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Temperature: An Influencing Factor on the Rheological and Energetic Parameters of Acid Pressure Technology Operations

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Abstract: In this work, a study was carried out on the effect of temperature as the main influencing factor on the rheological behavior of lateritic suspensions, raw material for the operations of pressurized acid technology (HPAL) used to obtain nickel and cobalt from of oxidized ores. From studies of X-ray diffraction, X-ray fluorescence, particle size analyzer, and mathematical modeling, the behavior of the interactions and rheological characteristics of the analyzed samples were obtained. In this study, it was concluded that the use of mathematical models that relate the temperature up to 90 °C and the energy parameters of the pumping system of flows, loads, hydraulic losses, power, and efficiency would allow finding ways to increase and stabilize the flow of fed hydromixture with a flow rate of 1600 m^3/h and a solids concentration of 48% (w/w) and guarantee the efficiency of the technological process.

Keywords: rheological parameters; temperature; pumping power; non-Newtonian fluid

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1. Introduction

The extraction of nickel and cobalt in the eastern region of Cuba is carried out from limonitic minerals (rich in iron) in vertical autoclaves at a pressure of 3619.7 kPa and a temperature of 240 °C. Under these conditions, it is well known that the iron solution is close to zero so that nickel and cobalt are selectively dissolved and in larger quantities. This process involves several multiple reactions, with selectivity for forming the desired product being a very important aspect to analyze. Poor selectivity requires waste or loss of reagent to achieve the given amount of desired product [1–3]. Mweene et al., 2021 [4], analyzed the possibilities of obtaining both higher recoveries and an increase in grade for Ni. High Pressure Acid Leach (HPAL) is recognized worldwide as the most efficient and economical technology for extracting nickel. Studies carried out on the different nickel production technologies [5,6] indicate that HPAL is the most economical alternative for processing nickel ores [7], even for low-grade ores. The trends in acid-leaching processes are operating the autoclaves with temperatures between 260 and 270 °C; indirectly heating feed pulps; employing direct preparation technology and hypersaline water [8,9]. Among the factors involved in hydromix transport for acid leaching, the effects of particle size distribution, pH, and mineralogical composition can be analyzed. The concentration of solids and the temperature of the suspension are of primary interest in this investigation. The temperature determines the operating conditions of HPAL [10], as the degree of solubility of the metals oxidized with sulfuric acid directly depends on temperature [11]. There is no reference in the literature consulted to previous investigations of the behavior of the rheological parameters of the preheated pulp processed in the leaching plant.

Lateritic pulps are non-Newtonian fluids and have the fundamental property that their viscosity is a function of velocity gradient, even when temperature and other conditions are held constant. Its rheological properties, which are of particular interest for the design of the efficient operation of the pumping system: μ_a, apparent viscosity of the suspension (Pa·s); τ_0, initial shear stress (Pa); K, consistency index (Pa·s^n), is a measure of the viscous degree of the material; n, flow index (dimensionless, which is a measure of the degree of non-Newtonian behavior of the material. In general, n varies little with changes in temperature and concentration, whereas K is strongly affected by variations in these variables. Initial shear stress and plastic viscosity change significantly with temperature and solids content. Surprisingly, systems such as dense emulsions, colloidal pastes, foams, or granular materials share many rheological properties. All of these systems can flow like a liquid if sufficiently high external stress is applied, but below a critical yield point, they become stuck in a rigid amorphous state [12].

In principle, the behavior of the fluid, in the absence of any reaction or physical process, could follow Arrhenius' Law. In general, a decrease in viscosity with increasing temperature has been observed for most liquids and suspensions [13–15]; in the case of pseudoplastic fluids, the parameter most affected is the consistency index, which shows little effect on the flow index [16,17]. The decrease in viscosity is due to two main causes [18–20]: the decrease in the viscosity of the dispersing medium and the weakening of the structures formed by the particles with increasing temperature. Very few studies have been carried out on the effect of temperature in the case of laterite suspensions [21–23]. According to the results obtained, it is confirmed that shear stress and viscosity, as well as other rheological properties, decrease with increasing temperature, which is the typical behavior expected for most liquids and suspensions. This analysis was carried out at temperatures of 28, 35, and 40 °C. The research has shown that the preheated pulp can reach temperatures of up to 90 °C, but the behavior of the rheological parameters at these temperatures has not yet been determined.

The main limitation of the studies carried out by various authors [16,17,20,24,25] is that temperature variations are not considered in the rheological behavior of the fluid, although they play a key role in the structure and properties of the material. As concluded by [26–30] on the influence of rheological properties on the behavior of the operating characteristics of pumping equipment, the simplest method for obtaining the operating parameters and reconstructing the characteristics by a varying viscosity is based on the use of specific correction coefficients for each fluid, obtained experimentally.

