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Research article

Geotechnical investigations of lead-silver ore processing residues at the Auzelles site, Auvergne (France)

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Abstract: Mining operations generate a significant quantity of mining waste in the form of sterile rocks and processing residues. These mining wastes are typically placed on the surface and can cause geotechnical and geochemical disturbances, as well as contaminants in surface water (through runoff) and groundwater (through infiltration), thus posing environmental risks. This article aimed to characterize the geotechnical properties of lead-silver ore processing residues at the Auzelles site in order to assess their stability and propose recommendations for their management and rehabilitation. The adopted methodology included in situ tests (such as density measurement and permeability) and laboratory analyses (grain size distribution, moisture content, methylene blue test, direct shear test, and standard Proctor test). The results showed a wet density of 1.63 g/cm³ for the residues compared with 1.65 g/cm³ for the waste rock, as well as a permeability of the residues measured at 5.5×10^{-5} m/s, indicating significant drainage capacity. Laboratory analyses revealed that the samples were primarily composed of very silty sands and gravel, classified as B5 according to the Guide to Road Settlements. The cohesion of the residues was found to be zero, while the internal friction angle varied between 28° for the residues and 30° for the foundation soils. These geomechanical properties, particularly density, lack of cohesion, and friction angle values, raise concerns about the long-term stability of the residues. Due to their high permeability and lack of cohesion, the residues are susceptible to mass movement and erosion, which may exacerbate contamination risks. Therefore, it is essential to integrate these parameters into any potential residue stability analysis. Proactive management, based on these results, requires the implementation of appropriate rehabilitation

techniques, such as drainage optimization and incorporation of vegetation covers, to minimize environmental impacts and ensure the long-term sustainability of mining waste structures.

Keywords: environmental risks; cohesion; mining processing; guide to road; ground and surface water; lead-silver ore

1. Introduction

Mining produces various types of waste in solid and liquid forms. Solid mining wastes can be separated into two main categories [1]: waste rock and mine tailings. These wastes and their surface storage methods are shown in Figure 1. Waste rocks are extracted from the surrounding rock and are generally stored in piles, containing little to no commercial value [2]. Mine tailings come from mineral processing and resemble fine soils, such as sand and silt [3]. Generally, they are deposited as a slurry in storage basins known as tailings ponds [2]. According to [4], tailings from hard rock mining are non-cohesive sandy silts that are typically deposited hydraulically. These tailings result from the extraction and processing of minerals from hard rock formations [5].

(a) (b)

Figure 1. Storage of solid mining waste at the Canadian Malartic mine [1]: (a) waste rock piles, (b) tailings area.

Tailings from hard rock mining are stored in tailings ponds to prevent soil and water contamination by heavy metals. The dams surrounding these ponds serve as protective barriers against potential environmental leaks. Despite the advantages of managing mining tailings, further research is needed to improve current practices in the mining sector. The geology of hard rock mining areas is closely linked to magmatic and hydrothermal processes resulting from the formation of ancient mountain ranges [6]. These tailings are unstable under seismic stress due to their physical properties and mode of deposition [7].

It is clear that at one time, operators tended to neglect mine tailings in favor of the commercially viable and revenue-generating concentrate. This is the case for the Auzelles tailings site, which is the subject of this study. The Auzelles mining site is an old silver-lead mine that was operated underground from 1873 to 1901 [8]. Covering an area of approximately 4.5 hectares, the site currently has a deposit of about 150,000 m^3 of material [9]. This material is comprised of tailings from ore treatment, which was conducted on-site, responsible for pollution of downstream waters (particularly arsenic and lead), making their management a major environmental protection challenge. These deposits are still visible today along the Miodet river, at the place known as "la Molette", as shown in Figure 2.

Figure 2 : Overview of the Molette deposit [9].

According to [10], at the end of mining operations, it is important to prepare the site for future use. It is possible to restore the site to its original state, but this requires an agreement between the operator, authorities, and stakeholders regarding its future use. Generally, the operator is responsible for preparing the site for future use. To obtain closure authorization, the operator must detail the characteristics of the materials retained, such as quantity, quality, and potential consequences. Records show that the exploitation of the veins was conducted underground through several levels of galleries with works leading to the surface. Despite investigations after the mine's closure in 1901, no success was encountered, leading to the cancellation of the mining concession in 1960 by ministerial decree. As no dossier for the cessation of mining activities was submitted by the operator or examined by the competent authorities, the mining police is still officially active.

Geotechnical investigations are fundamentally important in the management of mining tailings. They play a critical role in assessing the stability of containment structures, including tailings ponds and landslides or collapses. They also help assess the capacity of tailings to retain contaminants and limit the risks of potential leaks or contamination in the environment. According to [11], the waste from hard rock mines mainly comes from the extraction of lead, zinc, copper, gold, and nickel. Substantial quantities of solid and liquid waste are produced during mining operations. This material, often referred to as mining tailings, frequently contains heavy metals and hazardous chemicals that can contaminate nearby soils and water resources [12]. Proper characterization of tailings and waste rocks at a site is the only way to determine their long-term behavior. This includes chemical and mineralogical composition, pore pressure, settling, leaching, erosion stability, and physical stability. Mineralogical characterization of mining waste can lead to improved risk assessment and proper mining planning, both for planned and currently operating mines. The use of mineralogical approaches can enhance the assessment of health risks to humans and the long-term management of historical mining waste. In [13], researchers recommended improving the efficiency of tailings treatment to potentially recover minerals from ore and provide financial incentives for rehabilitation. For example, the tailings from the treatment of silver-lead ore at the Auzelles site present economic advantages, but their production requires a large amount of energy and has an inefficient environmental impact. [14] studied the phenomena of tailings and demonstrated the contribution of mineral processing to environmental hazards. According to their research, increasing the reduction of the particle size of treated tailings would accelerate the valorization process. Testing conducted in situ during mining operations or shortly thereafter does not reflect the long-term characteristics of mining tailings, as they are often under-consolidated when initially placed [4]. Tailings from hard rock mines exhibit properties such as low cohesion, fine particle size, low density, and high saturation, making them particularly susceptible to liquefaction in the event of seismic activity or disturbance [15]. The liquefaction of tailings can lead to environmental issues, such as the release of harmful substances into surrounding water bodies, as well as significant damage to infrastructure [16].

The specific issue of the mining tailings at the Auzelles site lies in their chemical composition and high contamination potential. By releasing heavy metals (lead, arsenic, etc.) into the environment, they could have detrimental consequences on human health and local ecosystems. It is therefore essential to conduct specific geotechnical studies to assess the risks associated with these mining tailings and propose appropriate management measures. The former mining activity at the "la Molette" site generates an impact on water, soil, and sediments downstream of the site [17]. The tailings from "la Molette" affect groundwater, with isotopic analyses showing a surface origin and rapid circulation [18]. Pollution from the former Auzelles mine primarily affects mining waste, treatment tailings, and the mining aquifer, spreading to the waters of the Miodet stream, adjacent soils, and contaminated vegetation [17].

