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Evaluation of mining solid waste: physical, mineralogical and rheological characterization for the study of tailings deposits

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ABSTRACT: The mining industry has undoubtedly been one of the key drivers of economic development in various countries around the world. However, this activity is causing a growing demand for mineral resources. Solid mining waste, known as tailings, generated from the mining extraction process, is deposited in special sites to prevent it from dispersing into the environment and contaminating soils, rivers, lakes, among other locations. The accumulation of tailings is one of the biggest sources of danger in a mine. The failure of a tailings dam can cause catastrophic damage, and typically, the failure of a tailings deposit occurs suddenly. To better understand the stability of a tailings dam and the impact of these materials when they fail, it is necessary to study the rheological properties of these materials. This study presents the results of the rheological, physical, and mineralogical characterization of three tailings samples from three different mines. The obtained results allowed identifying that there are different types of material flow, depending on its volumetric concentration, and how rheological parameters are highly influenced by the granulometry and solid density.

KEYWORDS: Tailings, rheology, mining solid waste, tailings deposits, viscosity.

1 INTRODUCTION

The accumulation of solid mining waste, commonly referred to as tailings, represents one of the primary sources of risk in mining operations (Wei et al., 2013). These wastes are deposited in specially designed facilities to prevent their dispersion into the environment and the contamination of soils, rivers, lakes, and other ecosystems. The structures where tailings are stored are known as tailings storage facilities (TSF) (see Fig. 1).

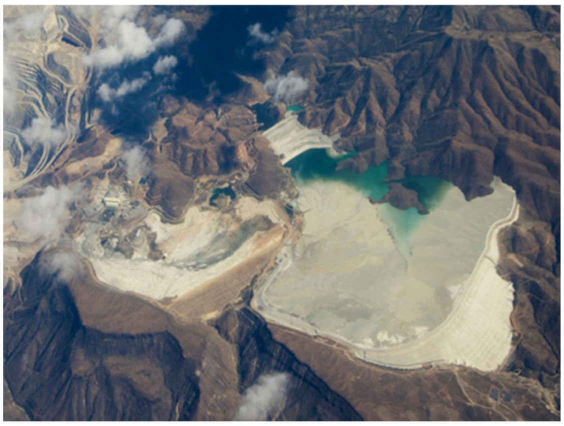

Figure 1. Aerial view of a tailings storage facility in Chile (CIPER Chile, 2022).

Tailings storage facilities exhibit a significantly higher probability of failure compared with concrete dams used for water storage and control (Martin and Davies, 2000). Since 1950, more than 120 major TSF failures have been documented worldwide (Piciullo et al., 2022). Between 2000 and 2009, 36 such failures were reported, releasing slightly more than 14 million m³ of tailings and causing 342 fatalities. Between 2010 and 2019, 45 additional failures were recorded, releasing 103 million m³ of tailings and resulting in 486 deaths (WMTF, 2022). One of the most recent and significant failures was the Brumadinho disaster, which occurred on 25 January 2019 in the state of Minas Gerais, southeastern Brazil. The failure of a TSF can lead to catastrophic and sometimes irreversible impacts (Hudson-Edwards et al., 2003). Such failures often occur suddenly, which underscores the growing interest within the geotechnical engineering community in understanding TSF behavior to prevent collapse and avert large-scale disasters. Globally, mining is estimated to generate approximately 5 billion tons (10 billion m³) of tailings each year, and this volume is expected to continue increasing (Bowker and Chambers, 2015). By 2025, the accumulated global volume of tailings is projected to reach 640 billion cubic meters, most of which will be stored in TSFs. However, many of these facilities lack adequate monitoring and maintenance, thereby significantly increasing the risk of failure (WMTF, 2022). When a TSF breach occurs, the tailings and the water contained within are released simultaneously, generating a large-scale mudflow that severely impacts downstream areas. A Tailings Dam Breach Analysis (TDBA) evaluates hypothetical failure scenarios and involves a series of analyses to estimate the flow characteristics of tailings and the resulting downstream impacts (Roman et al., 2022). Improving predictive models for potential TSF failures and their downstream consequences has become a critical priority for the global mining industry (Ghahramani et al., 2022). Melo and Eleutério (2023) demonstrated how rheological variability in tailings can substantially influence breach modeling results. For this reason, it is essential to determine the rheological parameters of tailings experimentally; relying on values derived from correlations reported in the literature often leads to significant discrepancies in predicted inundation areas, flow depths, arrival times, velocities, and other key outcomes. In this context, understanding the rheological properties of tailings is indispensable for anticipating the consequences of a breach and the subsequent flow behavior. The two key rheological parameters of tailings are yield stress and viscosity (Kheirkhah Gildeh et al., 2021). Yield stress is defined as the minimum shear stress required to initiate flow, while viscosity relates the resistance to flow with shear rate (Ghahramani et al., 2022). A comprehensive understanding of both rheological and physical properties is therefore crucial for assessing the stability of these structures and the effects associated with potential failure.

