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Original Article

Effect of rheology and dispersion degree on the regrinding of an iron ore concentrate

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ABSTRACT

This investigation addressed the study of the effects of the slurry's rheological behavior and the state of aggregation and dispersion on wet ultrafine grinding of an iron ore concentrate. Regrinding tests were conducted under different conditions of dispersion (pH 7.3, 8.5 and 10.0) and with the addition of 300 g/t of lime. The increase of pH from 7.3 to 10.0 increased the slurry dispersion degree, providing lower values of yield stress and apparent viscosity, and a reduction in specific energy consumption of 17.4%. So, sodium hydroxide, added at previous processing steps, has acted as a grinding aid. The addition of 300 g/t of lime caused an increase of 27% in specific energy consumption, with significant increase in yield stress and consistency index of the fluid, especially for the condition of 18 kWh/t.

1. Introduction

Comminution stages represent a challenge in the mineral industry due to the low mechanical efficiency and the huge energy consumption, corresponding to the highest operating costs in the concentrators.

The fraction passing 44 μm and the specific surface area (indirectly measured by Blaine permeabilimeters and designated as Blaine surface area or BSA) are specifications of iron ore concentrates for pellets production. In order to meet the specifications, the concentrates must be reground, operation performed in most companies, at least in a primary stage, in ball mills [1].

At Samarco, the grinding stages represent approximately 80% of the total energy consumption in the concentrators, regrinding reaching 60% of the overall consumption. Relevant investigations aiming at increasing the productivity and reducing the specific energy consumption have been performed, but none of them addressed the effect of rheology on grinding performance.

The influence of rheology on grinding is not yet well understood and, in view of this, it is rarely incorporated as a variable in projects, analyses and optimization. A major reason is the difficulty of studying the rheology of suspensions that settle, which occur in most mineral beneficiation processes.

Viscosity, and not the solids percentage, is the variable that rules the interaction between the pulp and the grinding media inside the mill [2].

Some references available in the technical literature [3–9] demonstrated gains in the grinding productivity with the use of dispersants designated as grinding aids. These reagents

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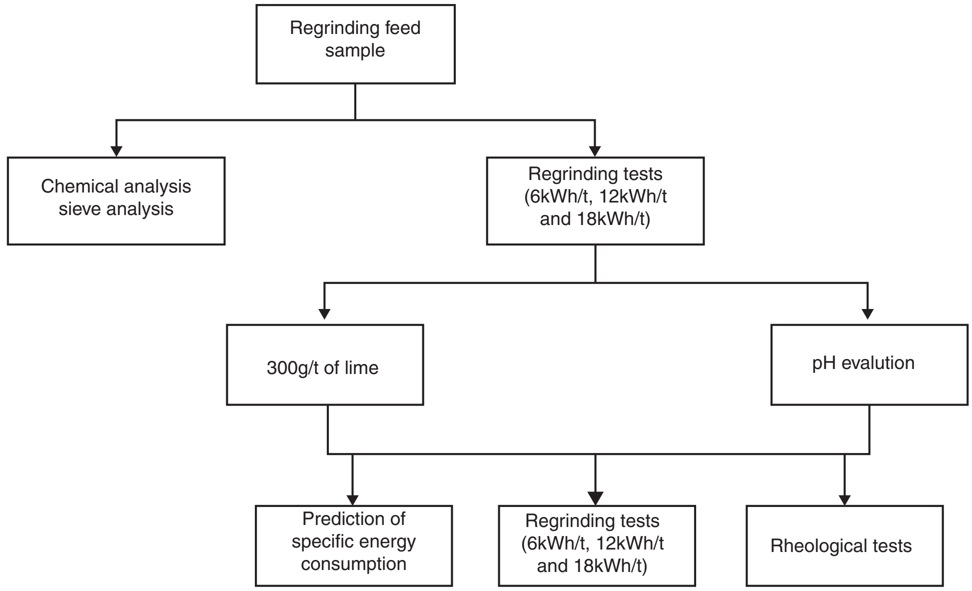

Fig. 1 – Simplified flowsheet of the study.

promoted decrease either on the pulp viscosity or in the yield stress, allowing higher solids percentage in the mill. Most of the grinding agents used are water soluble polymers.

