BX01 - Pilot Tests with Tertiary Cyclone for Reactive Silica Removal from Amazonian Bauxite

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Abstract

Bauxite is the main ore for metallic aluminum production, consisting of aluminum, iron oxides and kaolinite, a clay mineral commonly found in Amazonian bauxites, as the main carrier of reactive silica. In the process, due to the small particle size, kaolinite is usually removed by attrition and washing of coarse material followed by desliming using hydrocyclones. In the Bayer process, kaolinite reacts with sodium hydroxide, increasing reagent consumption in the process. Beneficiation process at Hydro Paragominas is based on the separation of coarser fractions with higher gibbsite content from the clay minerals, where kaolinite is more concentrated. The separation takes place in two-stage hydrocyclone circuits, equipment that inherently presents a bypass of fine particles to the underflow, consequently, contaminating the concentrate with kaolinite, and increasing the operating cost in the Bayer process. A Tertiary stage of cyclones was tested in a pilot plant using 254 mm diameter cyclone seeking a reduction on fine particles bypass and consequently, bauxite product with lower kaolinite levels. Average removal of fine particles below 10 µm, where clay minerals are concentrated, ranged between 80.8 % and 89.1 % on pilot tests. Consequently, available alumina grade increased from 43.3 % to 48.1 % and reactive silica reduced from 6.0 % to 3.3 %. The classification process was selective, with 89.3 % metallurgical recovery of alumina and 45.9 % recovery of silica to product.

Keywords: Bauxite beneficiation, Clay removal, Silica reduction, Hydrocyclones.

1. Introduction

Bauxite is the main ore for production of metallic aluminum. Production is generally carried out by the Bayer process to form alumina, followed by the Hall-Héroult process to carry out the reduction of alumina into metallic aluminum. Some factors that interfere in this process are available alumina and reactive silica contents in bauxite [1].

Bauxite is a rock composed of aluminum oxides. Bauxites can be “lateritic” or “karst” types. Lateritic bauxites are formed in equatorial regions and are mostly composed of gibbsite as the main mineral and gangue composed of kaolinite, iron oxides, titanium oxides and quartz. The Amazonian bauxite is of the lateritic type and is mostly located in Paragominas, Juruti, Trombetas and Almerim [2,3].

Kaolinite is a clay mineral commonly found in Amazonian bauxite and Brazilian iron ores. Due to its particle size, kaolinite is usually removed from the process in desliming steps using hydrocyclones. Kaolinite is the source mineral for reactive silica. In the Bayer process, kaolinite reacts with sodium hydroxide, increasing the consumption of the reagent in the process and forming desilication product [4, 5].

The hydrocyclone is a well-known mechanical classifier used for separations of particles of different sizes. Hydrocyclone performance characteristics such as coarse particle recovery to underflow, cut size and bypass reduction are related to operating parameters: pressure, solids percentage, apex diameter, vortex diameter and cone angle [6, 7].

Process simulations and pilot tests developed for coal classification have shown the potential of multi-stage circuits to reduce the hydraulic bypass of fine particles into the coarse product by reclassifying the cyclone underflow stream multiple times. Coal reclassification was able to reduce fine particles bypass from 14 % to 6 % [8].

Hydro Paragominas processes lateritic Amazon bauxite. To remove kaolinite, the beneficiation plant has two cyclone stages in two different circuits (fines and super-fines). Seeking to reduce the content of reactive silica in bauxite a pilot plant was installed in the super-fines circuit, with 254 mm diameter hydrocyclone, allowing the performance evaluation of tertiary cyclones.

