

Geotechnical Characterization of Vegetal Biomass Ashes Based Materials for Liner Production



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

Abstract This paper aims to evaluate geotechnically, chemically, mechanically, and hydraulically parameters of vegetal-based biomass ashes (VBA) and its soil incorporation with different ratios as potential liner material and soils strengthening. Composites were developed for testing with different ratios of VBA: soil, following 05:95, 10:90, 15:85, and 20:80%. All laboratorial testing program followed European standards. For geotechnical characterization, the following tests were performed for all mixtures, the soil and VBA: granulometric distribution, specific gravity and Atterberg limits. Chemical characterization was done by collecting pH values and energy-dispersive X-ray spectroscopy (EDS) parameters for elemental and oxides analysis. Also, x-ray diffraction (XRD) was done to evaluate all sample's mineralogical description. In addition, mechanical analysis was conducted by analyzing expansibility, one-dimension consolidation through oedometer, and consolidated undrained (CU) triaxial test, along with falling head permeability for additional permeability analysis. Results have shown a finer granulometry and decrease of plasticity, 5% to non-plastic behavior, as higher amounts of VBA are introduced, exposing a filling-material behavior. EDS and XRD analysis indicate quartz, muscovite, orthoclase and calcite composition, and VBA could possibly have pozzolanic properties due to high silica-alum-ferric oxides amount. Mechanical parameters have shown a stabilization of VBA within the analyzed soil, exposing a slight reduction on settlements while increasing friction angle, 25–30°, and decreasing cohesion, 5–0 kPa. Permeability values have shown their feasibility for liners application, as found values characterizes all mixtures as low-permeability materials, especially introducing 5% of the residue into soil which values were below 10^{-9} m/s. Thus, the incorporation of VBA into soils paves a solid alternative for reusing this material in varied applications, as the analyzed soft soil has been geotechnically enhanced. Additional analysis, mainly pozzolanicity levels and leachability tests, can contribute for this on-going study to stablish VBA as a feasible material for the industry.

L. Marchiori (✉) · A. Studart · M. V. Morais · A. Albuquerque · V. Cavaleiro
Civil Engineering and Architecture Department, University of Beira Interior, FibEnTech and
Geobiotec, Covilha, Portugal
e-mail: leonardo.marchiori@ubi.pt

Keywords Geotechnical characterization · Biomass ashes · Liner material · Soil reinforcement · Earthworks

1 Introduction

Vegetal biomass ashes (VBA) are by-products from combustion, pyrolysis, and incineration of varied type of vegetal biomass, mainly composed by tree ashes. Their combustion is mainly used for energy production, already representing a significant 10% of energy supply around the world [1]. To enhance the fuels' calorific value, it can be associated to coal powered plants as a co-combustion product, this activity produces filter, bottom, and fly biomass ashes as by-products, which present different physical–chemical characteristics compared to the original biomass [1], due to high temperatures and different furnaces processes. Also, although there is a belief that biomass is renewable—as the released CO₂ is the same used in the nature—this claim is not correct for biomass ashes, as the combustion processes alter the original biomass, transforming into a residue that could contaminate waters and soils [3]. Therefore, researching new applications for VBA are necessary to avoid general contamination, [3] indicated possible replacement of gravel in road construction while also feasible for fine-grained clays and soils' replacement in the construction of landfill liners due to its latent hydraulic properties. Thus, to mitigate environmental impacts, research around their reuse through soil's amendment in different ratios is needed looking to ameliorate soft soils' geomechanical characteristics, making feasible for varied earthworks, such as liners applications.

Waterproofing liners are normally based in clays or geomembranes. Clays are generally weak soils, normally stabilized with cement, lime and other industrial products that are not environmentally friendly and could represent an environmental hazard. Geosynthetics, although an effective material, is still a costly solution [4, 5] and can impact the general cost–benefit value of an earthwork. Therefore, these established methodologies could be improved through new methodologies and greener approaches, such as through the valorization of biomass ashes. Bagasse ash, rice husk ash, and palm oil fuel ash are prominent examples of such residues; cellulose and paper mill sludge, for example, consist mainly of fibbers and fillers can have low hydraulic conductivity (k) when properly compacted [6]. Leme and Miguel [7] analyzed the industrial potential for VBA and concluded the main advantage is the concentration and recovery of valuable components—SiO₂, Al₂O₃, CaO—which could indicate their feasibility for soft soil reinforcement, increasing effective friction angle while reducing voids and settlement, along with low permeability for liner production. A deeper investigation over chemical and mechanical parameters can also provide data to better understand and assess VBA's properties and its interaction with soils [7–9].

Therefore, understanding the characteristics of the analyzed VBA when introduced into soils could provide a better understanding for earthworks' application and contribute for its valorization, leading to an approach of production within the scope

of circular economy. Thus, this paper aims to investigate and characterize geomechanically a VBA mainly based on biomass pine and olive ashes, and mixtures of VBA and a weak soil for evaluating their feasibility for application as liner material.