This article aims to characterize the geotechnical properties of the lead-silver ore treatment tailings at the Auzelles site in order to assess their stability and propose recommendations for their management and rehabilitation. Specific objectives include determining the physical characteristics of the tailings, evaluating their mechanical properties, and proposing technical solutions to limit environmental impacts.

2. Material and methods

2.1. Historical context of the site and location

According to historical records, the extraction of veins was carried out underground through multiple levels of galleries [9]. Several openings leading to the surface (most of which are not marked on site) are present. The site included a washing facility, settling ponds, and deposits of processing residues, as well as local waste from mining operations. After the mine closed in 1901, research work was conducted several times without success. The mining concession was revoked by ministerial order in 1960. Since no request for cessation of mining operations was submitted by the operator and processed by the competent authority, mining oversight is considered still active.

The Auzelles site is located in the Auvergne-Rhône-Alpes region, in the Puy-de-Dôme department, approximately 40 km southeast of Clermont-Ferrand, in the municipality of Auzelles. It is bordered to the south and east by the departmental road RD 996, and to the north by the Miodet watercourse (Figure 3). The terrain is rugged, with altitudes ranging between 650 and 700 m above sea level.

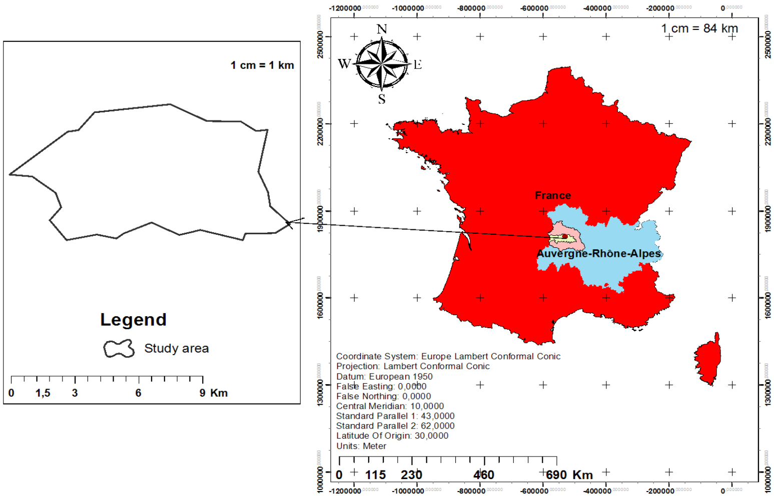


Figure 3. Site location map.

2.2. Description of the site and environmental characteristics

The Auzelles concession was granted by Imperial Decree on June 26, 1869. From 1873 to 1901, mining activities for the extraction and processing of argentiferous lead created a significant mining deposit—still visible today—along the Miodet river at the location known as “la Molette”. The site is included in the Natura 2000 area “Auzelles”, designated due to the presence of bats (for which a gallery opening onto the site serves as a roost) (Figure 4) and habitats of community interest primarily located along the river. The biodiversity of the site represents a high stake.

Figure 4. Entrance to galleries serving as a bat roost [8].

Six main zones without vegetation, exhibiting similar characteristics (slopes, grain sizes of materials, and surface cover), were defined by [8] BRGM (2021) to serve as a basis for the management plan, as indicated in Figure 5.

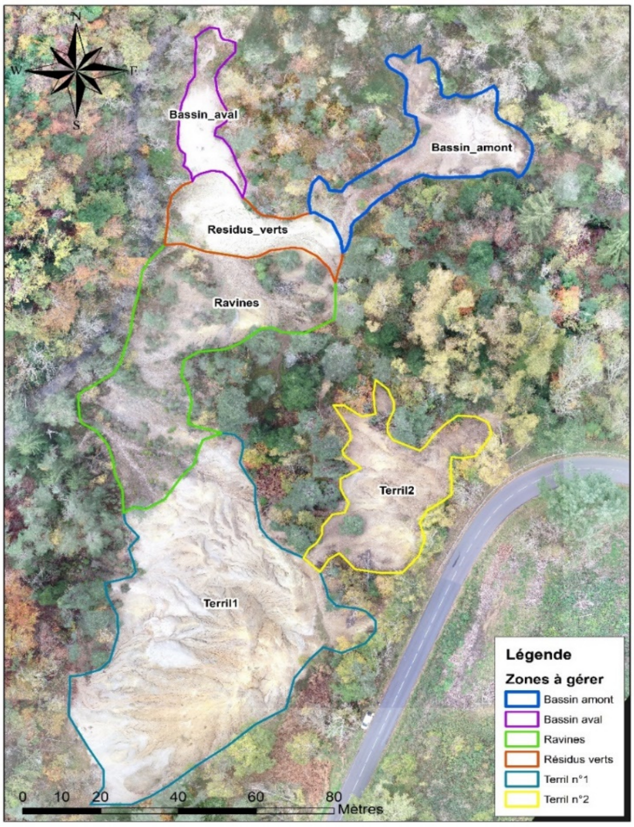


Figure 5. Identification of the different elements of the site [8].

The Tailings 1 and 2 correspond to deposits of processing residues, primarily sandy in texture and locally featuring ochre or bluish-grey clay layers (Figure 6) with variable slopes (approximately 30° in average for Tailings (a) and 20° in average for Tailings (b)). Erosion appears to be very significant visually. Aside from some tufts of herbaceous plants, no vegetation is present on the tailings.

(a) (b)

Figure 6. Tailings (a) and (b) [8].

The "Ravines" zone is characterized by heterogeneous grain size (mostly sandy but with numerous pebbles and blocks). This zone is very steep (35° on average) and highly ravined, as it is located downstream of the tailings. The “Green Residues” zone corresponds to a deposit primarily composed of sands with a slightly greenish color and an average slope of about 30°. Figure 7 represents the “Ravines” zone and the “Green Residues” zone.

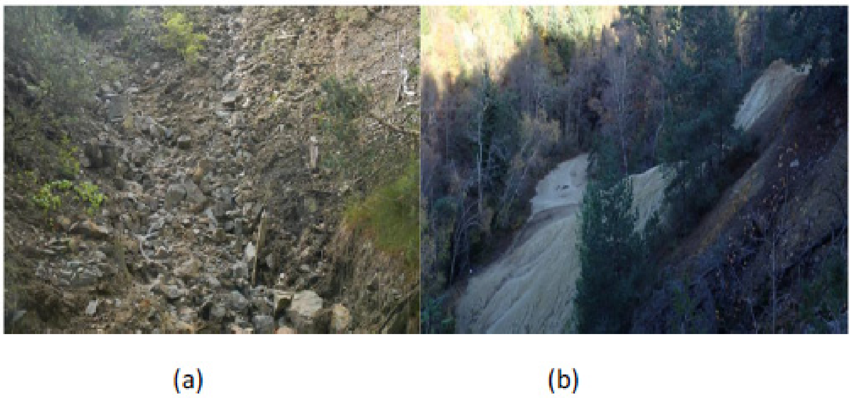


Figure 7. Ravines and green residues [8].