2. Materials and Methods

2.1 Hydro Paragominas' Beneficiation Plant

Hydro Paragominas' bauxite processing circuit includes three main classification steps to separate the coarser fraction, with higher gibbsite content, from the finer fraction, where most of the kaolinite is concentrated. The first step is also responsible for separating fine particles from pebbles, which is followed by the re-crushing process, and is carried out on vibrating screens. The second step, called fines classification circuit, is carried out in 660 mm diameter hydrocyclones and separates clay and finer bauxite particles, from mid-size particles, that feeds the ball mill. The third step, called superfines classification circuit, is carried out in 254 mm diameter hydrocyclones and is the final step for separation of clay, beneficiation process tailings, to fine bauxite particles, that forms the product. A simplified flowchart of the processing plant is presented in Figure 1.

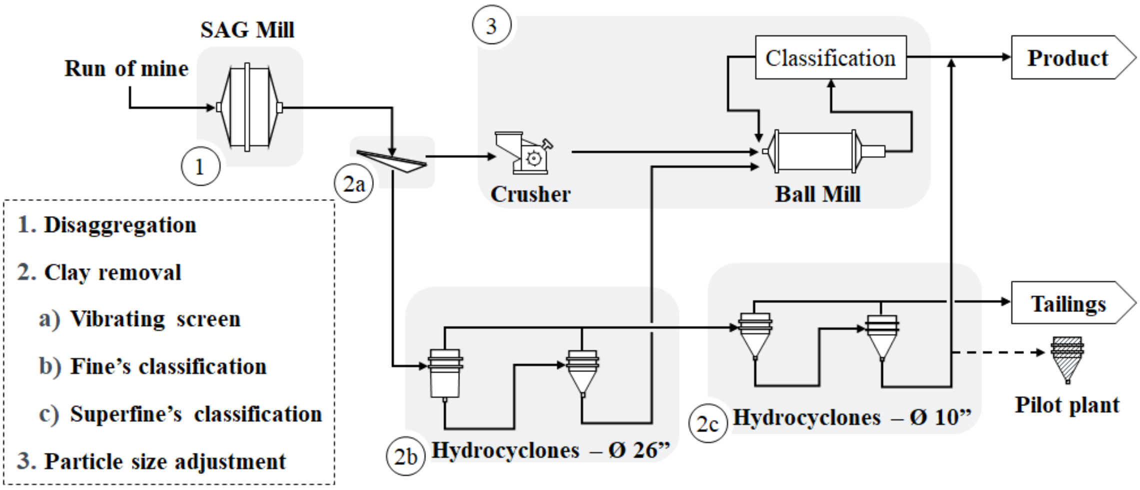

Figure 1. Hydro Paragominas' beneficiation plant simplified flowchart.

2.2 Pilot Equipment

A pilot plant was installed for reclassification of the underflow from the secondary step on the superfines circuit. Main design and operational specifications from the pilot plant are listed below:

- 1 hydrocyclone with 254 mm diameter (same from industrial superfine circuit);
- Flow rate: 85 – 150 m^3/h;
- Operating pressure: 245 – 314 kPa;
- Operation in batches, with a 3 m^3 slurry tank, with agitator.

Pilot tests were carried out by filling the slurry tank with water and bauxite slurry from the industrial plant, meeting the specified slurry densities from testing plan. The slurry pump was used to feed the hydrocyclone. Under and overflows were recirculated to the tank, forming a closed circuit. Sampling devices on the three cyclone flows were used to get bauxite samples for laboratory analysis, as shown in Figure 2.

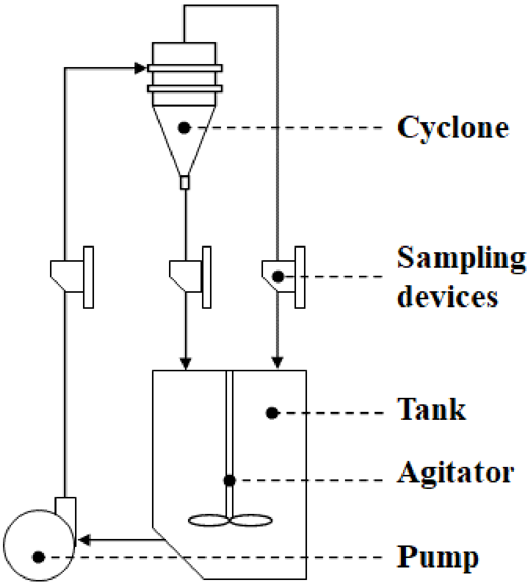

Figure 2. Pilot plant schematic flows.

