ABSTRACT

Objectives: The recent tailings dam disasters emphasize the need to adopt best management practices focusing on the stability of these structures. This study aims to present the use of a thickening channel as an alternative for ultrafine tailings dewatering in a small iron ore mine in the Quadrilátero Ferrífero.

Theoretical Framework: The research is based on the study of rheology, focusing on viscosity and yield stress as key parameters to characterize the behavior of thickened slurry.

Method: The study involved the production of thickened slurry in a channel, followed by rheological characterization through sampling at different points in the thickening process.

Results and Discussion: The findings indicate that the thickened slurry behaves as a non-Newtonian fluid, with all samples analyzed showing pseudoplastic behavior. There was an increase in viscosity and yield stress with increasing solids content. The deposition of thickened slurry resulted in a 36.9% increase in the volume of the studied reservoirs.

Research Implications: This approach offers advantages such as low capital cost, increased water reuse, and improved geotechnical stability of deposition sites, contributing to safer and more sustainable tailings management practices.

Originality/Value: The study provides a practical alternative for tailings dewatering, enhancing the safety and sustainability of tailings disposal practices in small iron ore mines.

Keywords: Rheology, Tailings, Thickened Slurry, Thickening Channel, Tailings Disposal.

PROPRIEDADES REOLÓGICAS DE UM REJEITO ESPESSADO EM UM CANAL ESCAVADO NO SOLO

RESUMO

Objetivos: Os recentes desastres em barragens de rejeitos destacam a necessidade de adotar melhores práticas de gestão, focando na estabilidade dessas estruturas. Este estudo tem como objetivo apresentar o uso de um canal de espessamento como alternativa para a desidratação de rejeitos ultrafinos em uma pequena mina de ferro no Quadrilátero Ferrífero.

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Referencial Teórico: A pesquisa baseia-se no estudo da reologia, com foco na viscosidade e na tensão de escoamento como parâmetros chave para caracterizar o comportamento da lama espessada.

Método: O estudo envolveu a produção de lama espessada em um canal, seguida de caracterização reológica por meio de amostragem em diferentes pontos do processo de espessamento.

Resultados e Discussão: Os resultados indicam que a lama espessada se comporta como um fluido não newtoniano, com todas as amostras analisadas mostrando comportamento pseudoplástico. Houve um aumento na viscosidade e na tensão de escoamento com o aumento do teor de sólidos. A deposição de lama espessada resultou em um aumento de 36,9% no volume dos reservatórios estudados.

Implicações da Pesquisa: Esta abordagem oferece vantagens como baixo custo de capital, maior reutilização de água e melhora na estabilidade geotécnica dos locais de deposição, contribuindo para práticas de gestão de rejeitos mais seguras e sustentáveis.

Originalidade/Valor: O estudo fornece uma alternativa prática para a desaguarmento de rejeitos, aumentando a segurança e a sustentabilidade das práticas de disposição de rejeitos em pequenas minas de ferro.

Palavras-chave: Reologia, Rejeitos, Lama Espessada, Canal de Espessamento, Disposição de Rejeitos.

PROPIEDADES REOLÓGICAS DE RELAVES ESPESADOS EN UN CANAL EXCAVADO EN EL SUELO

RESUMEN

Objetivos: Los recientes desastres en presas de relaves destacan la necesidad de adoptar mejores prácticas de gestión, centrándose en la estabilidad de estas estructuras. Este estudio tiene como objetivo presentar el uso de un canal de espesamiento como una alternativa para la deshidratación de relaves ultrafinos en una pequeña mina de hierro en el Quadrilátero Ferrífero.

Marco Teórico: La investigación se basa en el estudio de la reología, centrándose en la viscosidad y la tensión de cedencia como parámetros clave para caracterizar el comportamiento de la pulpa espesada.

Método: El estudio involucró la producción de pulpa espesada en un canal, seguida de una caracterización reológica mediante muestreo en diferentes puntos del proceso de espesamiento.

