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Experimental estimation of tailings rheological properties using the inclined plane ramp

Estimation expérimentale des propriétés rhéologiques des résidus par la rampe à plan incliné

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ABSTRACT: The occurrence of major catastrophes in the recent years related to tailings dams' collapses, pointed out a need to enhance post failure behavior analysis, in order to identify the area of potential damage. An alternative to predict the tailings suspension behavior during flow is the use of a small-scale inclined plane with controlled boundary conditions. This procedure is generally used to determine the suspension's yield stress. In this context, this work proposed a method to calculate the viscosity of the suspension assuming a flow in open channel. A silica rich micro filler was used with different water contents and, consequently, different rheological behavior, in order to evaluate its yield stress and viscosity. The results showed that the method presented as a practical and satisfactory technique to determine the viscosity and the yield stress of tailings suspensions during flow, notwithstanding its simplicity.

RÉSUMÉ : L'apparition de catastrophes majeures ces dernières années liées à l'effondrement des digues de résidus a mis en évidence la nécessité d'améliorer l'analyse des comportements après rupture, afin d'identifier la zone de dommages potentiels. Une alternative pour prédire le comportement de la suspension des résidus pendant l'écoulement est l'utilisation d'un plan incliné à petite échelle avec des conditions aux limites contrôlées. Cette procédure est généralement utilisée pour déterminer la limite d'élasticité de la suspension. Dans ce contexte, ce travail a proposé une méthode pour calculer la viscosité de la suspension en supposant un écoulement en canal ouvert. Un matériau de silice a été utilisé avec différentes teneurs en eau et, par conséquent, un comportement rhéologique différent, afin d'évaluer sa limite d'élasticité et sa viscosité. Les résultats ont montré que la méthode présentée comme une technique pratique et satisfaisante pour déterminer la viscosité et la limite d'élasticité des suspensions de résidus de minerai pendant l'écoulement, nonobstant sa simplicité.

KEYWORDS: tailings dam, landslide, flume test, viscosity, rheology

1 INTRODUCTION.

The risk of tailings dams flow failures, as well as its magnitudes, demonstrate a need to a better comprehension of these events. Therefore, the understanding of the tailings post failure behavior is an important factor of the risk analysis of these structures, as it is related directly to its consequences. After all, these events are a result of different failure mechanisms developed in the spill of a tailings and water suspension in an assortment of textures and physical-chemical properties (Rico, M., Benito, G., & Díez-Herrero 2007).

The flowslide of tailings post rupture can be considered as the flow of a multiphase suspension of soil particles in water, that hence presents a viscoplastic behavior. Therefore, the consequences of these events are highly influenced by the rheological parameters involved, as these influence heavily the velocities developed, the affected area and the mobilized material. However, there is still a shortage of works analyzing the post failure behavior of tailings and the possibility of tailings flow (Yu, Tang, & Chen 2020). The rheological characterization of this materials is, then, essential to solve flowslide problems, along with the parameters variations and its correlations (Della Vecchia, Cremonesi, & Pisanò 2019). Its influences were observed in runout analysis of landslides by Zhang et al. (2018), Zhang et al. (2020). Nguyen et al. (2019) observed that by the evaluation of ramp tests that the increase of the yield stress and the viscosity decrease the maximum velocities developed and the runout distance, and that both are more sensible to viscosity.

Variations of the inclined plan tests, or flume tests, are commonly used to the determination of the rheological parameters in landslides (Gao & Fourie 2015; Iverson & George 2016; Pellegrino & Schippa, 2018; Sakano, Brasileiro, Pileggi, & Futai 2018; Sakano, Brasileiro, Pileggi, & Futai 2018) and tailings dam breaks (Jeyapalan, Duncan & Seed 1983; Lyu, Chai, Xu, Qin & Cao 2019; Souza & Teixeira 2019) due to the similarities to flow in natural ramps. A diverse geometry of this test is also used to study the deposition angle in tailings storage facilities (Engels, McPhail, Jamett, & Pavissich 2011; Fitton, Chryss, & Bhattacharya 2006; Gao & Fourie 2015), however in slower rates for which the inertial effects are negligible. This procedure, however, is generally used to determine the suspension's yield stress. In this work, it is presented the results obtained from a method to calculate the viscosity of a silicate-rich suspension in a flume test, assuming a flow in open channel. In order to validate the results, these were compared to the parameters defined by the mini vane tests.

