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Comparative Study of Non-Newtonian Thickened Tailings in Function of Recovered Water for a Specific Energy Consumption

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ABSTRACT

As is well known, the availability of water for mining processes in Chile is limited. In addition, it should be considered that the vast majority of mining plants are located in the northern part of the country, which is for the most part desert, and mainly at a high altitude.

Given the low availability of water, various alternatives have emerged such as thickening tailings to high concentrations by weight (recovering more water in the thickeners) or using desalinated seawater.

The present study aims to define the optimum thickening concentration for copper tailings, applied to a case study of representative Chilean mine tailings, from a rheological and energy point of view, as a function of recovered water in the thickeners and specific energy consumption (SEC), transporting one ton of Non-Newtonian thickened tailings.

The specific energy consumption (SEC) should be related mostly to the solids transported than to the mixture, with thickening becoming a relevant parameter, since in slurry transport, the solids are usually the "payload", while the conveying fluid is simply the "vehicle".

The result of this paper provides the industry with an additional variable to consider in the optimum grade of tailings thickening and rheological design parameters for projects, which could be considered in conceptual and pre-feasibility stages or in the optimization of existing systems.

INTRODUCTION

Mining operations in Chile are mainly located in the northern sector of the country, in one of the driest and most arid areas of the world, with a progressively scarce availability of water. At the same time, day by day it has been imposed as a condition that mining operations cause the least possible impact to the environment, establishing for its control increasingly demanding restrictions and permits for its operation, so the engineering design must not only seek the maximum production at minimum cost, but also must have the least impact on the environment and communities.

Under this scenario, tailings are identified as one of the actors that contains the largest amount of water in its interior, if tailings are discharged as diluted slurry - conventional discharge. If the dewatering technology is applied, water contained reduce significatively.

Today, water supply has become an issue that is addressed from the early stages of projects, i.e. from profile or conceptual engineering, which often influences the decision to implement a project or expand or not a mine site. The requirements issued by the authority for the granting of water use rights are increasing, generating that in these areas, the cost becomes relevant in the budget.

Projections of mining water demand for the next ten years are shown in Figure 1 below.

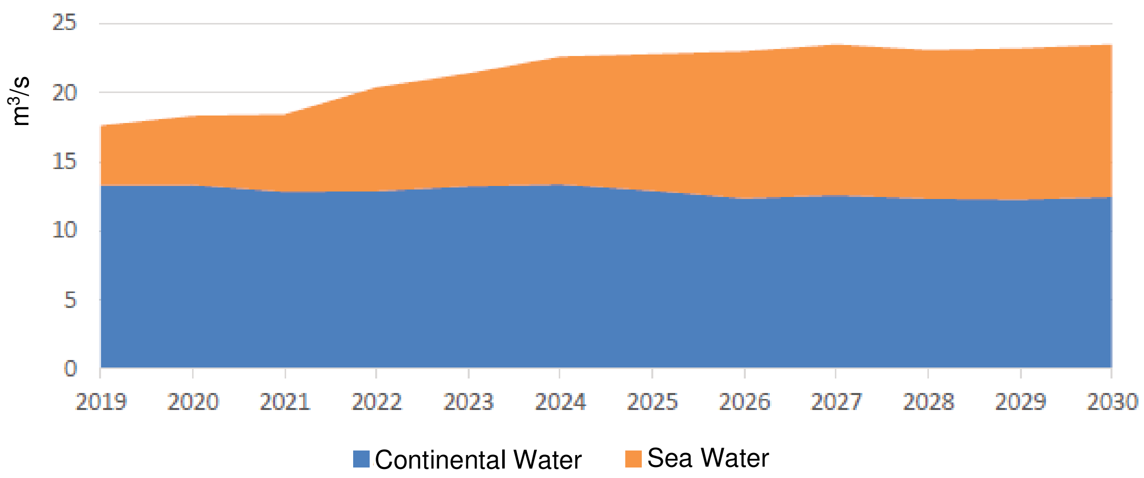

Figure 1 Projected water demand in Chilean mining. Source: Cochilco 2019

By 2030, national water consumption is expected to reach 23.5 m^3/sec, with an average annual growth rate of 2.7%. In general, the expected consumption of continental water in 2030 will reach 12.5 m^3/s, which represents a decrease of 6% regarding the consumption expected for 2019.