2. Methods

The iron ore concentrate sample was composed by increments collected during 10 days from the concentrate thickener feed (Samarco's concentrator I). A resulting pulp weighing 1000 kg was dewatered, homogenized by conical piles and stored in 200 L drums. A riffles sample splitter was used to produce samples for the technological tests.

The simplified flowsheet of the study is illustrated in Fig. 1.

The regrinding tests were performed according to a procedure developed at Samarco [1]. This method consists of performing grinding at three different times (22 min, 44 min and 66 min) in a laboratory mill (0.254 m × 0.254 m). Particle size and Blaine surface area analyses were performed with the feed and product of grinding. The specific energy consumption was obtained by multiplying the grinding time in minutes by the conversion factor 0.2727. This conversion factor is calculated using the Rowland JR's equation (1986).

The power absorbed per ton of grinding media is calculated by the Rowland JR's equation [10]. Multiplying this value by the weight of the load, the absorbed power in the pinion shaft of the mill is determined. The equation for mills with a diameter smaller than 2.44 m is:

$$kWb = 6.3 \times D^{0.3} \times sen\left[51 - 22 \times \left(\frac{2.44 - D}{2.44}\right)\right] \times (3.2 - 3V_p) \times C_S \times \left(1 - \frac{0.1}{2^{(9-10C_S)}}\right) \quad (1)$$

kWB is the kilowatts per ton of balls, in the pinion shaft; D is the diameter of the mill, in meters, inside liners; V_p is the volumetric fraction occupied by the balls; $C_\$$ is the fraction of critical speed.

The original method [1] was slightly modified: (i) distilled water was used and the pulp pH was adjusted to 10 (except in the case of tests in which the effect of pH was evaluated); (ii) there was no water addition to wash the mill after being discharged; after a few minutes of rest, the pulp supernatant

Table 1 – Size distribution and grades in each size fraction.

Size (μm)	Cumulative % passing	Fe (%)	SiO_2 (%)	Al_2O_3 (%)	P (%)	LOI (%)	MnO (%)
149	77.08	58.56	11.88	0.38	0.044	3.79	0.13
105	63.28	64.97	4.07	0.28	0.039	2.87	0.07
74	50.85	66.94	2.40	0.26	0.032	2.47	0.05
53	31.92	67.97	1.39	0.22	0.028	1.90	0.04
44	24.89	68.10	0.94	0.22	0.024	1.52	0.03
37	20.62	68.05	0.93	0.21	0.022	1.45	0.03
−37	–	68.05	0.89	0.29	0.026	1.48	0.07
Calculated head		65.30	4.13	0.28	0.033	2.41	0.07
Analyzed head		65.44	4.20	0.28	0.032	2.40	0.07