2 Methodology

VBA were collected at the industrial park of VALAMB, Castelo Branco, Portugal, and the soil was collected from the same region. Four mixtures of VBA:SOIL were developed based on dried masses in temperatures of 60–65 °C, with the following ratios:

Materials	VBA (%)	Soil (%)
Soil	0	100
VBA	100	0
05:95%	05	95
10:90%	10	90
15:85%	15	85
20:80%	20	80

All the materials, individually and the mixtures, were characterized for the determination of specific gravity (G_s), granulometry distribution (D_{10} , D_{50} and D_{90}) by sieves procedure, and consistency limits (W_L , W_P , PI) according to European standard ISO 17982 [10–12]. Normal Proctor compaction tests followed the procedure in BS1377-4 [13] for optimal characteristics ($\rho_{d, opt}$ and w_{opt}). Chemical compositions were determined through energy-dispersive X-ray spectroscopy (EDS) and scanning electrons microscopy (SEM) images by S-2700 Hitachi, Rontec, USA, and mineralogical analysis through X-ray diffraction (XRD), using a Phillips Analytical X-Ray B. V. from Rigaku, model DMAXIII, USA. EDS and XRD were also carried out for samples of the raw vegetal material (RVM) to compare the values with the ones for VBA.

Settlements during the oedometer tests were measured by an automatic LCR transducer strain gauge, through MPE with maximum strain of 25.8 mm and precision of 0.001 mm, connected to a data logger MPX3000, 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 1200-300-1 kPa, based on [14].

For the triaxial compression tests, the equipment from GDSLab was used. Several series of consolidated undrained triaxial compression tests (CU) with pore water pressure and axial strain measurements were carried out. Saturation was interrupted when Skempton parameter B reached 0.95, and consolidation, when there was no difference in the volume for a certain period. The tests were ended when the axial strain reached 22%. For each material, three CU tests were performed, with confining pressures of 100, 200, and 300 kPa.

Falling-head permeability tests were performed in replicates for each material, with initial hydraulic gradients (i) of 25 and 100, based on [15].

Mechanical and hydraulic tests were not performed for VBA by itself due to very bad workability.

3 Results and Discussion

3.1 Geotechnical Characterization

Geotechnical parameters results are presented in Table 1 and show that VBA granulometry is finer than the soil, possibly indicating good filling properties, as it would fill voids within analyzed mixtures. A non-plastic (NP) behavior is observed for the mixtures with 10–20% of VBA, although 5% of VBA:SOIL remained just as plastic as the soil, a low-plasticity material. The literature review showed variable results, [17] found ashes with around 2.0 while [26] 2.6 of specific gravity, and as plasticity results, most studies found no plasticity for VBA.

Compaction parameters revealed an increasing of optimum water content (w_{opt}) and decrease in optimum dry density ($\rho_{d, opt}$) when VBA was increased up to 20%, providing a lighter material and a clay similar performance. Soil amendment with VBA is providing a finer granulometry as higher introduced VBA's portions are. Therefore, this result is an initial positive result, as the decrease of the soil's plasticity while decreasing specific gravity (G_s) could indicate VBA filling properties and weight reduction capacity, both being desirable characteristics, as better logistics due to easier material transport. Further mechanical analysis will be discussed to evaluate the impact of such characteristics in the resistance and consolidation parameters.

Table 1 Geotechnical parameters for soil, VBA e mixtures

Material	Particle size				Density	Plasticity			Compaction	
	Fines	D ₁₀	D ₅₀	D ₉₀	G _s	W _L	W _P	PI	w _{opt}	ρ _{d, opt}
	%	μm	μm	μm	–	%	%	%	%	g/cm ³
Soil	11	80	850	2000	2.7	40	35	5	19	1.70
VBA	10	75	600	1500	1.9	NL	NP	NP	25	0.90
05:95%	10	75	750	1800	2.6	41	33	8	16	1.65
10:90%	12	80	550	1700	2.5	44	NP	NP	18	1.60
15:85%	11	80	500	1750	2.5	43	NP	NP	21	1.55
20:80%	12	80	500	1600	2.4	42	NP	NP	25	1.50

D₁₀, D₅₀, D₉₀: particle size below 10, 50 or 90% of all particles; G_s: specific gravity; W_L: liquid limit; W_P: plastic limit; PI: plastic index; NL: non-liquid; NP: non-plastic; w_{opt}: optimum water content; ρ_{d, opt}: optimum dry density

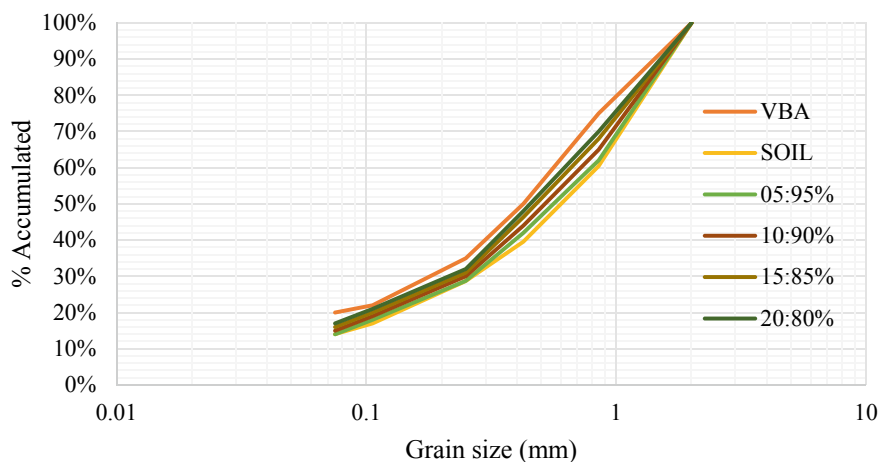


Fig. 1 Granulometric distributions for all samples

According to Unified Soil Classification System (USCS) in ASTM D2467, all tested materials are well-graded sand (SW), as exposed in Fig. 1, particle size distributions are very similar, the orange line and the yellow line show VBA and soil, respectively, being VBA finer than soil, therefore the mixtures are in between those curves, it is difficult to perceive due to the scale of granulometric distribution, however the material behaves as finer with greater VBA introductions. In the classification and compaction characteristics context, VBA around several studies [17–23, 26] behave like a typical sandy soil with silt.

