Soils and Rocks
An International Journal of Geotechnical and Geoenvironmental Engineering
www.soilsandrocks.com
ISSN 1980-9743
ISSN-e 2675-5475

Mechanical behavior analysis of polymer stabilized gold ore tailings

Giovanna Monique Alelvan[1#], Michéle Dal Toé Casagrande[1], Nilo Cesar Consoli[2]

Article

Keywords
Gold ore tailings
Direct shear test
Unconfined compressive strength
Polymer
Tailings stabilization

Abstract

Chemical stabilization for mining tailings is a promising alternative to enable their use as construction materials. For this, it is necessary to evaluate the behavior of these composites to ensure minimum design requirements. This research aims to demonstrate that an addition of 15% of polymeric solution content, corresponding to 6% of polymer by tailings mass unit, can improve considerably the mechanical strength of gold ore mining tailings. To this end, unconfined compression and direct shear tests were conducted, indicating an increase in compressive and shear strength, especially with 28 days of curing time and at maximum dry unit weight. Microstructural and chemical tests were also performed, demonstrating that the tailings have silt-sized particles, mostly composed of quartz, muscovite, and kaolinite. Despite its granulometry, the tailings do not exhibit cohesive behavior and require to be considered perhaps as rock sediments. Scanning Electron Microscope analysis showed that the particles are lamellar, and a more stable arrangement contributes to the polymer's performance as a binder. It was observed that the strength gain occurs due to polymer bond effect and to the matric suction.

1. Introduction

Wijewickreme et al. (2005) define mining tailings as being essentially crushed rock particles derived from ore processing. The mineralogy, grain size, and morphology of the ore tailings particles vary significantly as a function of the composition of the parent rock and the beneficiation process to which they were subjected (Kiventera et al., 2019). This evidence demonstrates the need to expand studies in this area, to understand the behavior of these materials through the classical theories of Geotechnics.

The investigation of the mechanical behavior of tailings is important not only for safe design inside the mine but also as validation to be used in other structures, such as compacted embankments, sub-base of pavements, and mining backfill (Consoli et al., 2017). The proposed use of tailings as construction materials is directly related to stabilization and reinforcement techniques, due to the need to improve the mechanical properties of these materials.

The investigation of tailings behavior through mechanical testing has been an approach used by many authors (Bhanbhro, 2014; Islam, 2021; Carneiro & Casagrande, 2020; Sotomayor et al., 2021). Several others have also been exploring reinforcement and stabilization alternatives to improve the properties of the tailings (Festugato et al., 2015; Consoli et al., 2017; Zheng et al., 2019; Xue et al., 2021).

Chemical stabilization has been an interesting proposal, especially using traditional additives such as lime, fly ash, and cement. On the other hand, non-traditional additives, such as polymers and enzymes, have been under-explored as solutions to enable the use of tailings as construction materials (Huang et al., 2021).

The objective of this work is to investigate gold ore tailings in a pure state and stabilized with a polymeric solution. The mechanical analyses were conducted through geotechnical characterization, compaction, unconfined compression and direct shear tests. Chemical, microstructural, mineralogical, and matric suction analyses were also performed to help understand the mechanical behavior.

2. Experimental program

The gold ore tailings used was extracted from the Morro do Ouro deposit in Minas Gerais State, Brazil.

[#]Corresponding author. E-mail address: giovannaalelvan@gmail.com
[1]Universidade de Brasília, Departamento de Engenharia Civil e Ambiental, Brasília, DF, Brasil.
[2]Universidade Federal do Rio Grande do Sul, Departamento de Engenharia Civil, Porto Alegre, RS, Brasil.

Submitted on September 29, 2021; Final Acceptance on January 7, 2022; Discussion open until August 31, 2022.
https://doi.org/10.28927/SR.2022.075421

The deposit is hosted in the carbonaceous phyllites of the Paracatu Formation belonging to the Canastra Group, which is composed of an association of detrital metasedimentary rocks characterized by layers of grey phyllites with quartz intercalations (Amorim, 2007).

The sample received was friable and with a large amount of gravel. Only the fine fraction of the tailings was used in this research. All the material was sieved on the 2.0 mm mesh to separate the coarse portion. A visual-tactile analysis indicated little roughness and plasticity only at higher moistures. The dry sample presented resistant clods and particles with low sedimentation speed, compared to sandy soils.