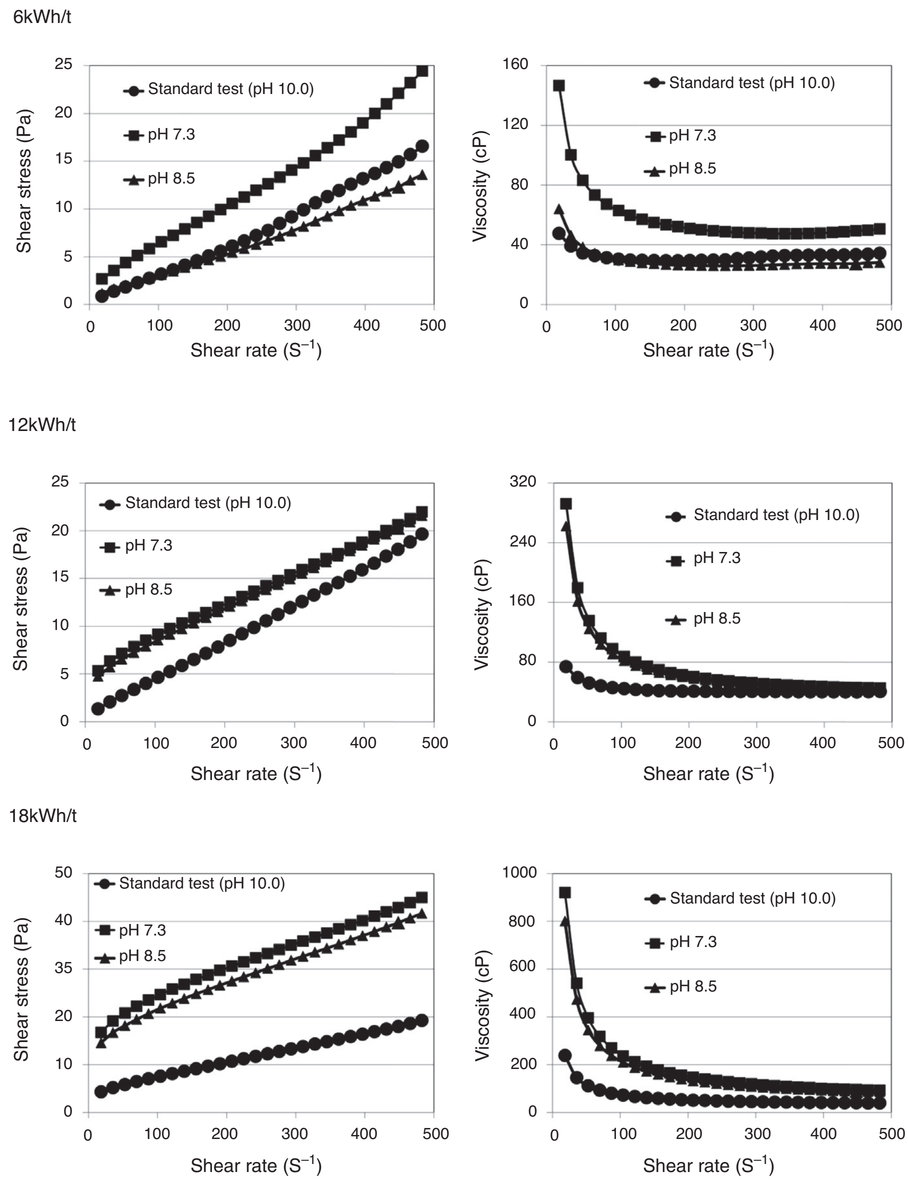

Fig. 2 – Effect of pH on the flux curves achieved after regrinding.

was used for washing; (iii) the flux curves were determined immediately after the pulp quartering.

The regrinding tests were performed at three different times (22, 44 and 66 min) and converted into energy in the pinion shaft with the use of the Rowland Jr's equation (6 kWh/t, 12 kWh/t, and 18 kWh/t). The pH conditions were used: 7.3 (natural), 8.5 (inflection point in the dispersion curve, Fig. 3), and 10.0.

The rheological curves were obtained with the use of a coaxial cylinder viscometer (Brookfield, model R/S+, sensor CC3-45). The shear rate was decreased from 500 s^{-1} at 1 s^{-1}, to 30 s, the readings being taken at every second. The flow curves were adjusted with the use of Bingham and Herschel–Bulkley models. The pH was set at 10.0 for all experiments. It was observed that: (i) rates higher than 500 s^{-1} caused turbulence to the pulp; (ii) time higher than 30 s caused sedimentation; (iii) the sedimentation effect was minimized by the use of a decreasing shear rate ramp instead of an increasing ramp.

3. Results and discussion

3.1. *Sample characterization*

Table 1 presents the grades of each retained size fraction and the grades of the head sample used in the study. Higher contents of silica, phosphorus, alumina, and LOI are present in the coarse fractions and the iron content is higher in the fine fractions.

3.2. *Influence of pH*

The objective of the first sequence of tests was to evaluate the possible effect of significant changes in the dispersion degree on the regrinding performance. Figs. 2 and 3 illustrate the flux curves and the coefficients achieved by fitting to the models of Herschel–Bulkley and Bingham for each pH