In the case of seawater, the situation is different from that of continental water, while the consumption of continental water maintains an average annual rate of decrease close to – 0.6%, seawater observes growth with an average annual rate of 9.3%, reaching 11 m^3/s by 2030.

Nowadays, mining environmental regulators are under increasing pressure to apply restrictions for both existing and proposed mining operations. Complicating this is the ability through increased efficiencies and economies of scale to profitably exploit large very low-grade resources once thought improbable. Consequently, mining industries search for step-changes in long-term solutions for tailings, rock and water management aligned with operational, environmental, technical, financial, risk and social issues.

The application of dewatering technologies is increasing significatively to produce dewatered tailings to improve the environmental performance of the site. Considering application of thickening technology to produce densified non-segregating tailings slurry, this is where the question arises as to what degree of thickening is appropriate, considering the benefit of recovered water compared to the energy cost of transporting these thickened tailings, with high density and complex rheology, to final deposition on the dam.

This article aims to define the optimum thickening concentration for copper tailings, applied to two types of copper tailings typical of Chilean mining based on data from industrial application, from a rheological and energy point of view, as a function of recovered water in the thickeners and specific energy consumption (SEC), transporting one ton of Non-Newtonian thickened tailings. A comparative analysis between the two tailings will be applied based on the obtained results.

METHODOLOGY

Specific energy consumption (SEC)

The efficiency of a tailings drive system is evaluated by a parameter called "specific energy consumption" (SEC). SEC is an appropriate optimization parameter because it is a function of the hydraulic gradient associated with a loss of head or energy in a pipeline and the amount of solids incorporated in the conveyed flow.

The SEC is defined as the energy in kilowatt-hours required to move one ton of solids in a horizontal distance of one kilometer through a pipeline.

This study follows the methodology proposed by Wilson (2006) to determine the "specific consumption of energy". The equation to determine SEC is:

$$SEC\left[\frac{\frac{kWh}{t}}{km}\right]=\frac{i_m\times g}{3.6\times S_S\times C_v} \quad (1)$$

Tailings information (case of study)

Tailings considered in the study are representative of tailings from a copper processing plant located in the north of Chile. The information was obtained from rheological tests for thickened tailings. The main granulometric and rheological information is shown below in Table 1 and Figures 3 and 4. The particle size distribution is shown in Figure 2.