1.1 *Physical Characterization*

The physical characterization of tailings is essential, as their behavior is influenced by multiple factors, among which particle size distribution is particularly relevant (Ramos and Pérez, 2020). It is therefore important to determine the particle-size distribution and key physical properties —such as specific gravity of solids and Atterberg limits—which together allow for a more accurate understanding of the material's behavior.

1.1.1 *Specific Gravity of Solids*

The specific gravity of solids is defined as the ratio between the unit weight of the particles and that of distilled water. This parameter is one of the fundamental physical properties in tailings characterization (Ruehlmann, 2020). Its value significantly influences the mechanical behavior of the material and is closely linked to the mineralogical composition of the tailings. The determination of this property is performed according to ASTM D854-14.

1.1.2 *Hydrometer Analysis*

This method quantifies the particle-size distribution of the material. Fractions larger than 75 µm (retained on the No. 200 sieve) are analyzed through sieving, while particles smaller than 75 µm are evaluated by sedimentation using a hydrometer, which provides the required data. This test is carried out in accordance with ASTM D422-63.

1.1.3 *Atterberg Limits*

These parameters are an integral part of various soil classification systems used to characterize the fine fraction of soils. The liquid limit is defined as the water content—expressed as a percentage—at which a soil in a plastic state begins to behave as a viscous fluid with any additional increase in moisture. This parameter also reflects the water content required for the soil to reach a minimum shear resistance. The plastic limit corresponds to the water content, relative to the dry mass of the sample, at which a cohesive soil transitions from a semisolid to a plastic state; at this point, the soil begins to lose cohesion due to moisture reduction. Both limits are commonly used for the classification and characterization of tailings (Saad, 2008). These parameters are determined according to ASTM D4318.

1.2 *Mineralogical Characterization*

Mineralogical characterization of tailings is a key component of rheological analysis, as the nature and distribution of mineral phases directly influence their mechanical behavior and flow capacity. Properties such as mineral morphology, size, and crystal structure govern particle interactions and affect key rheological parameters, including viscosity and yield stress. Identifying the mineralogical composition helps establish correlations between the presence of clay or sulfate minerals and the stability response of a TSF under shear loading or varying solids concentrations. This characterization can be carried out using techniques such as X-ray diffraction (XRD) (Ramón and Jiménez, 2006).

1.2.1 *X-Ray Diffraction*

X-ray diffraction is based on the interaction of electromagnetic radiation with the atoms within the sample. The sample is irradiated with an X-ray beam, which is diffracted as it interacts with the planes of the crystalline structure. Each plane satisfying Bragg's law produces a diffraction peak due to constructive interference of the waves. The resulting pattern shows diffraction intensity as a function of the incidence angle, which is characteristic of each material. Mineral phases are identified by comparing the obtained pattern with spectra stored in international databases (Litter et al., 2009; Ramos and Pérez, 2020).