The stabilizer used in this research consists of an organic acrylic-styrene copolymer obtained randomly and presented in the form of an aqueous emulsion of anionic character. The polymer has a pH of 8.0-9.0, a density of 0.98-1.04 g/cm^3, a viscosity of 3,000-10,000 centiPoise (cP) and is completely soluble in water. The product is frequently used as pavement sealing and soil stabilizer. Silva (2020) and Carneiro & Casagrande (2020) performed studies on the chemical and biological characterization of the polymer to better understand its composition. The X-ray Fluorescence Spectrometry (XRF/EDX) and Elemental Analysis of CHN tests indicated that the polymer has a large amount of carbon (69%), followed by hydrogen (7%), nitrogen (0.5%), and other chemical elements arising from the polymerization process. In addition, the same authors analyzed leachate from composites formed by sandy and ore tailings with this polymer. They concluded that the use of this stabilizer is not hazardous to the environment, since the chemical concentrations obtained were lower than the standard limits established by the National Council of Environment (CONAMA) in Brazil.

For physical characterization of pure tailings, the grain size was determined by laser granulometer. Besides that, specific gravity of soil was measured by the pycnometer equipment model PENTAPYC 5200e, as ASTM D5550-14 "Standard Test Method for Specific Gravity of Soil Solids by Gas Pycnometer" (ASTM, 2016).

Proctor Compaction Tests with normal compaction energy were performed for the pure tailings and the composite, where the polymeric solution was added (ABNT, 2016a; ASTM, 2011). The polymeric solution is composed of water and polymer, in the percentages of 60% and 40%, respectively. The amount of polymer solution inserted (15%, corresponding to the water content choose) is calculated according to the mass of tailings. Therefore, the composite tailings-polymer formed has 6% of polymer in mass of tailings.

Unconfined compression and direct shear tests were performed to evaluate the mechanical strength of the pure tailings and the composite, for two dry unit weight (1.7 g/cm^3 and 1.8 g/cm^3) and two curing periods (7 and 28 days). The dry unit weight values were chosen according to the compaction curve in order to evaluate the influence of the structure on mechanical strength.

The curing of the specimens was done through exposure to air, since the polymer flocculation occurs through exposure to atmospheric oxygen. The following criteria to accept the samples were considered: (i) height variation of ± 1 cm; (ii) degree of compaction ± 1%. All the samples were submitted to the ultrasonic test to verify their uniformity.

For the unconfined compression test, specimens of 5 cm in diameter and 10 cm height were molded (ABNT, 2016b). The specimens were statically compacted in three layers inside a steel cylinder. For each layer, the dry unit weight was verified, and the top of the layers was scarified for better adherence to the others. At the end of the process, they were immediately removed from the mold and weighed, and the dimensions were obtained. The unconfined compression test speed was 1.27 mm/min, and it was conducted until total loss of strength of the specimen. The tests were performed in triplicates and the arithmetic average of unconfined compressive strength was used.

The direct shear test was conducted to determine the soil strength parameters (cohesion and friction angle) from the establishment of the Mohr-Coulomb strength envelope (ASTM, 2012). The specimens were built using a mold, which has dimensions of the small shear box (60 mm × 60 mm × 25 mm), at the optimum moisture content, according to the compaction test. The following criteria to accept the samples were considered: (i) height variation of ± 0.5 cm; (ii) degree of compaction ± 1%. Normal stresses of 50 kPa, 100 kPa, 200 kPa were applied to obtain the strength envelope.

Suction measurement tests were performed on the pure tailings and the composite to evaluate the influence of suction on strength gain as curing progress. For this, the psychrometer equipment (WP4C) was used. Cylindrical samples were molded for the test at the two dry unit weight analyzed, and the curing times were defined as 7 days, 14 days, and 28 days.

Mineralogical characterization tests were conducted to identify the minerals present in the crystalline structure. Samples of the pure tailings and the composite were analyzed using the tests X-Ray Diffraction (XRD) and X-Ray Fluorescence Spectrometry (XRF/EDX). The microstructural characterization was done by analyzing the images from Optical Microscopy (OM) and Scanning Electron Microscopy (SEM). In the same way, the tests were performed for the pure samples and in the composites on the tested specimens.

3. Results and analysis

The specific gravity of soil particle obtained was 2.81 g/cm^3. The size distribution curve is shown in Figure 1. According to the ABNT NBR 6502 particle size classification (ABNT, 2016b), the tailings have silt size. Despite the granulometry, the tailings studied do not perform as a cohesive material since they have not undergone the geological process of soil formation. For this reason, the tailings are an intermediate material to the rocks and soils, which could be understood

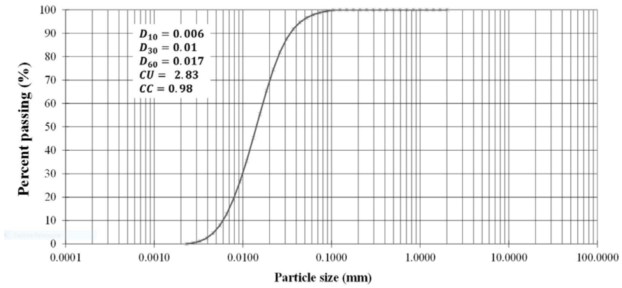


Figure 1. Soil particle size distribution.

as rock sediments. Hence, the considerations made to the mechanical behavior from the classification of soils should not be considered for tailings.

