Increase in Metallurgical Recovery of Alumina on Bauxite Beneficiation with Small-Diameter Hydrocyclones

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Abstract

Bauxite is the main ore for metallic aluminium production, mainly consisting of aluminium hydroxide, iron oxides, titanium dioxides and kaolinite. Amazonian bauxite beneficiation usually consists in attrition to disaggregate deleterious clay minerals from the aluminous rocky matrix, followed by classification steps to remove fine particles which are discarded to tailings. At Mineração Paragominas, cut size to separate product and tailings is 37 µm, and characterization works have shown that there are mid-size particles in tailings, between 10 and 37 µm that could potentially meet product chemical specifications. Pilot scale tests have been developed using a 40 mm diameter hydrocyclone to process current tailings seeking the recovery of particles between 10 and 37 µm to product and generation of new tailings, finer than 10 µm. Different apex and vortex diameters, operating pressures and a multi-stage circuit were evaluated. The selected circuit had three classification steps, with the primary step fed with current Mineração Paragominas' tailings, the secondary step processing primary step underflow and the tertiary step processing secondary step underflow. The evaluated circuit product is the tertiary step underflow and tailings are the combination of primary, secondary and tertiary steps overflows. As a result, 30 % available alumina recovery was achieved, with 41 % available alumina grade in the product. In addition, the particle size distribution results showed a reduction in material passing through 10 µm (P_{10}) in the first stage feed from 78 % to only 20 % in the third stage underflow.

Keywords: Bauxite beneficiation, Alumina recovery, Hydrocyclone classification.

1. Introduction

In mineral processing, fine particles represent a major challenge, especially in flotation, compromising the separation process. There are negative effects associated to these fine particles (slimes) on the process, as they have a high surface area, which causes high reagent consumption and, in some cases, coating of the surfaces of larger particles, compromising the efficiency of the process, a phenomenon known as slime coating [1, 2]. Specially on Amazonian bauxite processing, slimes have an additional deleterious effect as those particles usually present a low concentration of available alumina, the main mineral, and high concentration of reactive silica, a gangue mineral [3].

An alternative to this issue is the use of hydrocyclones, equipment that has a high volumetric capacity and has numerous applications, being used in closed grinding circuits, in mineral slurries dewatering and in ores desliming for further flotation [4]. The separation principle of the hydrocyclone is centrifugal sedimentation: the slurry is introduced under pressure through a duct located in the upper part of the cylindrical section, resulting in a descending helical flow in which the larger and higher density particles are directed to the hydrocyclone wall, exiting at the bottom (apex) establishing the underflow, while finer and lower density particles and the majority of the water rise towards the vortex finder forming the overflow. The performance of the hydrocyclone is directly linked to its dimensions (conical and cylindrical section), characteristics of the ore and its operational variables [5]. Operational variables such as feed pressure and the diameter of apex and vortex finder can affect the classification size and hydrocyclone efficiency.

Present work objective was to process a bauxite beneficiation tailings sample that has a high amount of clay, seeking the recovery of mid-size particles to product with minimized contamination with fine particles of clay. Different cyclone geometry and operating pressures were evaluated seeking to reduce the presence of fine particles in the desliming circuit product to less than 20 % finer than 0.010 mm, making it suitable for eventual additional concentration in flotation steps.

2. Materials and Methods

2.1 Mineração Paragominas' Beneficiation Plant

At the existing Mineração Paragominas' beneficiation plant in Brazil three main circuits can be highlighted. The first one is responsible for the disaggregation between rocky, alumina rich, particles and fine clay, where most of the kaolinite is concentrated. The disaggregation is promoted by the attrition between bauxite constituents with water and grinding media, inside semi-autogenous grinding mills. The slurry of bauxite particles and water obtained as the product of the disaggregation step follows to the clay removal circuit, with a series of separation steps carried out on vibrating screens and hydrocyclones, where particles finer than 37 µm are removed to tailings. Coarser particles, with high available alumina and low reactive silica grades follows to the third circuit, with crushers and ball mills, where bauxite particle size is adjusted to meet the specification to be transported to the Alunorte alumina refinery through a 244 km long pipeline.

A simplified Mineração Paragominas' beneficiation plant flowsheet with the representation of process flow submitted to pilot tests is presented in Figure 1.

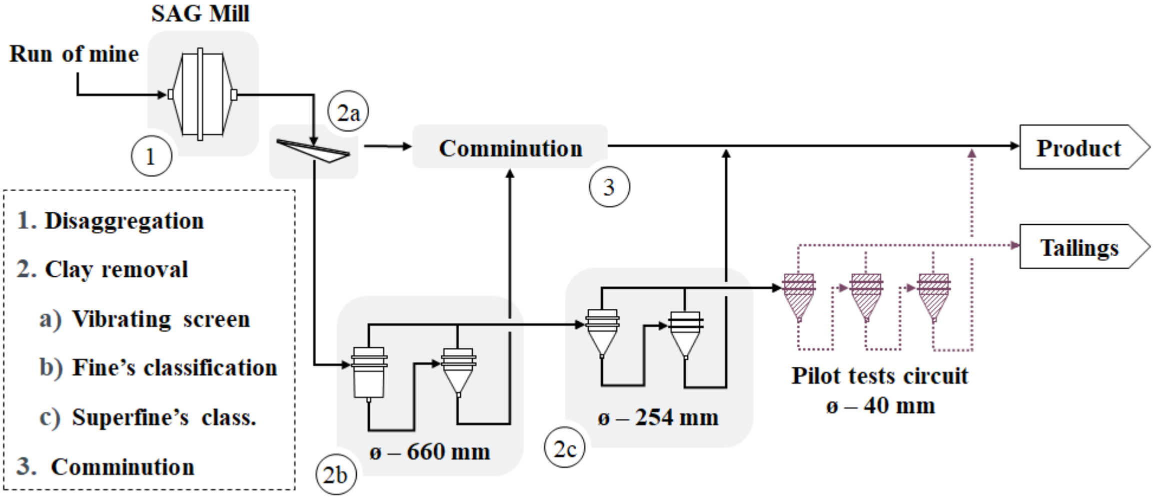

Figure 1. Mineração Paragominas' beneficiation flowsheet, indicating pilot test's location.