1.3 *Rheological Characterization*

Rheological characterization of tailings is essential for understanding and predicting their behavior under different flow and stress conditions. Since tailings often exhibit non-Newtonian flow properties, rheological analysis enables the determination of key parameters such as viscosity and yield stress. These parameters are fundamental for the efficient design of hydraulic transport systems, the planning of tailings deposition, long-term stability assessment, and the analysis of potential breaches. Proper rheological characterization also supports the development of predictive models that optimize industrial processes and reduce environmental risks associated with tailings management. Rheology is one of the most influential yet uncertain factors in TSF failure modeling, as an incorrect selection of rheological parameters can lead to significant discrepancies in breach analysis results (Roman et al., 2022). Figure 2 illustrates the different flow behaviors that these materials may exhibit.

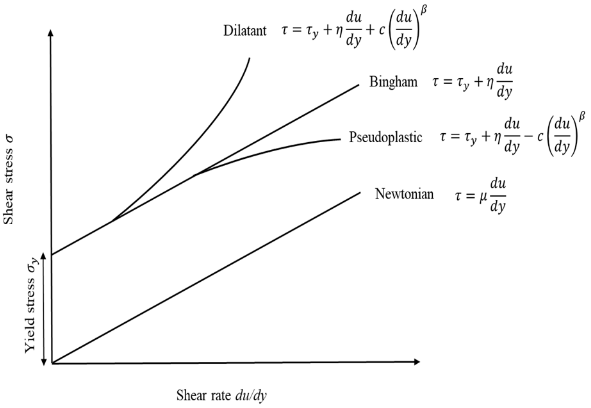

Figure 2. Shear stress as a function of shear rate (FLO-2D Manual).

In this study, a comprehensive rheological characterization is conducted through the experimental determination of their physical, mineralogical, and rheological properties, aiming to identify the key parameters governing their flow behavior. This information will provide reliable parameters for use in tailings dam breach analyses, reducing uncertainty in numerical simulations and improving the accuracy of predictions regarding material behavior under different failure scenarios.

2 MATERIALS

The tailings sample analyzed in this study was obtained from a mine located in the state of Durango, Mexico. This operation extracts gold (Au) and silver (Ag) through both open-pit and underground methods.

3 METHODOLOGY

3.1 *Physical Characterization of Tailings*

For the physical characterization of the tailings, several laboratory tests were performed, as briefly described below. These tests were conducted to ensure proper classification of the material and to support subsequent analyses.

3.1.1 *Specific Gravity of Solid Particles (Ss)*

To determine this parameter, three pycnometers were used to ensure the reliability and repeatability of the measurements. The procedure followed corresponds to ASTM D854-14, which describes in detail the steps for obtaining the specific gravity of solid particles in fine-grained materials. Figure 3 illustrates part of the process carried out during the test.

Figure 3. Test for determining the specific gravity of solid particles.

3.1.2 *Atterberg Limits*

The Atterberg limits were determined according to the procedure described in ASTM D4318. The liquid limit corresponds to the water content at which two portions of the same sample, separated by a standard groove, flow together after 25 well-defined blows in the Casagrande cup. The plastic limit is defined as the water content at which soil threads with a diameter of 3 mm can be formed without breaking or crumbling. Figure 4 shows part of the procedure carried out to obtain these parameters.

Figure 4. Test for determining the Atterberg limits.

3.1.3 *Hydrometer Analysis*

This test consisted of a quantitative determination of the particle-size distribution of the material using a 152H hydrometer. The procedure was carried out in strict accordance with ASTM D422-63.

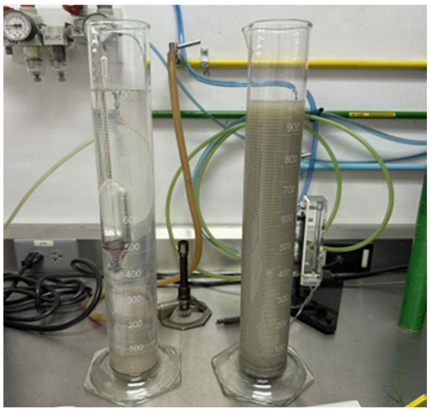

Figure 5. Hydrometer particle-size analysis test.