2 MATERIALS AND METHODS

This section presents the material studied and the methodology used to evaluate its rheological parameters.

1.1 *Material*

For this study it was used a silicate-rich micro filler, representative of hard-rock tailings. The material presents a particle density of 2.64 g/cm3, determined by a gas Helium pycnometer (Multi Pycnometer – Quantachrome). Its particle size distribution was determined by a laser granulometer with a detection range of 0.1 – 350 microns (Helos – Sympatec) and is presented in Figure 1.

The micro filler presents a liquid limit (wL) of 46% and a plasticity index (PI) of 18% (ASTM D4318). In order to evaluate suspensions with different characteristics, four water contents were defined: one under wL, with 43%, and two above wL, with 50% and 55%.

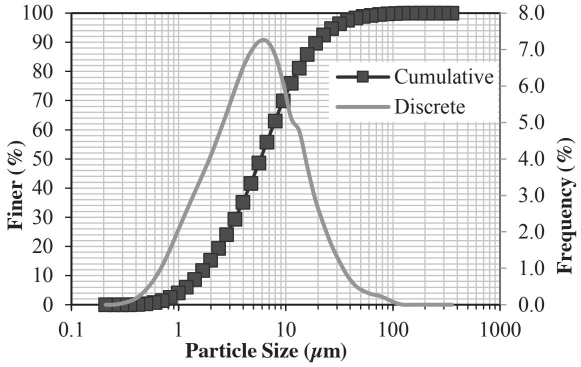

Figure 1: Particle size distribution of the material and suspension characteristics

Table 1: Suspension's density and air content.

Water content	Suspension density (g/cm³)	Air (%)
43%	**1.73**	**2.00**
50%	**1.68**	**1.40**
55%	**1.64**	**1.85**

The suspensions used in the flume test were mixed in a concrete rheometer (PHESO, Calmetrix) (Sakano 2016), with approximately 15kg of dry micro filler. It was mixed at a constant rotation of 690 rpm for 5 minutes and with water added at constant velocity for 30 seconds. The suspensions for the shear stepped flow test were mixed with a high shear energy equipment (adapted from, Makita RT0700C compact router) at 10000 rpm for 3 minutes.

1.2 *Flume Tests*

The rheological behavior of the micro filler were analyzed in the 'L-box' adapted by Sakano et al. (2018) from the self-compacted concrete test (EN 12350), as shown in Figure 2. This test was also previously adapted to study the rheology of tailings depositions (T. L. H. Nguyen, Roussel & Coussot 2006) and the mobilized materials for dam break studies (Souza & Teixeira 2019). The open rectangular channel presents dimensions of 0.6m long and 0.2m width, and a slope of 15°, and a total of 9000 cm^3 of material was used.

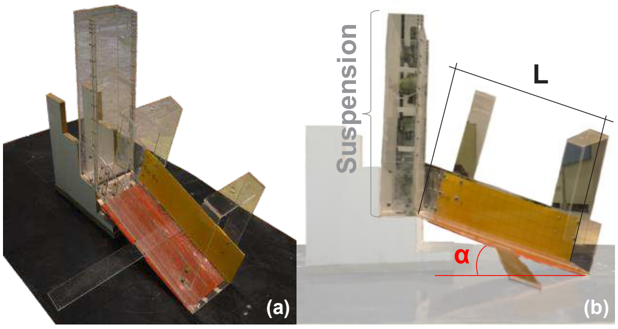

Figure 2: L-box used for the flume tests (a) panoramic view; (b) measurements (Sakano et al. 2018)

The movement was filmed using three action cameras (GoPro Hero 3+) disposed at the beginning, the end and laterally to the flow. The measurements of velocities and position during the flow were made by Digital Image Correlation (DIC), with the use of the kymograph to analyze the particles movement, according to the methodology developed by Sakano (2018a). Image processing was done with the FIJI software and the Multi Kymograph, and image treatment was realized as proposed by Sakano (2018a).