Table 1 Particle size and physical parameters

Parameter	Tailing A	Tailing B
P80	215 µm	230 µm
D50	65 µm	85 µm
S.G	2.72	2.65

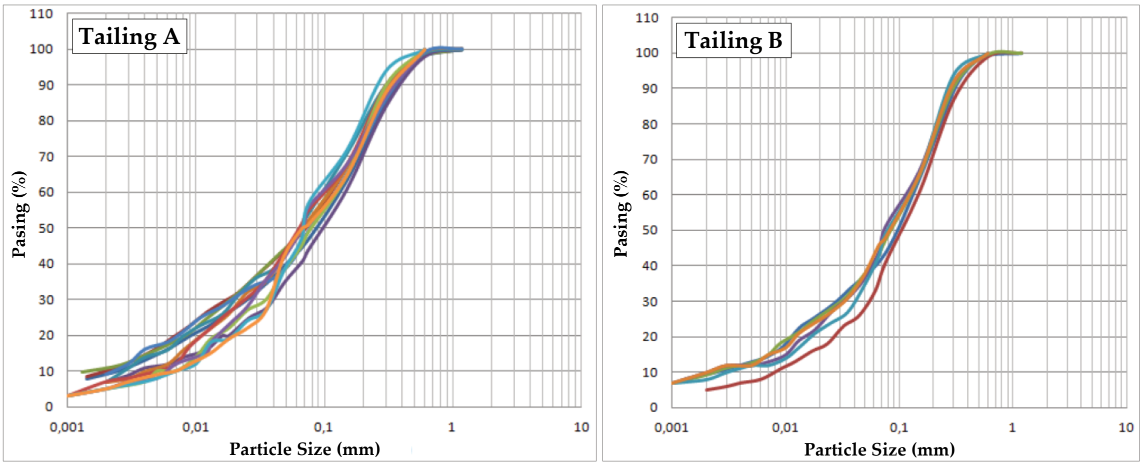

Figure 2 PSD (industrial application tailings)

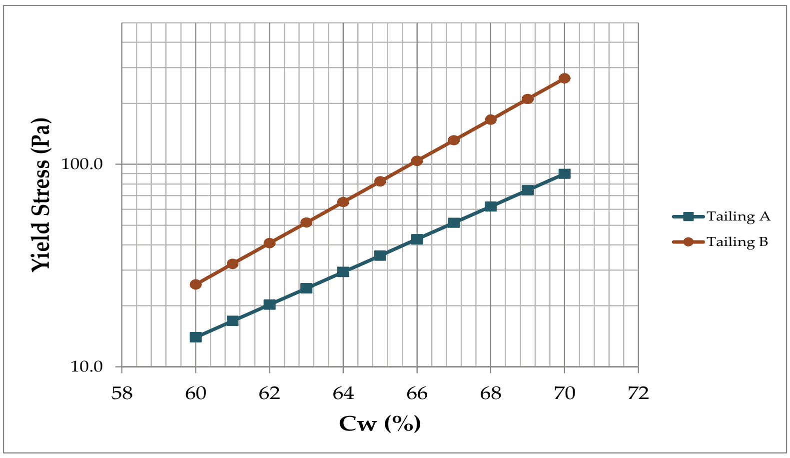

Figure 3 Yield Stress vs Cw of tailings

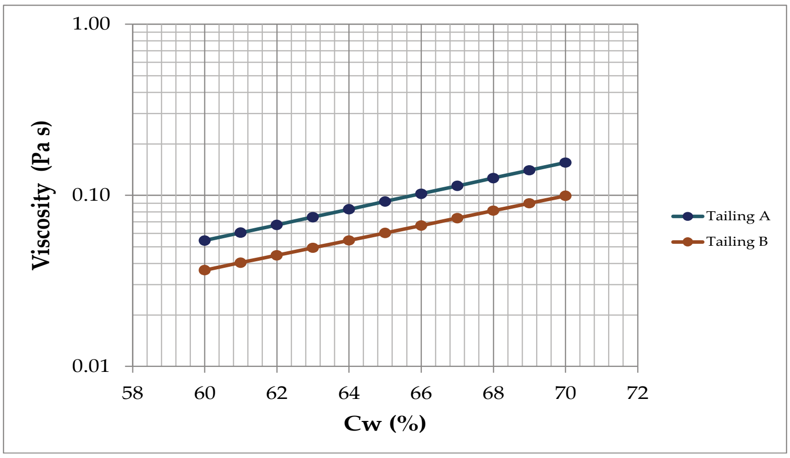

Figure 4 Plastic Bingham Viscosity vs Cw of tailings

Hydraulic Model

The thickened tailings from the study behave as a Non-Newtonian fluid with ideal plastic characteristics (Bingham), where the governing mathematical model is:

$$\tau_w = \tau_0 + \mu_b \dot{\gamma} \tag{2}$$

The flow regime for the analysis of this article is stable turbulent, the option of laminar flow was not considered. The transport velocity should be greater than the critical or transition velocity indicated by Slatter & Wasp (Slatter, 2005). For this study, the Hedstrom number is always greater than 150,000, so, the expression for determining the transition velocity is:

$$V_T = 26\sqrt{\frac{\tau_0}{\rho_m}} \tag{3}$$

The Wilson & Thomas model is used to calculate the coefficient of friction (Wilson, 2006):

$$\frac{V}{V_f} = \sqrt{\frac{8}{f}} = \frac{V_n}{V_f} + 11.6\,(\alpha - 1) - 2.5\,ln\,\alpha - \Omega \tag{4}$$

$$\alpha = 1 + \xi$$

$$\Omega = -2.5\left[\ln(1-\xi) + \xi(1 + \frac{1}{2}\xi\right]$$

$$\xi = \frac{\tau_0}{\tau_w}$$

Frictional losses are estimated as:

$$h_f = f\frac{L}{D}\frac{V^2}{2g} \tag{5}$$

Finally, the mixture Head Loss is obtained from the following expression:

$$i_m = f\frac{1}{D}\frac{V^2}{2g}\rho_m \tag{6}$$

Where the adjustment for mixture density gives the value in [m water/m].

Design Parameters

For the calculations and analysis of this study, the following reference values were used:

Table 2 Electrical Energy and Water values for Chilean mining

Resource	Unit	Cost	Source
Electrical Energy	kW_h	0.09 USD	CNE, 2020
Fresh Water	m^3	1.6	Morel, 2015
Desalinated Water	m^3	5.1	Morel, 2015

The values given in Table 2 correspond to final values; these already include all the operating, transportation and derating costs, that is, they are nominal values for direct consumption in a concentrator plant. The electrical consumption of small equipment is not considered.

For the hydraulic design of this article, it is considered that hydraulic diameter of the pipes changes to maintain constant the relation $V/V_T = 1.1$, where V_T is the value of V at laminar-turbulent transition defined by Slatter & Wasp in equation (3) (Slatter, 2005), which depends only on rheology. Figure 6, below, shows the result of the calculation of the V_T as a function of the tailings rheological properties of this study.

The hydraulic calculations were made considering a tailings production of 35 ktpd, in order to obtain pipes with a hydraulic diameter of 8 inches or more, since in smaller diameters the pressure gradients rise abruptly. The methodology is applicable for any higher tonnage, where the hydraulic diameter must be adjusted to maintain the velocity ratio indicated.

With this consideration, the hydraulic behavior of the tailings will depend on the rheology and not on the pipe, being the transport regime always fully turbulent.

RESULTS AND DISCUSSION

After analyzing of the tailings shown in Table 1, it can be obtained that for a typical Chilean mining application, where the thickening plant is fed with tailings at 50% Cw (assumption of the study), the recovered water for each thickening point is as shown in Figure 5.

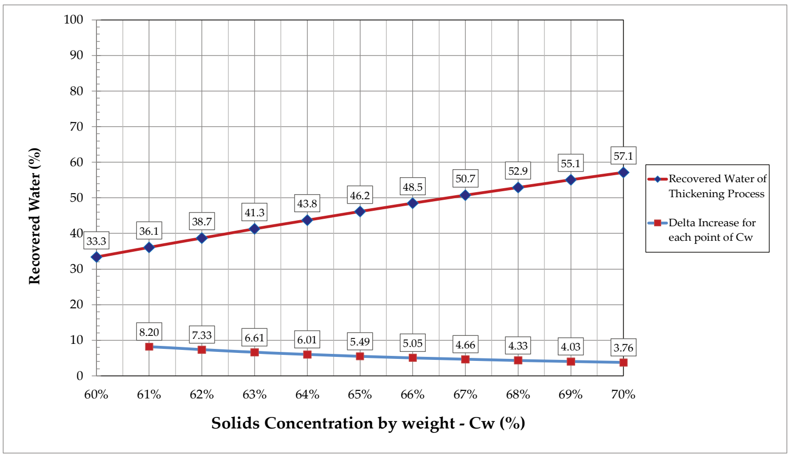

Figure 5 Water Recovery in Tailings Thickeners vs Cw

As tailings increase in degree of thickening, the water recovered increases as well, as shown in Figure 5, therefore the tailings flow at the thickener discharge will decrease.