2.3 Material

Bauxite used on pilot tests were from Hydro Paragominas beneficiation plant. The underflow from secondary step of superfine particles was submitted on the pilot tests to a tertiary step of classification.

The slurry tank was filled with process water until 50 % capacity, covering the agitator impeller and creating a turbulent environment to receive bauxite slurry and keep particles in suspension. Bauxite slurry was transferred to the tank following the quantities defined on each condition from testing plan and finally, additional process water was used to complete tank filling and fine tuning of slurry density.

On pilot tests, for each operating condition two samples were taken from each flow and were submitted to characterization as described below:

- Sample 1 – PSD: Total sample mass was submitted to wet screening for particle size distribution analysis from 600 µm to 37 µm. The fraction finer than 37 µm was submitted to laser diffraction analysis (Malvern);

- Sample 2 – Chemical analysis: The sample was dried in a laboratory stove at 105 ºC to determine the percentual of solids. Dry samples were quartered to generate aliquots for chemical analysis and specific gravity determination.
    - Chemical analysis: Samples were submitted to total oxides analysis (Al_2O_3, Fe_2O_3, SiO_2 and TiO_2) through X-Ray Fluorescence. Bauxite digestion and then titration and atomic absorption were used to determine available alumina and reactive silica grades respectively;
    - Specific gravity: Specific gravity was determined through helium pycnometer.

Besides the described characterization, the sample from first pilot tests was submitted to granulo-chemical analysis on the fractions coarser than 37 µm, between 37 and 10 µm and below 10 µm.

2.4 Testing Plan

The main hypothesis to be tested was that the difference between the reactive silica grade in the underflow of the pilot plant cycloning (tertiary stage) and the reactive silica grade in the feed (secondary stage underflow) is less than zero, the corresponding calculations were done using Equations 1-3.

$$d = RS_{TSF} - RS_{SSF}, \tag{1}$$
$$H_1: \mu_d < 0 \tag{2}$$
$$H_0: \mu_d = 0 \tag{3}$$

Where:

d	Difference between reactive silica grades, %
H_0	Null hypothesis
H_1	Alternative hypothesis
RS_{SSF}	Re. Silica grade - Secondary step of superfines classification (pilot test feed), %
RS_{TSF}	Re. Silica grade - Tertiary cycloning (pilot test underflow), %

The hypothesis was tested at a significance level $\alpha = 0.05$ using one tailed paired samples t test. Hypothesis was tested by analyzing the difference between reactive silica grade from superfines circuit secondary cyclone underflow and pilot scale tertiary cyclone underflow.

For each bauxite sample, two different slurry densities and apex diameter were evaluated, as described below:

- Slurry density: 1.08 and 1.10 t/m^3;
- Cyclone geometry – Apex diameter: 44.5 mm and 50.8 mm.

Operating pressure was kept constant in 294 kPa and vortex finder diameter was 88.9 mm. In this scenario, 5 bauxite samples were tested, generating 20 different testing conditions.

3. Results and Discussion

3.1 Bauxite Samples Characterization

Figure 3 shows the particle size distribution from the 5 samples submitted to tertiary cycloning on pilot tests. Concentration of slimes, particles finer than 10 µm, ranged from 15 to 20 %.