The suspension's yield stress was estimated from the force's equilibrium at the stopping moment of the flow with a ramp of 5°, assuming an open channel flow with wall effects, in Equation 1 (Coussot 1994; Coussot & Boyer 1995). In this, ρ is the suspensions' density, g the gravity acceleration, H_0 the average deposit's height, h_n the deposit's height in each side of the wall, L the box's width and $\sin\beta$ the ramp's adjusted inclination. The H_0 and h_n were measured after the end of the test. Due to the high yield stress, some material remained in the vertical conduit and did not enter the open channel (H_v), therefore its weight was included in the estimative.

$$\tau_y = \frac{\rho g H_0 L \sin\beta + H_v * \rho}{(L + 2h_n + H_v)} \tag{1}$$

The viscosity parameter was obtained for the 15° ramp by the adjustment of the flow to a rheological model. For this, the flow is considered laminar and invariant in the x-axis. It can be calculated by the Bingham and Heschel Bulkley models according to Equations. 2 and 3 (De Blasio 2011). Where μ is the Bingham's apparent viscosity, K is the Herschel-Bulkley consistency index, n an adjusment exponent of the fluids' behavior calculated from the shear stepped flow tests, u_{max} is the maximum velocity reached by the suspension, D is the laminar flow's thickness and D_S the shear layer thickness. For simplification, D_S were considered as the flow's thickness.

$$\mu = \frac{\tau_y}{u_{max}}\left[D - \frac{3}{2}\frac{\tau_y}{\rho g \sin\beta}\right] \tag{2}$$

$$K = \left(\frac{1}{u_{max}\left(1+\frac{1}{n}\right)}(\rho g \sin\beta)^{\frac{1}{n}} {D_S}^{1+\frac{1}{n}}\right)^n \tag{3}$$

1.3 *Stepped flow tests*

The results from the flume tests were correlated and validated by the use of a conventional rotational rheometer MARS 60 (Thermo Haake). It was used a vane geometry with 22 mm diameter and 16 mm height, in a cup of 74 mm diameter and 110 mm height total and a sample volume of approximately 350 mL (Valencia 2017). The dimensions respected relations proposed by Dzuy and Boger (1985) to diminish possible dimensions effects and contour conditions. To evaluate the rheological profile, it was proposed a shear stepped flow test in two logarithmic ramps with 5s steps with acceleration from 0 to 70 s-1 followed by deacceleration from 70 s-1 to 0. The test was executed with shear rate control, and the yield stress and viscosity were determined by the curves adjustment to the Bingham and Herschel Bulkley models in the deceleration curve in the second shear cycle.

2 RESULTS

2.1 *Stepped flow test*

This item presents the results obtained for the rheological parameters of the three studied suspensions. The results of the stepped flow tests for the three moisture content suspensions are presented in Figure 3**Error! Reference source not found.**. The results show that the suspensions behave as yield stress fluids, thus can be fitted to Bingham or Herschel-Bulkley models.

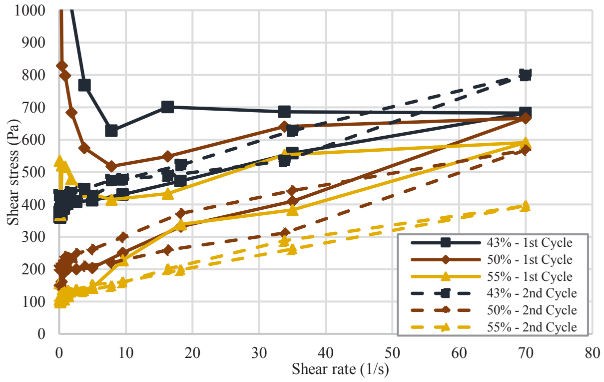

Figure 3: Results from the stepped flow tests with vane geometry and Bingham and Herschel Bulkley parameters.

The Bingham model consider the visco-elastic suspension as having a yield stress τ that needs to be surpassed before the material starts to flow with a constant plastic viscosity μ. The Herschel-Bulkley model also presents a yield stress τ, however with a non-linear relationship to the shear rate thar is represented by a power function with k (the consistency index) and n (the adjustment exponent). The results of the curve adjustments for the two flow models are presented in Table 2. In these, we can notice the parameter $n < 1$, what represents a shear thinning behavior that decreases and approximates to 1 with the increase on water content. Also, all the models presented were very well adjusted to the tests flow curves (with $R^2 > 0{,}99$).

