscopy—EDS), they are called MEV-EDS, and provide information about the chemical elements that compose them. The SEM produces images with a three-dimensional appearance, a direct result of the great depth of field and allows the examination in successive increases, with great depth of focus, combining information from electronic and optical images. According to other authors, the main reason for its use is the high resolution obtained when observing the samples.

3.5 Hydraulic Performance Methods

The methodology for permeability analysis in laboratory is very simple, although differs according to the soil to be studied, falling head permeameter is used for low permeability soils such as clays, and constant head permeameter for high permeability soils, like sands. Falling head permeability can be measure from upward or downward through the soil, however, downward flow can transport fines and occurring clogging of the sample. The sample to be studied is inserted into a measured cylinder with a cross section (A) and specimen height (L), this cylinder is connected through tubes to another graduated cylinder with a cross section (a) that contains water to a certain level. At a certain initial moment (t_1), there is a certain hydraulic load according to the height (h_1), at another moment (t_2) there is another hydraulic load (h_2), following [33].

Low hydraulic conductivity plays an important role in the applicability of WTS to landfilling [8]. But, due to the lack of research, it needs field application, mechanical stabilization, and long-term behavior. In addition to varying greatly according to the region and the source of the water to be treated, prior characterization must always be performed.

4 Conclusions

For future investigations over waste-based composites with soils, like water treatment sludge valorization in different ratios with or without additives, to achieve liner requirements, the author suggestion mixtures in Table 1 and laboratorial tests in Table 2, following literature’s path.

Besides that, must performed field small scale experimental liners, testing its compaction, compression resistance, and field permeability, also long-term behavior can be tested due to chemical and thermal resistances (wet-dry, freeze-thaw cycles, leaching resistance and biological degradation). Those characteristics should qualify the material as liner.

Table 1 Potential mixtures ratios for WTS, soils and additives for liner feasibility

Soil:Waste ratio	Soil:Waste ratio (if low ratios behave similar)	Soil:Waste:Additive ratio (choosing the best performance composite)
100:0%		+ 2.5% of additive taking 1.25% of each + 5% of additive taking 2.5% of each + 10% of additive taking 5% of each
20:80%	75:25%	
15:85%	50:50%	
10:90%	25:75%	
05:95%		

Table 2 Potential laboratorial tests methodology for residues application in liners

<i>Geotechnical</i>	<i>Mechanical</i>
Specific gravity (Density)	Compaction (Normal proctor)
Consistency limits (Atterberg)	Consolidation (Oedometric)
Particle Size Distribution (Sieve and laser)	Triaxial (Consolidated undrained)
<i>Chemical</i>	<i>Hydraulic</i>
Cation exchange capacity	Permeability (Falling head)
Mineralogy (X-Ray diffraction)	
Microstructure (Scanning electron microscope)	Leachability (Batch and column)
Composition (Energy dispersive spectrometry)	

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