The bibliographical review described in this study does not provide a satisfactory answer to the problem at hand. Most of them deal with the phenomenology of non-Newtonian fluids, which, although they form the basis of the research, do not fully describe the phenomenon under study (the transport of fluids at temperatures higher than the ambient temperature and the irregularities of the flow in the turbulent regime).

The objective of this research is to verify, under the current exploitation conditions of low-grade mineral deposits, the behavior of the rheological parameters for concentrations between 37 and 48% (p/p) of solids, when $n < 1$, when the plastic behavior of the lateritic pulps is maintained at a temperature of 90 °C as well as its impact on the energy parameters of the pumping system. The pulp is transported at room temperature of 28 °C to the preheaters where it reaches 90 °C. Then, it is sent with centrifugal and positive displacement pumps to the reactors where leaching takes place at temperatures of 260 and 270 °C. In order to optimize the rheological and energetic parameters, the pulp reaches a value of 90 °C for the first time in this research work.

2. Materials and Methods

Once the factors that can influence the rheological parameters have been selected, laboratory work and mathematical processing of the experimental data are required, as well as a large amount of historical data on the thickening and preheating process of the pulps, allowing the characterization of the main mineral suspensions that are handled at in this stage of the production process.

In the operational database, reported over the last 5 years, as well as the reports on the mechanical and operational characteristics of the pumps used in the process, to define the solids concentration, it has been found that the solids concentration of the raw pulp varies ranges between (36–46)%, although the most common value is around 43%, due to changes in the characteristics of the mineral fed, so that the desired value of 48% of solids content at the discharge of the thickeners, which must be sent to the Leaching Plant is not reached. When preheating the raw pulp, due to the addition of water vapor, the solids content decreases by (1.5–3)%, 40% solids is the highest frequency value, which negatively affects the acid/ore ratio and the percentage of nickel and cobalt extracted (see Table 1).

Table 1. History of the concentration of solids in the raw pulp and in the preheated pulp.

Statistical Analysis	Raw Pulp		Preheated Pulp	
	Value	%	Value	%
Minimum value	36.97	-	34.44	-
Maximum value	46.85	-	45.33	-
Average value	43.17	-	40.90	-
Standard deviation	1.62	-	1.646	-
Coefficient of variation	3.76	-	4.02	-
Greater than 45	99.0	12.0	4.0	0.5
Less than 40	383.0	47.9	238.0	29.8
Between 40 and 45	421.0	40.1	559.0	69.7
Total		100		100

It was determined in the investigation that the preheating process is not carried out at 82 °C as indicated in the operations manual, see Table 2.

Table 2. Historical temperature values.

Statistical Analysis	Value °C	%
Minimum value	75.48	-
Maximum value	94.07	-
Average value	90.02	-
Standard deviation	1.88	-
Coefficient of variation	2.10	-
Greater than 90 °C	434	54.32
Less than 82 °C	8	
Between 82 and 90 °C	357	44.68
Total		100

2.1. Equipment

The following equipment was used: HAAKE VT 550 (Thermo Fisher Scientific, Waltham, MA, USA) for rheological measurements, Mettler Toledo digital technical balance (Mettler Toledo International Inc., Columbus, OH, USA), Ohaus dryer balance (Ohaus Corporation, Parsippany, NJ, USA), IKA RW 28 mechanical stirrer (IKA Group, Staufen, Germany), Cimarec thermal plate (Thermo Fisher Scientific, Waltham, MA, USA), Master Flex model 77601-10 water pump (Avantor, Radnor, PA, USA), Humber thermostat. The chemical composition of the samples studied was determined by the X-ray fluorescence method, also known as the X-ray method on a PW 1480 X-ray Fluorescence Spectrometer (Philips) (Malvern Panalytical, Malvern, Worcestershire, UK). The determination of the granulometric distributions of the samples studied was carried out using a particle size analyzer of the type "Analysette 22" COMPACT (FRITSCH GmbH, Idar-Oberstein, Germany).

2.2. Preparation of Mineral Suspensions

In order to carry out the experiments, the operating range of the thickening and Leaching Plants was determined in accordance with the process control program used in the company (CITECT). The experimental work was carried out in the Acid Pressure Leaching Laboratories of the Centre for the Development of the Nickel Industry (CEDINIQ), the Company's Chemical Laboratory, and the University of Moa.

