Proceedings of the 9ICEG
9th International Congress on Environmental Geotechnics
25-28 June, 2023 | Chania, Greece

https://doi.org/10.53243/ICEG2023-268

Geotechnical comparison of water treatment sludge and biomass ashes for soft soils' application: A greener approach analysis

A. Studart[1], L. Marchiori[1], A. Albuquerque[1], V. Cavaleiro[1], M.E.G. Boscov[2], F. Rocha[3], E.F. Silva[3]

[1]Civil Engineering and Architecture Department, GeoBioTec, FibEnTech, University of Beira Interior (UBI) Covilhã, Portugal, email: andre.studart@ubi.pt; leonardo.marchiori@ubi.pt; antonio.albuquerque@ubi.pt; victorc@ubi.pt

[2]University of São Paulo (USP), São Paulo, Brazil, email: meboscov@usp.br

[3]Geosciences Department, GeoBioTec, University of Aveiro (UA), Aveiro, Portugal, email: tavares.rocha@ua.pt; eafsilva@ua.pt

ABSTRACT

Water treatment sludge (WTS) and vegetal biomass ashes (VBA) are largely generated around the world and require sustainable management to minimize potential negative environmental impacts and risks for public health. Wastes' bad management represents a risk for soils and water's contamination. Several international programs and goals have demanded the industries to introduce greener approaches to their processes. One of the sustainable alternatives for the management of those wastes is their valorization in the development of new materials for application in geotechnical works. Soft soils are known for having high volumetric variation and low resistance values, needing treatment or reinforcement. The research's objective was to characterize an alum-sulphate coagulant-based WTS, pines'-based VBA, two soft soils and four mixtures of each residue in different percentages (5%, 10%, 15% and 20%) to evaluate the potential of WTS and VBA in chemical-mechanical properties. Therefore, particle size distribution, normal proctor compaction, specific gravity, plasticity indexes, permeability, oedometric consolidation, triaxial testing, physical-chemical composition by x-ray diffraction (XRD) and x-ray fluorescence (XRF), scanning electron microscope (SEM) and leaching tests were performed on all mixtures. Results indicate properties' enhancement of the two soft soils used in this research through the introduction of 15% of WTS and 20% of VBA, enhancing internal friction angle, reducing cohesion and plasticity, serving as a geomaterial while encapsulating heavy metals. Thus, the use of WTS and VBA for strengthen the properties of soft soils indicate a sustainable and ecological application for these wastes within the framework of the circular economy.

Keywords: Geotechnical application, water treatment sludge, vegetal biomass ash, soil reinforcement, waste valorisation.

1 INTRODUCTION

The production of industrial waste is a worldwide problem that can lead to significant negative impacts on the environment, especially on soil and water and its uses, and risks to public health. As (Chowdhury, et al., 2022) pointed out that as waste production has grown a significant number of landfills have been built in order to receive all undesired material. This solution, although effective in the short-term, is not sustainable in the long-term. It uses large areas with ever-growing necessity of expansion. Furthermore, leachate generated in the landfills, despite being drained and treated, may, during certain occurrences, infiltrate into the subsoil, contaminating and compromising soils and groundwater. (Fuller et al., 2022) exposed that modern pollution risk has grown up to 66% since 2000, appointing lead (Pb) as an example of a chemical element that could add to such high numbers and that little real progress has been achieved to prevent further advance. In this context, the research of new options for waste valorisation emerges as a strand in order to find a new application for undesired materials, namely its inclusion in geotechnics and environmental sanitation works. The valorisation of industrial wastes in construction materials (waste-based geomaterials), in addition to being a solution considered sustainable, fits within the circular economy models as it can allow the development of new value-added products (Marchiori & Albuquerque, 2020; Marchiori, et al., 2022a; Marchiori, et al., 2022b).

Vegetal biomass ashes (VBA) from coal-biomass co-combustion from energy production at thermoelectrical facilities are highly generated, as varied countries and communities – European Union (EU), USA, Brazil and Japan as examples - use this technology to generate energy, reaching values up to 26% individually for electricity production based on biomass (Sahu, et al., 2014). Several processes can occur in such facilities and the generated by-products can be resumed by (Agrela, et al., 2019; Loo & Koppejan, 2008) in:

- Bottom ashes – the most produced ash with a sand-sized granulometry.
- Cyclones ashes - Finer-granulometry material (5-50µm), with considerable content of heavy metals.
- Fly ashes – the least produced material precipitated in filters, mainly composed of aerosols, with a finer granulometry (0,01-1µm).

There is a belief that vegetal biomass is a sustainable material, as it releases the same CO_2 that it encapsuled in the nature before. However, the by-product here analyzed is considerably different when compared to the original biomass (Studart et al., 2022), and shows contamination potential due to several chemical-physical alterations which take place in the coal-biomass combustion (Sami, et al., 2001). The chemical composition of coals contains variable number of oxides and mineralogy, considerably changing depending on the type of coal, which wis chosen according to the processes of combustion plants. During combustion, several chemical reactions intensity occur, inducing several oxides' enrichment, namely calcium, aluminum and magnesium oxides while thermal-conversions take place enriching generally carbonated minerals, inducing calcite's decomposition in favor of lime (CaO) content (Tan & Lagerkvist, 2011;Vamvuka & Zografos, 2004; Vassilev, et al., 2013). Thus, VBA are a very chemically varied by-product which are tied to the type of vegetal biomass origins, associated coal, and inherent combustion processes. However, they mainly consist of a fine-grained material with low specific gravity and low to no plasticity. These may be interesting properties for soils, and, hence, open a promising study strand for the treatment of soft soils. Previous researches have obtained soil-VBA susceptible for embankments' construction (Agrela et al., 2019; Galvín, et al., 2020; Marchiori, et al., 2022).