Previously, to define which content of polymer solution (P) would be investigated, a battery of unconfined compression tests was performed on specimens. For this, polymeric solutions with different polymer and water contents were elaborated: 10% polymer and 90% water (P_1.5); 20% polymer and 80% water (P_3); 30% polymer and 70% water (P_4.5); 40% polymer and 60% water (P_6); and 50% polymer and 50% water (P_7.5). The results are shown in Figure 2. The legend is composed of the acronym GT, which stands for Gold Tailings, followed by the letter P and the polymer content in the sample. These specimens were molded at the optimum moisture content (15%) of the pure tailing and with a dry unit weight of 1.8 g/cm^3.

For all composites, the curves have a similar shape, where it is noted a well-defined peak with a rapid loss of strength in the post-peak region. It is observed that an increase in polymer content leads to a gain in unconfined compressive strength, except for the 50% (GT_7.5). From these results, it was decided to investigate the composites with 6% of polymer in mass of tailings (GT_P6).

The compaction curve for the gold ore pure tailings (GT) and the gold ore tailings polymer solution stabilized composite (GT_P6), with 6% of polymer by tailings mass unit, is shown in Figure 3. Analyzing the presented curve and comparing the behavior of GT and GT_P6, it is observed that the composite curve has a slightly closer shape. In addition, there is a decrease of approximately 5% of the optimum moisture content. Carneiro & Casagrande (2020) and Silva (2020) observed the same decrease in composites of iron ore and sand matrix.

The flocculation and dispersion theory proposed by Lambe & Whitman (1979) can also assist in the comprehension of the compaction curve. As discussed by the author, during compaction there is a physical-chemical interaction between the particles that leads to the well-known parabolic behavior of the compaction curves of soils.

On the dry side the amount of added water is insufficient for chemical interaction. This causes a high electrolyte concentration and the repulsion forces are not fully developed. With this, the forces of attraction predominate and then a flocculated structure with a disordered arrangement of the particles and a lower specific dry weight.

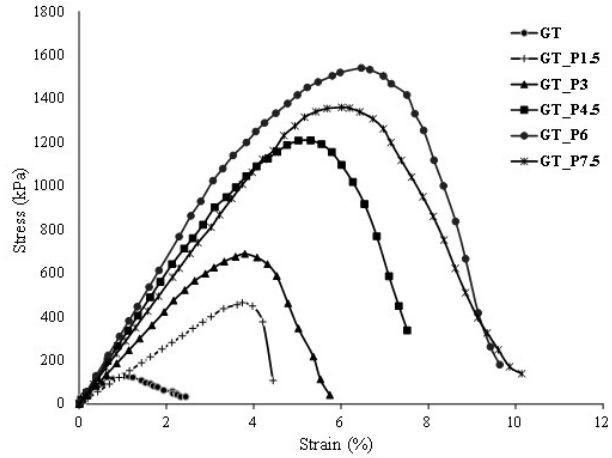


Figure 2. Unconfined compression test curves for distinct polymer content.

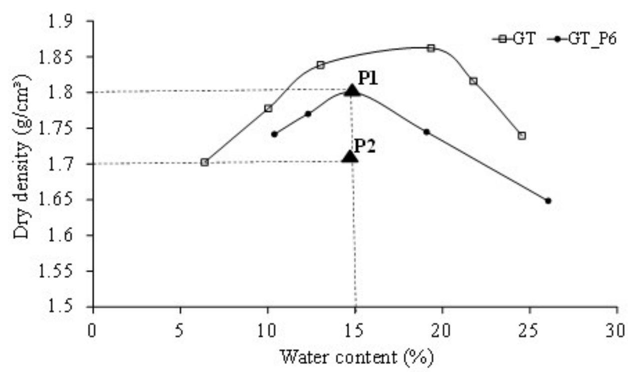


Figure 3. Compaction curves for gold ore pure tailings (GT) and composite (GT_P6).

From this observation, comparing the dry unit weight of the GT and GT_P6, it is observed a decrease in the composite, since the inclusion of the polymer leads to a more flocculated structure. This flocculation is exactly the expected behavior of this synthetic organic polymer.