To carry out the experiments, the procedure and sampling program established in each mill were followed. During six alternate weeks, depending on the mining front, samples of 500 mL of pulp were taken every hour from 7 a.m. to 7 p.m. at selected points in a 1000 mL volumetric flask to prepare 12 composites in 20 L containers, see Table 3. A total of five samples of 200 g were prepared with three replicates for the concentrations of solids selected from the composite samples by the Demonstration Production Unit, contained in covered 250 mL flasks.

Table 3. Concentration of solids in the samples.

Sampling Points	Composite Samples	Solids Concentration, %	Mineral Number
Point 1. Discharge Thickener A	MC1	44.70	3.97
	MC5	45.41	9.74
	MC9	44.11	9.16
Point 2. Discharge Thickener D	MC2	39.34	9.07
	MC6	37.64	9.65
	MC10	37.23	9.23
Point 3. 508 mm transfer line	MC3	43.56	9.75
	MC7	43.28	9.41
	MC11	42.54	9.48
Point 4. At the suction of the volumetric pump	MC4	40.28	12.19
	MC8	41.17	9.21
	MC12	40.78	9.06

Each composite sample was subjected to chemical and granulometric analysis, and the mineral number was determined. As the chemical and granulometric compositions are maintained at the historical values of the company, four composites, MC1, MC6, MC11, and MC4, were selected for the rheological analysis due to the differences in their mineral numbers. Samples MC5, MC2, MC9, MC7, and MC12 remain as a database to validate the mathematical models obtained. The samples were left to settle, and the water was removed by decantation to reach 48% (p/p), the upper limit of the experiments. To obtain the fixed solids, each of the samples was diluted according to the procedure used in the company, considering that the density of laterite is 3.55 g/cm^3 and that of water is 0.9963 g/cm^3.

2.3. Variable Selection

The rheological properties or dependent variables of particular interest are: μ_a: apparent viscosity of the suspension; τ: initial shear stress, K: consistency index; n: flow rate, which are the responses when certain properties of the pulps are experimentally varied, namely:

s: characteristic parameter of the granulometry (Polydispersion Coefficient); % S: solids content (mass of solids in the pulp); T: temperature; Nrmin: mineral number (it is determined from the knowledge of the chemical composition of the lateritic pulp).

The arithmetic mean and the standard deviation of the corresponding measured variables were calculated and taken as sample values, which, due to their intervals, positively supported the precision of the sampling process, with 420 samples. In order to validate the use of these properties as independent variables, of the models used to explain the behavior of the rheological properties of the pulps, linear models were determined from the data obtained, (r is the correlation coefficient) and the validity of the level of influence of the independent variables on the dependent variables was verified by means of hypothesis tests.

2.4. Rheological Measurements

After preparing the suspensions of each sample, with the percentages of solids defined for the experiments (37, 40, 43, 46, and 48% (*p*/*p*)), the rheological measurements were started at room temperature and then the temperature was increased (from 28 to 90 °C), heating the pumped water until the value of each measurement was reached and stabilized.

A HAAKE 550 rotational viscometer was used for the rheological measurements, connected to a flow pump to circulate water at different temperatures to preheat the pulp. A standard SV DIN sensor was used in this viscometer rather than an elliptical SV2 sensor, which was not available. The possibility of sedimentation of the pulp during the measurement process and the resulting loss of accuracy were taken into account. To obtain the shear stress values, three replicates were measured for each value of the velocity gradient, and the corresponding arithmetic mean, standard deviation, and coefficient of variation not exceeding 5% were determined.

3. Results and Discussion

The study of the properties of raw and preheated lateritic pulp has been deepened based on the experiment and the study of its main transport characteristics; thus, it has been possible to determine the use of specific mathematical models adapted to the studied fluid.

3.1. Chemical Composition of Lateritic Suspensions

According to the Thickener Plant Operations Manual, the raw pulp is sent from the Pulp Preparation Plant with 25% (*p*/*p*) solids and 10% (*p*/*p*) sand; it consists of nine elements as shown in Table 4. The product pulp retains the same chemical properties as the input pulp, only the solids content increases to values between 46 and 48% (*p*/*p*).

Table 4. Chemical composition of the solid (mineral) phase of the pulp fed to the plant.

Components	Content (%)	Components	Content (%)
Nickel (Ni)	1.20–1.33	**Copper (Cu)**	0.02
Cobalt (Co)	0.12–0.13	**Aluminum (Al)**	4.0–4.9
Iron (Fe)	47.5	**Zinc (Zn)**	0.040
Magnesium (Mg)	0.4–0.8	**Chromium (Cr)**	1.5–2.3
Manganese (Mn)	0.65–1.0	**Silica (SiO_2)**	3.5–4.5

Considering the previous values as a reference, the four selected pulps were chemically analyzed and the results obtained are presented below, in Table 5.