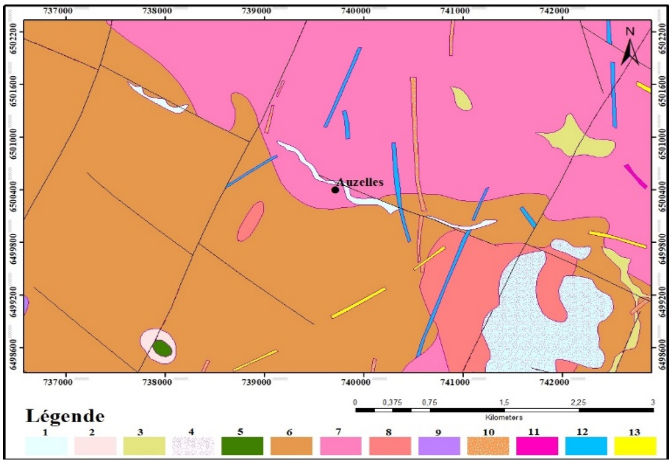
The “Upland Basin” zone corresponds approximately to the area of the former washing facility and the first basin that the Miodet runs along (thus, it is the highest hydraulic basin). Its surface grain size is predominantly sandy with a sparse presence of pebbles. The “Downstream Basin” corresponds to the last basin that the Miodet flows past. The surface grain size of the materials is primarily sandy. The upland and downstream basins are represented in Figure 8.

Figure 8. Upland and downstream basins [8].

The study area is characterized by low urbanization (low population density and housing), encompassing two main villages, Auzelles (337 ha with 10.1 inhabitants/km^2) and Saint-Dier-d’Auvergne (577 ha with 28.6 inhabitants/km^2). It mainly consists of meadows and forested areas. In the Molette site, vegetation remains sparse on the mining residue deposits (absence of organic matter, ravined and steep deposits). However, in some areas, a few pines or birches can be observed. The zones adjacent to the Miodet stream, on the other hand, are well-vegetated.

2.3. Geological characterization of the site

According to the geological map of the site (BRGM, geological map at a scale of 1/50,000, Issoire sheet no. 718), the site is located at the contact between the Saint-Dier granite to the northeast and the metamorphic basement formations to the southwest (migmatitic gneisses), as shown in Figure 9.



Legend:

1: Alluvial deposits from rivers. **2**: Various volcanic rocks (pyroclastics, basalt scoria, basalts, rhyolites, picrites, etc.). **3**: Slope and valley floor colluvium. **4**: Plutonic and/or metamorphic and/or volcanic rocks. **5**: Miocene volcanism (ankaramites, basalts). **6**: Upper unit of gneiss (granitoid diatexites-anatexites with biotite and cordierite). **7**: Hercynian basement (calco-alkaline granites with biotite and cordierite from Saint-Dier). **8**: Hercynian basement (leucocratic porphyroid granite from the Bois de Sérat). **9**: Hercynian basement (leucogranites with fine grains and two micas). **10**: Microgranites to microleucogranites, porphyritic, in small masses or veins. **11**: Pegmatites, aplo-pegmatites, in veins or small bodies. **12**: Lamprophyres, microdiorites, quartz microdiorites; in veins. **13**: Quartz veins.

Figure 9. Geological map of the study area.

The outcrops of the bedrock are only visible in a few places in the study area: along a slope near the RD 996, at the bottom of the Molette stream, in the gully between the green residues and the Ravines area, and at the level of the rocky spur to the north of the site. The distinction between gneiss and granite has not been thoroughly explored, as the focus has been on characterizing the mining deposits. Nevertheless, the outcrops observed on the site tend to indicate that the substrate here is mostly composed of granite.

2.4. Fieldwork and in situ tests

Fieldwork involved collecting samples and determining soil density in situ using a membrane densitometer according to standard [19]. The Porchet-type permeability test was conducted by the Bureau of Geological and Mining Research [8].

2.4.1. Sampling and density measurement

The sampling of materials was carried out in June 2023 during the complementary investigations, based on their location on the spoil tip, derived from the Digital Terrain Model (DTM) created by the

BRGM in 2019 during the topographical survey of the site. The collection of samples was conducted during the in-situ density measurement using a membrane densitometer, in order to reflect the composition of the spoil tip residues and its foundation. The residues from the spoil tip (R-01, R-02, R-03, and R-04) were sampled at different representative points of the spoil tip to obtain a comprehensive view of the composition of these materials. Similarly, the foundation of the spoil tip (S-01, S-02, and S-03) was sampled to obtain representative samples of the mixture of processing residues and waste materials from extraction. Figure 10 illustrates the location of the sample collection points(a) and the soil profile of the spoil tip(b).

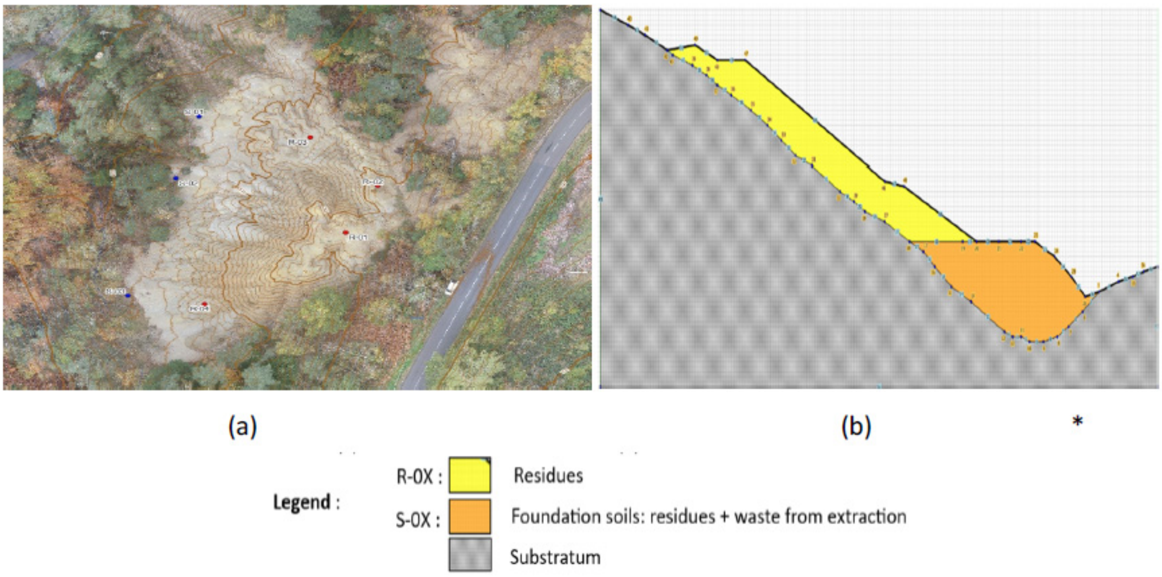


Figure 10. Location of sample collection points(a) and soil profile(b).

The in situ density was measured in accordance with standard [18] as illustrated in Figure 11. The test involves digging a cavity, collecting and weighing all the extracted material, and then measuring the cavity volume using a membrane densitometer. The device is equipped with a piston that, under the operator's action, pushes the volume of water into a flexible watertight membrane that conforms to the cavity shape. A graduated rod allows for direct volume reading.