However, as the moisture content increases reaching the optimum point, the amount of water inserted is sufficient to reduce the electrolyte concentration and generate an increase in the repulsion forces. Thus, there is a more oriented structure for the composites, but still more flocculated than in the pure tailings and therefore lower specific weight.

From the composite compaction curve were defined the molding points of the specimens for the unconfined compression test and direct shear test. They are indicated in Figure 3 as P1 and P2. The analysis of two dry unit weights was done to verify the effectiveness of the polymer in different structures.

The results for the GT_P6 compared to GT are presented in Figure 4. While pure tailings have maximum stress of 50 kPa, the composite reached close to 1000 kPa. It is also possible to see the stiffness gain with increasing density, by the initial slope of the curves. These results indicate that curing time and the dry specific weight are significant in increasing the strength of the composite.

The direct shear tests were performed under the same curing time and dry unit weight conditions. The results are shown in Figure 5. Peaks have been observed with a slight drop-off before reaching the residual resistance, especially for a dry unit weight of 1.8 g/cm^3.

Figure 6 shows the results of the strength envelopes. The results for cohesion and friction angle found are presented in Table 1. The cohesive intercept and the friction angle increased for the composite. The best mechanical arrangement was defined by the dry unit weight of 1.8 g/cm^3 at 28 days.

In the case of GT, the cohesive intercept increases with curing time. This increment is probably due to the increase in suction. There was no significant modification in the friction angle. However, analyzing the composites, the curing time caused an increase in the cohesive intercept only for the dry unit weight of 1.8 g/cm^3. In the case of 1.7 g/cm^3, the enhancement probably did not occur since the structural arrangement was not efficient in creating the bridges between the particles with adsorbed polymers.

As shown in the microstructural results, the tailings particles are lamellar. Therefore, a higher dry unit weight provides a more stable arrangement, since the particles are closer, and a larger surface area is available to create bridges between them.

Regarding friction angle, an increase is observed with the dry unit weight. This demonstrates that with a more solid arrangement, the polymer acted on the frictional characteristics of the particles. This supports the previous finding regarding cohesive intercept.

The XRF/EDX analysis indicated the following components in pure tailings: Si (53%); Al (21%); K (13%); Fe (9%); others. The analysis conducted on the composite showed no differences since the polymer is mostly composed of carbon that is not detected in this test.

The XRD analysis indicated minerals for the pure tailings namely: quartz, muscovite, and kaolinite, as shown

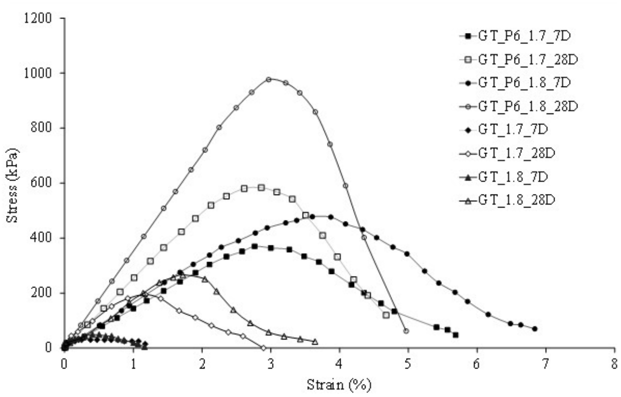


Figure 4. Uniaxial compression curves of GT and GT_P6 for distinct dry specific weight and curing time.

Table 1. Cohesive intercept and friction angle for GT and GT_P6.

	Sample	Cohesive intercept (kPa)	Friction angle (°)
GT	GT_1.7_7D	29	22.78
	GT_1.7_28D	31.5	27.55
	GT_1.8_7D	18.5	22.87
	GT_1.8_28D	27.5	24.91
GT_P6	GT_P6_1.7_7D	72.5	32.68
	GT_P6_1.7_28D	29.5	37.29
	GT_P6_1.8_7D	64	44.17
	GT_P6_1.8_28D	83.5	44.46