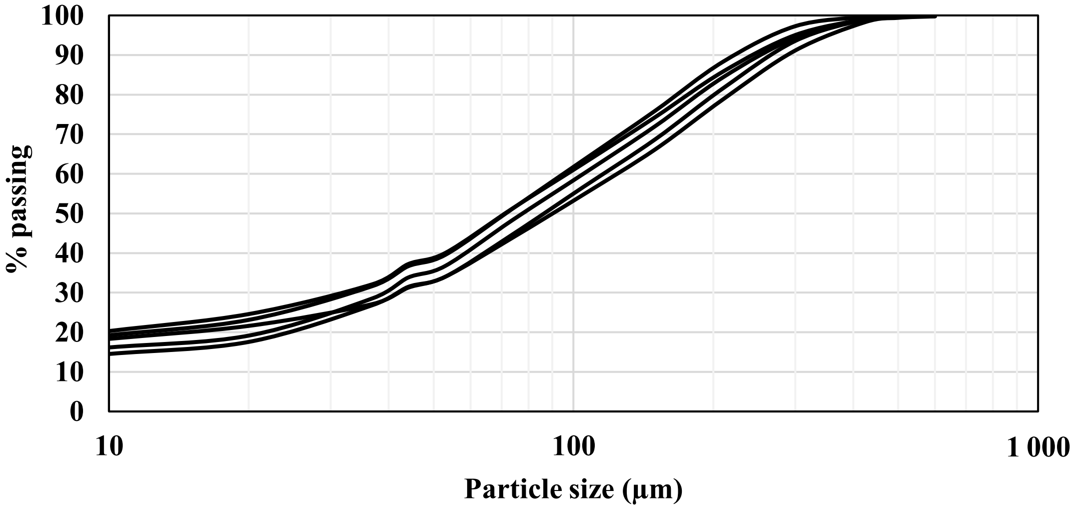

Figure 3. Particle size distribution from pilot tests feed.

Particles finer than 10 µm have high relevance in the context of bauxite beneficiation as most of the gangue minerals are concentrated in this size fraction. The characterization from the pilot plant feed (sample 1) shows that available alumina grade on particles finer than 10 µm is less than half when compared to the coarser fractions, while reactive silica grade is more than 7 times higher than on the fraction coarser than 37 µm (Figure 4). The deterioration on chemical quality as particle size gets finer, with a more prominent quality loss on the finer particles of clay is one of the key motivations to seek a minimization of fine particles bypass to the coarse flow.

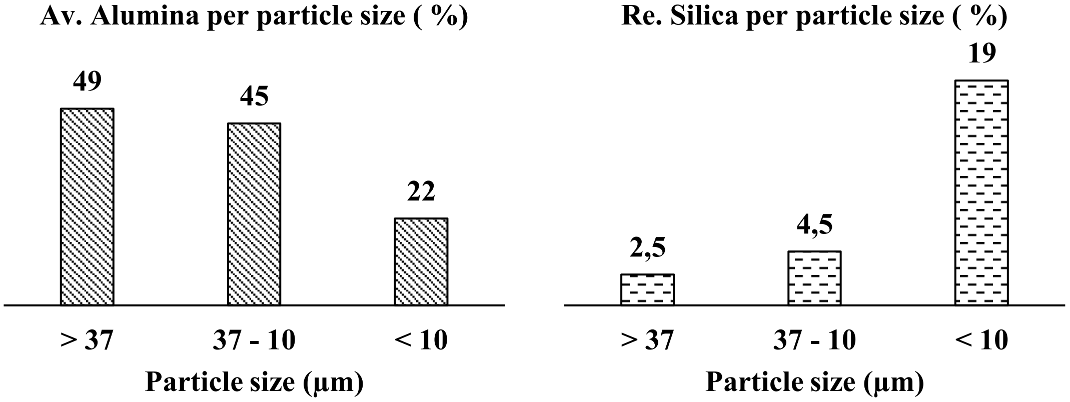

Figure 4. Pilot test feed chemical grade on different particle sizes.

Pilot tests feed specific gravity were on average 2.71 ranging between 2.70 and 2.72 g/cm³.

Chemical composition on pilot tests feed is shown in Table 1. On average, tertiary cyclone feed presented 43.95 % of available alumina and 5.96 % reactive silica.