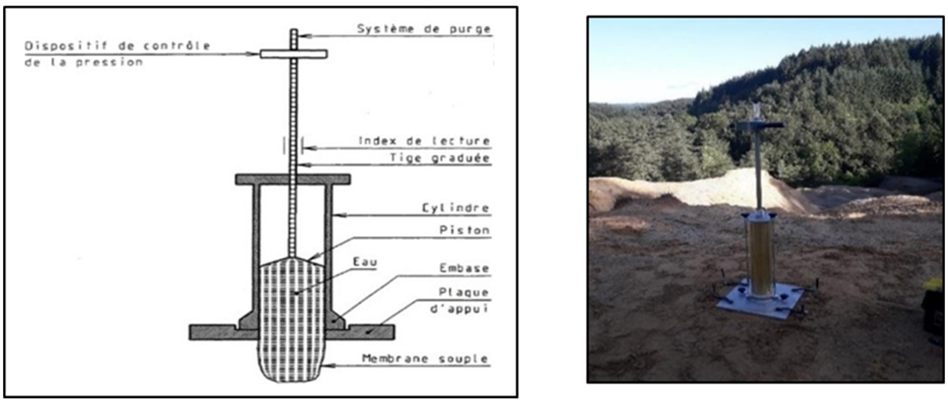


Figure 11. Membrane densitometer schematic diagram.

Three parameters were measured: the initial volume (V_o), the wet mass (m_h), and the total volume (V_t). To measure the initial volume, a substantially horizontal flat surface is prepared by leveling, at least equal to that of the base plate. Then, the base plate is fixed with anchoring stakes (pegs); the device is attached to the plate, and then the piston is pressed until the desired pressure is obtained (greater than 5 kPa), and the volume V_o is measured on the reading system.

Next, to determine the wet mass m_h, a hole is excavated through the orifice of the plate, the depth being equal to the diameter of the orifice plus or minus half the radius. The cavity shape must be regular, avoiding fissures and roughness while limiting compression/decompression of the wall under tool action. The minimum volume of the cavity depends on the maximum diameter (Dmax) of the material, ensuring that the mass of the extracted material is greater than 200 Dmax and never less than 1500 g. Then, all extracted material is collected from the excavation, without loss, and placed in an airtight bag to weigh the wet material m_h.

To determine the volume V_t, the device is again fixed on the base plate, and the piston is operated until the desired pressure is reached (the pressure exerted by the water must be equal to or greater than 5 kPa but must not deform the material). Thus, the volume V_t is measured on the measuring system. The relationship for determining the wet bulk density is given in equation (1).

$$\rho_h = \frac{m_h}{V_t - V_0} \tag{1}$$

The dry density is determined by the equation (2).

$$\rho_d = \frac{\rho_h}{1 - W} \tag{2}$$

where ρ_h: wet density (g/cm^3); m_h: wet mass (g); V_t: total volume (cm^3); V_o: initial volume (cm^3); ρ_d: dry density (g/cm^3); W: natural water content (%).

2.4.2. Porchet-type permeability measurement

In [8], five Porchet-type permeability tests were conducted, preceded by an auger drilling to a depth of 50 cm, in various areas of the site as depicted in Figure 12. In this figure, zone E1 corresponds to waste heap 1, which is the main focus of the current study.

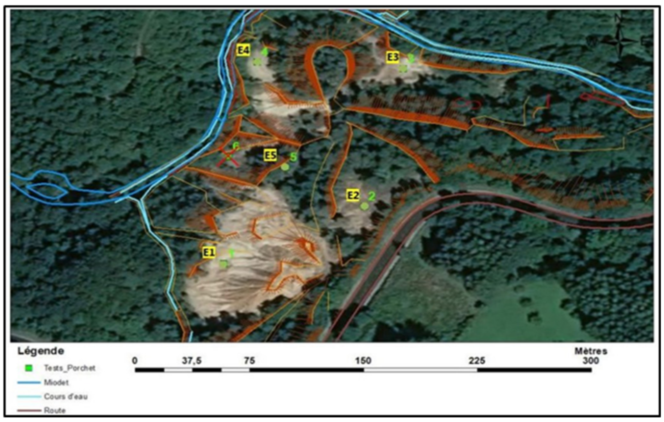


Figure 12. Location of Porchet-type permeability tests [8].

The measurement technique used by [8] is as follows (Figure 13). A hole is created with a minimum diameter of 0.20 m and a depth of 0.60 m; the hole is equipped with a device allowing for permeability measurements while maintaining a constant water level; the soil is saturated at a constant flow rate during a 4-h imbibition phase; and finally, permeability measurements (using a graduated cylinder) are performed. The measurement data are directly recorded on a measurement sheet, enabling the calculation of permeability values K in mm/h from the reading values. Each reading corresponds to a volume of water, and by relating this volume to the surface area of the infiltration tube and the infiltration time, permeability can be obtained. The formula (3) mathematically expresses this conversion.

$$K = (145{,}3 * \text{lecture}) / (172 * (t/60)) \tag{3}$$

where t represents the infiltration time (minutes), and K represents the coefficient of permeability (mm/h).

Figure 13. Schematic diagram of Porchet-type permeability test.

2.5. Laboratory analysis

Laboratory tests were conducted at the Geology-Geotechnics-Hydrology laboratory of Toulouse. These tests included the determination of particle size distribution by dry sieving, measurement of moisture content, evaluation of methylene blue value, determination of cohesion and internal friction angle, as well as determination of optimum water content and maximum dry unit weight, in accordance with current French standards.

2.5.1 Particle size analysis

The particle size analysis, conducted according to standard [20], involved dry sieving on 7 material samples collected from the site. Each sample, initially wet and weighing 12,000 g, underwent a drying process in an oven at a temperature of 105 °C to remove any moisture. Once dry, the sample was poured into a sieve column equipped with sieves of various opening diameters, covering a range from 0.08 to 80 mm. The main objective of this analysis was to simplify material characterization for classification in accordance with the guidelines of the GTR (Guide to Road Settlements). The maximum particle diameter observed during this analysis was 20 mm.

2.5.2 Water content

According to standard [20], the moisture content was evaluated on 7 soil samples. Each soil sample, weighing 4,000 g, was placed in an oven at a temperature of 105 °C to determine the mass of solid particles (M_s). Subsequently, the moisture content was calculated by dividing the mass of evaporated water (M_w) during the oven-drying process by the mass of solid particles (M_s) corresponding to the same volume of soil. This result is expressed as a percentage, as indicated by formula (4).

$$W = \frac{M_w}{M_s} \times 100\% \quad (4)$$

where M_w represents the mass of evaporated water (g); M_s represents the mass of solid particles (g); and W represents the natural water content (%).