Another highly generated residue all over the world is the water treatment sludge (WTS). Water treatment facilities provide clean and potable water. However, such facilities produce a large amount of by-product (waste) – WTS – on values that can reach up to 100.000 ton/year in a typical WTP (Ahmad, et al., 2016a). Thus, WTS is as a complex and chemically varied material as the raw water solubilizes and carries varied minerals and composites that will affect its composition as it seeps through the soils. Also at the WTP, as inherent processes, coagulants and chemicals are chosen according to the water and WTP design, impacting on the WTS final composition and properties (Coelho & Albuquerque, 2016). WTS is largely impacted by processes of water treatment. A major process of water treatment is the coagulation, with the function of agglomerating solid particles through ions removal, and the chosen coagulants are generally based on the design of the WTP and region, being the most common ferric chloride ($FeCl_3$), alum sulphate ($Al_2(SO_4)_3$) and polyaluminum chloride (PACl). These coagulants are positively charged, aiding on the removal of negatively charged compounds, affecting which compounds will be removed and also contributing for the chemical alteration of the WTS (Bağrıaçık & Güner, 2020; Montalvan & Boscov, 2021; Parsekian, 1998). Thus, the complex behaviour of WTS is a directly consequence of chosen coagulant and processes, differing on their characteristics from WTP to WTP. Despite these differences, WTS generally presents a chemical composition of ferric, alum and silica minerals and a sand-silty granulometry, inducing several authors to evaluate their introduction into soft soils, obtaining successful results by increasing friction angle while reducing cohesion and plasticity (Marchiori, et al., 2021a, 2021b, 2021c, 2021d; Montalvan & Boscov, 2021; Shah et al., 2020).

However, VBA and WTS may also contain heavy metals in worrying concentrations, namely arsenic (AS), cadmium (Cd), copper (Cu), lead (Pb), nickel (Ni) and zinc (Zn) (Ahmad et al., 2016b; Zajac et al., 2018; Scalize et al., 2019), whose leaching power in mixtures with soils is not well known. In a previous characterization, (Studart et al., 2022) observed significant concentrations of As (33.8 ppm) and Cd (5.0 ppm) in VBA, which questioned its eventual leaching once incorporated into the soil, thus raising the need to carry out leaching tests for these wastes.

In the geotechnical engineering context, soft clays are considered difficult to work with, since they are a plastic material susceptible to high volumetric change due to high cation exchange capacity while having low friction angle and considerable cohesion (Colin & Jones, 1985; Gomes, 1986). Thus, soft soils generally need treatment and/or reinforcement to adequate their use for general constructions. Geotechnical enhancements of these soils are a desired objective. Civil engineering employs different materials in a large range of different applications, several possibilities could be pavemented through a geotechnical complete analysis. Therefore, this research analyses physical and chemical characteristics of a WTS, a VBA, two soft soils and four mixtures of the soft soils with each referred waste in different percentages (5%, 10%, 15% and 20%) for evaluating their potential in reinforcing soil properties. Leaching tests were also carried out on the soil/waste mixtures and the final eluate was characterized in terms of heavy metals (As, Cd, Cu, Pb and Ni) through the scope of a greener analysis.

2 MATERIALS AND METHODS

The analyzed materials consist of two soft soils – defined as O1 and O2 - and two industrial wastes – VBA and WTS. Both soils and VBA were retrieved from local companies located in Castelo Branco, Portugal. WTS was collected in a WTP from Guarda, Portugal. The materials were individually analysed and then VBA and WTS were added in O1 and O2, respectively, following the rates below:

- WTS05:95%: 05% WTS and 95% of soil O2;
- WTS10:90%: 10% WTS and 90% of soil O2;
- WTS15:85%: 15% WTS and 85% of soil O2;
- WTS20:80%: 20% WTS and 80% of soil O2;
- VBA05:95%: 05% VBA and 95% of soil O1;
- VBA10:90%: 10% VBA and 90% of soil O1;
- VBA15:85%: 15% VBA and 85% of soil O1;
- VBA20:80%: 20% VBA and 80% of soil O1.

The chosen rates were considered based on published researches and on the intention of evaluating the impacts of added wastes through their progressive introduction. Geotechnical characterization was based on ISO 17892 standards for determination of particle size distribution, specific gravity (G_S), plasticity limits - liquid limit (w_L), plastic limit (w_P) and plastic index (PI) and Normal Proctor compaction for optimum water content (w_{opt}) and optimum dry density ($\gamma_{d,max}$).

Chemical characterization comprehended x-ray fluorescence (XRF) for elemental analysis determination, scanning electron microscope (SEM) for magnified images coupled with energy-dispersive X-ray spectroscopy (EDS), using a S-2700 Hitachi equipment and Axios by Malvern Panalytical, respectively and X-ray diffraction (XRD), for mineralogical characterization, using a Phillips Analytical X-Ray B.V and X'Pert-Pro MPD by Malvern Panalytical. Oxides values, obtained through XRF, were normalized without loss on ignition (LOI) value, to have the correct value of each oxide in the treated samples' composition. Leachability tests were based on the US EPA 1311 and BS 12457-2 standards to obtain the heavy metals concentration. Samples were filtered under acetic acid and the eluate material was proceeded to a laboratory to evaluate the concentration of As, Cd, Cu, Pb and Ni.

Free expansibility tests were based on D4829-19. One-dimensional oedometric consolidation, falling head permeability and triaxial shear tests were based on ISO 17892 with samples being extracted from the Proctor cylinder at optimal water content (w_{opt}). Oedometric tests were conducted by an automatic LCR transducer strain gauge, through MPE with maximum strain of 25.8mm and precision of 0.001mm, connected to a data logger MPX3000, made by VJ Technology. Readings were performed on a logarithmic time scale, following the load scale of 1-30-150-300-600-1200 kPa, and the unload for 1200-300-1kPa. Triaxial tests equipment is by GDSLab; a series of three consolidated undrained (CU) triaxial tests for each material with 100, 200, and 300 kPa of confining pressures; saturation was considered completed when B value reached 0.95 and consolidation when there was no difference in the volume; shear tests were stopped at 22% of axial strain. Falling-head permeability tests was based on the above-mentioned ISO and were performed on a duo-set for each material, with initial hydraulic gradients (i) of 50 and 100.