3.2 Mechanical Performance

Mechanical parameters results are presented in Table 2 and show that VBA's feasibility for both enhancing soil's resistance and slightly reducing its consolidation. Although expansibility parameter (S) has not decreased, VBA's introduction has not significantly impacted the original soil's expansibility, exposing their possible introduction without altering some original parameters of the soil. S was not performed to RVM due to its coarse particle size distribution, being unable to sieve the amount required for the test.

One-dimensional oedometric consolidation samples were remoulded compacting a Normal Proctor mould and extruded from it in laboratory, for the test there were only the initial consolidation due to the pore stone and top cap, then the loads were applied. Initial void ratios distinguished in between 50 and 65% due to rearrange of particles within different VBA introduction ratios, possibly filling the voids for 05–10% and for 15–20% increasing the size of the pores. Figure 2 exposes oedometer curves, the chosen loads for oedometer were mainly to evaluate the compressibility

Table 2 Mechanical parameters

Material	Expansibility	Consolidation				Triaxial	
	S (%)	e ₀ (%)	C _c (-)	C _s (-)	C _R (-)	c' (kPa)	φ' (°)
Soil	22	55	0.100	0.015	0.015	10	25
VBA	18	–	–	–	–	–	–
05:95%	20	50	0.100	0.024	0.013	0	25
10:90%	22	52	0.090	0.021	0.017	0	25
15:85%	22	59	0.080	0.018	0.018	0	30
20:80%	20	65	0.070	0.017	0.021	0	25

coefficient (C_c) progressively from 30 to 1200 kPa, exposing a slight C_c reduction, which indicate lower settlement which could eventually minimize damage within civil structures, such as fissures. S values fluctuated in 20% with a little reduction when introducing VBA, also stabilizing the composites. For liner, it can help prevent residues and heavy metals to percolate and infiltrate into subsoil and groundwater. Consolidation behaviour for VBA:SOIL mixtures do not change significantly the soil's performance, which can be seen as a positive characteristic, as the residue's introduction did not worsen the soil. Corroborating with [26–29] long-term data which consolidated VBA as a stabilizer for many types of soils, as expansive, soft, and organic ones.

Consolidated undrained triaxial specimens were recompacted inside a triaxial mould using similar energy to Normal Proctor compaction, they followed the procedure of firstly saturate the sample with a confining stress of 100 kPa and then consolidate until there was no pore volume change. Stress path curves are presented in Fig. 3, in accordance with the results presented in Table 2, 15:85% composites seem to be the most susceptible reinforcement, with high effective friction angle (ϕ') of 30° and no cohesion (c') making the composite susceptible for varied earthworks, such as

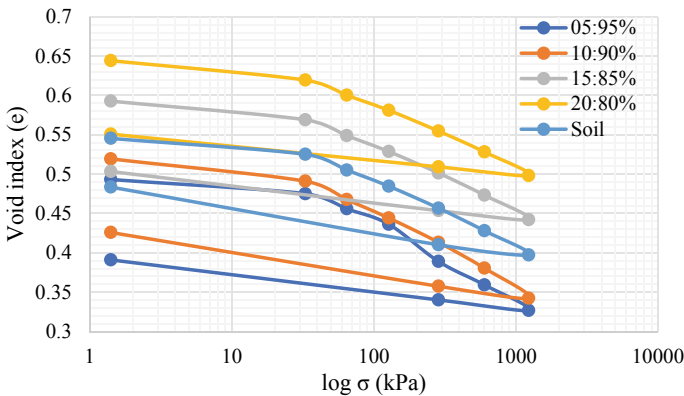


Fig. 2 Oedometric curves for soil, and mixtures

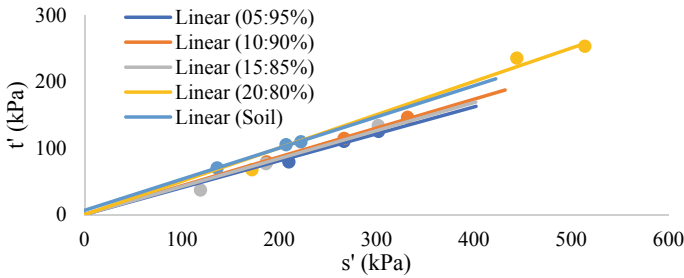


Fig. 3 Stress paths envelopes for soil and mixtures

retaining structures or liners [16, 17]. Other mixtures presented the same behaviour, $c' = 0$ and the no interference in φ' of the soil, stabilizing the soil. Previous studies have presented VBA’s successful introduction into soils, enhancing some parameters, such as shear resistance increase, or maintaining soils’ original values, such as plasticity indexes and consolidation parameters [18, 19]. Thus, found results corroborate to the VBA’s successful introduction ameliorating geomechanical parameters of soils.