2.5.3 Methylene blue value (VBS)

Using the [22] standard, the methylene blue test was conducted on a material fraction of 0/5 mm, as shown in Figure 14. This fraction was separated by sieving. The objective was to determine the amount of clay in the soil to classify the material according to the GTR (Guide to Road Settlements). The test involved continuously injecting a methylene blue solution into a continuously stirred soil suspension (at a speed of 400 rpm ± 100 rpm) in increments of 5 to 10 cm^3 (depending on the clay content of the material) and periodically placing a drop of the suspension on chromatographic paper. The injection continues until a light blue peripheral halo, one millimeter wide, appears in the wet area of the spot. At this point, the adsorption of blue on the clay particles is complete, and the excess methylene blue in the halo makes the test positive. From this moment on, the blue color of the solution is allowed to continue to adsorb and color, minute by minute, without adding more solution. If the test becomes negative again by the fifth coloring at the latest, additional injections of blue are made in steps of 2–5 cm^3.

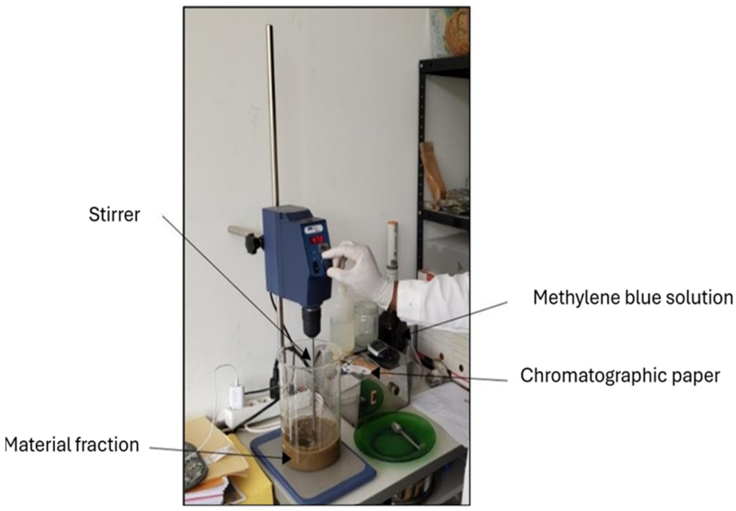


Figure 14. Principle of the methylene blue test.

2.5.4 Direct rectilinear shear

This test was performed according to standard [23] to determine soil shear strength parameters, primarily the effective cohesion (c') and effective friction angle (φ') in the case of a CD (consolidated, drained) test. In the shear test, a soil sample in the form of a parallelepiped, 63.5 mm in diameter and 19.5 mm in height, placed in a box formed by two superimposed half-boxes, is subjected to a given normal stress, then a shear movement in the horizontal plane between the two half-boxes is applied. The evolution of the shear stress in the horizontal plane is then measured as a function of the shear displacement. The obtained curve shows an increase in shear stress as a function of shear displacement up to a maximum value corresponding to the sample's rupture. This value represents the maximum shear strength of the soil for the applied normal stress. Beyond the peak, the shear stress decreases or remains constant, and the shear continues without any significant variation in stress. The test was repeated on 3 specimens of the same material, reconstituted and smoothed to 5 mm, subjected to increasing normal stresses. The curve giving the shear strength τ as a function of the normal stress σ was plotted. This is the Mohr-Coulomb line with the formula (5).

$$\tau = c' + \sigma \times tg\varphi' \quad (5)$$

where τ: shear strength; c': effective cohesion; σ: normal stress; φ: effective friction angle.

2.5.5 Proctor normal compaction

The optimal water content (W_{opt}) and the maximum dry unit weight (γ_{opt}) were determined using the Standard Proctor compaction test, following the [23] standard, on a 0/20 mm soil fraction in a CBR mold. The principle of this test involves wetting the material at different water contents, followed by compacting it at each water content using conventional procedures and energy. For each examined water content value, the dry unit weight (γ_{opt}) of the soil is determined (6), and a curve representing the variation of this dry unit weight with water content is established.

$$\gamma_d = \frac{\gamma}{1+W} \quad (6)$$

γ_d: dry unit weight (kN/m^3); γ: wet unit weight (kN/m^3); W: natural water content (%).

3. Results and discussion

This section aims primarily to identify and classify the materials present on the site. It also aims to assess the geotechnical characteristics of these materials, focusing in particular on their mechanical properties.

3.1. Fieldwork

To obtain data on field conditions, we conducted in situ density measurements using a membrane densitometer. Additionally, Porchet-type permeability was evaluated [8]. The results of these measurements are presented below.

3.1.1. In situ density measurement

The results of the in situ density measurement, conducted according to the [19] standard, are presented in Figure 15.

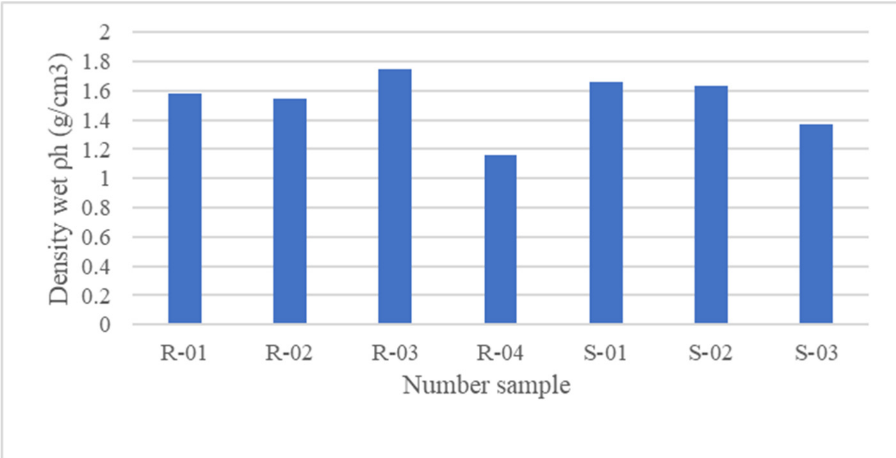


Figure 15. In situ density measurement results.

The residue samples, designated as R-01, R-02, R-03, and R-04, as well as the foundation samples, named S-01, S-02, and S-03, exhibit distinct characteristics in terms of in-place wet density, reflecting their composition and structure.

For the residue samples, R-01 and R-02 are classified as highly clayey gravels, while R-03 consists of coarse, loamy sands with clay nodules. Their in-place wet bulk density varies relatively uniformly, ranging from 1.55 to 1.75 g/cm^3. In contrast, sample R-04 exhibits a very low in-place wet density, around 1.16 g/cm^3.

As for the foundation samples, S-01 and S-02 are characterized by a mixture of ore processing residues and mining waste, featuring centimeter-sized pebbles. Their in-place wet bulk density is relatively consistent, ranging between 1.63 and 1.66 g/cm^3. In comparison, the sample from the Slag heap 1 foundation, S-03, shows a lower in-place wet bulk density, measured at 1.37 g/cm^3. The latter is composed of slightly plastic clayey silt.

In summary, the residue and foundation samples exhibit significant variations in in-place wet bulk density, reflecting their differences in composition and structure, particularly in terms of particle size distribution, clay content, and compactness.