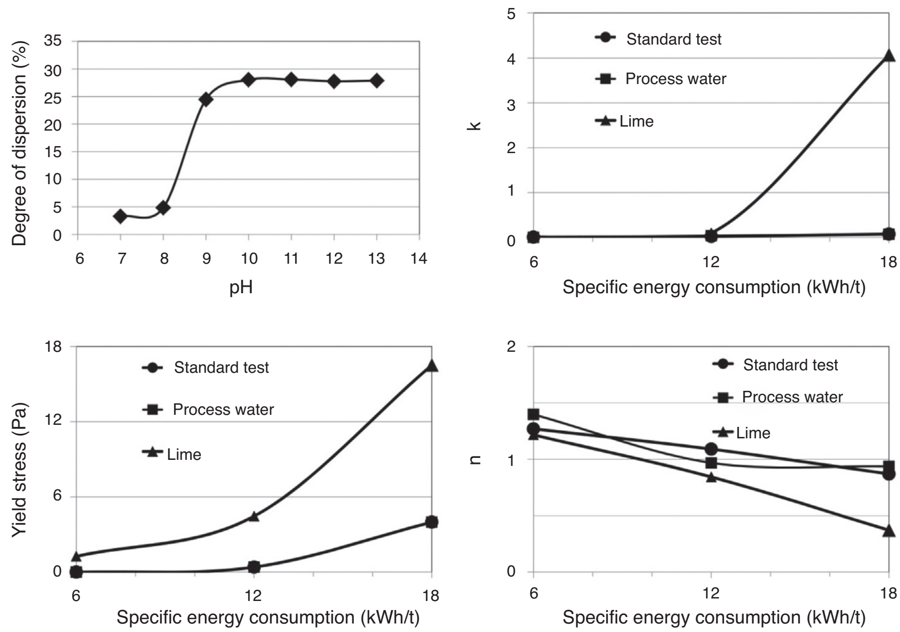

Fig. 3 – Effect of the pH on the dispersion degree and on the *k* and *n* (Herschel–Bulkley) coefficients and on the yield stress (Bingham).

condition. Coherence among the curves is observed: increasing the pH from 7.3 to 10.0, the dispersion degree is increased and the yield stress and apparent viscosity decrease. The increase in applied energy, due to the higher production of ultrafine particles, causes exponential increase in the k coefficient and also in the yield stress.

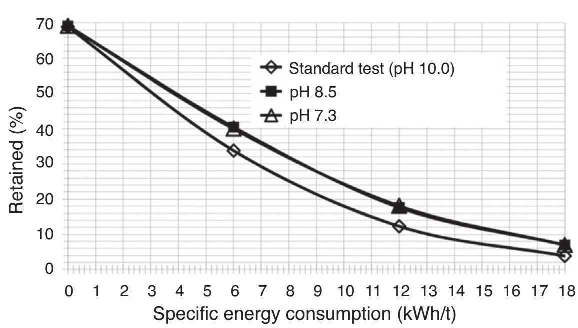

Fig. 4 – Effect of pH on the curves of percent retained in 0.044 mm as a function of applied energy.

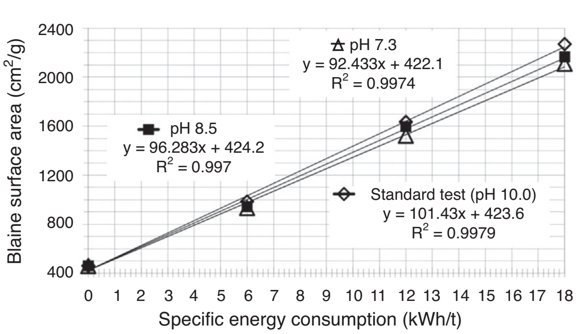

Fig. 5 – Effect of pH on the curves of BSA as a function of applied energy.

[Fig. 4](#) shows the effect of pH on the curves of percent retained in 0.044 mm as a function of applied energy. It is observed that the curves obtained at pH 7.3 and 8.5 are close to each other, but coherent: increasing the pulp pH causes decrease in the specific energy consumption, probably due to reduction in the yield stress caused by the higher thermodynamic stability of the pulp. The energy consumption levels predicted in the laboratory for % passing 0.044 mm