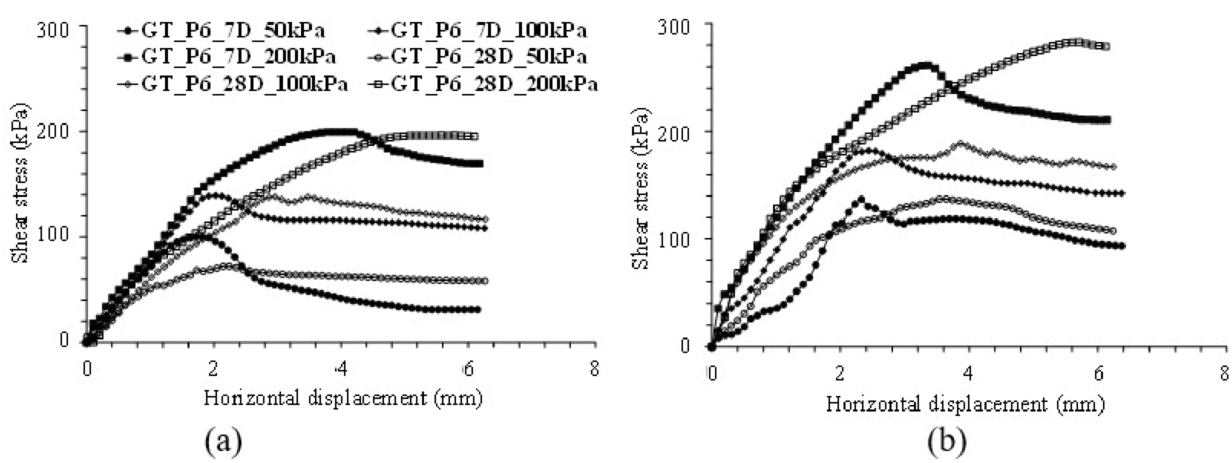


Figure 5. Shear-horizontal displacement curve. (a) composite with dry specific weight of 1.7 g/cm^3; (b) composite with dry specific weight of 1.8 g/cm^3.

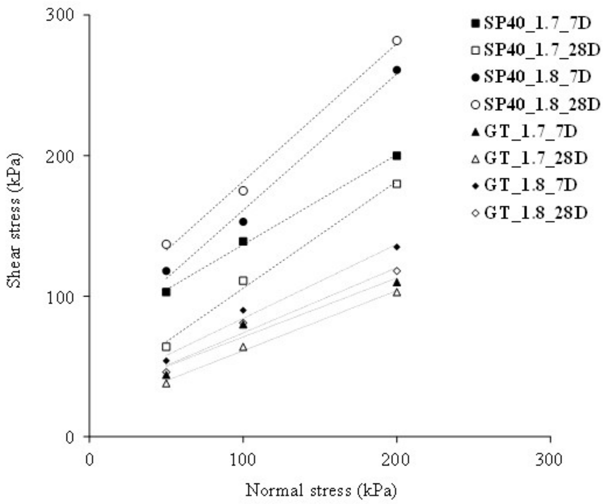


Figure 6. Shear strength envelopes.

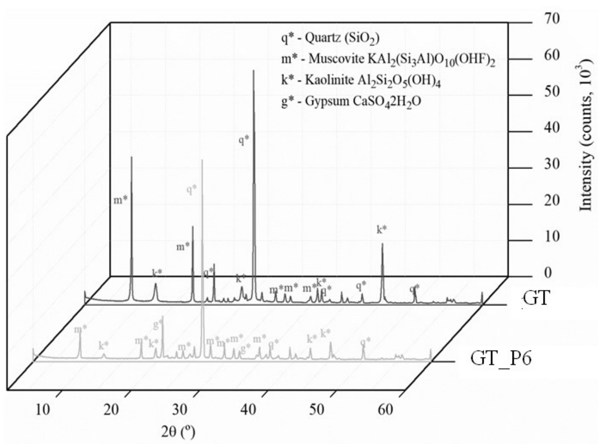


Figure 7. XRD results for GT and GT_P6.

in Figure 7. These minerals are the most present in the carbonaceous phyllites of the ore extraction region. This statement corroborates the fact that tailings are a material that should be treated as a rock sediment. The ore beneficiation process (fragmentation) that originated this material acted only as a physical weathering.