3.1.2. Porchet-type in situ permeability measurement

The in-situ permeability of the Slag heap 1 residues (E1), measured by the [8] and displayed in Figure 16, is 5.5 × 10^{-5} m/s. This high value indicates that the residues have significant drainage capacity, characteristic of a medium that allows water to flow easily through it. During our site assessment in June 2023, no signs of seepage or resurgence at the Slag heap 1 level were observed. This observation suggests that water does not accumulate on the surface of the Slag heap but rather efficiently infiltrates through the residues. The sandy nature of the Slag heap residues, combined with their morphology, reinforces this conclusion. Sand typically allows for rapid drainage, while the morphology of the Slag heap appears to promote direct flow of infiltrated water downstream.

Taking these factors into account, we conclude that the formation of a perched water table in the residue deposit seems unlikely. Instead, infiltration water from the residues appears to drain directly downstream, thus limiting the potential risks of water saturation and stagnation in the deposit.

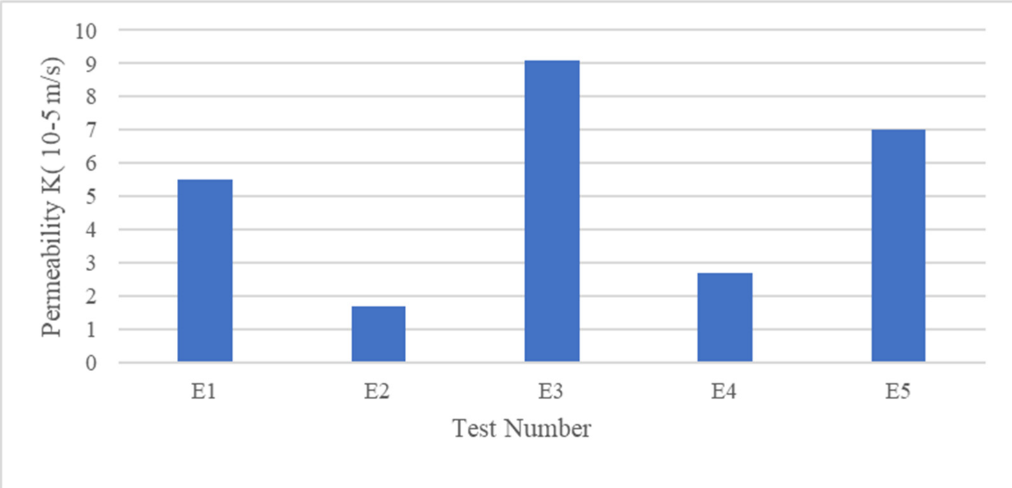


Figure 16. Results of permeability tests carried out at the site.

3.2. Laboratory analyses

Laboratory test results include physical characterization, which encompasses dry sieving analysis and methylene blue tests, as well as geomechanical characterization, including normal Proctor tests and direct shear tests.

3.2.1. Particle size analysis by dry sieving

The dry sieving grain size analysis, compliant with the [20] standard, allowed establishing two distinct grain size distribution curves: one for the mine waste from the spoil heap and one for the underlying soils.

The grain size distribution curve of the mine waste, presented in Figure 17, highlights that over 35% of the particles have a diameter greater than 80 µm. This observation suggests a predominance of the coarse fraction in the composition of the waste. This characteristic qualifies the soil as sandy and gravelly with a presence of fines, according to the GTR (Guide to Road Settlements) classification.

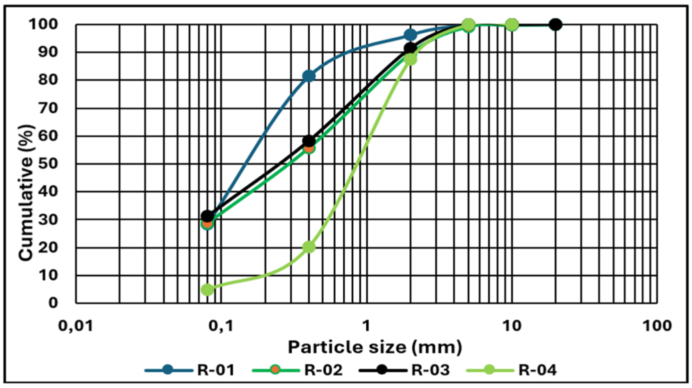


Figure 17. Particle size distribution of residues.

The results of the grain size analysis of the underlying soil samples, presented in Figure 18, highlight that over 35% of the particles in these soils have a diameter greater than 80 µm. This observation indicates an abundance of the coarse fraction in the composition of these soils. Consequently, according to the criteria defined in the Guide to Road Settlements (GTR), these soils are classified as sandy and gravelly with fines.

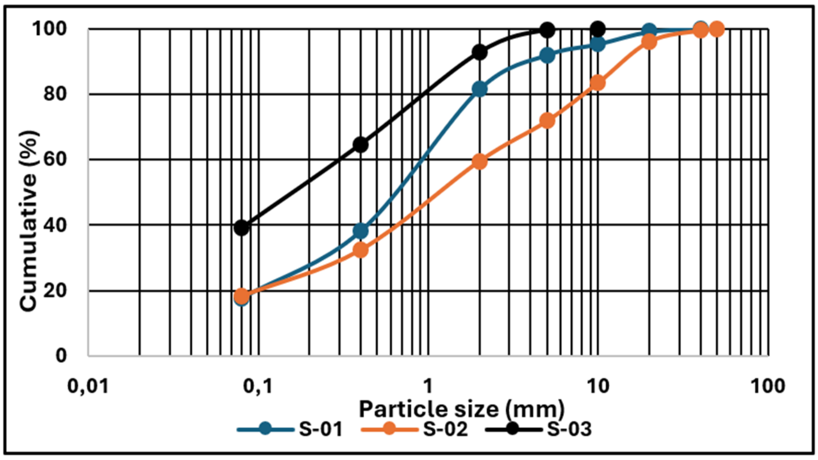


Figure 18. Grading diagram for subgrade soils.

The results of the grain size analysis of the samples show that most of them have a percentage of fine soil greater than 10%, except for R-04, which contains only 4.9%. Additionally, the percentage of sand is greater than 50% in most cases, but it is less than 50% in S-02, specifically 41.2%. As for the gravel fraction, it is generally less than 30%, but in the case of S-02, it is also 41.2%. These observations are based on the data presented in Figure 19.

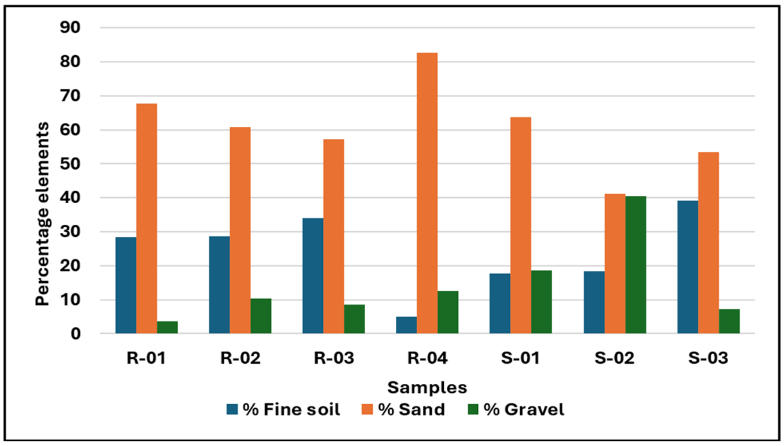


Figure 19. Elemental composition of samples.