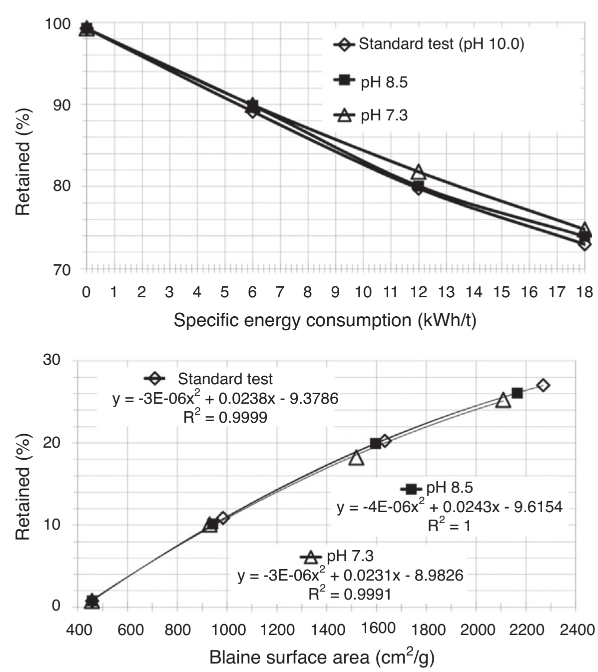

Fig. 6 – Effect of pH on the curves of percent retained in 10 μm as a function of the energy and of the percent passing in 10 μm as a function of BSA.

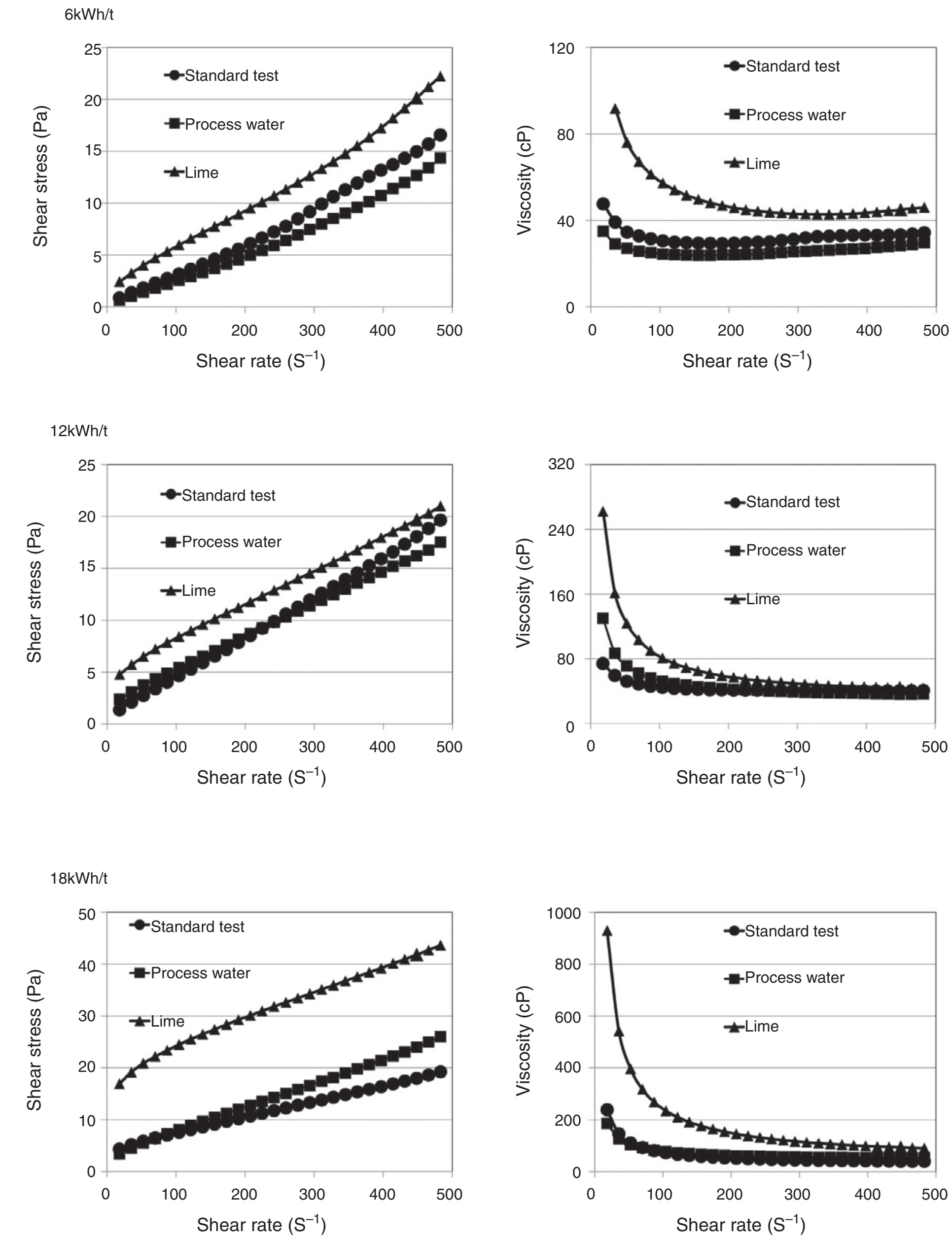

Fig. 7 – Flux curves obtained after regrinding with addition of 300 g/t of lime and with the use of process water.