3.2 *Mineralogy*

3.2.1 *X-Ray Diffraction*

X-ray diffraction was conducted to determine the mineralogical composition of the tailings sample using a diffractometer. Approximately 5 g of material were subjected to a collimated X-ray beam. The source emitted electromagnetic radiation with wavelengths comparable to the spacing between atomic planes in crystalline structures, causing the incident rays to diffract upon interacting with these planes. The diffracted radiation was then captured by a detector that recorded its intensity as a function of the diffraction angle. The resulting intensity–angle data were plotted to generate a diffractogram (see Fig. 6). This diffractogram was subsequently compared with international reference databases to identify the mineral phases present in the sample.

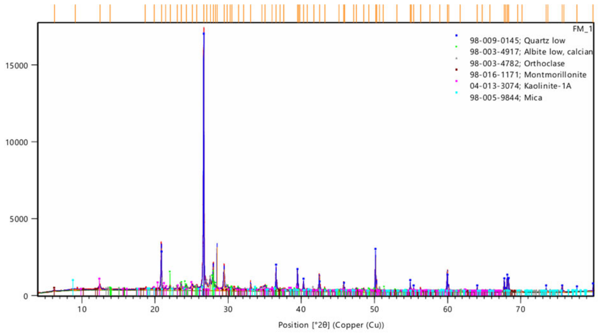

Figure 6. Diffractogram obtained from the X-ray diffraction test.

3.3 *Rheology of Tailings*

The rheological parameters of the tailings were obtained using a rotational viscometer (see Fig. 7) under different shear rates and solids concentrations.

Figure 7. Rotational viscometer used in this study.

This test enabled the determination of viscosity and shear stress, which in turn allowed for the calculation of the yield stress. These results made it possible to identify the flow behavior exhibited by the material. Figure 8 shows the viscometer during a rheological test.

Figure 8. Test for obtaining the rheological properties of the tailings sample.

4 PRESENTATION AND ANALYSIS OF RESULTS

4.1 *Physical Characterization of Tailings*

The results of the physical characterization tests performed on the tailings sample are presented below.

4.1.1 *Specific Gravity of Solid Particles (Ss)*

Table 1 summarizes the results obtained from the specific gravity tests. The final reported value corresponds to the average of the three pycnometers used.

Table 1. Results of the specific gravity of solid particles.

	Pycnometer 1	Pycnometer 2	Pycnometer 3
Ss	2.74	2.75	2.75
$Ss_{Average}$	2.75		

4.1.2 *Atterberg Limits*

The results obtained for the Atterberg limits of the tailings sample are presented below. Figure 9 illustrates the flow curve used to determine the liquid limit, and Table 2 summarizes the plastic limit test results.

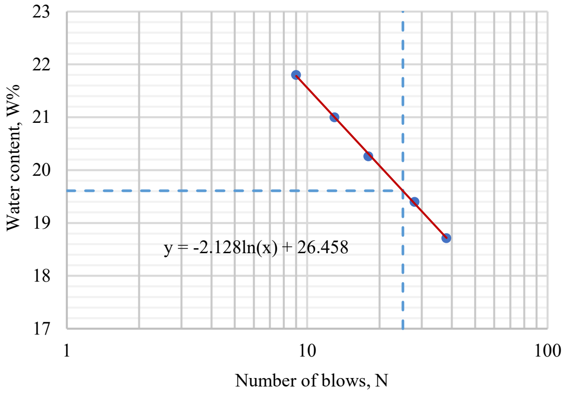

Figure 9. Flow curve used for the determination of the liquid limit.

Table 2. Results obtained from the plastic limit tests.

	Test 1	Test 2	Test 3
Plastic Limit (P.L.)	17.76	17.78	17.76
$P.L._{Average}$	17.77		

4.1.3 *Hydrometer Grain Size Analysis*

Figure 10 presents the particle-size distribution curve of the tailings sample obtained from the hydrometer analysis.