Table 2: Bingham and Herschel-Bulkley parameters determined from the shear stepped flow tests.

Water content	Bingham			Heschel Bulkley			
	τ	**μ**	**r^2**	**τ**	**k**	**n**	**r^2**
43%	389.00	6.07	0.997	391.80	22.36	0.65	0.996
50%	232.32	5.20	0.991	227.20	12.59	0.80	0.999
55%	125.50	3.96	0.996	119.00	6.91	0.85	0.998

The results of the yield stress estimated by the Bingham and Herschel Bulkley models were noticeably similar. Both, the shear stresses and the slope of the curve, decrease with the increase of the moisture content. The yield stress and the viscosity measured by the stepped flow test were compared to estimates from the flume test.

2.2 *Yield Stress Estimation by the Flume Test*

The stress results for the flume tests are shown in Figure 4. It also presents the run-out distance and the average deposit's height (H_0), and the deposit's height in each side of the wall (h_1, h_2). Also, as it was observed in the flow tests, the yield stress increases with the decrease of moisture content. Similar behavior observed in the stepped flow test. These results were used to determine the yield stress, presented in Figure 5.

It is noticeable that the results obtained for the yield stress in the two geometries vary to an order of magnitude. According to (Dinkgreve, Paredes, Denn, & Bonn, 2016) is expected to observe significant difference in the yield value when measured by different method. However, both presented the same dependence of water content independently of the way in which the yield stress was experimentally obtained and is proved by a good correlation ($R^2 = 0.997$).

The relation between the two experimental geometries for the yield stress can be observed in Figure 6.

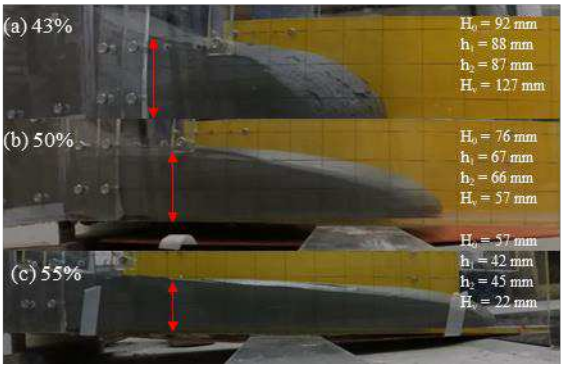

Figure 4: Measurements of the flume test at the three different water contents: (a) 43%; (b) 50%; and (c) 55%.

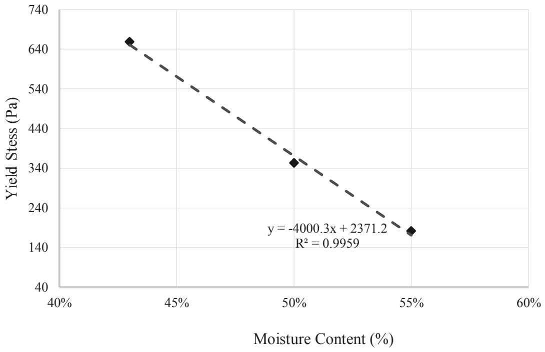

Figure 5: Yield stress calculated by the flume test at different water contents.

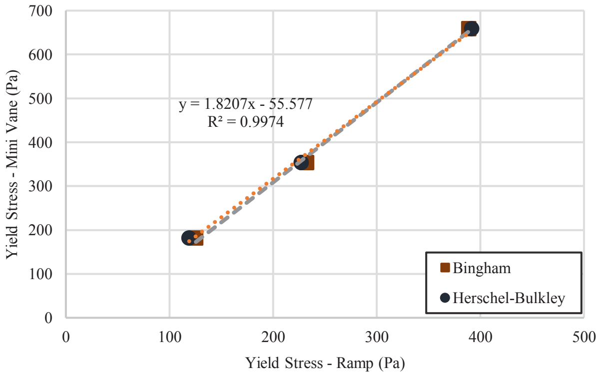

Figure 6: Relationship between the yield stress obtained in the mini vane and in the ramp.

Lastly, Figure 7 presents the linear regression of the water content and the ratio between the yield stress obtained for the ramp and the flow tests, for both the Bingham and Herschel-Bulkley models.