3 RESULTS AND DISCUSSION

3.1 Geotechnical characterization

The soil O1 and O2 are very similar soils, being both sands with a small portion of clay. Considering previous researches on both WTS and VBA (Marchiori, et al., 2021a, 2021b, 2021c, 2021d; Marchiori, et al. 2023) further research was conducted and both residues re-assessed for a comparative analysis. Both residues have no plasticity and, according to their granulometry, are classified as well-graded sand with silt. As they are finer than the soils, void-filling property might be possible, which can be verified by the surface area value – the higher, the finer particles are. This behaviour is also corroborated by SEM images, although this capacity will also depend on their grains' shape and general intermingling of the particles, impacting also on the hydraulic-mechanical properties (Terzaghi, et al., 1996). In addition, their introduction has led to a reduction in the soils' plasticity and lower specific gravity, which could be considered as advantages for geotechnical engineering, as it is known that soft soils generally present design challenges due to their high-water absorption, retention capacity and volumetric variation. Table 1 presents the particle size parameters of analyzed materials, and Table 2 the geotechnical parameters.

Table 1. *Particle size parameters*

Material	D_{10}(mm)	D_{50}(mm)	D_{90}(mm)	SS (cm^2/g)	USCS
WTS [a]	0.002	0.18	1.53	168.0	SW-SM
O2 [a]	0.028	0.42	1.58	27.33	SW
WTS05:95% [a]	0.093	0.74	1.77	33.10	SW-SM
WTS10:90% [a]	0.027	0.63	1.65	40.32	SW-SM
WTS15:85% [a]	0.053	0.57	1.66	49.60	SW-SM
WTS20:80% [a]	0.053	0.58	1.66	52.17	SW-SM
VBA	0.050	0.10	0.74	272.2	SM
O1	0.070	0.85	2.68	27.43	SW-SC
VBA05:95%	0.130	0.55	2.51	42.75	SW-SC
VBA10:90%	0.120	0.45	2.00	52.09	SW
VBA15:85%	0.090	0.53	1.81	55.02	SW-SM
VBA20:80%	0.090	0.35	1.62	60.56	SM

[a] Adapted from Marchiori, et al., 2022c. D_{10}, D_{50}, D_{90}. Nominal diameters of 10, 50, and 90% of the particle size distribution, respectively; USCS. Unified Soils Classification System.

Table 2. *Geotechnical parameters*

Material	G_S (-)	W_L (%)	W_P (%)	PI (%)	W_{opt} (%)	$\rho_{d,opt}$ (g/cm^3)
WTS [a]	2.04	-	-	-	85	0.70
O2 [a]	2.77	36	29	7	20	1.74
WTS05:95% [a]	2.59	38	32	6	18	1.68
WTS10:90% [a]	2.48	39	34	5	22	1.58
WTS15:85% [a]	2.42	42	39	3	25	1.50
WTS20:80% [a]	2.30	55	54	1	27	1.44
VBA	2.32	-	-	-	-	-
O1	2.74	38	31	7	15	1.91
VBA05:95%	2.72	41	35	6	18	1.70
VBA10:90%	2.67	41	-	-	18	1.76
VBA15:85%	2.63	42	-	-	18	1.65
VBA20:80%	2.61	43	-	-	20	1.56

[a] Adapted from Marchiori, et al., 2022c. W_L. liquid limit; W_P. plastic limit; PI. Plastic index; W_{opt}. optimal water content; $\rho_{d,opt}$. optimal dry density.

3.2 Mechanical analysis

Comparisons between WTS-O2 (Marchiori et al., 2022c) and VBA-O1 and the original soils evidenced an improvement in the mechanical properties of both materials with the addition of the residues: the mixtures are less compressible and more resistant than the soils, as exposed in Table 3.

Table 3. *Mechanical parameters*

Material	c' (kPa)	φ' (°)	EI (%)	σ'_{vm} (kPa)	Cc (-)	Cs (-)	Cr (-)
O2 [a]	10	20	22	27	0.100	0.030	0.030
WTS05:95% [a]	7	24	15	32	0.065	0.025	0.015
WTS10:90% [a]	5	25	13	32	0.080	0.020	0.020
WTS15:85% [a]	0	31	12	33	0.130	0.030	0.300
WTS20:80% [a]	0	30	10	31	0.090	0.020	0.015
O1	7	22	17	36	0.077	0.013	0.012
VBA05:95%	0	26	13	31	0.070	0.010	0.010
VBA10:90%	0	26	15	31	0.068	0.010	0.010
VBA15:85%	0	27	16	34	0.076	0.014	0.015
VBA20:80%	0	28	15	33	0.056	0.012	0.012

[a] Adapted from Marchiori, et al., 2022c. c'. Cohesion; φ'. Effective friction angle; EI. Expansibility index; σ'_{vm}. Pre-consolidation stress; Cc. Compression index; Cs. Swelling coefficient; Cr. Recompression coefficient.

For soil reinforcement, the introduction of both by-products into the soils has had a positive impact, as the effective friction angle was higher, and the material's behaviour was closer to a granular material. Clays usually have a lower friction angle; USCS characterizes a 22° friction angle for organic clays while higher friction angles are more commonly related to granular materials, which may reach values as high as 40°. The friction angle of the WTS15:85% and VBA20:80% mixtures are similar to that of uniform sand with round grains (Carter & Bentley, 1991; Obrzud & Truty, 2018). (Giwangkara, et al., 2020) have analysed the friction angle of natural crushed aggregate and recycled concrete aggregate for road base materials, obtaining mainly values between 26-29º. (Huang, et al., 2019) also stated similar values for asphalt mixtures under different temperatures. However, it is important to reiterate the consideration of other parameters for pavement materials and design. (Terzaghi et al., 1996) report friction angles between soil and retaining walls of 24-30º depending on the granulometry. (Uzundurukan & Saplioglu, 2022) analysed an optimal design of retaining walls of 2-7m height and concluded that foundation soils with a friction angle higher than 28º could decrease the overall construction cost. Such results indicate possible uses for WTS15:85% and VBA20:80% mixtures from the friction angle point-of-view, to be further analysed according to other specifications for each particular application.