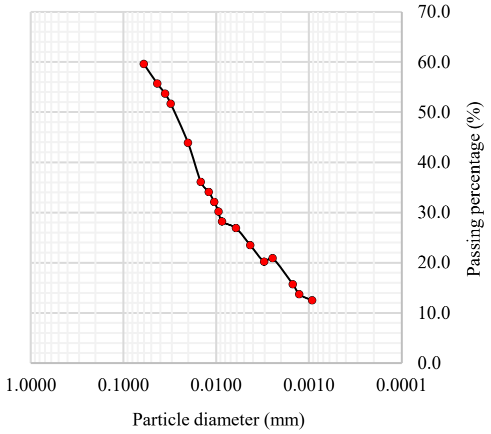

Figure 10. Particle size distribution curve.

In the resulting curve, it can be observed that the sample exhibits a broad range of particle sizes, spanning from 75 µm to 9 µm.

4.2 *Mineralogy*

Table 3 presents the results obtained from the X-ray diffraction analysis performed on the tailings sample.

Table 3. X-ray diffraction results.

Tailings sample	
Identified phases	Percentage (%)
Quartz (SiO_2)	55
Plagioclase	18
Potassium feldspar (orthoclase)	12
Smectite type phyllosilicates	8
Mica–illite type phyllosilicates	2
Kaolinite type phyllosilicates	5
% Total	100

The results of this analysis allow for the inference of potential implications for the rheological behavior of the material. The high proportion of quartz (55%), together with plagioclase (18%) and potassium feldspar (12%), suggests a predominantly rigid, low-plasticity matrix, typical of materials governed by frictional behavior. However, the presence of phyllosilicates (15% overall)—particularly smectite (8%)—may induce a more complex rheological response. Smectite is well known for its high water-absorption capacity and thixotropic behavior, both of which can significantly increase viscosity. Likewise, kaolinite (5%) and mica–illite (2%) contribute additional plasticity, albeit to a lesser degree. Overall, this mineralogical composition indicates that although the material exhibits a predominantly sandy matrix, the fine clay-type minerals may play an important role in its rheological behavior, particularly under high-moisture conditions.

4.3 *Rheological Parameters of the tailings*

For each experimental condition, three independent specimens were prepared and tested. The triplicate measurements were conducted to verify the repeatability and internal consistency of the results, ensuring that the observed trends reflect the actual behavior of the material rather than random measurement noise. The close similarity among replicates demonstrated the reliability of the testing procedure, making additional statistical treatment unnecessary. Figures 11 and 12 present the viscosity and shear stress curves, respectively, both plotted as a function of shear rate for the solid concentrations evaluated in this study (Cv = 0.5, 0.4, and 0.3).

The viscosity values obtained for the analyzed concentrations are consistent with those reported by Wang et al. (2018) for materials with similar particle-size distributions and mineralogical characteristics. The test was performed by applying rotational shear at a constant rate, following the procedures established in ASTM D2196-20. Figure 13 presents the static yield stress values for each concentration for which this parameter was determined. It is important to note that, for the determination of this parameter, two additional solid concentrations were included (Cv = 0.35 and 0.45).

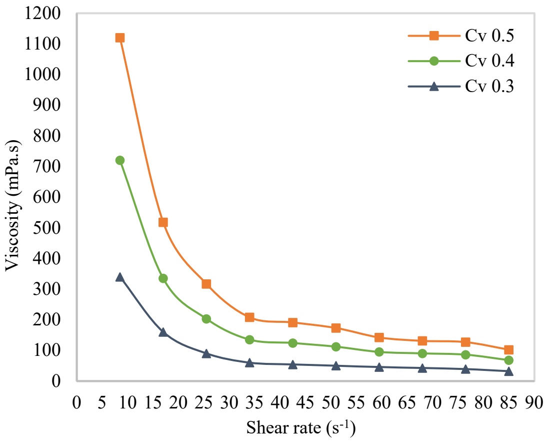

Figure 11. Viscosity-shear rate graph.