Table 5. Chemical composition of the samples selected for the experiment.

Elements (%)	Samples Composites			
	MC1	**MC6**	**MC11**	**MC4**
Ni	1.21	1.3	1.22	1.21
Co	0.11	0.121	0.115	0.112
Fe	42.9	43.9	43.2	43.1
Mg	1.77	1.94	1.72	1.61
Al	4.43	4.32	4.42	4.44
SiO_2	6.61	5.21	6.39	6.52
Cr	1.55	1.68	1.56	1.57
Mn	0.75	0.79	0.74	0.73
Cu	0.029	0.03	0.028	0.028
Zn	0.036	0.036	0.036	0.036
Ni + Co	1.32	1.421	1.335	1.322
Nr min	9.74	7.85	9.48	9.65

The mineral feedstock entering the HPAL process has an iron content of the order of (35.5 to 53.4)%, including other constituents such as aluminum (2.23 to 5.99)% and magnesium (0.1 to 3.3)%, confirming the ferruginous nature of typical laterite samples, in which iron oxides are abundant. In the mineralogical composition of poorly sedimented materials, there is a marked difference between the coarse and fine fractions, because while the fraction (<0.074 mm) is composed of mineralogical phases traditionally known in laterites as goethite, haematite, and magnetite, the coarse granulometric class contains silicates of magnesium silicate, chlorite, olivine and quartz, which are light metal minerals with low density; their presence in the pulp is an unfavorable factor for sedimentation [31,32]. The mineral number Nrmin characterizes the behavior of the pulp in sedimentation [33]. It has been found that when $7 < N_{rmin} < 14$, the pulp has good sedimentation in the process because there is an adequate correlation between light and heavy (ferrous) metals.

3.2. Granulometric Analysis

In the granulometric distributions of the four composite samples, it can be seen that they are all made up of small particles, less than 50 µm, which are the ones that impart plastic properties to the pulps. In general, there is a predominance of fine fractions and the D80 corresponds to that of particles smaller than 7 µm, which means that 80% of the sample has a diameter smaller than this value; therefore, the finest particles are in the majority and determine the sedimentation rate of this mineral, as well as its rheological behavior, i.e., the particles of all these materials have a behavior typical of polydisperse systems.

3.3. Experimental Results of Rheology in Raw and Preheated Pulp

Nowadays, modern viscometers have software that allows them to analyze the models from the measurements of the velocity gradient and the shear stress. Examples of these applications are Rheocalct fron Brookfield viscometers and Rheowin 4 for Windows 8 from HAAKE, which is more advanced than the one used in this research. In the absence of these, a computer application was developed to model the flow curves using least squares fitting of the best-known rheological models. In each case, the correlation coefficient is given as an indicator of the quality of the models.

The flow curve is the basic tool for the rheological analysis of a flow system, and fluid. From its shape, it is possible to identify the rheological nature of the material and to determine the viscosity and the basic rheological properties (depending on the model used) under different working or operating conditions. The most general rheological classification of viscous fluids is presented by [34,35], which indicates a variant to that of Bingham fluids, supported by the classical one, which indicates two more possibilities for non-Newtonian fluids that begin to move from a certain shear stress but whose performance index "n" is greater or less than 1.

On the basis of the results obtained in this study and of the experiments carried out on samples of lateritic hydromixes reaching a solids concentration of 48% (p/p) and a temperature of 90 °C, it is proposed to classify them into two new types, see Figure 1, namely Bulkley–Herschell dilatant, when $n > 1$, and Bulkley–Herschell pseudoplastic, when $n < 1$.

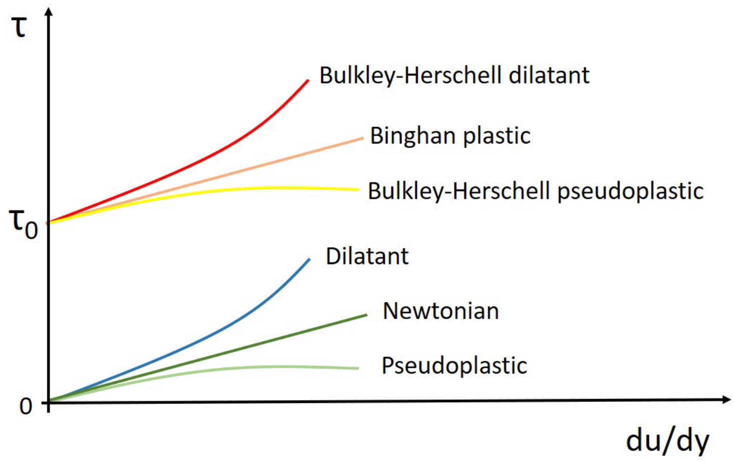

Figure 1. Proposed typical flow curves. Adapted from [29,30].