3.3 Permeability analysis

Permeability tests were conducted with a hydraulic gradient of 50 and 100. Obtained results stated an average hydraulic conductivity (k) order of magnitude of 10-10 m/s for the soils, 10-9 m/s for WTS15:85% and 10-7 m/s for VBA20:80%. k-values were increased as residues were added. The original soils showed very low permeability, increased ten-fold with WTS addition and by 2 orders of magnitude with VBA addition, probably due to the residues coarse granulometry, as exposed in Table 1. For liners of storage waste facilities, the hydraulic conductivity is the main parameter to evaluate, and should be less than or equzal to 10-9 m/s of k (Khalid, et al., 2019). Therefore, the WTS-O mixtures could be used for this application, while the VBA-O mixtures do not comply with this specification.

3.4 Chemical analysis

The investigated materials are similar to those of (Marchiori, et al., 2021a, 2021b, 2021c, 2021d; Marchiori, et al. 2023), being re-assessed over different collection over time due to periodicity changes of the material. 180 days after the initial analysis on VBA and its mixtures. XRD has shown several peaks for VBA, being considerably different from the original biomass – before combustion – and difficult to classify precisely. Due to the high amount of inherent chemical reactions, materials, and procedures within the coal-biomass co-combustion, affecting VBA composition, there is a high number of peaks. Different peaks indicate different minerals, although in small quantities and percentages. These alterations difficult to fully understand the whole chemical alteration that the biomass goes through.

On the other hand, it was easier to correctly identify the peaks of the analysed WTS, as most of its structure is amorphous, probably a consequence of the organic matter, altering the WTS structure, as exposed also in (Silva & Boscov, 2021). Materials' XRF values can be found on Table 4.

Table 4. *Percentage of oxides on the samples' composition.*

Material	Na_2O	MgO	Al_2O_3	SiO_2	SO_3	Fe_2O_3	K_2O	TiO_2	CaO
WTS [a]	-	0.59	60.4	29.9	-	5.0	1.15	-	2.88
O2 [a]	0.42	1.61	29.5	54.0	-	9.22	4.23	0.98	-
WTS05:95% [a]	0.36	1.66	32.7	51.0	-	8.55	4.39	1.24	-
WTS10:90% [a]	0.28	1.65	33.0	50.0	-	9.23	4.47	1.30	-
WTS15:85% [a]	0.27	1.55	34.3	49.4	-	9.20	4.06	0.83	-
WTS20:80% [a]	0.36	1.50	34.6	48.7	-	8.84	4.76	0.97	-
VBA	0.99	3.81	17.76	44.51	2.62	6.63	7.31	0.66	13.3
O1	0.70	2.17	23.64	57.82	0.01	7.70	4.0	0.89	0.03
VBA05:95%	0.78	2.81	24.41	54.88	0.41	7.48	4.63	1.05	2.85
VBA10:90%	1.13	2.24	23.81	58.29	0.02	6.38	4.74	0.89	2.11
VBA15:85%	1.15	2.67	24.07	56.45	0.01	6.81	4.79	0.67	3.07
VBA20:80%	1.75	2.45	22.38	56.92	0.03	5.60	4.76	0.47	4.19

[a] Adapted from Marchiori, et al., 2022c.

The region of Castelo Branco – Portugal, which is constituted by metamorphic shales and quartz (Cunha, 1987), provides natural Silica and Aluminium as main elements of such minerals. Both soils, being from the same region, present these materials in form of Quartz, Muscovite, and Kaolinite.

The minerals that compose WTS are related to the soils through which the raw water percolates and the added chemicals during the treatment process. The analysed WTS is characterized by a black colour due to the use of granular activated carbon during the phase of filtration to remove certain chemicals. WTS composition can be mostly or partially explained by the carried minerals during water's percolation, such as silica and aluminium. Its higher content of Al_2O_3, for example, can also be explained by the used coagulant – Alum Sulphate ($Al_2(SO_4)_3$) - which plays a major role for such concentration. Also, during the phase of remineralization, calcium hydroxide is introduced, impacting as well in the final composition.

The results of the leaching tests of As, Cd, Cu, Pb and Ni metals are shown in Table 5. Results show that both wastes have not shown a high lixiviated concentration, probably due to the encapsulation of such heavy metals within the mixtures. In the most extreme mixtures, 20:80% for WTS and VBA, no hazardous leachable amount was found within the analysed heavy metals and the materials' concentration respected the referenced regulatory range. Also, it is important to reiterate that differences will be found among different batches of the same material, as procedures and materials change at the processing facilities while the material itself can differ due to its inherent natural composition or anthropogenic actions. UE's 1986 Directive present the regulatory limits for diverse heavy metals to assure soils' integrity, being the method of analysis a sample recovery and digestion through strong acid. Obtained lixiviated amount of the analysed samples were obtained through acetic acid, it would pass set standards, although important to reiterate the existence of other acids appliable for leaching procedures, such as hydrochloric, nitric or sodium hydroxide that could provide different results.

Table 5. *Final concentration on leachate procedures.*

Material	As	Cd	Cu	Pb	Ni	Units
WTS	2.2	0.4	10.9	3.3	6.1	µg/kg
O2	6.2	0.2	33.2	5.2	2.8	µg/kg
WTS05:95%	3.4	1.5	12.7	11.8	41.9	µg/kg
WTS10:90%	4.3	2.6	15.2	11.2	44.2	µg/kg
WTS15:85%	7.4	4.2	31.4	4.9	67.6	µg/kg
WTS20:80%	6.1	3.1	37.8	9.0	72.9	µg/kg
VBA	124.1	2.2	10.8	3.8	28.2	µg/kg
O1	7.42	0.1	24.5	4.3	11.6	µg/kg
VBA05:95%	28.8	3.8	15.0	9.5	23.1	µg/kg
VBA10:90%	45.7	13.1	19.1	10.7	62.5	µg/kg
VBA15:85%	62.7	17.4	34.5	9.2	77.6	µg/kg
VBA20:80%	114.0	24.4	26.7	6.6	94.7	
Regulatory Limits [a]	-	3000	140000	300000	75000	µg/kg

[a] (Communities, 1986)

Figures 1 to 6 show scanning electron microscopic images for all the studied materials, as shown in (Marchiori et al., 2022; Marchiori et al., 2023).

