Influence of solids concentration on the rheological properties of iron ore tailings

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ABSTRACT: Above certain concentrations, mining pulp starts to behave usually as a non-Newtonian fluid and the knowledge of its rheological properties is extremely important in dam break studies, since the modeling softwares use this information as an input parameter for the simulations. The objective of this research was to study the rheological properties of an iron ore tailing, varying the form of preparation of the samples, for simulations of propagation wave resulting from the rupture of the containment structure of the tailings deposit. Disturbed samples and undisturbed samples were prepared, and then a set of flow test, amplitude and frequency sweep tests were performed. Tailings behaved like a pseudoplastic fluid and was observed that the solids content and the way of preparing the samples influenced the yield stress and the viscoelastic properties of the material. The undisturbed samples and samples with higher solids content presented both higher yield stresses and the elastic behavior for longer time.

KEYWORDS: Rheology, viscoelastic materials, iron ore tailings, laboratory tests

RESUMO: Acima de certas concentrações, a polpa minerária começa a se comportar como um fluido não-Newtoniano e o conhecimento de suas propriedades reológicas é extremamente importante nos estudos de ruptura de barragens, uma vez que os softwares de modelagem usam essas informações como parâmetro de entrada para as simulações. O objetivo deste trabalho foi realizar a caracterização reológica de um rejeito de minério de ferro, variando a forma de preparação das amostras, para simulações de onda de propagação resultante da ruptura de estrutura de contenção do depósito. Foram preparadas amostras deformadas e indeformadas, e então foram feitos ensaios de fluxo, de varredura de amplitude e de frequência. O rejeito se comportou como um fluido pseudoplástico e foi observado que o teor de sólidos e a forma de preparar as amostras influenciaram a tensão de escoamento e as propriedades viscoelásticas do material. As amostras indeformadas e amostras com maior teor de sólidos apresentaram maior tensão de escoamento e o comportamento elástico foi mantido durante um maior tempo.

PALAVRAS-CHAVE: Reologia, materiais viscoelásticos, rejeito de minério de ferro, ensaios de laboratório

1 Introduction

Due to the recent events related to upstream tailings storage facilities (TSFs) failures in Brazil and the requirement to de-characterize and decommission those structures, alternative forms of tailings disposal, such as thickening, filtering or paste disposal, which consist of reducing the amount of water present in the tailings, are being giving more attention.

In order to change the way in which the tailings are disposed of with alternative methods in future projects and even to de-characterize the containment structures of the new deposits as a dam, it is important that rheological studies be carried out with the material under different conditions. It will also allow the optimization of pumping projects, the better understand of the occupation and evolution of the tailings reservoirs, and it will produce more realistic and accurate simulations of the material flow in cases of dam break.
Above certain concentrations, the mining pulp starts to behave as a non-Newtonian fluid and, according to Machado (2017), the hydraulic models commonly used in these dam rupture studies do not allow the simulation of a hyperconcentrated fluid (non-Newtonian) and adopt the hypotheses developed for water dams.

Tailings generally have the characteristics of a pseudoplastic fluid, that is, the viscosity decreases with the increase in the shear rate. In addition, these fluids also require a minimum shear stress (yield stress) before they can begin to flow. This behavior must be taken into account in dam breaks studies (Moon et al. 2019).

There are some computational fluid dynamics softwares (CFDs), such as FLOW-3D, that are able to simulate flow of these types of fluids. However, even with appropriate programs, a good understanding of the rheological properties and their condition according to the evolution of the physical processes (sedimentation, consolidation and desiccation) is required (Oliveira-Filho & vanZyl, 2006).

Figure 1 presents a typical approach in conducting a non-Newtonian dam break assessment.

![Figure 1. Overview of typical dam break assessment approach (Adapted from Moon et al. 2019)](image)

Fluid behavior in these models is represented by a relationship between apparent viscosity and the rate of deformation or shear rate. The Herschel-Bulkley equation can be used to describe this relationship, as shown in Equation 1 (Mehta et al. 2018 apud Moon et al. 2019), from which the apparent viscosity can be calculated, using Equation 2.

\[
\tau = \tau_0 + K \left( \frac{du}{dy} \right)^n
\]

(1)

\[
\tau = \eta \frac{du}{dy}
\]

(2)

where \(\tau\) is the shear stress, \(\tau_0\) is the yield stress, \(K\) is the consistency index, \(n\) is the power law exponent, \(du/dy\) is the shear rate or shear strain and \(\eta\) is the apparent viscosity.