Oedometric and triaxial tests were not performed for the VBA by itself because the materials do not have workability for moulding, and the main objective is to incorporate the by-product into soils.

3.3 Hydraulic Conductivity

Hydraulic conductivity is the main parameter for analyzing a materials’ susceptibility for liners application. Low permeability is highly recommended for soils and materials in such applications [20]. Found k values are summarized in Table 3. The same sampling procedure of the oedometer consolidation tests were done for the permeability, although introduced in a permeameter with the same diameter, and as the specimens had 2.0 cm height, the rest of the permeameter were filled with water.

Presented data states the soil is a low permeability material and a proper material for liner applications. When introducing VBA, k values had an impact on the average of a magnitude order of 10x, indicating a behavior closer to a granular material,

Table 3 Permeability results for soil and mixtures

Material	k (m/s)
Soil	6×10^{-11} – 3×10^{-9}
05:95%	6×10^{-10} – 1×10^{-9}
10:90%	6×10^{-10} – 1×10^{-8}
15:85%	1×10^{-9} – 2×10^{-8}
20:80%	1×10^{-9} – 2×10^{-8}

although generally maintaining low permeability characteristics. Regarding 05:95% mixtures, found results were close to the limit for liners making feasible for this application. Although unsatisfactory values were also obtained for the 10–15–20% mixtures, exposing a necessity of treatment for the sample.

Osinubi and Eberemu [21] tested residual compacted granite soil treated with 0–15% biomass ash, which should behave like VBA due to combustion, to assess its hydraulic conductivity for use in landfills and resulted in an improvement in soil plasticity, also showed for the 05:95% sample, although differs for the others mixtures, while $\rho_{d, \text{opt}}$ and w_{opt} decreased and increased, respectively, increasing biomass ash content. In general, k decreased to a 10% biomass ash content, for which k was around 10^{-9} m/s, but with 15% increased to k around 10^{-7} cm/s, unsuitable for liners. [21] also tested on a reddish-brown lateritic soil treated with up to 12% of biomass ash to assess its suitability in applications of waste containment barriers and in the 4–12% range of residue into composite material, compacted samples recorded hydraulic conductivity values below 10^{-9} m/s, making it suitable for use in barrier applications of waste containment.

Abovementioned works on VBA:SOIL composite had shown great impact on permeability up to 10% of residue's incorporation, corroborating with Table 3 results, and concluding that for granular soils, VBA can decrease k , and for clayey, increase k , although not very significantly, making possible a controlled introduction of VBA into soils for geotechnical purposes.

Analyzing collected data, the 05:85% seems to be the optimal mixture, as it managed to reach values below 10^{-9} cm/s in all tests, characterizing itself as a possible liner material. In addition, the 20:80% mixture has suffered a drop on the hydraulic performance, which can be due to an excess of granular material behavior without plasticity, allowing greater water percolation and, therefore, k values above the limit.

3.4 Chemical and Mineralogical Composition

Chemical analysis were conducted to evaluate all samples' composition and investigate their origins and a larger understanding of their behaviour, in addition, the raw vegetal material (RVM) of the combusted VBA was analysed to possibly trace some elements. Therefore, EDS oxides are in Table 4. [1, 8, 9] made a comprehensive and extensive study around biomass ashes chemical composition aligned with the raw material, and concluded that it can vary in oxides percentages mainly due to raw material typology, incineration or industrial processes and location of the culture or the power plant because of weathering effect.

As stated in [18], VBA is considerably different from RVM, having higher amounts of Na, Si, Ca, S and Fe and a crystalline structure as there are many minor peaks hard to characterize apart from the above-mentioned. Also, a generally amorphous structure is also present, mostly due to physic-chemical alterations as calcination through incineration process occur. These elements' enrichment has different and varied causes as the incineration process of RVM involves different

Table 4 EDS results for soil, VBA and RVM

Material	Soil	VBA	RVM	05:95%	10:90%	15:85%	20:80%
Na ₂ O (%)	0.6	1.2	0.4	0.8	0.9	1.0	1.1
MgO (%)	2.3	4.2	7.6	2.6	2.9	3.4	3.6
Al ₂ O ₃ (%)	27	18	34	26	25	24	23
SiO ₂ (%)	56	45	4.6	54	53	52	51
CaO (%)	–	15	3.3	2.4	3.6	6	8
K ₂ O (%)	4.5	7.1	8.8	4.8	5.2	5.4	5.7
SO ₃ (%)	–	1.8	0.5	–	–	–	–
Fe ₂ O ₃ (%)	8.3	5.8	0.1	8	7.7	7.6	7.5
TiO ₂ (%)	0.9	0.7	0.8	0.9	0.8	0.7	0.7
MnO (%)	–	–	27	–	–	–	–
Others (%)	0,4	0,2	12,9	–	–	–	–

methodologies and chemical products. Different type of coals can be used as fuel while granular materials, such as silicious sand, are also commonly used within fluidized bed methodology [22]. Silica, for example, was the element that suffered the highest increase, probably due to the use of silicious sand during the fluidized bed combustion process of RVM.