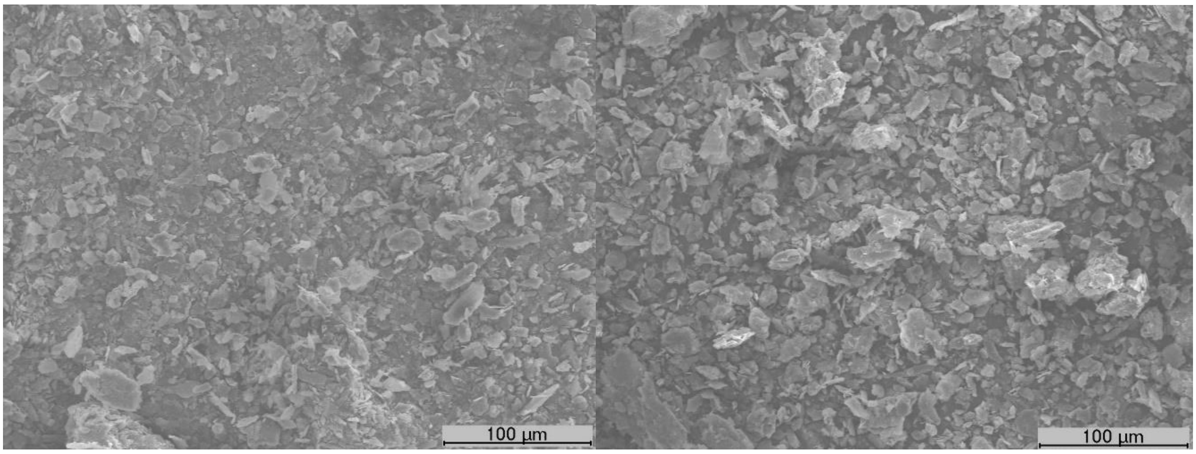

Figure 1. *SEM - O2 (left). SEM – O1 (right).*

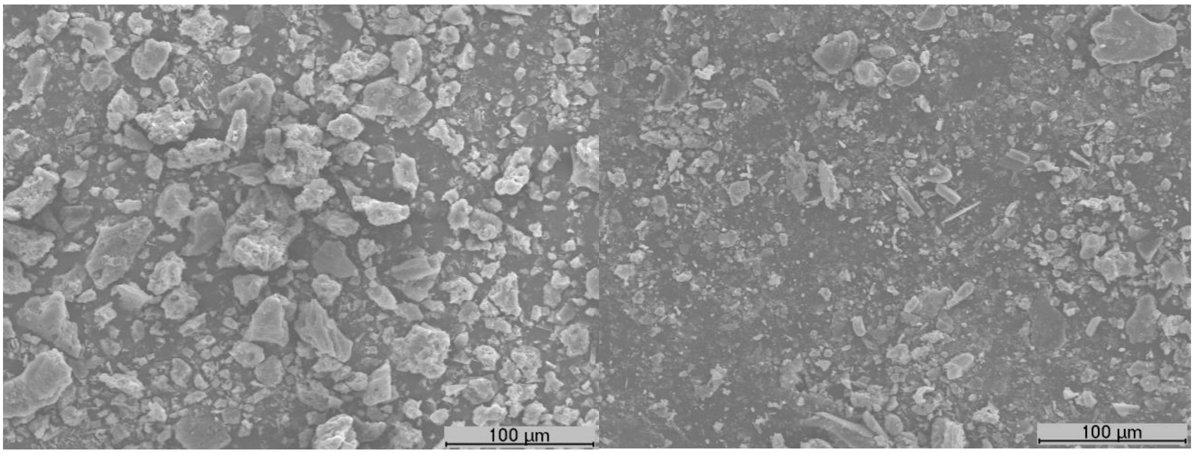

Figure 2. *SEM - WTS (left). SEM - VBA (right).*

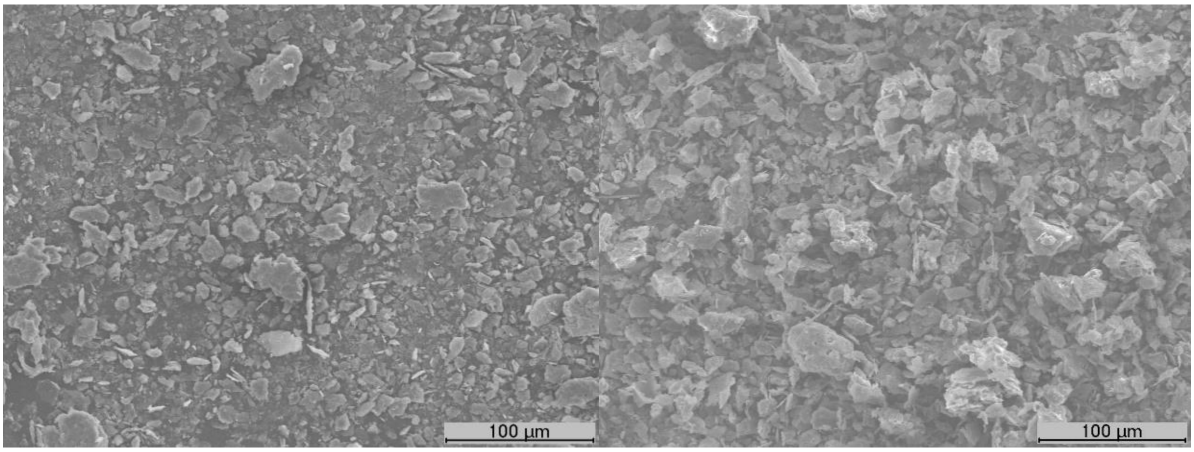

Figure 3. *SEM - WTS05:95% (left). SEM - VBA05:95% (right).*

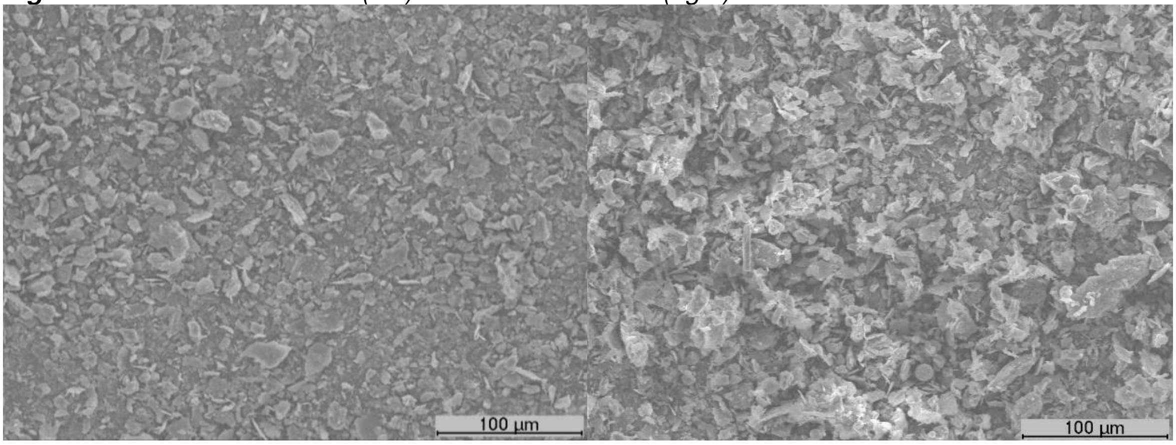

Figure 4. *SEM – WTS10:90% (left). SEM – VBA10:90% (right).*

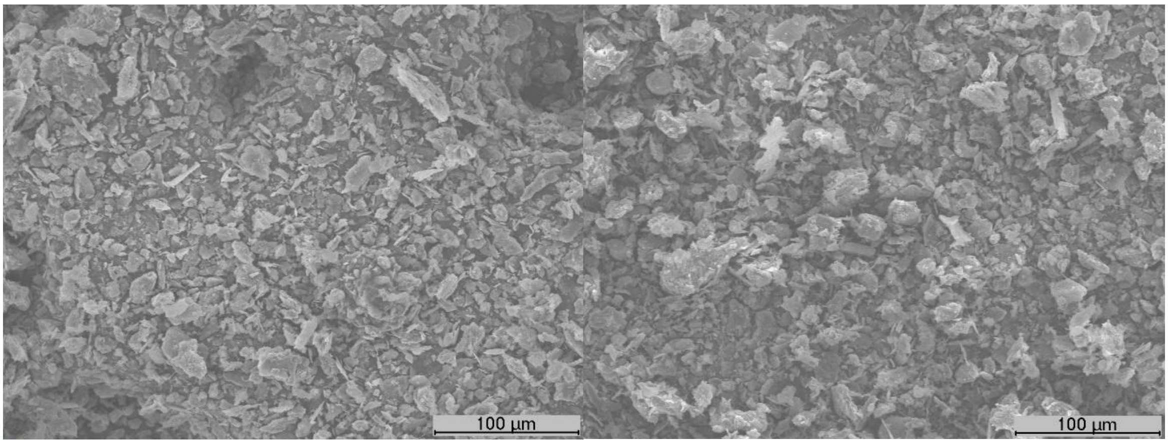

Figure 5. *SEM – WTS15:85% (left). SEM – VBA15:85% (right).*

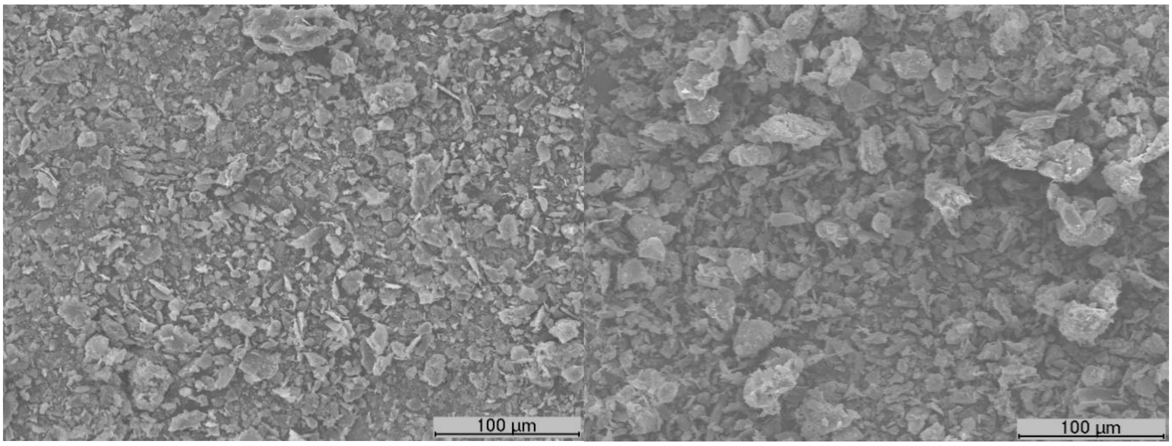

Figure 6. *SEM – WTS20:80% (left). SEM – VBA20:80% (right).*

SEM pictures exposed that both residues have blended well when introduced into the soils, although VBA seems to have fulfilled with a higher granulometric rangen. Granulometry should not be analyzed alone, rather together with other physical-chemical aspects. Considering that both residues have brought mechanical and chemical enhancements, or at least not worsened the original soils' behaviour, the results are promising for the geotechnical application of the soil-residues mixtures.