Figure 6 below shows how Tailing A has less restrictive hydraulic transport parameters than Tailing B, for the study range of 60% to 70% of Cw.

Tailing A can be transported throughout the thickening spectrum since pressure drop and flow velocity, while they are high, are acceptable in turbulent flow (maximum 6.4 m/s and 2.84 kPa/m), not limiting thickening for the range of study.

On the other hand, the Tailing B has a bad behavior, since for a Cw of 60%, the tailing cannot be transported at less than 3.6 m/s, increasing the minimum transport velocity and the load loss of the system quickly. For a Cw of 65%, a minimum transport velocity of 6.33 m/s is required, when the pressure drop is 1.94 kPa/m, while for a Cw of 70%, the system requires a minimum velocity of 11.6 m/s and has an associated pressure drop of 9.3 kPa/m. Figure 6 is clear, for Tailing B above 65% Cw, the hydraulic transport conditions are very unfavorable and not recommended.

From the previous analysis, it is clear that higher yield stress tailing results in the necessity of higher transport velocity, since the transition velocity increases forcing faster transport of the tailings. Also, a higher specific gravity of the solids increases the density and consequently the head losses, and although the viscosity of the Tailing A is 50% higher than the Tailing B, the most relevant parameter that defines the operational range for hydraulic transport is yield stress (τ_0).

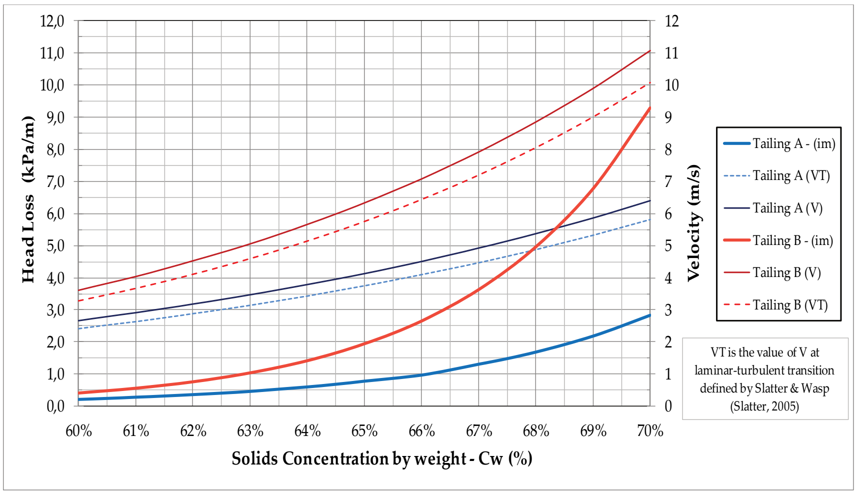

Figure 6 Head Loss and Transport Velocity vs Cw

Figure 7 shows the Specific Energy Consumption (SEC) as a function of tailings thickening, showing that Tailing B requires much more specific energy to move one ton per kilometer of pipe than Tailing A.

For a Cw of 65%, the energy required by Tailing B more than doubles the amount required by Tailing A, where the difference increases in a quadratic way, since the most influential parameter is the transport velocity, which is conditioned by yield stress.

Therefore, tailings with higher yield stress levels are associated with higher Specific Energy Consumption (SEC).