Table 1. Pilot tests feed chemical analysis.

	Av. Alumina (%)	Re. Silica (%)	Al_2O_3 (%)	Fe_2O_3 (%)	SiO_2 (%)	TiO_2 (%)
Average	43.95	5.96	49.96	10.82	7.21	3.26
Minimum	42.87	5.12	49.27	9.70	6.27	3.09
Maximum	44.93	6.80	50.58	12.03	8.08	3.49

3.2 Pilot Tests

3.2.1 Silica Reduction on Pilot Tests

As shown in Figure 5, average pilot test feed reactive silica grade was 6.0 % and with the removal of low-grade fine particles on tertiary cyclones, average 3.3 % silica grade was achieved on the underflow.

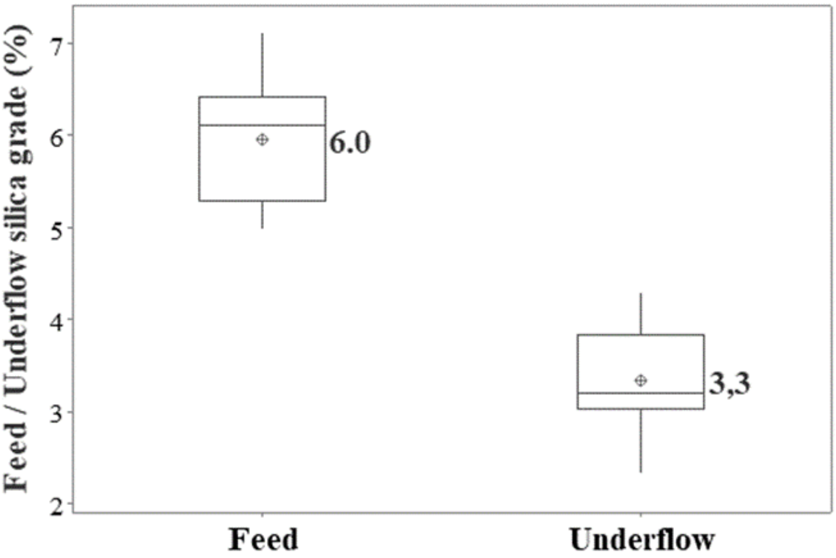

Figure 5. Pilot tests feed and underflow reactive silica grade.

Pilot test data was submitted to one tailed paired t test at a significance level α = 0.05 and null hypothesis could be rejected as there is a significative difference between reactive silica grade on pilot test feed and underflow. The results from statistical test are shown in Table 2.

Table 2. Paired sample t-test result

Sample size	Average difference	95% CI paired difference	Standard Deviation	p-value
20	2.6268	(2.3397; 2.9139)	0.61342	0.00

3.2.2 Effect of Pilot Tests Variables

Tertiary cyclone key objective is to reduce the bypass of low grade, fine particles to underflow and consequently reduce reactive silica grade on product. Table 3 presents the experimental order generated on tests DOE and results of fine particles bypass to underflow. Results ranged from 9.0 to 21.5 %, with lower values on tests with 44.5 mm apex.

Table 3. Experimental order and results of fine particles bypass to underflow.

StdOrder	TestOrder	CentralPoint	Block	Apex	Density	Bypass of fines
1	1	1	1	1.75	1.08	11.8
2	2	1	1	2.00	1.08	19.6
3	3	1	1	1.75	1.10	11.2
4	4	1	1	2.00	1.10	19.3
5	5	1	1	1.75	1.08	9.9

6	6	1	1	2.00	1.08	20.3
7	7	1	1	1.75	1.10	10.1
8	8	1	1	2.00	1.10	18.4
9	9	1	1	1.75	1.08	9.0
10	10	1	1	2.00	1.08	21.5
11	11	1	1	1.75	1.10	11.8
12	12	1	1	2.00	1.10	18.6
13	13	1	1	1.75	1.08	11.6
14	14	1	1	2.00	1.08	20.5
15	15	1	1	1.75	1.10	12.2
16	16	1	1	2.00	1.10	19.0
17	17	1	1	1.75	1.08	11.0
18	18	1	1	2.00	1.08	17.5
19	19	1	1	1.75	1.10	10.8
20	20	1	1	2.00	1.10	17.0

Figure 6 shows the standardized effects chart of fine particles bypass (<10 µm) for the analysis of significance of variables apex diameter and feed slurry density. Only apex diameter has significance over fine particles bypass and thus this variable was further analyzed.