Followed by the silica, calcium suffered high enhancement, which although hard to precisely explain the reason, several studies have also stated this behaviour on pine-based biomass and could trace it back to thermal-conversions happening from 500 °C, being more pronounced on carbonated minerals, such as Calcite's (CCaO₃) disintegration that releases CO₂ and forms CaO [8, 9]. In addition, coals' varied composition and generally high amount of alkali metals [23] could also induce the conversion of some elements to new composites through the iteration of the coals' reactive part with released gases during incineration, such as sulphur.

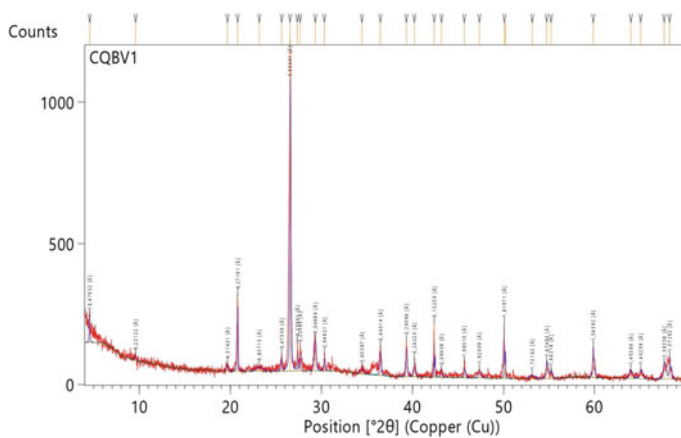
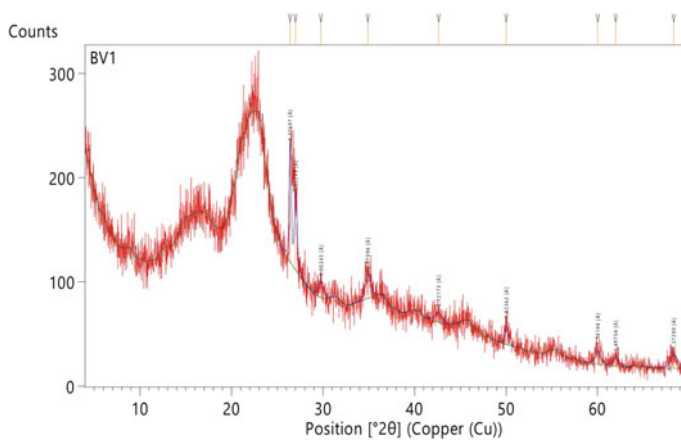
Mineralogical composition were conducted for VBA, RVM, and the soil, and RVM, XRD were not done for the mixtures due to supposed no mineralogical change. Table 5 shows found mineralogy for VBA, RVM, and SOIL, respectively, along with XRD diffractograms shown in Figs. 4, 5 and 6.

Although similar minerals were found among their composition, the quantities vary considerably, while also being hard to identify every peak through VBA's sample as there are many minor peaks hard to trace back. In addition, all samples have shown mineralogy compatible with the collection location—Castelo Branco's region—which is mostly corresponded by metamorphic schists, feldspars, and granites [24]. Therefore, although presenting mostly similar mineralogy, the chemical number of oxides and the structure itself change considerably to the point of being basically a new material. This new material is also characterized by having the sum of Si + Al + Fe content around 70%, indicating pozzolanic properties, as [25] defines this amount for possibly having good levels of pozzolanicity, creating a silica-gel that could minimize voids while enhancing resistance.

Table 5 Mineralogical results for soil, VBA and RVM

Mineral	RVM	VBA	SOIL
Quartz	X	X	X
Muscovite	X	X	X
Orthoclase	X	X	
Calcite	X	X	
Kaolinite	X		X

Quartz (SiO_2); Muscovite ($\text{Al}_2.8\text{Fe}0.1\text{H}_2\text{K}0.6\text{Mg}0.04\text{Na}0.37\text{O}12\text{Si}_3.04\text{Ti}0.02$); Orthoclase (AlKO_8Si_3); Calcite (CCaO_3); Kaolinite ($\text{Al}_2\text{H}_4\text{O}_9\text{Si}_2$)