Resultados y Discusión: Los hallazgos indican que la pulpa espesada se comporta como un fluido no newtoniano, con todas las muestras analizadas mostrando un comportamiento pseudoplástico. Hubo un aumento en la viscosidad y en la tensión de cedencia con el aumento del contenido de sólidos. La deposición de pulpa espesada resultó en un aumento del 36,9% en el volumen de los reservorios estudiados.

Implicaciones de la Investigación: Este enfoque ofrece ventajas como bajo costo de capital, mayor reutilización de agua y mejora en la estabilidad geotécnica de los sitios de deposición, contribuyendo a prácticas de gestión de relaves más seguras y sostenibles.

Originalidad/Valor: El estudio proporciona una alternativa práctica para la deshidratación de relaves, mejorando la seguridad y la sostenibilidad de las prácticas de disposición de relaves en pequeñas minas de hierro.

Palabras clave: Reología, Relaves, Pulpa Espesada, Canal de Espessamento, Disposición de Relaves.
1 INTRODUCTION

Electrostatic and viscous media forces are more representative of the rheology of ultrafine tailings' pulp than the mechanical forces typical of coarser tailings' pulp. Thus, rheological studies are fundamental for understanding the behavior of ultrafine tailings pulp and for assessing the effects of viscosity on the fluid dynamics of the pulps (Barnes, Hutton, and Walters, 1989; Coussot, 2014; Garcia, Le Bolay, and Frances, 2003; Roussel, 2005).

The increasing complexity of tailings disposal systems and the recent disasters caused by dam ruptures and tailings releases into the environment necessitate the study of new technologies and alternatives for tailings management (Verburg, 2001; Watson et al., 2010; Chambers and Higman, 2011; Chryss et al., 2012; Cacciuttolo and Tabra, 2015; Carneiro and Fourie, 2018; Yin et al., 2020). Paste disposal is an alternative that reduces free water in the structures and significantly increases dam safety levels (Hart and Boger, 2005; Meggyes and Debresczen, 2006; Guimaraes and Araujo, 2017; Beltrán-Rodríguez et al., 2018).

A mineral paste is a colloidal system that presents itself as a homogeneous fluid without particle segregation (Jewell and Fourie, 2015). Rheology, including viscosity yield stress, and the angle of repose are correlating parameters that define and characterize the behavior of a mineral paste (Boger, 2013; Garcia et al., 2003). Understanding the deformation and flow of matter is the primary purpose of studying the rheological properties of a pulp (Barnes et al., 1989; Trampus and França, 2019). The determination of apparent viscosity and yield stress are fundamental parameters for understanding the rheology of suspensions. Viscosity measures the resistance to the displacement of fluid molecules as a function of internal friction; the greater the friction, the higher the viscosity (Garcia et al., 2003). However, variations in temperature, pressure, and solids concentration, as well as particle shape and size, and changes in particle aggregation level (due to the presence of salts, dispersing agents, or pH changes) cause variations in the rheological properties of a pulp (Sofrá and Boger, 2002; Trampus and França, 2019).

Yield stress is the force required to initiate the displacement of molecules that causes a non-Newtonian fluid to flow. For a non-Newtonian fluid to deform indefinitely, a stress above a critical value is required. After transitioning between these two states, if no chemical reaction occurs, the material retains its intrinsic mechanical properties (Coussot, 2014).

However, paste tailings disposal is not common in Brazil. Following the collapse of Samarco's Fundão dam and Vale's B1 dam, tailings filtering and disposal in piles have become widely used. In response to these disasters, according to Brazilian Law 23,291, of 2019, all
upstream tailings dams, whether inactive or in operation, must be de-characterized within a maximum period of three years. To evaluate the thickened slurry process, this paper presents the steps from the beginning in the thickening channel to the removal of thickened slurry from the channel, and then to the truck transportation and deposition of the slurry in the final Tailings Storage Facility (TSF). This process is conducted at a small iron-ore mine with an annual production of about 1.5 million tonnes per year of iron ore concentrate and 21.2 thousand tons per month of ultrafine tailings. Furthermore, this paper presents the methods followed to characterize the rheological properties of the thickened slurry and draws attention to the closure or de-characterization actions implemented for the Principal TSF to comply with Law 23,291.