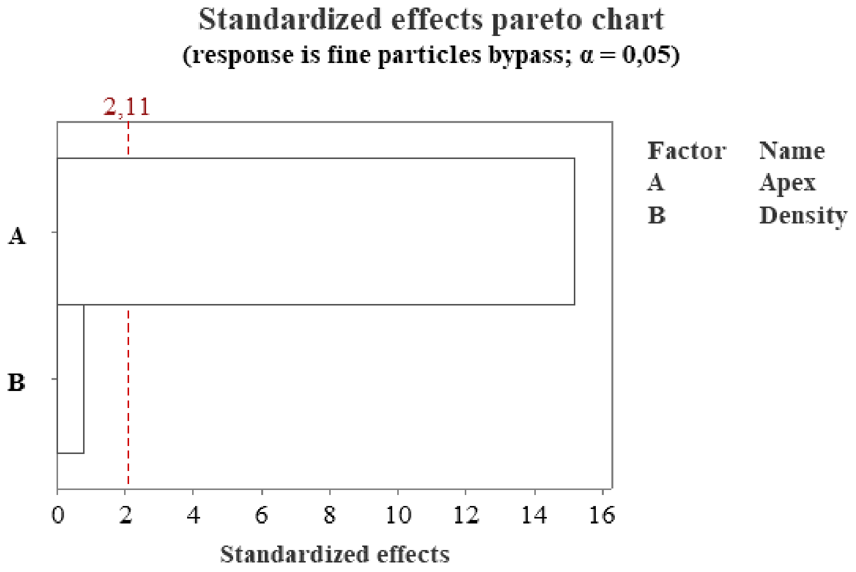

Figure 6. Standardized effects chart for fine particles bypass.

Figure 7 shows the partition to underflow for the two different levels of apex diameter and the three key particle size groups, >37 µm (coarse and high grade particles), 37 – 10 µm (mid-size and mid quality particles) and < 10 µm (fine and low grade particles).

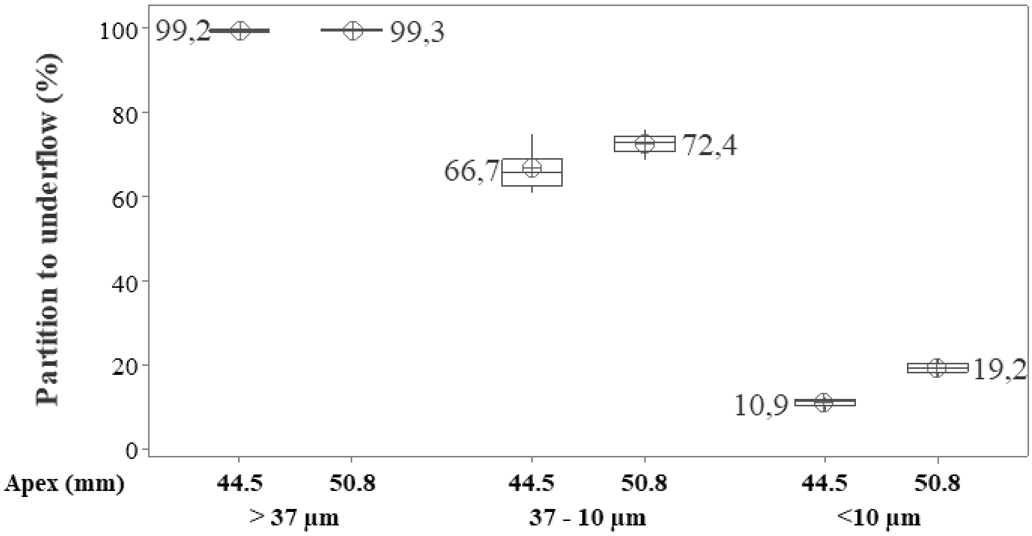

Figure 7. Partition to underflow for different particle sized and apex diameter.