From the analysis of the graphs of the shear stress and velocity gradient values, see Figure 2, it is concluded that all the samples conform to the pseudoplastic Bulkley–Herschell model, and the rheological parameters are obtained (initial shear stress, consistency index, and flow rate). The behavior of the pseudoplastic Bulkley–Herschell model can be described mathematically according to Equation (1).

$$\tau = \tau_0 + K\gamma^n \quad (1)$$

where τ is the shear stress, τ_0 is the yield stress, K is the consistency index, γ is the shear rate and n is the flow index.

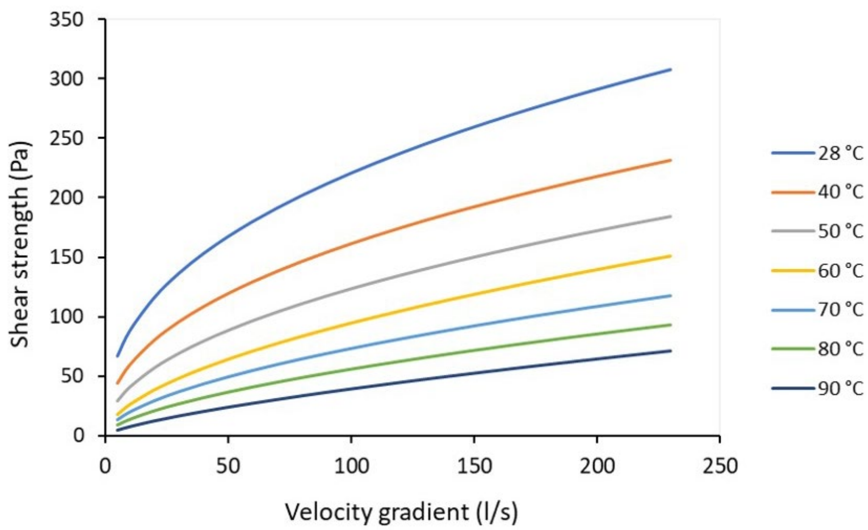

Figure 2. Flow curves at 46% (p/p) solids at different temperatures.

The results obtained represent the typical behavior of non-Newtonian suspensions for solids concentrations of (37 to 48) % (p/p) and temperatures of (28 to 90 °C), see Table 6, which will allow the influence of the rheological parameters in the lateritic hydromix pumping system to be determined.

Table 6. Mathematical models of the rheological parameters of lateritic pulp.

Shows 1 TK-A		Herschel Bulkley Pseudoplastic Mathematical Model:						
% Solid	**Parameters**	**T = 28 °C**	**T = 40 °C**	**T = 50 °C**	**T = 60 °C**	**T = 70 °C**	**T = 80 °C**	**T = 90 °C**
37	τ_0	2.978	1.648	1.283	0.969	0.68	0.421	0.207
	K	3.438	2.211	1.406	1.144	0.64	0.436	0.328
	n	0.63	0.65	0.7	0.72	0.75	0.78	0.85
40	τ_0	4.006	2.586	1.994	1.453	1.099	0.87	0.567
	K	5.721	3.528	1.934	1.45	0.989	0.846	0.542
	n	0.6	0.63	0.66	0.67	0.7	0.75	0.8
43	τ_0	6.357	4.622	3.842	2.669	1.681	1.092	0.833
	K	10.023	7.651	4.258	4.278	2.407	1.844	0.654
	n	0.55	0.57	0.6	0.63	0.65	0.7	0.75
46	τ_0	12.95	7.419	5.166	3.755	2.549	1.497	0.963
	K	20.611	16.81	12.146	7.812	4.696	2.932	1.345
	n	0.54	0.55	0.56	0.59	0.6	0.65	0.73
48	τ_0	16.109	9.503	7.752	7.412	7.3081	2.7717	1.887
	K	28.943	17.952	13.075	8.939	5.637	3.752	2.893
	n	0.5	0.52	0.53	0.54	0.56	0.6	0.65

The mathematical models obtained as a result of the experimentation process are shown in the following equations.