The results of the grain size analysis indicate that samples R-01, R-02, R-03, S-01, and S-02 are mainly composed of sand and gravel with the presence of fines, classifying them in category B according to the GTR classification. When these results are combined with those of the methylene blue test, they are classified as B5 according to the GTR classification, meaning they are very silty. These conclusions are consistent with those obtained by [25] on mining residues from the Zeïda and Mibladen mines in Haute Moulaya (Morocco), thus reinforcing the reliability of the results. Furthermore, samples R-04 and S-03 are classified differently, with sample R-04 being classified as B2 (coarse sand) and sample S-03 as A1 (clayey silt) according to the GTR classification. This difference in classification can be attributed to variations in the grain size composition and the presence of fines in these specific samples. The grain size distribution curves of the samples show little spread. According to [26], grain size spread can decrease the mechanical strength of the soil due to the reduction of interactions between particles of different sizes, which can influence soil compaction and cohesion.

3.2.2. GTR (Guide to Road Settlements) soil classification

The synthesis of the results of the physical identification tests conducted on the soil samples is documented in Table 1. The results of the grain size analysis and methylene blue test allowed for a GTR classification of the soils.

Table 1. GTR soil classification (mine tailings).

N° sample	Soil type according to GTR	Water content natural W (%)	VBS	Lower sieve at 80 µm	Classification GTR
R-01	Very silty sand and gravel	12.1	0.76	28.5	B5
R-02	Very silty sand and gravel	11.8	0.57	28.7	B5
R-03	Very silty sand and gravel	12	0.80	31.4	B5
R-04	Clayey coarse sand	8	0.21	4.9	B2
S-01	Very silty sand and gravel	10.5	0.31	17.8	B5
S-02	Very silty sand and gravel	11	0.23	18.3	B5
S-03	Clay loam	26.1	0.30	39.2	A1

According to the data in Table 3, samples R-01, R-02, R-03, S-01, and S-02 exhibit methylene blue values (VBS) ranging from 0.23 to 0.80, with a percentage of material passing through the 80 µm sieve varying from 18.3% to 31.4%. These values indicate the presence of fines in these samples, categorizing them as very silty sands and gravels, in accordance with the GTR classification, where they are classified as B5. Conversely, sample R-04 displays a VBS of 0.21 and contains over 12% of material passing through the 80 µm sieve (with a sieve fraction at 80 µm of 4.9%). This composition suggests a lower quantity of fines compared to the other samples, classifying it as coarse sand, ranked as B2 according to the GTR classification. As for sample S-03, it presents a VBS of 0.3 and contains 39.2% of material passing through the 80 µm sieve. This high proportion of fines indicates a significant presence of fine particles in this sample, thus classifying it as clayey silt, belonging to class A1 according to the GTR classification.

In summary, these results demonstrate the diversity of grain size characteristics among the samples, reflecting the variability of soil types present in the study.

3.2.3. Straight shear CD (consolidated-drained)

According to the results presented in Figure 20, the shear tests conducted on the residue samples demonstrate the absence of cohesion as well as a range of internal friction angles, ranging from 26.7° for sample R-03 to 29.7° for sample R-04, with an average of 29°.

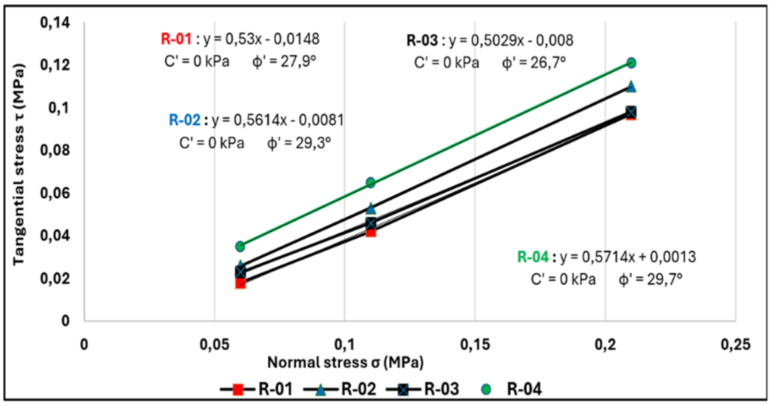


Figure 20. Residue shear curve.

The tests conducted using the shear box, as depicted in Figure 21, on the samples of underlying soils (S-01, S-02, and S-03), demonstrated a lack of cohesion and relatively consistent internal friction angles, measuring 33.1°, 28.94°, and 26.62°, respectively, with an average of 30°.

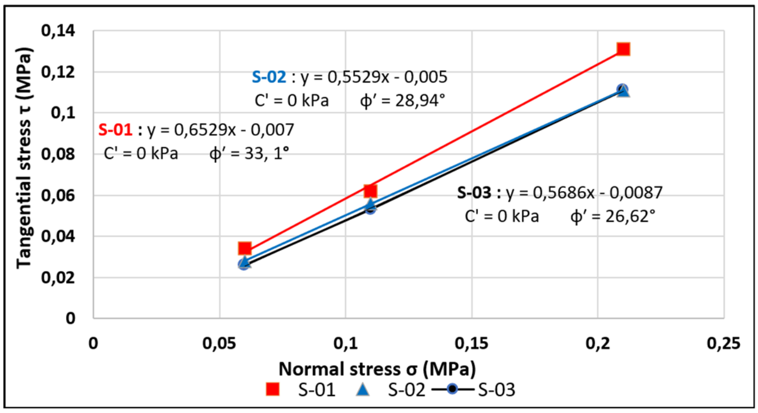


Figure 21. Shear curve for subgrade soils.

The results of the direct shear tests, presented in Figures 20 and 21, show zero cohesion, which may seem surprising given the results of the grain size analysis indicating the presence of some proportion of fines. However, it is likely that this lack of cohesion is explained by the origin of the waste, which comes from ore processing and results from the crushing of rocks from the substrate, especially gneisses. Therefore, the fines present would not be clay particles but rather siliceous particles. The average values of the measured friction angles are 29° for the waste and 30° for the underlying soils, which is consistent with results obtained in other studies, such as those conducted by [27] on waste from the Canadian Malartic mine and [28] on waste from uranium ore processing in Arlit, Niger. [29] argues that the shear strength of waste from hard rocks is mainly due to internal friction, with no significant contribution from cohesion due to the non-plasticity or very low plasticity of these rocks. Depending on density, grain size distribution, angularity, and confinement pressure, it is estimated that the effective internal friction angle of mining waste can range from 30 to 41°, as suggested by [7]. These details highlight the importance of understanding the geotechnical characteristics of mining waste to assess their mechanical behavior.