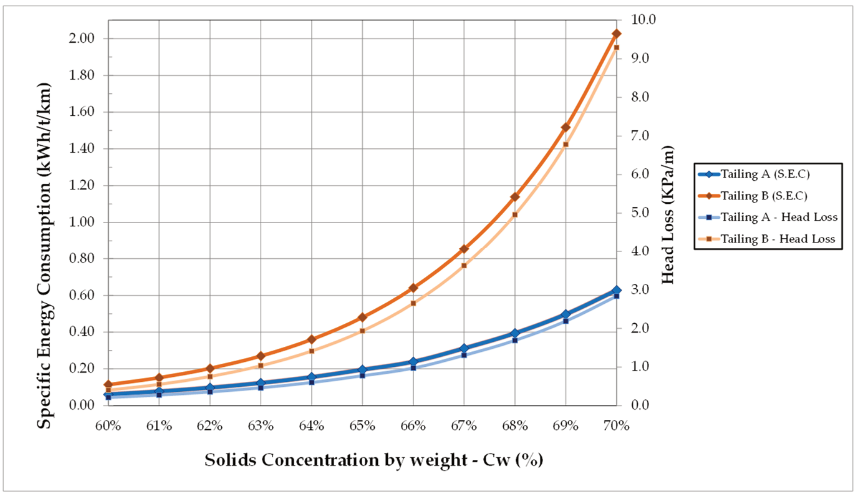

Figure 7 Specific Energy Consumption vs Cw

Finally, Figure 8 and Figure 9 show the results obtained for the Energy Cost per one cubic meter (m^3) of recovered water in the thickeners as function of the thickened tailings discharge distance.

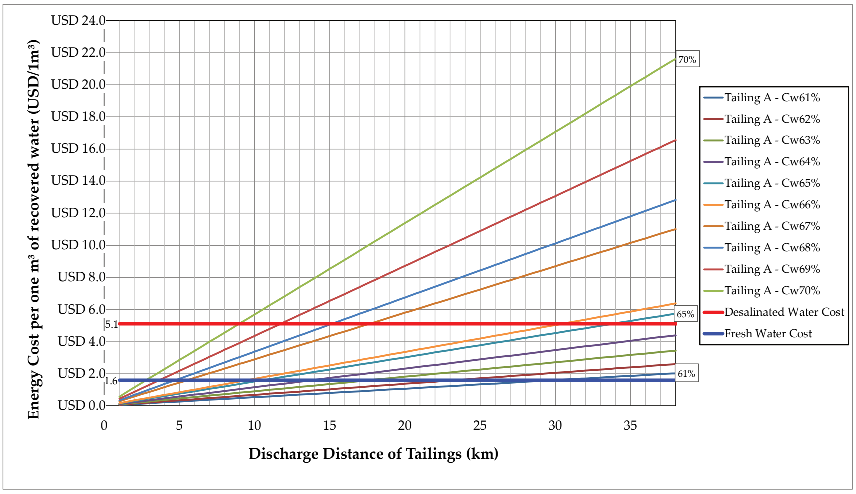

Figure 8 Energy Cost per m^3 of recovered water from the process vs discharge distance – Tailing A

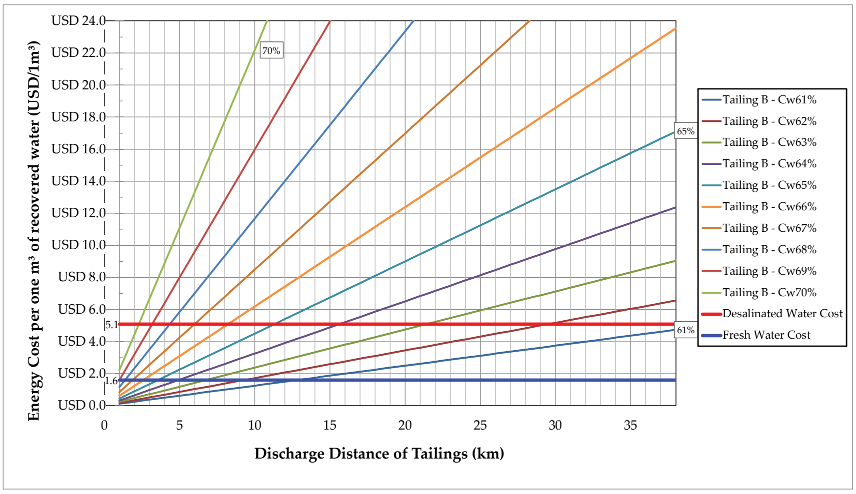

Figure 9 Energy Cost per m^3 of recovered water from the process vs discharge distance – Tailing B