The results of this research are promising regarding the use of WTS and VBA as geomaterials to reinforce the properties of the two analyzed soft soils, also verifying a good control of the leaching of heavy metals contained in the wastes. Therefore, a greener approach for managing these wastes can be made in the industries, although it is always necessary their characterization and testing, since their characteristics vary in relation to the involved processes used in the industries. Further research shall be conducted to better understand the chemical iteration and reactions of both wastes with soils, namely their impact on hydro-mechanical characteristics and durability in a long-term and field scale.

4 CONCLUSIONS

The belief that industrial waste has no economic value as building materials is slowly being debunked, as the results of this study expose. Found results have stated both WTS and VBA laboratory feasibility for reinforcing soft soils, which could indicate their use as new sustainable geomaterials for geotechnical works.

Several geotechnical characteristics were evaluated and found to be enhanced, such as the increase of friction angle and reduction of plasticity, while not making the geomechanical properties of the soil worse, which itself is already an advantage, as soft soils' generally present undesired geotechnical properties. Such characteristics could lower the occurrence of structures' pathologies, such as fissures, through the eradication or attenuation of the soft soils' high volumetric variation while minimizing the water retention and absorption capacity, leading to a general consolidated soil structure.

In addition, WTS and VBA are finer than the soil, although the fine particles have not exposed the general behaviour of clay particles. Such a behaviour indicates the replacement of the soil's fine matrix for the waste's fine matrix, providing a more stable skeleton-structure. Also, the chemical analysis has shown a non-hazardous leachability under acetic acid, indicating the non-contamination of the soil. Thus, obtained enhancements indicate possible applications of the produced mixtures for retaining walls or embankments applications. Optimal produced mixtures are understood to be 15% of WTS and 20% of VBA, as these percentages exposed improved characteristics while retaining major heavy metals.

5 ACKNOWLEDGEMENTS

The researchers acknowledge the involved companies for the soils and wastes material supply, also Ana Paula Gomes from Optical Center, University Beira Interior (UBI), Denise Terroso and Cristina Sequeira for the chemical analysis, University of Aveiro (UA). The research is supported by national funds within the UIDB/00195/2020 (FibEnTech) and UIDB/04035/2020 (Geobiotec) projects, both funded by the Foundation for Science and Technology (FCT), Portugal.

REFERENCES

Agrela, F., Cabrera, M., Morales, M. M., Zamorano, M., & Alshaaer, M. (2019). Biomass fly ash and biomass bottom ash. In *New Trends in Eco-efficient and Recycled Concrete* (pp. 23–58). Elsevier. https://doi.org/10.1016/B978-0-08-102480-5.00002-6

Ahmad T., Ahmad K. & Alam M. (2016b). Characterization of water treatment plant's sludge and its safe disposal options. Procedia Environmental Sciences, V. 35, 950-955. https://doi.org/10.1016/j.proenv.2016.07.088

Ahmad, T., Ahmad, K., & Alam, M. (2016a). Sustainable management of water treatment sludge through 3'R' concept. *Journal of Cleaner Production*, *124*, 1–13. https://doi.org/10.1016/j.jclepro.2016.02.073

Bağrıaçık, B., & Güner, E. D. (2020). An Experimental Investigation of Reinforcement Thickness of Improved Clay Soil with Drinking Water Treatment Sludge as an Additive. *KSCE Journal of Civil Engineering*, *24*(12), 3619–3627. https://doi.org/10.1007/s12205-020-0111-5

Carter, M., & Bentley, S. P. (1991). Correlations of soil properties. *Correlations of Soil Properties*.

Chowdhury, A., Naz, A., & Chowdhury, A. (2022). Waste to resource: Applicability of fly ash as landfill geoliner to control ground water pollution. Materials Today: Proceedings, 60, 8–13. https://doi.org/10.1016/j.matpr.2021.10.367

Coelho, G. M. R., & João Carvalho de Albuquerque, A. (2016). Avaliação da Capacidade Reativa de uma Lama de ETA para Remoção de Metais Pesados de Escorrências Rodoviárias. Universidade da Beira Interior.

Colin JFP, Jones; F.G, B. (1985). Earth Reinforcement and Soil Structures. Butterworth-Heinemann.

Communities, O. J. of the E. (1986). Directive 86/278/EEC.

Cunha, P. P. (1987). Evolução Tectono-Sedimentar Terciária da Região de Sarzedas (Portugal). Comunicações Dos Serviços Geológicos de Portugal, pp. 67–84.

Fuller, R., Landrigan, P. J., Balakrishnan, K., Bathan, G., Bose-O'Reilly, S., Brauer, M., … Yan, C. (2022). Pollution and health: a progress update. The Lancet Planetary Health, 6(6), e535–e547. https://doi.org/10.1016/S2542-5196(22)00090-0

Galvín, A. P., López-Uceda, A., Cabrera, M., Rosales, J., & Ayuso, J. (2020). Stabilization of expansive soils with biomass bottom ashes for an eco-efficient construction. Environmental Science and Pollution Research. https://doi.org/10.1007/s11356-020-08768-3

Giwangkara, G. G., Mohamed, A., Nor, H. M., Hafizah A., N., & Mudiyono, R. (2020). Analysis of Internal Friction Angle and Cohesion Value for Road Base Materials in a Specified Gradation. Journal of Advanced Civil and Environmental Engineering, 3(2), 58. https://doi.org/10.30659/jacee.3.2.58-65

Gomes, C. (1986). Argilas: O que são e para que servem.

Huang, T., Qi, S., Liu, H., Yu, H., & Li, S. (2019). Shear Properties of Asphalt Mixtures under Triaxial Compression. Applied Sciences, 9(7), 1489. https://doi.org/10.3390/app9071489

Khalid, N., Mukri, M., Fadzil Arshad, M., Sidek, N., & Kamarudin, F. (2019). Effect on Salak Tinggi residual soil mixed Bentonite as compacted clay liner. IOP Conference Series: Materials Science and Engineering, 513(1), 012024. https://doi.org/10.1088/1757-899X/513/1/012024

Loo, S. van, & Koppejan, J. (2008). The Handbook of Biomass Combustion and Co-Firing. Earthscan United Kingdom.