were: (i) pH 7.3 → 15.3 kWh/t (21.4% above the standard test); (ii) pH 8.5 → 14.5 kWh/t (15.0% above the standard test); pH 10 → 12.6 kWh/t.

The conclusion of this stage is that sodium hydroxide, added in earlier stages (desliming and mechanical flotation), prior to the concentrate regrinding is already acting as grinding aid.

Fig. 5 shows the effect of the pH on the curves of the Blaine surface area, BSA, as a function of applied energy. The BSA/kWh/t coefficient increases slightly with the increase of the dispersion degree of the particles in the pulp. Taking the standard test, at pH 10 as reference, the BSA/kWh/t index in the pH level 8.5 was reduced by 5.1%. For the pH level 7.3 the reduction reached 8.9%.

The effect of the pH on the production of ultrafine and colloidal particles was evaluated with the help of curves presenting the percent retained in 10 μm as a function of the applied energy and percent passing 10 μm as a function of BSA, as visualized in Fig. 6.

The first graph shows that increase in the pH (and consequent increase in the dispersion degree) affected the production of ultrafine and colloidal particles. This graph is coherent with Fig. 4, where the same effect was observed in the kinetics of coarser particles breakage (≥44 μm). The second graph shows a high correlation between the percent retained in 10 μm and the BSA (R^2 above 0.99). This high correlation indicates that the first graph in Fig. 6 is coherent with the curves shown in Fig. 5. So, the increase in the dispersion degree

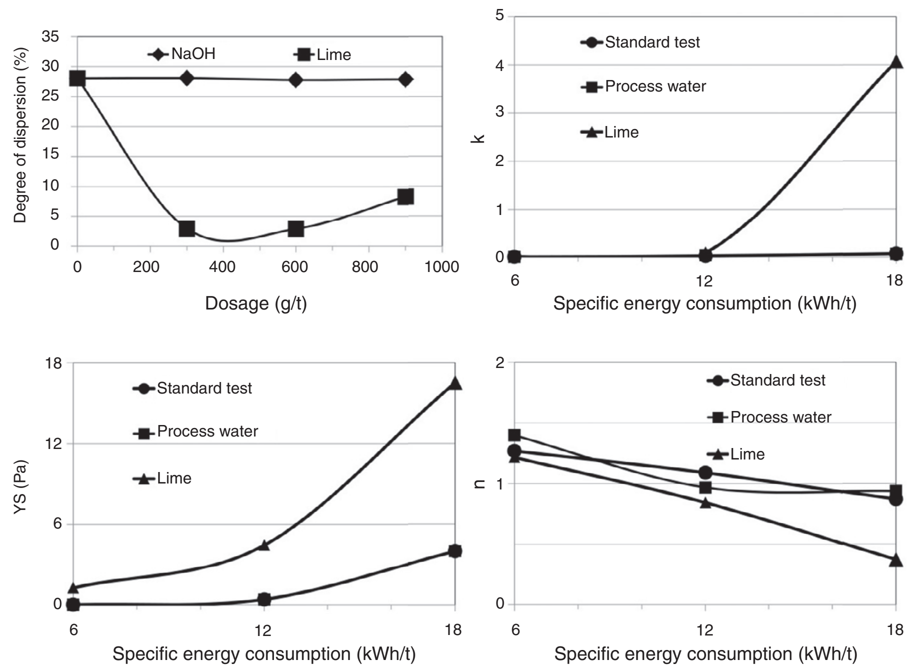

Fig. 8 – Effect of lime addition on the dispersion degree and evaluation of dosing 300 g/t of lime on the *k* and *n* coefficients (Herschel–Bulkley) and on the yield stress (Bingham).

caused an increase in the BSA/kWh/t index, in agreement with the observed enhanced production of ultrafine and colloidal particles.