3.2.4. Proctor normal compaction

The Standard Proctor test, illustrated in Figure 22 and conducted on the underlying soil samples, aims to establish curves showing the variation of dry unit weight with water content. These curves help determine the optimal compaction values of soils to ensure their maximum density and optimal strength. The results of this test indicate that for samples R-01, R-02, and R-04, the maximum values of dry unit weight are 17.4, 19.3, and 16.9 kN/m^3, respectively. These values correspond to the highest compaction conditions, indicating that these samples have been compacted to the fullest extent. Additionally, the optimal water content values for these samples are 14.4%, 13.5%, and 6.9%, respectively. This optimal water content represents the amount of water needed to achieve the best soil compaction during compaction, ensuring adequate mechanical strength while avoiding excessive water saturation, which could weaken the soil structure.

In summary, the Standard Proctor test provides crucial information for determining the optimal compaction conditions of the underlying soils, which is essential for ensuring the stability and durability of infrastructures built on these soils.

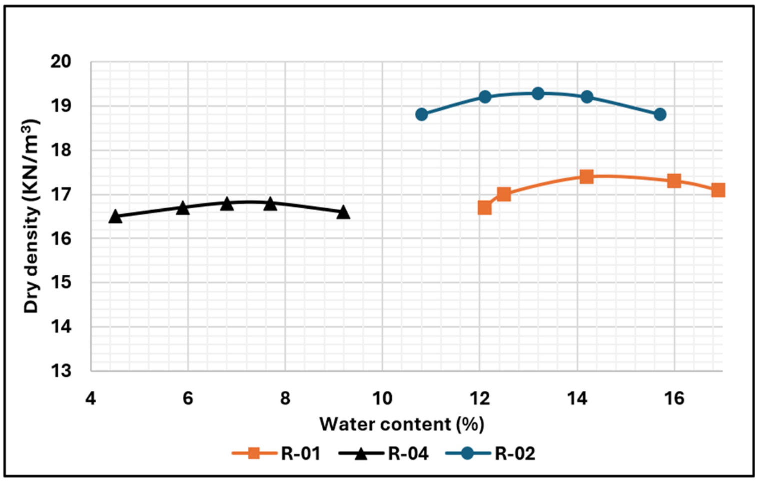


Figure 22. Proctor normal compaction curves.

3.3. Implications for the long-term stability of tailings and the environment

The particle size of tailings has a significant influence on their long-term stability and the environment. It indicates a predominance of coarse fractions in their composition, classifying them as sandy and gravelly with fines according to the GTR. The abundance of coarse fractions can lead to erosion phenomena and particle dispersion. It is essential to take these findings into account in tailings management to reduce environmental risks and ensure long-term safety.

The high permeability of tailings from the dump could be interpreted as a factor ensuring the stability of the tailings, as it limits water flow and facilitates their infiltration into the materials, thereby reducing the risks of erosion and saturation. However, in terms of water quality control, ease of infiltration may also pose challenges, as contaminants can easily spread into soils and groundwater. Best practices for managing mining tailings recommend confining the tailings and implementing a monitoring system to limit the risk of soil and water pollution.

Shear tests conducted on samples of tailings and substrate soils indicate zero cohesion, as well as optimal internal friction angles, with average values ranging from 29° to 30° for the tailings and substrate soils, respectively. These friction angle values indicate a certain resistance to sliding. However, the absence of cohesion warrants particular attention and necessitates regular monitoring and strict management of the tailings to ensure their long-term stability, thereby preventing landslides or slips that could impact the environment.

The interpretation of results from measurements of wet bulk density can have implications for stability and the environment. Samples R-01, R-02, R-03, and S-01, with bulk densities from 1.55 to 1.75 g/cm^3, are considered relatively dense materials and, therefore, exhibit good stability. However, it is important to remember that high water content can reduce their stability. Additionally, samples R-04, S-02, and S-03, which have lower wet bulk densities ranging from 1.16 to 1.37 g/cm^3, may present risks of settling or sliding. They could also be more prone to spreading contaminants in the environment in the event of dispersion.

In accordance with the results of the Standard Proctor test, samples R-2 and R-01 show good resistance to compaction. However, inadequate water content can lead to a decrease in this resistance, causing phenomena of shrinkage (due to desiccation) or swelling (due to humidification). This suggests that inappropriate management of tailings could result in problems of erosion and landslides during extreme weather conditions, thereby compromising surrounding ecosystems.

3.4. Recommendations for future management of residues to limit environmental risks and ensure long-term safety

To eliminate transfer pathways due to the erosion of residues and ensure their long-term stability, we recommend the following technical solutions for future residue management:

- Explore stabilization techniques, such as the use of vegetation cover on the reject pile brought in from outside, to limit erosion and the dispersion of fine particles.
- Reshape the reject pile through earthworks to lower the slopes of the embankments.
- Create integrated water management structures during the reshaping process to control rainwater infiltration and prevent water accumulation on the surface of the reject pile. Infrastructure such as drain benches, downspouts, and ditches could be considered to redirect water to safe areas, thereby minimizing both erosion facilitation and soil saturation.
- Establish a regular monitoring system to assess the stability of the residues and detect any water accumulation or signs of sliding. Measurement instruments should be implemented to evaluate permeability, compressibility, and variations in wet bulk density.

Adopting these management strategies will help reduce the environmental impacts of mining residues and ensure their long-term stability.

4. Conclusion

The results of the tests and analyses conducted on the samples of residues and substrates from the site present a clear picture of the composition and geotechnical properties of these materials. They highlight a significant variability in their geotechnical properties, which has significant implications for the management of mining residues.

The homogeneous bulk densities of the residues and substrate soils, although within a similar range to those found in other studies, show some anomalies, particularly the low bulk density of R-04, which is attributed to a possible overestimation due to measurement constraints in the field. Samples with a lower moist bulk density (S-02, S-03) are particularly concerning, as they may be prone to settling and sliding, potentially introducing additional environmental risks through contaminant spread. The presence of coarse fractions, along with a high permeability of the residues, provides a certain level of hydric stability, thus ruling out the possibility of perched water tables; however, it raises concerns regarding erosion and contaminant dispersion. Shear tests indicate an absence of cohesion, highlighting the need for stringent management to prevent unfavorable ground movements. However, the internal friction angles found are consistent with those reported in other studies on similar mining residues, underscoring the importance of internal friction in the shear resistance of these materials. Additionally, the results of the normal Proctor tests emphasize the importance of managing water content in the residues to maintain their compaction and strength.

To further improve the understanding of the geotechnical properties of the mine waste and underlying soils, additional investigations could be considered. These investigations could include more in-depth studies on the impact of in situ measurement constraints on density results, as well as supplementary analyses to better characterize the nature of fines present in the samples.

Furthermore, long-term behavior studies of the mine waste, particularly regarding their response to moisture and drought cycles, could be beneficial in assessing their long-term stability. Finally, advanced geotechnical modeling could be utilized to simulate different loading and drainage scenarios to better understand the behavior of the mine waste under real conditions and to guide decisions in site design and management.

Author contributions

Diaka Sidibé: She did analysis and interpretation of the data, and the drafting of the paper. Mamadou Diallo: He did the conception and design of the paper. Ahmed Amara Konaté: He revised paper critically for intellectual content; and the final approval of the version to be published. Muhammad Zaheer: He revised the paper critically for intellectual content.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Conflict of interest

No potential conflict of interest was reported by the author(s).

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