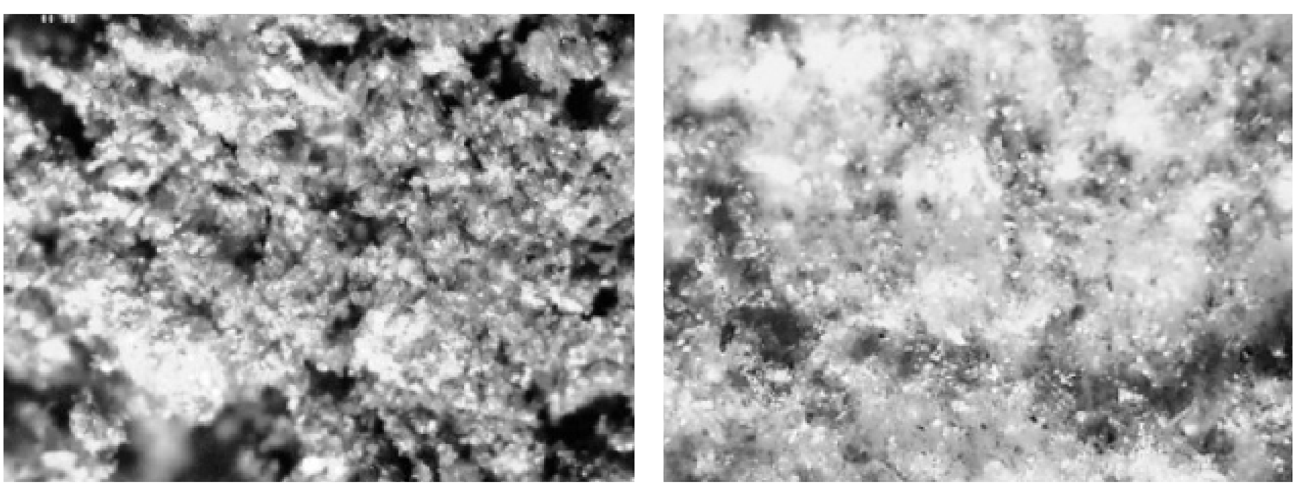
Gypsum was also identified in the composite in addition to the three minerals mentioned. Gypsum belongs to the class of hydrated sulfates, and is the most abundant mineral in this class. However, in fact, the composite did not generate a new mineral. This XRD identification is due to the classification technique used, which consults the mineral database through the JADE 9.0 software.

Each crystalline structure produces a characteristic diffraction pattern. Therefore, for interpretation of the results, a database is used, and comparison is made with the patterns produced by known, previously analyzed structures. In this case, the polymer was classified as isostructural to the gypsum.

Figure 8 shows an optical microscopy image at 10x magnification for the pure tailings and the composite. It is possible to observe the fine grain size of the material and the conglomerates formed by the flocculation process of the polymer. However, due to the grain size of the material, SEM analysis is more appropriate for analyzing the interface grain-polymer.

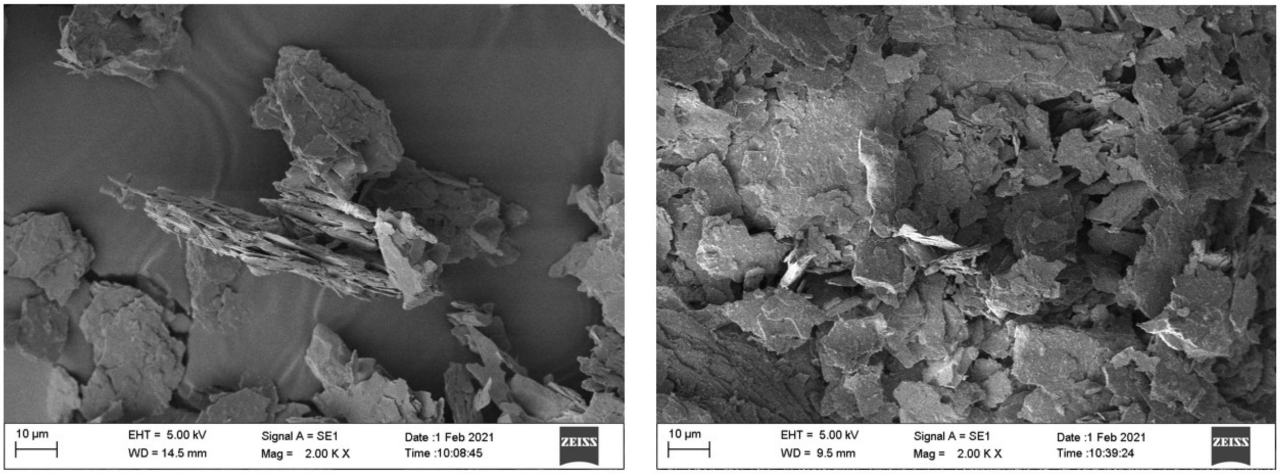
Figure 9 shows the morphological analysis obtained by SEM. It is observed that the pure tailings are composed of a lamellar isotextural structure, randomly oriented and with tightly interlocking packets. Keller et al. (1986) say that micromorphology and texture can be used to support mineral identification. In comparison with other authors, it is observed that kaolinite and muscovite are detected, in agreement with the XRD analyses (Relosi et al., 2018).

The tendency to form aggregates (polymer flocculation effect) in the composite, shown in Figure 9b, is directly related to particle size and surface area availability (Relosi et al.,



(a) (b)

Figure 8. Optical Microscopy. (a) pure tailings; (b) composite.



(a) (b)

Figure 9. SEM analysis. (a) pure tailings; (b) composite.