## 2 SITE DESCRIPTION AND MATERIALS AND METHODS

Located in the western part of the Itabirito mountain range, the iron ore mine is situated at the contact of the Cauê and Gandarela Formations within the Itabira Group, Minas Supergroup. The mine presents three different types of mineralization: the first type has Fe contents between 40% and 50%, the second type comprises itabirite fragments from the primary mineralization (Cauê Formation) with Fe contents of up to 67%, and the third type is characterized by the enrichment of carbonate rocks of the Gandarela Formation in Fe. The main mineralogical compounds include magnetite/martite, clay (from carbonate alteration), and quartz. Tailings from the mining operation are deposited as paste in tailings disposal structures, which are part of the storage tailings facility (TSF) of the iron ore mine.

Initially, tailings are disposed of into a thickening channel. After thickening, the paste is removed with excavators and transported by trucks to the TSF. The mine has an operational license for 1.5 million tons of Run of Mine (ROM) per year with a stripping ratio of approximately 0.3. The mine equipment includes excavators, trucks, tractors, a concentration plant, a thickening channel, and other support vehicles.

The thickening channel was adopted instead of drying bays due to operational problems and the low water recovery presented by these bays. The thickening channel is divided into seven stages for optimal visual control of water recovery and the thickening process. The U-shaped channel is 490 m long, 8 m wide, and 5.5 m deep, with a gap from the first to the last stage of approximately 3.5 m. The channel is separated into seven stages by 12-inch pipes. The level difference from the first stage to the last is approximately 3.5 m. A thickener feeds the material into the channel with 55% solids for 24 hours a day at a feed rate of 24 m³/h. After thickening in the channel, the slurry, with about 67.9% solids, is removed by excavators
operating at the highest densification points visually controlled by the operators. The excavators load the thickened slurry into trucks for transportation to the deposition sites. Figure 1 illustrates the excavation and loading, haulage, and dumping of the thickened slurry.

**Figure 1**

*Thickened slurry excavation and loading (a), haulage (b) and deposition (c).*

To study the rheological properties of the slurry, samples were collected at various points in the thickening channel and at the deposition point. The sample collection points were:

- Sample I: Collected at the thickener discharge point;
- Sample II: Collected at the beginning of the thickening channel, i.e., at the point of paste removal;
- Sample III: Collected at the point immediately after removal of the paste;
- Sample IV: Collected at points II and III at the end of the thickening channel operation cycle where the material is less densified;
- Sample V: Collected at the thickened slurry dumping point. Samples from this point represent the junction of samples from points II, III, and IV;

Figure 2 shows the sample collection points. Sample I was collected close to the underflow thickener discharge point. Samples II, III, and IV were collected at the same location but at different times in the slurry excavation cycle, and sample V at the thickened slurry discharge in the reservoir.
Rheological Properties of a Tailing Thickened in an Excavated Ground Channel

Figure 2

Sample collection points: (a) thickening channel - samples I, II, III, IV; (b) dumping point - sample V.

Trucks dump the thickened slurry at various points of the tailings reservoir to allow quick drying of the layers. The overlying layers fill the cracks formed by drying, helping create a stable structure. In the dry season, the slurry disposed of has a high drying rate. Figure 3 shows a slurry surface one day after being dumped (a) and a slurry layer one month after being dumped (b).

Figure 3

Thickened slurry layer 1 day after deposition (a) and thickened slurry one 1 month after deposition (b).