$$\mu_a = -1.8231510 - 0.0245581\ s + 0.0757792\ \%S - 0.0124297\ t + 0.0077888\ Nrmin \quad (2)$$

$$\tau_0 = -7.5155524 - 12.5114987\ s + 2.0090722\ \%S - 0.4978136\ t + 5.5938357\ Nrmin \quad (3)$$

$$K = -7.7626341 - 0.5617544\ s + 0.4372325\ \%S - 0.1077145\ t + 0.3126353\ Nrmin \quad (4)$$

$$n = 0.4832387 + 0.0416324\ s + 0.0007904\ \%S + 0.0022183\ t - 0.0262450\ Nrmin \quad (5)$$

In the results obtained from the analysis of the TKA thickener sample, the trend of the rheological parameters is confirmed: by increasing the solids concentrations at room temperature, the initial shear stress and the consistency index increase and the flow index decreases. This behavior is as expected; it shows the plastic properties of lateritic hydromixes. In the more dilute suspensions, they have lower initial shear stress values due to less interaction between the particles since the repulsive forces are higher; however, in the most concentrated suspensions, the particles are close together and the Van der Waals forces prevail, which contributes to the formation of flocs and aggregates that give rise to much stronger structures and, therefore, higher initial shear stress values. This confirms that at high temperatures the plastic properties of lateritic pulps tend to decrease and exhibit pseudoplastic behavior; hence the high viscosity problems sometimes experienced with lateritic pulps at room temperature.

In Figure 3, it can be seen that the values of apparent viscosity, initial shear stress, and consistency index, decrease with increasing temperature, while the values of flow index increase; this is the typical behavior expected for most liquids and suspensions. It is then confirmed that at high temperatures the plastic properties of lateritic pulps decrease since they show a behavior similar to that of pseudoplastic materials. It is highlighted that the apparent viscosity of the lateritic pulp decreases with increasing temperature, as it can be seen that for the lower values of the velocity gradient, there is a significant change in viscosity, which agrees with the literature [17,18,25].

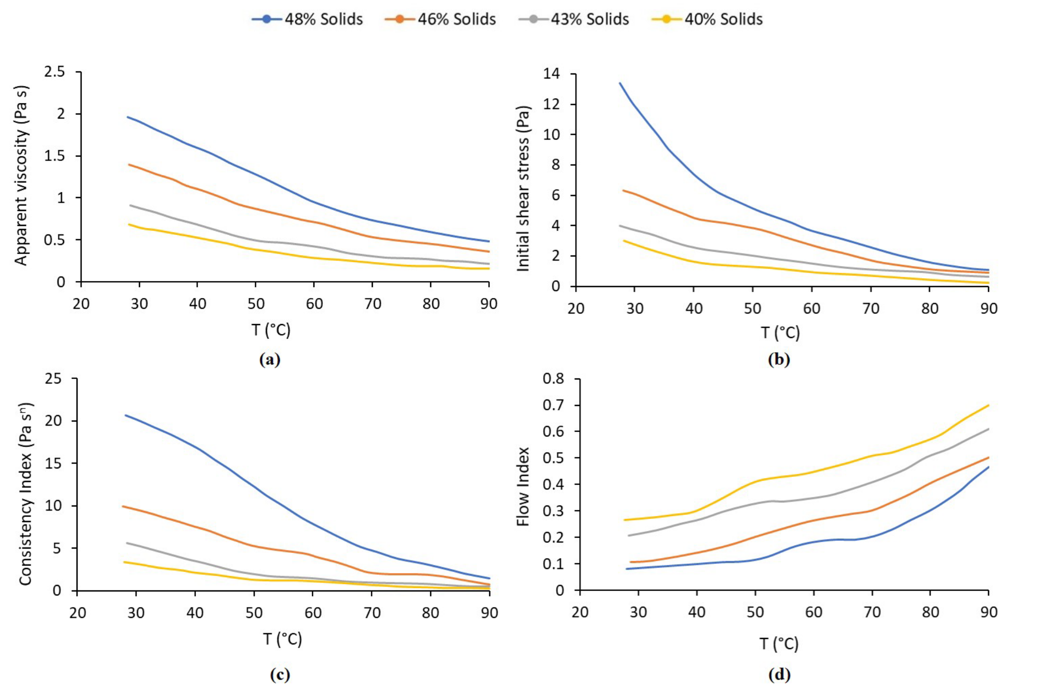

Figure 3. Influence of temperature on rheological parameters: (**a**) apparent viscosity; (**b**) initial shear stress; (**c**) consistency index; (**d**) flow index.