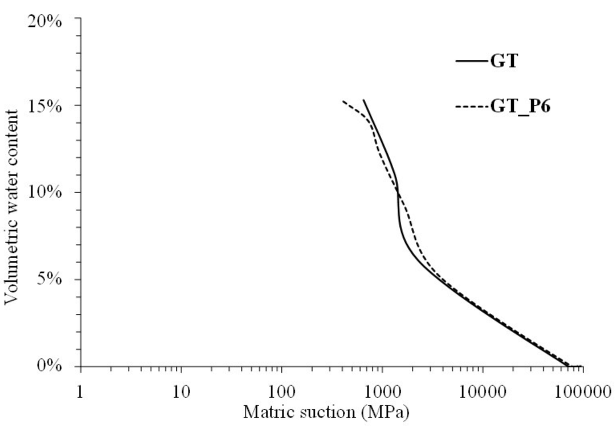


Figure 10. Matric suction results in pure tailings and composite.

2018). The lamellar packages present in the pure tailings decrease the surface area for polymer contact. This may generate the brittle behavior observed in the mechanical tests.

The analysis of the matric suction showed similar behavior for the pure tailings and the composite, as shown in Figure 10. From this analysis, it may be concluded that there are two parcels contributing to the strength gain: (i) polymer cure effect; (ii) matric suction increase.

The contribution of each parcel could not be evaluated by this work. For this, it is recommended to conduct mechanical tests with saturated specimens and monitoring the pore water pressures. In the case of this material, due to the significant loss of fine material, saturation was not possible.

4. Conclusions

This work investigated the mechanical, chemical, and microstructural behavior of a gold ore tailings stabilized with a polymer solution. From the tests conducted, it was possible to conclude that the stabilization was efficient in improving the mechanical properties of the material.

The polymeric solution used was composed of water and polymer, which react with atmospheric oxygen to initiate the curing process and gain strength. Thus, two curing periods for two dry unit weight were evaluated.

A 40% polymer solution was chosen to be investigated since in the initial tests it proved to be more efficient. The solution was then added by mass to the polymer at the optimum moisture content, representing approximately 6% by mass.

The tailings matrix, which has silt size, showed neither plastic nor cohesive behavior. Therefore, the polymer proved to be an interesting alternative to increase cohesion between the particles, as shown in the direct shear tests, compaction curve and microstructural analysis. The matric suction analysis also showed that the strength gain happens due to two factors: (i) polymer flocculation effect; (ii) suction increase.

The results of the mechanical tests showed increased stiffness and unconfined compressive strength, especially in cases of higher dry unit weight. This stabler arrangement contributes to the cohesive effect of the polymer and to the frictional characteristics of the particles, as observed in direct shear test. This finding is interesting since it is directly related to the lamellar shape seen in the SEM analysis.

The mineralogical characterization also showed the relationship of the tailings to the parent material. This corroborates the fact that the tailings need to be evaluated through a different optic than soils and rocks, and perhaps as a rock sediment.

Therefore, the chemical stabilization using the polymeric solution that was investigated in this work is feasible. The recommendation for the compacted composite is to perform at the optimum moisture content and dry unit weight. This enables the use of tailings as construction materials in various engineering structures.

Acknowledgements

The authors thank the Brazilian research funding agencies *Conselho Nacional de Desenvolvimento Científico e Tecnológico* (CNPq) and *Coordenação de Aperfeiçoamento de Pessoal de Nível Superior* (CAPES).

Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the contents of the paper and there is no financial interest to report.

Authors' contributions

Giovanna Alelvan: conceptualization, data curation, investigation, visualization, writing – original draft. Michéle Casagrande: conceptualization, data curation, methodology, supervision, validation, ting – review and editing. Nilo Consoli: conceptualization, data curation, methodology, supervision, validation, writing – review and editing.

List of symbols

CONAMA	National Council of Environment
GT	Gold Tailings
GT_P6	Composite tailings-polymer
OM	Optical Microscopy
SEM	Scanning Electron Microscopy
WP4C	Water Potential Meter
XRD	X-ray Diffraction
XRF/EDX	X-ray Fluorescence Spectrometry

References

ABNT NBR 12770. (2016b). *Solo coesivo – Determinação da resistência à compressão não confinada – Método de ensaio*. ABNT - Associação Brasileira de Normas Técnicas, Rio de Janeiro, RJ (in Portuguese).

ABNT NBR 7182. (2016a). *Solo – Ensaio de compactação*. ABNT - Associação Brasileira de Normas Técnicas, Rio de Janeiro, RJ (in Portuguese).

Amorim, E.F. (2007). *Efeitos do processo de deposição hidráulica no comportamento de um rejeito de mineração de ouro*. [Master's dissertation, University of Brasilia]. University of Brasilia's repository (in Portuguese). http://repositorio.unb.br/handle/10482/2673

ASTM D1557-12e1. (2011). *Standard test methods for laboratory compaction characteristics of soil using modified effort*. ASTM International, West Conshohocken, PA. https://doi.org/ 10.1520/D1557-12.