A surface modeling program was used to measure the tailings slope in the reservoir as well as the angle of repose of the slurry, the current reservoir volume, and the volume considering the angle of repose equal to zero. Figure 4 shows the geometric shape of the reservoir.
The theoretical framework in a study comprises a critical and organized analysis of the literature relevant to the topic, providing a theoretical contextualization and defining the key concepts. It must comprehensively contain theories, models, and previous research, identifying gaps, contradictions and consensuses in the literature that are important for the focus of the work being developed.

3 TAILINGS’ SAMPLES CHARACTERIZATION

3.1 FLUME TEST

The flume test is conducted to predict the angle of repose or slope formed by the deposition of de-watered tailings. The thickened slurry angle of repose ($\theta_R$) was obtained according to the methodology developed by Sofrá and Boger (2002) (Figure 5), with $\theta_R$ given by the equation (1).

$$\theta_R = \arctan\left(\frac{H_1 - H_2}{L}\right)$$

Where:

- $H_1$: The fluid height at the origin and were measured.
- $H_2$: the height of the tailings at the end (toe) of the flow.
- $L$: The length of flow.
θr: The natural angle of repose of the tailings.

**Figure 5**
*Inclined plane apparatus and schematic diagram of stationary fluid on the inclined plane.*

![Inclined plane apparatus and schematic diagram of stationary fluid on the inclined plane.](image)

Source: Sofrá and Boger, 2002.

### 3.2 SLUMP TEST

Slump tests were conducted using a 10 cm diameter and height PVC cylinder. The yield stress from the slump test was obtained using equation 2 developed by Pashias et al. (1996) and modified by Baudez et al. (2002). The Solver program was used for the solution of equation 2.

\[
s = H - (h_0 + h_1) = H + Z_0 - \frac{2\tau_0}{\rho g} \left(1 + \ln \frac{\rho g (H + Z_0)}{2\tau_0}\right)
\]

(2)

Where:

- \(Z_0\) is the fictitious rise in height with the addition of the plate.
- \(H\) is the height of the filled cylinder.
- \(\tau_0\) is the yield strength.
- \(\rho\) is specific mass.
- \(g\) is acceleration of gravity.
3.3 VISCOSITY AND YIELD STRESS TESTS

The accurate measurement of yield stress of thickened tailings is crucial for thickened tailings disposal from preparation through transportation to final deposition (Gawu and Fourie, 2004). For the viscosity experiments, a voltage-controlled rotational rheometer manufactured by Anton Paar with a stem vane type was used. The geometry of the vane shaft was chosen based on the high percentage of solids and the rapid densification process of the slurry observed throughout the tests.

The yield stress test was conducted during the viscosity test, with the equipment itself calculating the yield stress. The samples were subjected to progressive shear stresses with fixed initial and final values, and readings at predefined intervals. The programmed voltage for samples II, III, and IV was 100 Pa to 1000 Pa in 300 seconds, with a reading every 5 seconds, totaling 40 points. For samples with a high solid percentage, the programmed tension was higher. For sample II, the range was from 1500 Pa to 3000 Pa, and for sample V, it ranged from 600 Pa to 2000 Pa.

4 RESULTS AND DISCUSSIONS

The methodology of an article outlines the procedures employed to conduct the research, including the type of study, sample selection, data collection and analysis methods, ethical considerations, and limitations of the study. Its detailed and transparent description is essential to guarantee the replicability and reliability of the results, in addition to providing a solid basis for the interpretation and generalization of the findings.

4.1 SAMPLE CHARACTERIZATION

Table 1 presents the particle size distribution and chemical analysis by fraction. One can observe that 92.69% of the sample is below 0.038 mm, with an average content of Fe equal to 46.26% and 16.61% of SiO2. The determined average density for the samples was 3.55 g/cm3. The sample was mineralogically characterized as goethite hematite by conventional microscope of reflected light.
4.2 ANGLE OF REPOSE (θ<sub>R</sub>)

The flume tests were conducted with zero slope. The angle of repose (θ<sub>R</sub>) obtained in the tests ranged from 12° to 24°, while the samples with solids content above 60% achieved angles of repose exceeding 18° (Table 2).