The ratio between the Bingham and Herschel Bulkley and ramp's yield stress is higher than 1. Thus, the flow in the ramp in the range studied have higher resistance than in the stepped flow tests, and there is a scale and geometry influence on this parameter. It can be noted that the ratio decreases with the water content, with R^2 higher than 0.94, signifying that at lower water contents the discrepancy between the two tests decreases.

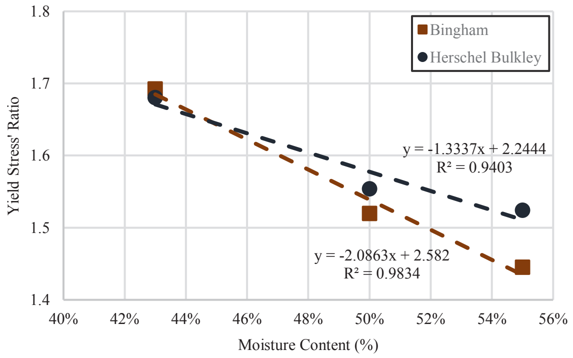

Figure 7: Relationship of the ratio between mini vane and ramp's yield stress and moisture content.

2.3 *Viscosity Estimation by the Flume Test*

For the viscosity estimation, it is necessary the measurements of flow velocity and height for the flume tests for the 15° inclination. Figure 8 (a-c) presents the front flow velocity and the final position for the suspension at the end of the ramp for the 43%, 50% and 55% was presented in Figure 4. As it was expected, the runout distance for the moisture content below the liquid limit, of 43%, was noticeably smaller than the moisture contents above wL. Also, the velocity profiles were very different, with the first flow starting deacceleration almost immediately after the release of the material, with a maximum velocity of 0.01 m/s. For the higher moistures, the runout distance surpassed the L-box, and this movement was studied by Sakano et al. (2018a; 2018b). For the 50% suspension the maximum velocity observed was of 0.8m/s and for the 55% suspension the maximum velocity was of 1.4m/s, indicating the higher flowability of the material. The flow height (H_0) was measured by image analysis as presented in Figure 4.

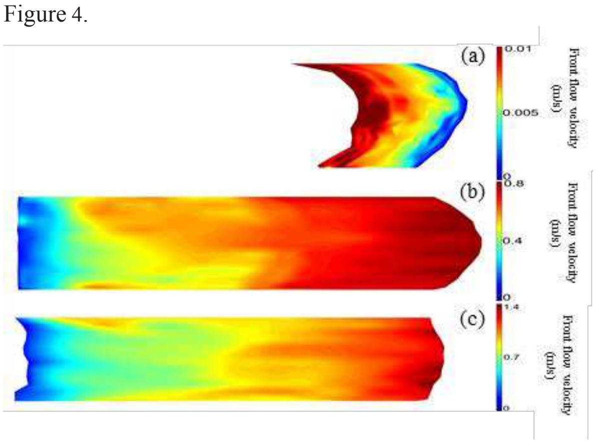

Figure 8: Front flow velocities profile of the suspensions with (a) w = 43%; (b) w = 50% and (c) w = 55%.

The viscosity estimation results for the flume tests are shown in Figure 9. Firstly, the results of the viscosity obtained for the Bingham and Hershel Bulkley models were divergent, to two magnitude orders. Also, the viscosity decreases with the increase of moisture content, as observed in the flow tests.

The values obtained for the two rheological models in the ramp are very different, as well as the scale factor. Also, it can be noticed that the results obtained from the two geometries are of different magnitudes, and as the viscosity if the flume test with a same model vary of more than 100 times for the three different moisture contents, the difference on the mini vane is of only 2 times. Although the results obtained for the different geometries were remarkably different, as it was expected, both present good correlations.

The relation of the viscosity obtained by the two experimental geometries for the Bingham and Heschel Bulkley models can be observed in Figure 10.