Marchiori, L. & Albuquerque, A., 2020. Critical review of industrial solid wastes as barrier material for impermeabilization of storage waste facilities. Venice, Italy, CISA Publisher.

Marchiori, L., Albuquerque, A. & Cavaleiro, V., 2022a. Industrial solid wastes acting as barrier material for storing solid wastes (SW) and wastewaters - A critical review. Sydney, Australia, Australian Geomechanics Society, pp. 4829-4834.

Marchiori, L., Studart, A., Vitoria Morais, M., Alburquerque, A., & Cavaleiro, V. (2023). Geotechnical characterization of vegetal biomass ashes based materials for liner production. Testing and Experimentation in Civil Engineering - From Current to Smart Tecnologies.

Marchiori, L., Studart, A., Vitoria Morais, M., Albuquerque, A., Andrade Pais, L., Boscov, M.E.G. & Cavaleiro, V. (2022b). Geotechnical Characterization of Biomass Ashes for Soil Reinforcement and Liner Material. KnE Materials Science, 1–6. https://doi.org/10.18502/25

Marchiori, L., Studart, A., Albuquerque, A., Pais, L. A., Boscov, M. E., & Cavaleiro, V., 2022c. Mechanical and Chemical Behaviour of Water Treatment Sludge and Soft Soil Mixtures for Liner Production. The Open Civil Engineering Journal, 16(1). https://doi.org/10.2174/18741495-v16-e221115-2022-27

Marchiori, L. et al., 2021a. Geotechnical characterization of water treatment sludge for liner material production and soft soil reinforcement. Materials Science Forum, Volume 1046, pp. 83-88.

Marchiori, L. et al., 2021b. Avaliação do potencial de utilização de resíduo de estação de tratamento de água como impermeabilizante de obras de terra para a contenção de resíduos. São Paulo, s.n.

Marchiori, L. et al., 2021c. Evaluation of the potential use of water treatment sludge as a waterproofing material for waste containment earthworks. In: Coleção Desafios das Engenharias: Engenharia Sanitária 2. Ponta Grossa, Paraná, Brazil: Atena Editora, pp. 205-212.

Marchiori, L. et al., 2021d. A substituição de geossintéticos e solos através da valorização de resíduos de estação de tratamento de água em obras de terra. Lisboa, s.n., pp. 1423-1432.

Montalvan, E. L. T., & Boscov, M. E. G. (2021). Geotechnical properties of mixtures of water treatment sludge and residual lateritic soils from the State of São Paulo. Universidade de São Paulo.

Obrzud, R. F., & Truty, A. (2018). The hardening soil model - a practical guidebook. Zace Services Ltd, Software Engineering, 05, 205.

Parsekian, M. P. S. (1998). Análise da proposta de formas de gerenciamento de estações de tratamento de águas de abastecimento completo em cidades de porte médio do estado de São Paulo. Universidade de São Paulo.

Sahu, S. G., Chakraborty, N., & Sarkar, P. (2014). Coal–biomass co-combustion: An overview. Renewable and Sustainable Energy Reviews, 39, 575–586. https://doi.org/10.1016/j.rser.2014.07.106

Sami, M., Annamalai, K., & Wooldridge, M. (2001). Co-firing of coal and biomass fuel blends. Progress in Energy and Combustion Science, 27(2), 171–214. https://doi.org/10.1016/S0360-1285(00)00020-4

Scalize P., Souza L. & Albuquerque A. (2019). Reuse of alum sludge for reducing flocculant addition in water treatment plants. Environment Protection Engineering, 45(1), 57-70. https://doi.org/10.37190/epe190105

Shah, S. A. R., Mahmood, Z., Nisar, A., Aamir, M., Farid, A., & Waseem, M. (2020). Compaction performance analysis of alum sludge waste modified soil. Construction and Building Materials, 230, 116953. https://doi.org/10.1016/j.conbuildmat.2019.116953

Silva, A. R. da, & Maria Eugenia Gimenez Boscov. (2021). Comportamento Geoténico de Misturas de Areia Argilosa Laterítica e Lodo da Estação de Tratamento de Água Taiaçupeba, Município de Suzano, São Paulo. Universidade de São Paulo.

Studart, A., Marchiori, L., Vitoria Morais, M., Albuquerque, A., Gabriel Almeida, P., & Cavaleiro, V. (2022). Chemical and Mineralogical Characterization of Biomass Ashes for Soil Reinforcement and Liner Material. KnE Materials Science, 1–7. https://doi.org/10.18502/kms.v7i1.11625

Tan, Z., & Lagerkvist, A. (2011). Phosphorus recovery from the biomass ash: A review. Renewable and Sustainable Energy Reviews, 15(8), 3588–3602. https://doi.org/10.1016/j.rser.2011.05.016

Terzaghi, K., Peck, R. B., & Mesri, G. (1996). Soil Mechanics in Engineering Practice.pdf. John Wiley & Sons, 534.

Uzundurukan, S., & Saplioglu, K. (2022). Evaluation of the effect of soil bearing capacity on optimum design of retaining wall. Arabian Journal of Geosciences, 15(3), 296. https://doi.org/10.1007/s12517-022-09590-6

Vamvuka, D., & Zografos, D. (2004). Predicting the behaviour of ash from agricultural wastes during combustion. Fuel, 83(14–15), 2051–2057. https://doi.org/10.1016/j.fuel.2004.04.012

Vassilev, S. V., Baxter, D., Andersen, L. K., & Vassileva, C. G. (2013). An overview of the composition and application of biomass ash. Fuel, 105, 19–39. https://doi.org/10.1016/j.fuel.2012.10.001

Zajac G., Szyszlak-Barglowicz J., Golebiowski W. & Szczepanik M. (2018). Chemical characteristics of biomass ashes. Energies, 11, 2885. https://doi.org/10.3390/en11112885.

The paper was published in the proceedings of the 9th International Congress on Environmental Geotechnics (9ICEG), Volume 4, and was edited by Tugce Baser, Arvin Farid, Xunchang Fei and Dimitrios Zekkos. The conference was held from June 25th to June 28th 2023 in Chania, Crete, Greece.