**Fig. 4** XRD results for VBA**Fig. 5** XRD results for RVM

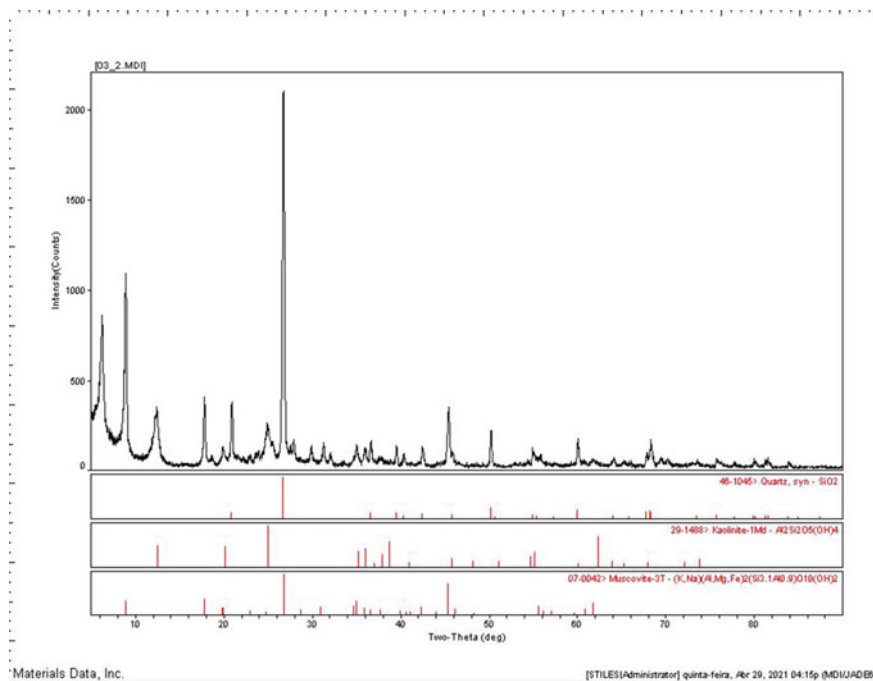
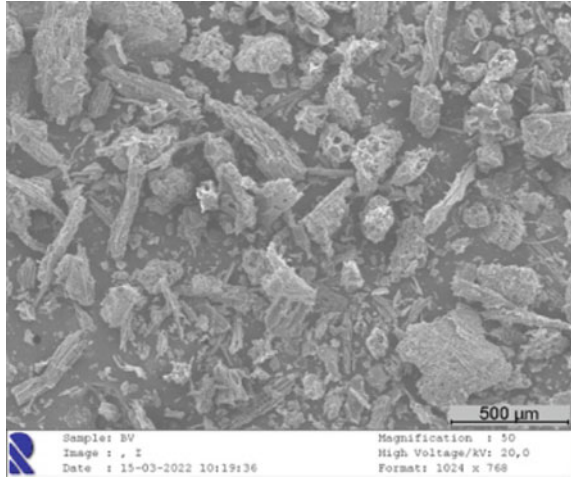
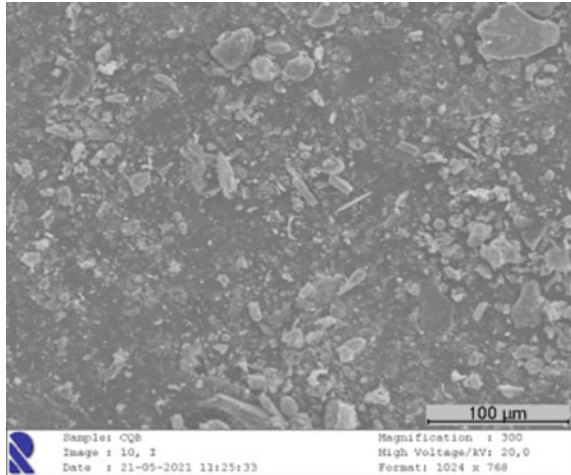


Fig. 6 XRD results the soil

To complement, SEM evaluation on a magnification of $300\times$ was conducted for VBA, soil, and mixtures, and due to bigger particle size, $50\times$ for RVM. Results can be observed through Figs. 7, 8, 9, 10, 11, 12 and 13 for RVM, VBA, soil, and mixtures, respectively. Although RVM has a coarse granulometry comparing with other even with lower magnification images. VBA presents a finer granulometry compared to RVM and soil, corroborating with previous analysis of void-filling capacity, as it can also be stated throughout analysed mixtures. This decrease in particle size can be attributed to combustion processes which disintegrated the raw material and deeply impacted their physic-chemical characteristics.

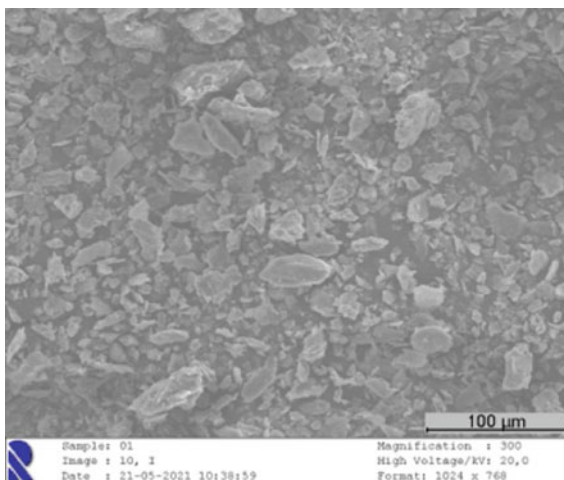
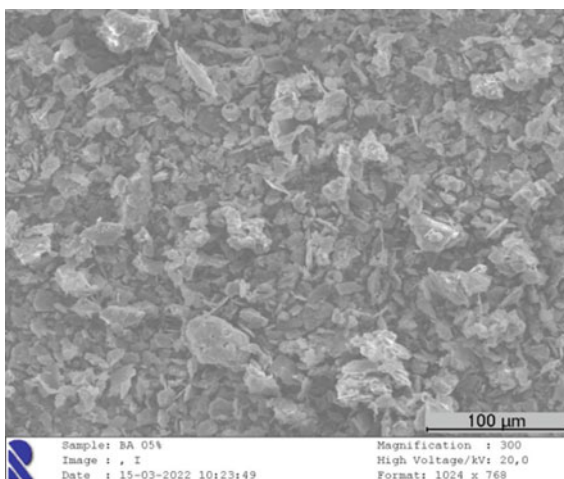
4 Conclusion

The analysed biomass ashes seem to be a feasible soil substitute for liners applications on the 05:95% proportion due to hydraulic conductivity and geotechnical characteristics. It can mitigate the utilization of clayey soil, a scarce raw material, and geosynthetics which are still a costly solution.