To support statistical analysis of the results from different particle sizes partition to underflow with different apex diameters, t tests were carried out and the results are shown in Table 4. Null hypothesis (H_0) can be accepted for the particle size > 37 µm, as there is no significative difference between average recoveries to underflow with 44.5 mm and 50.8 mm diameter apex. Regarding to particle sizes between 37 and 10 µm and < 10 µm, null hypothesis (H_0) can be rejected, as there is a significative difference between average recoveries to underflow on different apex diameters.

Table 4. Estimation for difference and hypothesis test results.

Particle Size (µm)	Difference	95 % CI for difference	T-value	DF	P-value
> 37	-0.080	(-0.319; 0.159)	-0.71	17	0.489
37 – 10	-5.71	(-10.09; -1.32)	-2.86	11	0.015
< 10	-8.244	(-9.384; -7.105)	-15.34	16	0.000

Smaller apex diameter with 44.5 mm diameter presented a 10.9 % bypass of fine particles to underflow, 43 % lower when compared to 50.8 mm apex, that presented a 19.2 % bypass. The reduction on fine particles bypass was obtained keeping the same recovery levels for, high grade, coarser particles (> 37 µm) and an 8 % reduction (from 72.4 to 66.7 %) on the recovery of mid quality particles, between 37 and 10 µm.

Fine particles removal on pilot tests brought a reduction on available alumina recovery to product and an increase on reactive silica recovery to tailings when compared to the beneficiation plant as currently is, without tertiary cyclones, as shown in Figure 8. Average available alumina recoveries to product were 88.9 % and 89.8 % with 44.5 mm and 50.8 mm diameter apex respectively. Average reactive silica recovery to tailings were 56.9 % and 51.3 %, with 44.5 mm and 50.8 mm diameter apex respectively.

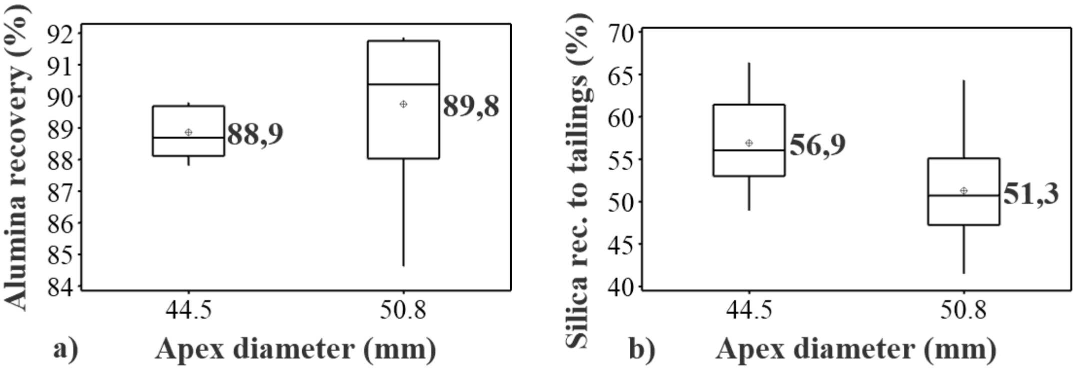

Figure 8. Available alumina recovery to product (a) and reactive silica recovery to tailings (b) on pilot tests.