ASTM D3080-11. (2012). *Standard test method for direct shear test of soils under consolidated drained conditions*. ASTM International, West Conshohocken, PA. https://doi.org/ 10.1520/D3080_D3080M-11.

ASTM D5550-14. (2016). *Standard test method for specific gravity of soil solids by gas pycnometer*. ASTM International, West Conshohochekn, PA. https://doi.org/10.1520/D5550-14.

Bhanbhro, R. (2014). *Mechanical properties of tailings: basic description of a tailings material from Sweden*. [Doctoral thesis, Luleå University of Technology]. Luleå University of Technology's repository. http://urn.kb.se/resolve?urn=urn:nbn:se:ltu:diva-16952

Carneiro, A.A., & Casagrande, M.D.T. (2020). Mechanical and environmental performance of polymer stabilized iron ore tailings. *Soils & Rocks*, 43(4), 679-689. http://dx.doi.org/10.28927/SR.434679.

Consoli, N.C., Silva, A.P., Nierwinski, H.P., & Sosnoski, J. (2017). Durability, strength and stiffness of compacted gold tailings-cement mixes. *Canadian Geotechnical Journal*, 55(4), 486-494. http://dx.doi.org/10.1139/cgj-2016-0391.

Festugato, L., Consoli, N.C., & Fourie, A. (2015). Cyclic shear behaviour of fibre-reinforced mine tailings. *Geosynthetics International*, 22(2), 196-206. http://dx.doi.org/10.1680/gein.15.00005.

Huang, J., Kogbara, R.B., Hariharan, N., Masad, E.A., & Little, D.N. (2021). A state-of-the-art review of polymers used in soil stabilization. *Construction and Building Materials*, 305, 124685. https://doi.org/10.1016/j.conbuildmat.2021.124685

Islam, S. (2021). A study on the mechanical behaviour of three different fine-grained mine tailings. *Journal of King Saud University*. In Press. http://dx.doi.org/10.1016/j.jksues.2021.04.001.

Keller, W.D., Reynolds, R.C., & Inoue, A. (1986). Morphology of clay minerals in the smectite-to-illite conversion series by scanning electron microscopy. *Clays and Clay Minerals*, 34(2), 187-197.

Kiventera, J., Piekkari, K., Isteri, V., Ohenoja, K., Tanskanen, P., & Illikainen, K. (2019). Solidification/stabilization of gold mine tailings using calcium sulfoaluminate-belite cement. *Journal of Cleaner Production*, 239, http://dx.doi.org/10.1016/j.jclepro.2019.118008.

Lambe, T.W., & Whitman, R.V. (1979). Soil Mechanics, SI version. New York: John Wiley & Sons.

Relosi, N., Neuwald, O.S., Zattera, A.J., Piazza, D., Kunst, S.R., & Birriel, E.J. (2018). Effect of addition of clay materials on the properties of epoxy/polyester powder coatings. *Polímeros*, 28(4), 355-367. http://dx.doi.org/10.1590/0104-1428.01616.

Silva, N.A.B.S. (2020). *Desempenho de um compósito solo-polímero para aplicabilidade em obras geotécnicas e de pavimentação*. [Master's dissertation, University of Brasília]. University of Brasília's repository (in Portuguese). https://repositorio.unb.br/handle/10482/38789.

Sotomayor, J.M.G., Alelvan, G.M., & Casagrande, M.D.T. (2021). Influence of polypropylene fiber-reinforcement on the mechanical behavior of gold ore tailings through direct shear tests. *Journal of Materials in Civil Engineering*, 33(10), 04021256. https://doi.org/10.1061/(ASCE)MT.1943-5533.0003878

Wijewickreme, D., Sanin, M.V., & Greenaway, R.G. (2005). Cyclic shear response of fine-grained mine tailings. *Canadian Geotechnical Journal*, 42, 1408-1421. http://dx.doi.org/10.1139/t05-058.

Xue, G., Yilmaz, E., Feng, G., & Cao, S. (2021). Bending behavior and failure mode of cemented tailings backfill composites incorporating different fibers for sustainable construction. *Construction and Building Materials*, 289, 123163. https://doi.org/10.1016/j.conbuildmat.2021.123163.

Zheng, B., Zhang, D., Liu, W., Yang, Y., & Yang, H. (2019). Use of basalt fiber-reinforced tailings for improving the stability of tailings dam. *Materials*, 12(8), 1306. https://doi:10.3390/ma12081306.