<table>
<thead>
<tr>
<th>Sample</th>
<th>% of solids</th>
<th>θ&lt;sub&gt;R&lt;/sub&gt; (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>55.93</td>
<td>12.44</td>
</tr>
<tr>
<td>II</td>
<td>67.90</td>
<td>24.65</td>
</tr>
<tr>
<td>III</td>
<td>61.35</td>
<td>18.78</td>
</tr>
<tr>
<td>IV</td>
<td>56.27</td>
<td>15.42</td>
</tr>
<tr>
<td>V</td>
<td>63.91</td>
<td>19.33</td>
</tr>
</tbody>
</table>

The angle of repose obtained for sample V, which represents the material deposited in the dams, was 19.33°. However, the average angle of the slurry deposited in the dams is around 10°. The reduction in the repose angle from the test to the actual scenario is due to three factors. First, the flume test was conducted in static flow and to a lesser extent, allowing a larger angle of repose as noted by Clayton, Grice, and Boger (2003). Second, increased shear rate during transport (Hofman, Paterson, and van Sittert, 2007) increases the fluidity of the slurry. Third, the potential energy generated by the height difference between the pivoting point and the beach reduces the slurry viscosity and thus the angle of repose. Despite these factors, there is a volume gain in the tailings disposal structures of 37.6%, 54.7%, and 18.4% respectively. Table 3
presents the data for the three considered reservoirs, including angles of repose of the slurry, the current volume \( (\theta_R = \text{actual}) \), and the volume considering \( \theta_R = 0^\circ \) for each reservoir.

### Table 3

**Data for the tailings disposal structures**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Structure 1</th>
<th>Structure 2</th>
<th>Structure 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope of the disposed paste in the reservoir ( (\theta_R) )</td>
<td>10.3°</td>
<td>10.6°</td>
<td>9.1°</td>
</tr>
<tr>
<td>Actual volume of the reservoir ( (m^3) )</td>
<td>108,511.00</td>
<td>437,114.00</td>
<td>325,720.00</td>
</tr>
<tr>
<td>Volume of the reservoir ( (m^3) ) considering ( \theta_R = 0^\circ )</td>
<td>67,676.00</td>
<td>197,877.00</td>
<td>265,755.00</td>
</tr>
<tr>
<td>Extra volume ( (m^3) )</td>
<td>40,835.00</td>
<td>239,237.00</td>
<td>59,965.00</td>
</tr>
<tr>
<td>Difference in terrain level from discharge point to bottom of reservoir ( (m) )</td>
<td>15.00</td>
<td>24.00</td>
<td>17.00</td>
</tr>
<tr>
<td>Area of the reservoir ( (m^2) )</td>
<td>62.00</td>
<td>122.00</td>
<td>48.00</td>
</tr>
<tr>
<td>Increment of volume ( (%) )</td>
<td>37.6%</td>
<td>54.7%</td>
<td>18.4%</td>
</tr>
</tbody>
</table>

#### 4.3 Viscosity

The samples were subjected to a progressive increase of shear stresses with fixed initial and final values. Although pre-programmed, the final values were not reached since in all tests the minimum viscosity was obtained – the shear rate reached the maximum value of the equipment, 1500 l/s, before the predefined values.

Figure 6 shows the viscosity results of the samples. The viscosity value of the mineral slurry increases directly with the solids content. Sample II had the highest viscosity, approximately 76.5M mPa·s, and sample V had 44.1 mPa·s, higher than the average viscosities reported in the literature. The high viscosity found in the samples is due to the use of floculant and the high percentage of ultrafine particles, as mentioned by Garcia et al. (2003), who related the increase in viscosity to the decrease in particle size.