In terms of main elements on the product, available alumina grades increased from pilot tests feed to product, while reactive silica grades decreased, as shown in Figure 9. Average available alumina upgrades were 1.106 and 1.083 with 44.5 mm and 50.8 mm diameter apex respectively. Average reactive silica downgrades were 0.536 and 0.587, with 44.5 mm and 50.8 mm diameter apex respectively.

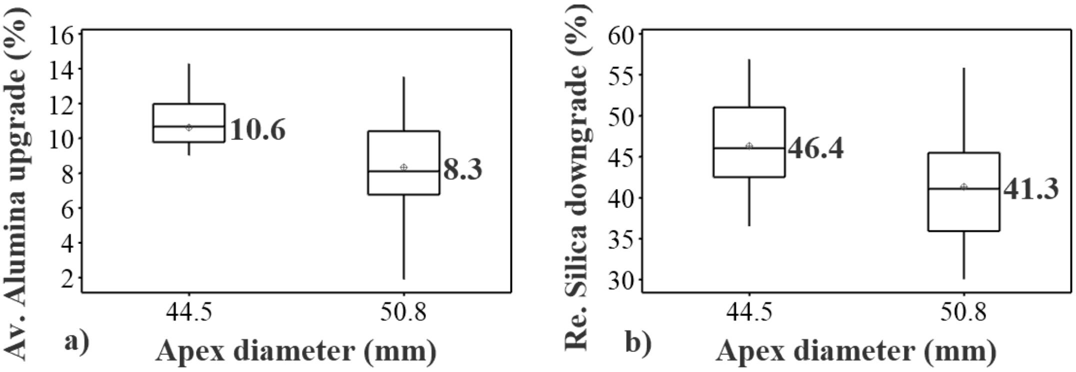

Figure 9. Available alumina upgrade (a) and reactive silica downgrade (b) to product.

4. Conclusion

Pilot tests have shown that tertiary cyclones can be a technical solution to increase available alumina and decrease reactive silica grades on bauxite beneficiation, keeping high levels of metallurgical recovery of alumina.

On the different apex diameter evaluated, average available alumina upgrade ranged between 1.083 and 1.106, while for reactive silica downgrade range was between 0.536 and 0.587.

Average metallurgical recovery of alumina ranged between 88.9 % and 89.8 % and reactive silica recovery to tailings ranged between 51.3 % and 56.9 %.

5. References

1. F. M. Meyer, Availability of Bauxite Reserves. *Natural Resources Research*, Volume 13, pages 161-172, September 2004, *Springer Science and Business Media LLC*.
2. Marcondes L. Costa et al., On the geology, mineralogy and geochemistry of the bauxite-bearing regolith in the lower Amazon basin: Evidence of genetic relationships, *Journal of Geochemical Exploration*, Volume 146, November 2014, *ELSEVIER BV*.

3. Peter Smith, The processing of high silica bauxites – Review of existing and potential processes. *Hydrometallurgy*, Volume 98, August 2009, *ELSEVIER BV.*
4. José F. Gomes et al., The formation of desilication products in the presence of kaolinite and halloysite – The role of surface area, *Hydrometallurgy*, Volume 203, August 2021, *ELSEVIER BV.*
5. Otávia M. Rodrigues et al., Kaolinite and hematite flotation separation using etheramine and ammonium quaternary salts. *Minerals Engineering*, Volume 40, January 2013, *ELSEVIER BV.*
6. Adão B. Luz, João A. Sampaio, Silvia C. França, *Tratamento de Minérios,* 5th Edition, Rio de Janeiro, CETEM/MCT, 2010. 932 pages.
7. Mandakini Padhi, Teja R. Vakamalla, Narasimha Mangadoddy, Iron ore slimes beneficiation using optimised hydrocyclone operation, *Chemosphere*, Volume 301, August 2022, *ELSEVIER BV.*
8. Ricky Q. Honaker et al., Ultrafine coal classification using 150 mm gMax cyclone circuits, *Minerals Engineering,* Volume 20, Issue 13, November 2017, *ELSEVIER BV.*