The results obtained justify the research objective of knowing the rheological parameters of lateritic pulps in order to design and evaluate their transport systems, a very important aspect when working with this type of fluid. With this temperature analysis, technological improvements in the acid-leaching process can be considered [36], such as indirect heating of the pulps or the use of water at 70 °C.

3.4. Energy Parameters of the Pumping System

In order to evaluate the practical value of the research results, a computer application [37] was developed to automate the main procedures, designed and programmed in Delphi 7.0 [38], which facilitates decision-making in the operation of lateritic hydromix pumping systems, given the need to obtain adequate predictions of the rheological parameters, whatever the measured values of solids concentration and temperature in the actual production process.

The main results of the Balance of Mechanical Energy (BEM) [34,39,40] are presented in Table 7, and it can be seen that for different concentrations of solids and rheological parameters, there is a variation in the characteristics of the parameters of the hydraulic network with a higher pumping power to guarantee the desired flow.

Table 7. Results of the BEM with a temperature of 28 °C.

Solids Concentration, % (*p*/*p*)	Reynolds Number Downlod	Fanning's Friction Factor	Darcy's Friction Factor	Net Required Height, m.c.a	Pump Head, m.c.a.	Pump Power, kW
37	207.62	0.077	0.308	8.59	38.60	114.33
40	131.00	0.122	0.488	13.17	43.17	134.26
43	78.71	0.203	0.813	20.77	50.78	166.22
46	40.40	0.396	1.584	40.06	70.06	242.10
48	29.879	0.535	2.141	52.09	82.10	294.58

In the case of natural limonitic pulps (untreated) with a high solids concentration, they are considered non-pumpable and it is necessary to inject water into the settler cone for pumping. Under these conditions, the pulp is diluted at the entrance to the preheater and autoclave, which reduces production. To achieve the productivity of the TKA thickener centrifugal pump at 48% (*p*/*p*) solids, a head of 82.10 m and a pumping capacity of 294.58 kW must be overcome.

With regard to the operation of the pumping systems, it is necessary to consider the regulation and control systems that allow the desired flow and pressure to be obtained, as well as the problems of cavitation, instabilities, and transients that may occur [41,42]. Once the cavitation diagnosis has been carried out, and in the absence of any anomalies regarding its occurrence, the operational diagnosis of the system is carried out based on the verification that it delivers the required flow to the process (Q_{req}) for which this transport service is provided. This is possible as long as the operating flow (Q_{op}) is greater than or equal to the required flow, i.e., $Q_{op} \geq Q_{req}$. Otherwise, the system does not meet the industrial requirements, and measures must be taken to ensure its efficiency, either by changing the operating parameters, selecting a new pump, or redesigning the system. The economic criterion must decide between the alternatives formulated [43].

Part of this operational diagnosis is to compare the operating flow with the flow for the point of maximum efficiency (Q_d). A pumping system operates efficiently if the operating flow has an efficiency that differs up to 10% from the maximum efficiency of the pump [44–46]. This procedure is proposed, which allows the evaluation of the pumping system from the knowledge of the rheological properties of lateritic hydromixes and the relationship with the load–discharge characteristic curves of networks and pumps [47]. The results are presented in Figure 4. The operating point is determined under the current operating conditions of the extraction pumping system of the thickener tanks.

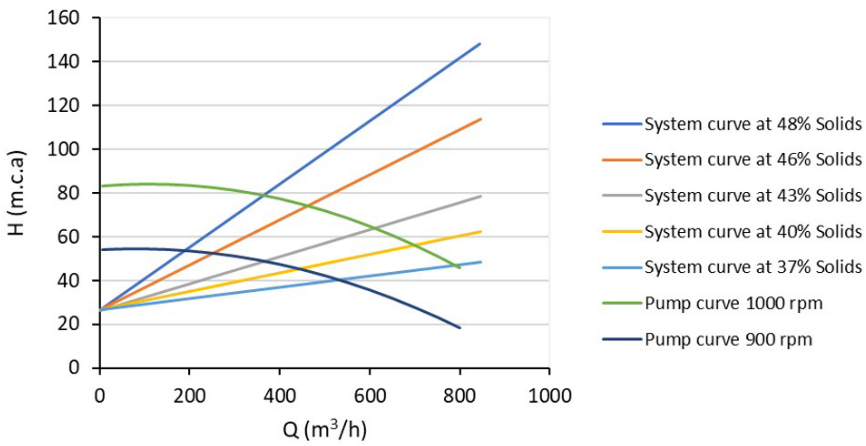

Figure 4. Operating points under current conditions.