In Figure 8 and Figure 9 it is possible to see the optimum tailings pumping distances for different degrees of tailings thickening so that, the energy cost per kW_h associated with the recovery of one m^3 of water and for a given distance, is lower than the alternative cost per m^3 of process water, either fresh water or desalinated water. In other words, until discharge distance is beneficial to the system to drive the tailings, as a function of the cost of recovered water obtained and returned to the system, compared to the cost of introducing one m^3 of fresh water or desalinated water

From the previous graphs (Figure 8 and 9), it can be seen that for a Cw of 65%, the equilibrium distance where the recovered water entering the system as an alternative cost of fresh water is 10.5 km for Tailing A and 3.5 km for Tailing B, that is, above this distance the cost of water recovered in the plant becomes higher than the cost of fresh water.

On the other hand, if the water feeding the plant as make up is desalinated water, for a Cw of 65%, the equilibrium distance for the recovered water entering the system as recovered water in the thickeners is 34 km for Tailing A and 11 km for Tailing B, that is, for any shorter distance, the cost of tailings pumping, recovering one m^3 of water will be less than the cost of entering the system with one m^3 of desalinated water.

CONCLUSION

For the case of engineering designs, the study of the specific energy consumption (SEC) linked to the recovered water becomes very relevant, since it allows the selection of an optimal thickening concentration.

Generally, the location of the plant and the location of the deposit are defined in advance and depend, in addition to technical factors, on environmental permits and authorization by the authority. For this reason, in the vast majority of engineering study cases, the distance between plant and dam becomes an input data.

Then, and according to the tailings rheological parameters, its characterization, thickener capacity, available spaces, power supply, geotechnical aspects, geological aspects, among others, an optimal "thickening range" is defined, in a very similar way to how it has been elaborated in the present article, considering all the mentioned variables.

It is at this point that the specific energy consumption (SEC) model associated with water recovery shown in this article becomes relevant and can be a design input, since the SEC is able to suggest a concentration by weight of tailings thickening that increases the benefits of water recovery, optimizing the energy consumption of the system, that is: balance between the cost for additional energy in driving thicker tailings (higher water recovery) and the cost of alternative process water arriving as make up (fresh water or desalinated water), for a given drive distance.

Even though the study was developed for two representative tailings, the same methodology can be applied to any type of tailings, including more variables if it is necessary.

NOMENCLATURE

SEC	Specific energy consumption (kWh/tonne-km)
i_m	Mixture head loss (m water/m)
g	Acceleration due to gravity (m/s^2)
S_S	Solid’s relative density (-)
C_v	Solid´s concentration by volume (-)

C_w	Solid´s concentration by weight (-)
τ_W	Shear stress at the wall (Pa)
τ_0	Yield Stress (Pa)
μ_b	Plastic Bingham viscosity (Pa s)
$\dot{\gamma}$	Shear rate (1/s)
ρ_m	Density of mixture (kg/m^3)
V	Velocity of mixture (m/s)
V_f	Shear velocity at the wall (m/s)
V_n	Value of V for equivalent newtonian flow (m/s)
V_T	Value of V at laminar-turbulent transition (m/s)
f	Frictión factor of Darcy-Weisbach (-)
h_f	Frictional head loss (mcf)
α	Rheogram area ratio
Ω	Wall shear stress effect over velocity profile
ξ	Stress ratio
D	Pipe inside diameter (m)
P80	Diameter for which 80% (by mass) of the particles are finer (μm)
D50	Mass-median particle diameter (μm)
S.G	Relative density of solids (-)

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