Fig. 7 SEM image for RVM**Fig. 8** SEM image for VBA

Although other mixtures could possibly be used through samples' treatment, lowering permeability values. Furthermore, the conclusions of this research towards the valorisation of residues within the scope of circular economy were:

- Granulometry distribution generated finer materials within VBA incorporation.
- Resistance and consolidation were ameliorated by VBA's filling properties and lowering plasticity characteristic.
- All samples showed soil's strengthening, principally the 15:85% and 20:80% ratios due to an increase on friction angle and decrease of cohesion.
- Results have shown enhancement of the analysed soil' geomechanical characteristics and, mostly, conserving soil's parameters.

Fig. 9 SEM image for Soil**Fig. 10** SEM image for 05:95%

- Chemical analysis indicated a possible pozzolanic activity, which could also be useful, principally if associated to leachability and FTIR tests, needing this future evaluation.
- 05:95% ratio of VBA within soil as composite material seems to be an alternative liner material, reaching required k values, not changing consolidation, plasticity, and shearing performance of the soil.

Fig. 11 SEM image for 10:90%

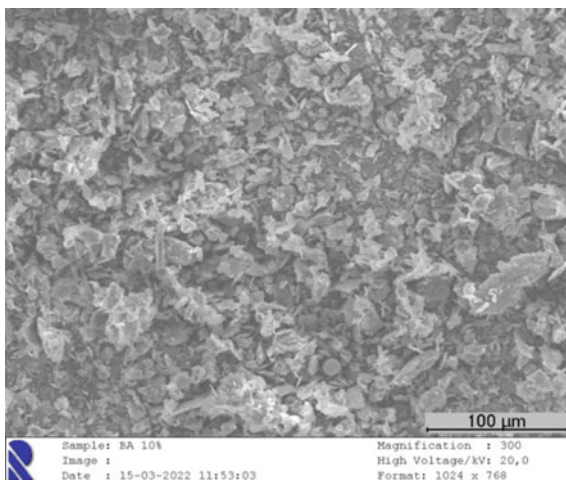


Fig. 12 SEM image for 15:85%

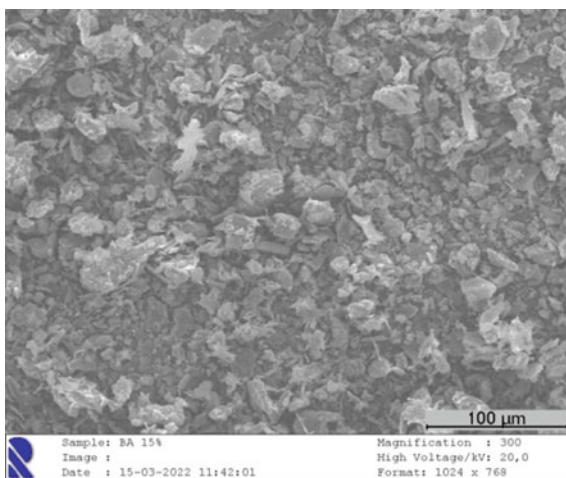
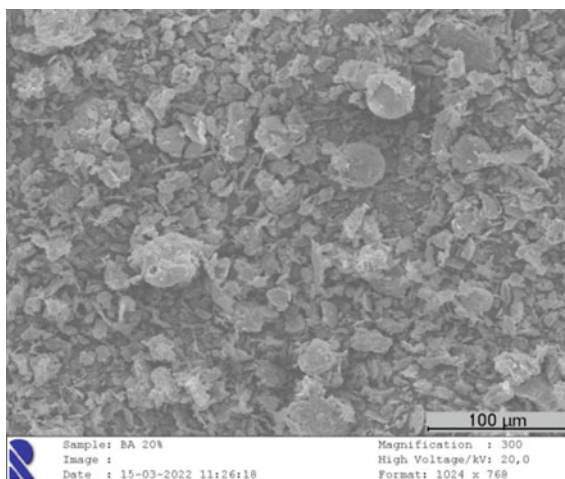


Fig. 13 SEM image for 20:80%



Acknowledgements The authors are grateful to the Foundation for Science and Technology (FCT, Portugal) for financial support by national funds through the projects UIDB/00195/2020 (FibEn-Tech) and UIDB/04035/2020 (GeoBioTec). The authors are also grateful to João Dias das Neves, VALAMB—Grupo Razão, who provided the biomass ashes' material, and Dra. Ana Gomes, from UBI's Optical Center with the EDS, XRD and SEM analysis.