4. Effect of lime addition

Fig. 7 shows the flux curves obtained in the regrinding tests using process water (overflow of slimes and concentrate thickeners) and with the addition of 300 g/t of lime. The curves achieved in the standard test (using distilled water) and in the test using process water are similar. Nevertheless, in the presence of lime the values of apparent viscosity and shear stress, for the same shear rate, are higher. These values are even more significant after 66 min grinding (corresponding to 18 kWh/t at the pinion shaft).

The curves shown in Fig. 7 were fitted using the models of Herschel–Bulkley and Bingham. The coefficients obtained in each test are presented in Fig. 8. Results from the standard test and those performed with process water were similar.

The test done in the presence of 300 g/t of lime yielded the highest values of the *k* and YS coefficients, mainly at the condition of 18 kWh/t. Due to the increased presence of finer particles caused by the higher applied energy, added to the coagulant addition, the aggregation effects were probably more significant than the hydrodynamic effects, leading to higher levels of the yield stress. These two effects represent the main kinds of interaction contributing to rheological properties [11].

Beyond increasing the yield stress values, the increase in applied energy observed in the test in the presence of 300 g/t of lime increased the pseudoplastic character of the pulp.

Fig. 9 presents the curves of percent retained in 0.044 mm as a function of applied energy. It is observed that the curves for the standard test and the test in the presence of process water are superimposed, indicating that the concentration

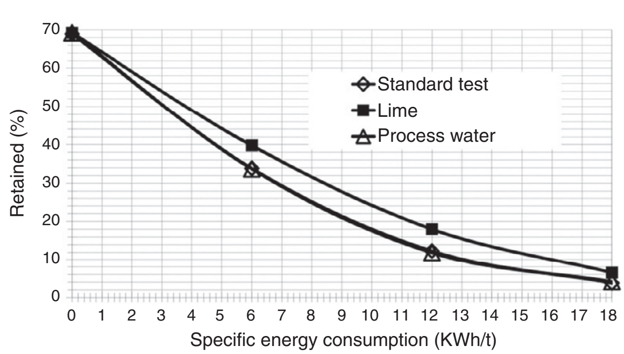

Fig. 9 – Curves of percent retained in 0.044 mm as a function of applied energy, with addition of 300 g/t of lime and using process water.

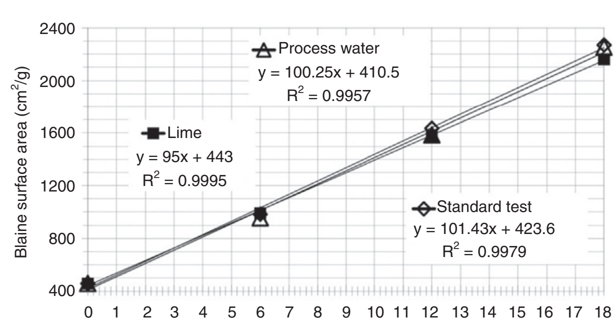

Fig. 10 – Curves of BSA as a function of applied energy with addition of 300 g/t of lime and use of process water.