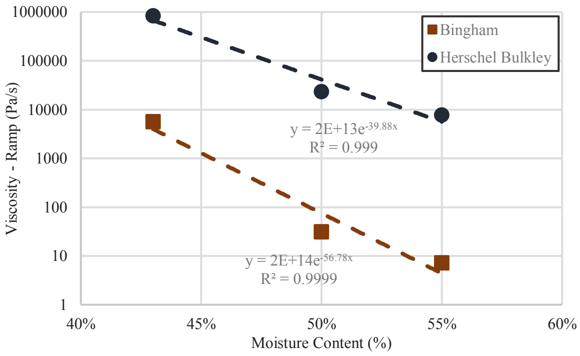

Figure 9: Relationship between ramp's viscosity and suspensions' water content.

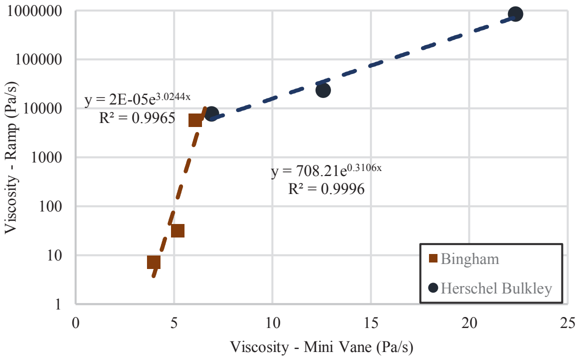

Figure 10: Relationship between the viscosity obtained in the mini vane and in the ramp.

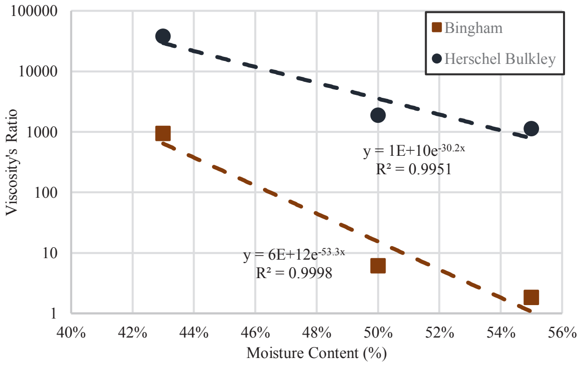

Figure 11 Relationship of the ratio between mini vane and ramp's viscosity and moisture content.

As last, Figure 11 presents the trendlines of the water content and the ratio between the viscosity obtained for the ramp and the flow tests, for both the Bingham and Herschel-Bulkley models. It can be noted that like the yield stress, the viscosity's ratio is higher for lower water contents, with the exponential correlation. The ratio may present difference of two orders of magnitude depending on the rheological model used for the estimative. Thus, the viscosity is greatly influenced by the geometry used. Therefore, it is important to evaluate the better geometry to be used on the determination of the rheological parameters on dam break.

3 CONCLUSIONS

The flowslide of a tailings dam collapse is a flow of the multiphase suspension of soil particles in water, that hence presents a viscoplastic behavior. The flume test is an experimental procedure that can satisfactorily represent the rapid mass movement of these events, however, is generally used to determine only the suspension's yield stress. This work, then, presented rheological parameters of a silica-rich micro filler suspension calculated by a flume test at three different moisture contents. For this, the flow was assumed as a Bingham and a Herschel Bulkley models, and the results for both models were validated by the comparison with the stepped flow test with a mini vane geometry.

It was observed that for both geometries, the value of the viscosity and the yield stresses decreased with the increase of moisture content. For the Herschel Bulkley model, also, the suspensions should be understood as having a pseudoplastic, or shear thinning behavior that decreases with the increase of water content. Besides, it can be observed a notable difference of the parameters obtained from the flume test and the stepped flow tests for all the parameters analyzed, as expected due to the difference in geometry. In the case of the viscosity, the different is of two orders of magnitude, and to the yield stress is closer to one. However, it can be calculated correlations that can satisfactorily correlate the results for the parameters from the two different tests. Lastly, this relation between the ratio of each parameter obtained from the geometries was observed to be similarly dependent on the water content. The increase on moisture decreases both the yield stress ratio and the viscosity ratio.

Finally, the flume test is shown to be a valid and interesting method to determine the rheological parameters of tailings for dam break studies. Especially due to its better representation of the flow in open channel that is developed during these events. Although there are simplifications needed to the calculate the yield stress and the viscosity, its values show good correspondence with values determined from the stepped flow test.

4 ACKNOWLEDGEMENTS

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