The daily production of the Leaching Plant is 9000 to 10,000 t/day of mineral, equivalent to 375 and 417 t/h. Between 1600 and 1800 t/day need to be extracted from each thickener, with an extraction flow of 450 to 478 m^3/h and a solids content of 48% (*p*/*p*). Under current operating conditions, rheological parameters are not considered, and the transported fluid is characterized as Newtonian. When the solids concentration exceeds 45% (*p*/*p*), the extraction flow is reduced to less than 200 m^3/h.

From Table 8, it can be seen that as the temperature increases, less pumping power is required due to the influence of temperature on the rheological parameters of the pulp. The apparent viscosity and initial shear stress values decrease. It can be seen that the lateritic hydromix increases the flow index at high temperatures without becoming a Newtonian fluid.

Table 8. BEM results for 48% (w/w) solids and 90 °C temperature.

Solids Concentration % (*p*/*p*)	Temperature, °C	Reynolds Number Downlod	Fanning's Friction Factor	Darcy's Friction Factor	Net Required Height, m.c.a	Pump Head, m.c.a	Pump Power, kW
48	28	29.87	0.535	2.141	52.09	82.10	294.58
	40	48.17	0.332	1.328	32.94	62.94	225.85
	70	153.41	0.104	0.417	10.77	40.77	146.30
	80	230.48	0.069	0.277	7.48	37.49	134.52
	90	298.92	0.053	0.214	6.11	36.12	129.60

Figure 5 shows the operating point with the results obtained in the investigation where it can be seen that as the temperature increases up to 90 °C, lateritic hydromixes with 48% (p/p) of solids concentration are pumpable and thickener extraction volumes in excess of 470 m^3/h are achieved.

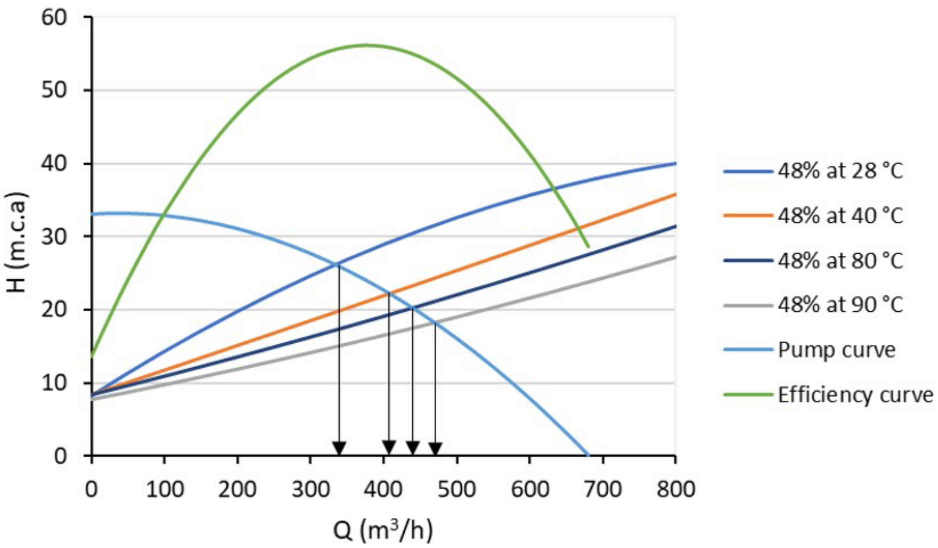

Figure 5. Operating point with preheated pulp.

A diagnosis of the operation of the plants analyzed revealed that the pumping capacity was currently reduced to 60% because the maximum efficiency points of the pumps installed were not taken into account. Based on the simulations and predictions provided by the computer application, the results were found to be of practical use in making technological decisions that have a positive economic and environmental impact.

4. Conclusions

Mathematical models are obtained of the rheological parameters that determine the influence of temperature and solids concentration on the productivity of the raw and preheated lateritic hydromix pumping system, such as flows, loads, hydraulic losses, power, and efficiency, which determine the point of maximum efficiency for the transport of lateritic hydromix. The influence of temperature on the apparent viscosity is determined by increasing the flow index, without losing the non-Newtonian behavior. The results obtained will make it possible to increase the productivity of the thickener plant by 1600 t/day, with high concentrations of solids, which will make it possible to evaluate the technological improvements in HPAL applied internationally. Considering that lateritic pulps exhibit non-Newtonian rheological behavior, with an increase in the apparent viscosity when pumping pulps with a high solids content, and analyzing the above study, it can be assumed that the main variables involved in evaluating the efficiency of the pump-motor unit are: apparent viscosity (μa), density determined by the solids concentration, pressure drop (ΔP), flow rate (Q), hydraulic power (Nh) and electric power (Nm).

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