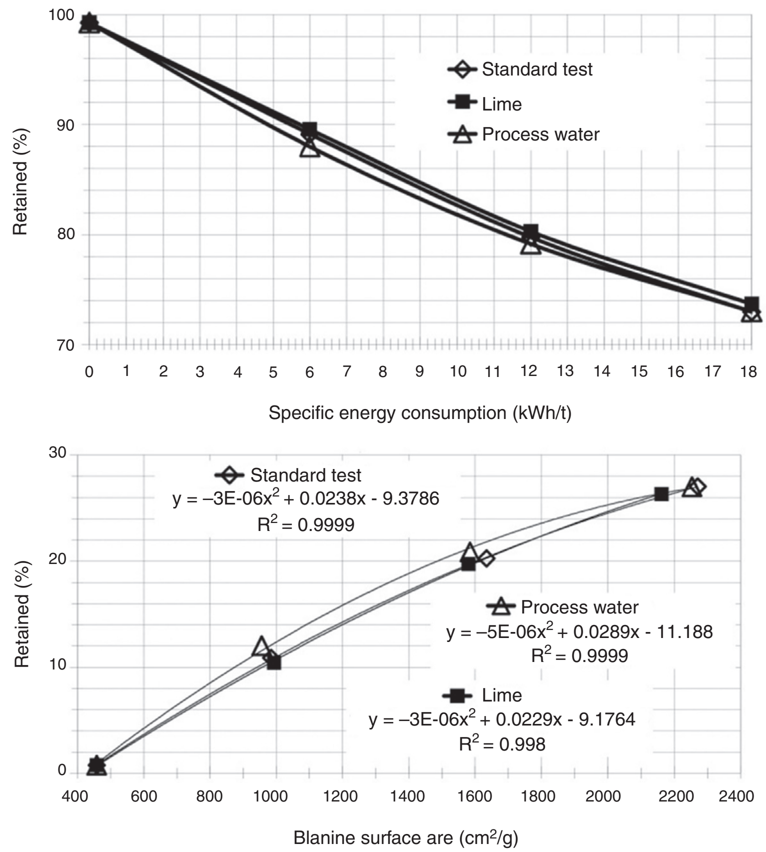

Fig. 11 – Effect of using process water and addition of 300 g/t of lime on the curves of percent retained in 10 μm as a function of energy consumption and of the percent passing 10 μm as a function of the BSA.

of calcium ions present in Samarco's concentrator I process water is not high enough to affect the specific energy consumption for a same size range. Nevertheless, high concentrations of calcium and its complexes may increase the specific energy consumption, as evidenced by the test in the presence of 300 g/t of lime. For this condition, the consumption for a size distribution presenting 88% passing 0.044 mm was 16 kWh/t (27% higher in comparison with the standard test).

Fig. 10 shows the curves of BSA as a function of applied energy, both curves presenting R^2 above 99%. It may be observed that the surface area generation (BSA/kWh/t index) of the test done with 300 g/t of lime is slightly lower than those achieved in the tests performed with distilled water and process water. Probably the addition of lime affected mainly the kinetics of breakage of coarse particles (≥44 μm), since from the analysis of the curve of percent retained in 0.044 mm as a function of energy consumption in the presence of lime (Fig. 9) one would expect also the production of a smaller amount of ultrafine and colloidal particles, fact that would cause a more significant reduction of the BSA/kWh/t index than that observed in Fig. 10.

With the objective of evaluating the effects of adding 300 g/t of lime and the use of process water on the production of ultrafine and colloidal particles, curves of percent retained in 10 μm as a function of applied energy and of percent passing 10 μm as a function of BSA were plotted, as visualized in Fig. 11. The first plot confirms the earlier assumption that the addition of 300 g/t of lime affects mainly the kinetics of coarse particles breakage. The BSA/kWh/t indexes shown in Fig. 10 are coherent with the curves shown in the first plot of Fig. 11. Again a high correlation between the percent passing 10 μm and the BSA (R^2 above 0.99) was observed, as illustrated in the second plot of Fig. 11.

5. Conclusions

The determination of the dispersion degree using sedimentation tube combined with the analysis of flux curves and the coefficients of the Herschel–Bulkley and Bingham models is adequate to describe the rheological behavior of ore pulps under different aggregation and dispersion conditions.

The increase of the pulp pH from 7.3 (natural pH) to 10.0 caused an increase in the dispersion degree of the particles in the pulp from 3% to 28%. As a consequence, decreases in the values of the yield stress and apparent viscosity were observed and the specific energy consumption was reduced by 17.4%. So, sodium hydroxide used in process stages preceding regrinding is already acting as grinding aid.

The increase in grinding time, converted into applied energy, caused exponential increases in the fluid consistency indices and in the yield stress. Both, pH decrease and addition of 300 g/t of lime, promoted even more significant increases in the parameters value. For all tests, the increase in applied energy caused a change in the rheological behavior of the pulp, from dilatant to pseudoplastic, with associated yield stress.

No differences were observed in the specific energy consumption Blaine surface area generation between the tests performed with distilled water or process water, indicating that the concentration of calcium ions in the process water of Samarco's concentrator I is not significant to the point of affecting the regrinding performance. Nevertheless the addition of 300 g/t of lime caused increase of 27% in the specific energy consumption, with significant increases in the yield stress and the fluid consistency index, mainly for the condition of 18 kWh/t.

Conflicts of Interest

The authors declare no conflicts of interest.

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