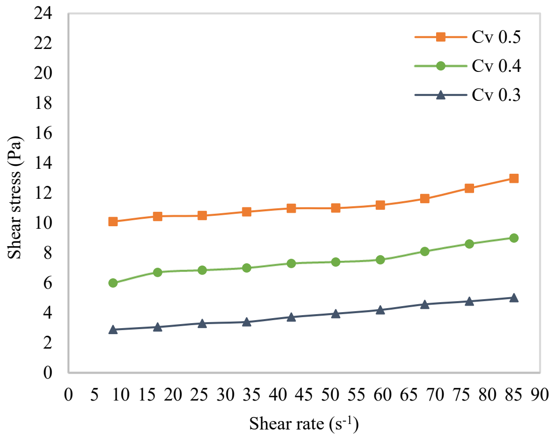

Figure 12. Shear stress-shear rate graph.

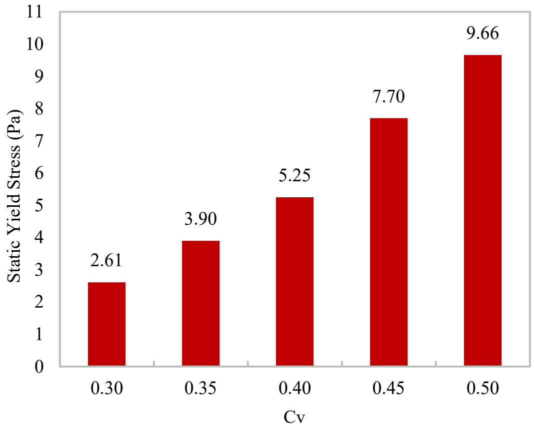

Figure 13. Static yield stress-volumetric concentration graph.

Based on the observations from Figure 12 and taking Figure 2 as a reference—where the different fluid deformation models are presented—the material studied can be classified within one of these models. This classification enables the development of analytical models that more accurately represent the actual behavior of the material, rather than relying solely on correlations reported in the literature based on similarities with other materials. It is important to note that flow deformation begins once the applied shear stress exceeds the yield stress. The yield stress values obtained for each solid concentration (see Fig. 13) are presented in Table 4; these were determined using the static yield stress test performed with the rotational viscometer. It should also be noted that the evaluated solid concentrations correspond to water contents higher than the liquid limit of the sample, as rheological behavior must be analyzed within this moisture range.

Table 4. Results obtained from the static yield stress tests.

Tailings sample			
Cv	Static Yield Stress (Pa)	*L.L.*	*Ss*
0.3	2.6	19.61	2.75
0.35	3.9		
0.4	5.2		
0.45	7.7		
0.5	9.7		

5 CONCLUSIONS

The detailed characterization of tailings is a fundamental step for understanding their physical, chemical, and rheological properties, and thus for predicting their behavior under different failure scenarios. This investigation demonstrates that obtaining specific parameters through laboratory testing enables a much more accurate representation of the material under analysis, which is essential when modeling tailings dam breach analyses (TDBA).

The use of experimentally determined rheological parameters—rather than relying on generalized or literature-based correlations—adds significant value to the simulation and modeling process. This approach substantially reduces the uncertainty associated with numerical models and increases the reliability of the results, allowing for more accurate estimations of variables such as flow velocity, runout distance, and flow volume in the event of a failure. Moreover, the findings confirm that tailings with higher Cv values require greater shear stress to initiate flow and, once flowing, tend to reach lower velocities and shorter travel distances due to their higher viscosity, in addition to other influencing factors such as the topographic and hydrological characteristics of the terrain.

The methodological approach adopted in this study contributes to strengthening tailings evaluation mechanisms and decision-making processes related to tailings storage facilities, particularly in contexts where geotechnical and geochemical conditions may vary significantly between sites. Overall, the findings underscore the importance of incorporating site-specific and material-specific characterizations into safety assessments and TDBA modeling efforts.

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