References

1. Vassilev, S.V., Baxter, D., Andersen, L.K., Vassileva, C.G.: An overview of the chemical composition of biomass. *Fuel* **89**(5), 913–933 (2010). <https://doi.org/10.1016/j.fuel.2009.10.022>
2. van Loo, S., Koppejan, J.: *The Handbook of Biomass Combustion and Co-Firing*. Earthscan (2008)
3. Obernberger I, Supancic K: Possibilities of ash utilisation from biomass combustion plants. (2009).
4. Duffy, D.P.: *Landfill Economics—Part 1—Getting Down to Business*. MSW Management (2015)
5. Duffy, D.P.: *Landfill Economics—Part 2—Getting Down to Business*. MSW Management (2016)
6. Vassilev, S.V., Baxter, D., Andersen, L.K., Vassileva, C.G.: An overview of the composition and application of biomass ash. *Fuel* **105**, 19–39 (2013). <https://doi.org/10.1016/j.fuel.2012.10.001>
7. Alves de Godoy Leme, M., Gonçalves Miguel, M.: Permeability and retention to water and leachate of a compacted soil used as liner. *Water, Air, Soil Pollut.* **229**(11) (2018). <https://doi.org/10.1007/s11270-018-4001-0>
8. Vamvuka, D., Zografos, D.: Predicting the behaviour of ash from agricultural wastes during combustion. *Fuel* **83**(14–15), 2051–2057 (2004). <https://doi.org/10.1016/j.fuel.2004.04.012>
9. Vamvuka, D., Pitharoulis, M., Alevizos, G., Repouskou, E., Pentari, D.: Ash effects during combustion of lignite/biomass blends in fluidized bed. *Renew. Energy* **34**(12), 2662–2671 (2009). <https://doi.org/10.1016/j.renene.2009.05.005>

10. ISO17892-3: Geotechnical investigation and testing—Laboratory testing of soil—Part 3: Determination of particle density (2015)
11. ISO17892-4: Geotechnical investigation and testing—Laboratory testing of soil—Part 4: Determination of particle size distribution (2016)
12. ISO17892-12: Geotechnical investigation and testing—Laboratory testing of soil—Part 12: Determination of liquid and plastic limits (2018)
13. BS 1377-4: Methods of test for Soils for civil engineering purposes—Part 4: Compaction-related tests. British Standards Institution, UK (1990)
14. ISO17892-5: Geotechnical investigation and testing—Laboratory testing of soil—Part 5: Incremental loading oedometer test. (2017)
15. ISO17892-11: Geotechnical investigation and testing—Laboratory testing of soil—Part 11: Permeability tests. (2019)
16. Rubinos, D.A., Spagnoli, G.: Utilization of waste products as alternative landfill liner and cover materials—a critical review. *Crit. Rev. Environ. Sci. Technol.* **48**(4), 376–438 (2018). <https://doi.org/10.1080/10643389.2018.1461495>
17. Marchiori, L., Albuquerque, A.: Critical review of industrial solid wastes as barrier material for impermeabilization of storage waste facilities. In: SUM2020—5th Symposium on Urban Mining and Circular Economy (2020)
18. Studart, A., Marchiori, L., Morais, M.V., Albuquerque, A., Almeida, P.G., Cavaleiro, V.: Chemical and mineralogical characterization of biomass ashes for soil reinforcement and liner material. In: 1st International FibEnTech Congress (FibEnTech21) New Opportunities for Fibrous Materials in the Ecological Transition, pp. 1–7, Covilhã (2021)
19. Marchiori, L. et al.: Geotechnical characterization of biomass ashes for soil reinforcement and liner material. In: 1st International FibEnTech Congress (FibEnTech21) New Opportunities for Fibrous Materials in the Ecological Transition, pp. 1–6, Covilhã (2021)
20. Khalid, N., Mukri, M., Fadzil Arshad, M., Sidek, N., Kamarudin, F.: Effect on Salak Tinggi residual soil mixed Bentonite as compacted clay liner. *IOP Conf. Ser. Mater. Sci. Eng.* **513**(1), 012024 (2019). <https://doi.org/10.1088/1757-899X/513/1/012024>
21. Osinubi, K.J., Eberemu, A.O.: Hydraulic conductivity of compacted lateritic soil treated with bagasse ash. *Int. J. Environ. Waste Manag.* **11**(1), 38–58 (2013). <https://doi.org/10.1504/IJEW.2013.050522>
22. Pinto, J.C.F.: Características da cinza de combustão de biomassa em leito fluidizado. Universidade de Aveiro (2011)
23. Vassilev, S.V., Vassileva, C.G.: A new approach for the classification of coal fly ashes based on their origin, composition, properties, and behaviour. *Fuel* **86**(10–11), 1490–1512 (2007). <https://doi.org/10.1016/j.fuel.2006.11.020>
24. Cunha, P.: Evolução tectono-sedimentar terciária da região de Sarzedas (Portugal). *Comunicação Serviço de Geologia Portugal* **73**(1/2), 67–84 (1987)
25. ASTM C618: 12a Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete”. <https://doi.org/10.1520/C0618-12a>
26. Edil, T.B., Berthouex, P.M., Vesperman, K.D.: Fly ash as a potential waste liner. In: *Geotechnical Practice for Waste Disposal 87’*, GSP13 (1987)
27. Li, L., Benson, C.H., Edil, T.B., Hatipoglu, B.: Sustainable construction case history: fly ash stabilization of recycled asphalt pavement material. *Geotech. Geol. Eng.* **26**(2), 177–187 (2008). <https://doi.org/10.1007/s10706-007-9155-2>
28. Tastan, E.O., Edil, T.B., Benson, C.H., Aydilek, A.H.: Stabilization of organic soils with fly ash. *J. Geotech. Geoenviron. Eng.* **137**(9), 819–833 (2011). [https://doi.org/10.1061/\(ASCE\)GT.1943-5606.0000502](https://doi.org/10.1061/(ASCE)GT.1943-5606.0000502)
29. Senol, A., Bin-Shafique, M.S., Edil, T.B., Benson, C.H.: Use of class c fly ash for stabilization of soft subgrade. In: *Fifth International Congress on Advances in Civil Engineering* (2002)