2 Material and experimental methods

To carry out this work, fine tailings from an iron ore tailings dam, located in the Quadrilátero Ferrífero, were used.

2.1 Basic characterization

The characterization consisted of the determination of the mineralogical composition, using X-ray diffractometry; grading analysis, by wet sieving and laser granulometer; specific gravity, using the Helium
gas pycnometer; and plasticity of fines, by Casagrande's liquid and plastic limits. Table 1 presents the results that were obtained.

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mineralogy</td>
<td>Quartz, hematite, goethite, kaolinite, magnetite</td>
</tr>
<tr>
<td>Grading</td>
<td>27% clay</td>
</tr>
<tr>
<td></td>
<td>73% silt</td>
</tr>
<tr>
<td>Plasticity index</td>
<td>5%</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>4.0850 g/cm³</td>
</tr>
</tbody>
</table>

2.2 Rheological tests

The rheological tests were carried out using Anton Paar's MCR 92 rheometer, an Austrian company device. This equipment has a highly accurate air-bearing motor technology, which allows measurements in both rotation and oscillation. The results were analyzed using data provided by the embedded RheoCompass™ software. The lower geometry used was a stationary cylindrical cup and the upper one (mobile) a vane, both made of stainless steel as shown in Figure 2. Figure 2 also shows the equipment during the performance of a test.

For the upper geometry, the vane was chosen because it is the most used for this kind of sample, since, when using cylindrical geometry, there may be slips between its surface and the material surface (KWAK et al. 2005).

Rotational and oscillatory tests were performed. The rotational tests were performed with a logarithmic increase in shear stress (controlled shear rate, CSS), which started at 0.1 Pa and the end varied according to the solids content, the higher the solid content, the greater the stress that was possible to reach. The measuring points interval varied according to a logarithmic ramp, in which the first points were taken every 10 seconds and the ending points every 5 seconds. After inserting the vane in the sample, it was waited 2 minutes before the test was started, so that the sample had time to recover the deformation caused by penetrating the vane and thus start the test with the least possible disturbance in the sample. This test provides values of deformation, shear rate, viscosity and yield stress, determined by the software (RheoCompass™).

The oscillatory tests allow measuring more efficiently the viscoelastic properties of the material. The amplitude sweep tests were also performed with a logarithmic increase in shear stress, which started at 0.1
Pa and the end varied according to the solids content of each sample, however the measurements were made in an oscillatory manner, varying the amplitude and maintaining a constant frequency, equal to 10 rad/s.

The frequency sweep tests were performed within the linear viscoelastic range (LVE range), a region in which the deformations do not cause irreversible changes in the internal structure of the sample. This region is obtained through the amplitude test. A constant strain range was maintained and the oscillation frequency was varied from 0.1 to 100 rad/s.

2.2 Sample preparation

Two types of samples were prepared for the rheological tests: disturbed and undisturbed samples. The disturbed ones were prepared with a desired solids content. The amount of dry material and water was weighed, mixed, and the pulp formed was homogenized in a shaker for 5 minutes.

The undisturbed samples reached the solids content tested in a natural way, only sedimenting and consolidating or consolidating and desiccating, depending on the solids content. Samples were prepared with initial solids content of 36% and 50%. Material was placed in the rheometer cup, filling its entire volume, and left to sediment and/or consolidate for 24 hours. After this time, the layer of supernatant water was removed and then a second layer of material was placed and left to consolidate for 24 hours and then the supernatant water was removed.

The materials prepared through the desiccation process, in addition to the steps described above, were kept at a temperature of 50 ºC for a few hours, to accelerate the water evaporation process. The preparation time of each sample subjected to desiccation varied according to the desired solids content.