#### 4.4 Yield Stress

The yield stress results for the five samples were obtained using both the rotational rheometer and the slump test using the Pashias technique (Pashias et al., 1996). In both tests, the yield stress increased as the solids’ percentage increased (Figure 7).

Both tests showed the same exponential behavior observed by Boger (2013). The slump test gives a good result for voltages below 300 Pa. Above this value, the data was undersized. This indicates that samples II and V did not reach the critical value to reach the yield stress; the
weight itself was sufficient. This discrepancy was also noted by Roussel et al. (2005) in high yield stress materials.

**Figure 6**

*Viscosity versus shear rate graph for samples I, II, III, IV and V.*

![Viscosity versus shear rate graph](image)

**Figure 7**

*The yield stress results of rotational rheometer and the slump test.*

![Yield stress results](image)
4.5 PRINCIPAL TAILINGS DAM CHARACTERISTICS AND CLOSURE PLAN ACTIONS

The foundation consists of residual soil made of sandy silt, a product of rock alteration, ranging from compact to very compact. The dam was built with compacted mine waste, predominantly silty clay, little sand, and fragments of decomposed rock. The elevations were upstream, always using overburden from the mine. The dam reached a maximum height of 25 m with a top berm 6.80 m wide at an elevation of 1305 m and 192 meters long. The heightening slopes had an average gradient of 2.2H:1V with intermediate berms 4.5 m wide at elevations 1290, 1295, and 1300 m. The general slope had a gradient of 3H:1V.

The Brazilian Standard NBR-13028 provides for a Liquefaction Study for a dam in normal operating condition, a drained Safety Factor equal to or greater than 1.5, and for the non-drained condition, a Safety Factor greater than 1.3. The safety factors found for the drained conditions were 2.56 and 1.38 respectively, classifying it as geotechnically stable and not susceptible to liquefaction.

The closure plan, which involves the total removal of the deposited paste tailings and the dam itself to return to the natural topography of the site, considered the stability of the structure itself and the stability of the valley by erosion via the installation of drainage systems through geotechnical, hydrological, and hydraulic assessments.

The dam and the paste tailings were removed by backhoes operating in horizontal slices of 4 m in height, leaving upstream slopes of 1V:2H with a maximum height of 8 m between 5 m wide berms reaching the natural terrain. At each removal of the massif/tailings, a free edge of 1.0 m was maintained with the drainage directed to the spillway in a gutter on the right abutment until complete closure of the dam, leaving the area closest to the natural terrain. The materials removed, totaling a volume of 422,951.28 m³, were transported by trucks and disposed of in a waste pile located 3.0 km away.

5 FINAL CONSIDERATIONS

The studied samples exhibited pseudoplastic behavior, characterized by a decrease in viscosity with increasing shear rate. However, it was observed that at the end of the tests, all samples returned to their initial characteristics, also showing thixotropic behavior.

The variation of yield stress as a function of the percentage of solids was consistent with the results found in the literature for this type of material, reinforcing the validation of the methods employed. Sample V had a yield stress of 1663.3 Pa.
At the iron ore mine under study, the thickening of the slurry in a dug channel requires a low capital investment. However, the operating cost is high when considering thickened slurry transport operations, which limits the potential for increased mining production.

Recent tailings dam disasters highlight the need to adopt best management practices focusing on the stability of these structures, including the disposal of filtered or thickened tailings. A key issue in these alternatives is how tailings can be cost-effectively drained. Conventional tailings disposal in dams has been strongly opposed by stakeholders, necessitating a more holistic analysis beyond the cost issue.

In the mine under study, the results of increased dam safety and the 36.9% increase in reservoir volume justify the use of the thickening channel and thickened slurry disposal.

Finally, the thickened slurry disposal methodology facilitates the closure process by ensuring safety during the removal of the main dam and the tailings deposited, allowing for the restoration of the natural landscape of the area in a safe and economical way.

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REFERENCES


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