3 Results and discussion

Figures 3 and 4 show the results of rheological tests of samples with 57% and 62% solids. The results of disturbed and undisturbed samples with the same solids content were plotted on the same graph. The "a" graphs show the flow curves and the red dots mark the yield stress. The "b" graphs show the viscosity curves, it was noted the reduction in viscosity with the increase in the shear rate. In the "c" graphs, which show the deformation as a function of the shear stress, the yield stress is evidenced by the abrupt increase in the deformation. The "d" plots show the results of the amplitude sweep.

Table 2 shows the yield stress values. It was observed that it increased with increasing solids content, which was expected. Boger (2015) reports that most suspensions of mineral tailings exhibit an exponential increase in yield stress with an increase in the concentration of solids. It was also observed that the form of sample preparation is another factor that affected the yield stress. The viscosity did not change due to the way of preparing the samples.
Figure 3: Results of rheological tests of samples with 57% of solids
Figure 4. Results of rheological tests of samples with 62% solids

Table 2. Yield stress results

<table>
<thead>
<tr>
<th></th>
<th>57% disturbed</th>
<th>57% undisturbed</th>
<th>62% disturbed</th>
<th>62% undisturbed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield stress (Pa)</td>
<td>24.40</td>
<td>50.00</td>
<td>41.05</td>
<td>120.91</td>
</tr>
</tbody>
</table>

The results of the amplitude sweep tests, graphs "d" of Figures 3 and 4, show that the Flow Point (point from which the viscous portion, \(G''\), overcomes the elastic portion, \(G'\), that is, the material starts to behave like a fluid) is also influenced by the type of sample and the solids content, as well as the linear viscoelastic range. The viscoelastic solid (VE solid) behavior prevails until even higher stresses and strains in the undisturbed samples, the same occurs with the increase in the solids content, as shown in Table 3.
Table 3. Comparison of the results of the amplitude sweep tests

<table>
<thead>
<tr>
<th>Solids content (%)</th>
<th>Sample</th>
<th>Flow Point (G'=G&quot;)</th>
<th>LVE range</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>τ (Pa)</td>
<td>γ (%)</td>
<td>G' (Pa)</td>
</tr>
<tr>
<td>57</td>
<td>11.560</td>
<td>1.164</td>
<td>759.30</td>
</tr>
<tr>
<td>Disurbed</td>
<td>20.370</td>
<td>2.045</td>
<td>746.60</td>
</tr>
<tr>
<td>Undisturbed</td>
<td>14.610</td>
<td>1.109</td>
<td>1030.00</td>
</tr>
<tr>
<td>62</td>
<td>43.040</td>
<td>2.074</td>
<td>1561.00</td>
</tr>
</tbody>
</table>

The results of the frequency sweep test, shown in Figure 5, show that the undisturbed samples showed VE solid behavior (G'>G") for the entire tested frequency range. This is a typical behavior of stable dispersions. These dispersions show intermolecular interactions that form three-dimensional network forces, in the form of a physical structural network (Mezger, 2006). As the test is performed in the LVE range, it is expected that this structures remain stable throughout the entire frequency range. This behavior does not repeat in disturbed samples. When at rest (low frequencies), the VE liquid behavior (G">G') prevailed. This is because their internal structures are not yet fully formed and are in the process of consolidation.

Figure 5. Results of the frequency sweep test

4 Conclusions

Rheological tests of fine tailings have shown a decrease in viscosity with the increase in the shear rate, typical behavior of pseudoplastic fluids. It was also observed that the tailings rheology is influenced by both the solids content and the way of preparing samples for tests.

The type of sample, disturbed or undisturbed, and the solids content can influence the value of the yield stress. Undisturbed samples, that is, samples that reached the solids content tested in a natural way, going through the physical processes of sedimentation, consolidation and/or desiccation (natural thickening), present relatively higher yield stress, as well as samples with higher solids contents.

The viscoelastic properties are also influenced by the solids content and the type of sample. Initially, at rest and low shear deformation VE solid behavior was observed and, with the increase of the shear stress, the material started to behave like VE liquid. This change in behavior was delayed with increase in the solids content and also in case of undisturbed samples.
All these findings when taken into account in tailings dam break’s simulations have a chance to very much influence the results. Thus, it is important to mimic as much as possible field conditions when preparing the samples for the rheological tests in order to have realistic and meaningful flooding analyses.

REFERENCES