2.2 Pilot Equipment

Hydrocyclone tests were carried out using a 40 mm diameter cyclone at The Centre for Mineral Technology (CETEM), a research institute of the Brazilian Ministry of Science, Technology and Innovations (MCTI). A schematic view of the equipment used on the tests is shown in Figure 2.

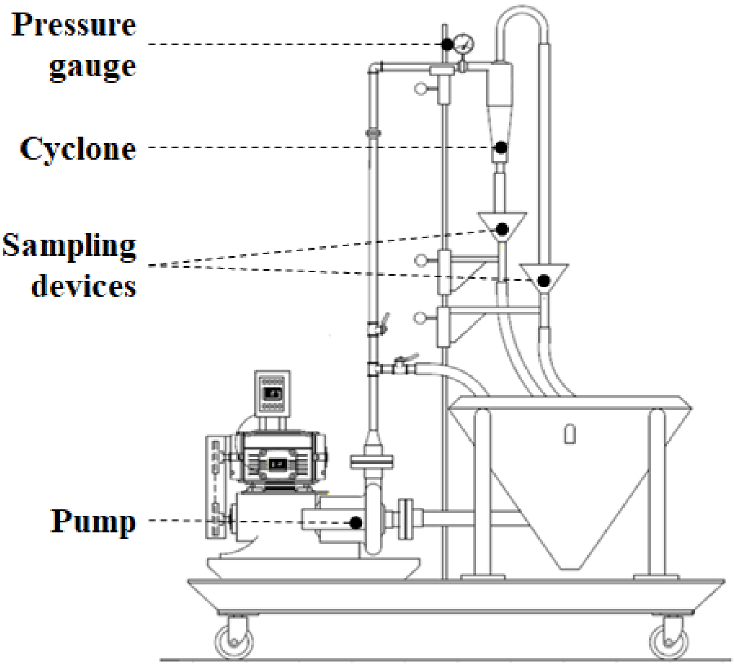

Figure 2. Schematic view of the hydrocyclone pilot tests used on the present work.

2.3 Materials and Characterization Methods

The tests were carried out with a sample of tailings from Mineração Paragominas' beneficiation process. Tailings sample characterization included particle size analysis by laser diffraction, solids specific weight by helium gas pycnometer and chemical analysis by X-Ray Fluorescence combined with bauxite digestion to determine available alumina and reactive silica grades.

Sample preparation for characterization started by separating an aliquot of slurry for particle size analysis followed by drying the remaining material in a lab stove at 105 °C to determine solids concentration by weight and further chemical analysis. For available alumina and reactive silica grades determination, after 25 minutes digestion with caustic soda in PARR bombs, at 150 °C, samples were submitted to slow filtration with #42 filter paper, generating two fractions:

- Liquor passing the filter paper: The liquor was prepared to the determination of available alumina grade using titration. The samples received hydrochloric acid, methyl red indicator, complexing agent CDTA, hexamethylenetetramine buffer solution, orange xylene indicator and were then submitted to titration with zinc sulphate solution on Oil Titrando 905 equipment.
- Solids retained on filter paper: The solid material from the filtration process were submitted to acid digestion with hydrochloric acid for further reactive silica analysis on Agilent 240 FS Atomic Absorption spectrometer.

Experimental data was balanced using JKSimMet, a software for mineral process modelling and simulation developed at Julius Kruttshnitt Mineral Research Centre (JKMRC), University of Queensland, Australia

2.4 Testing Plan

Multi-stage cycloning circuits are an option to improve classification efficiency. Several basic circuits are possible with hydrocyclones in series and the option of underflow re-classification can be a powerful solution to minimize fine particles by-pass to underflow [6]. A schematic representation of the classification circuit selected for the present work, with three classification stages is shown in Figure 3.

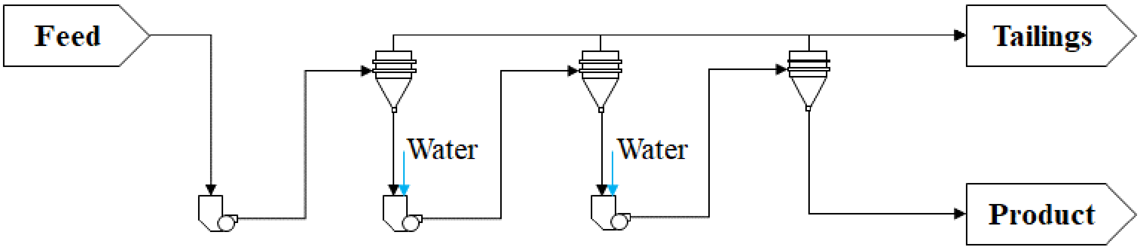

Figure 3. Schematic representation of the classification circuit selected for tests.

The first part of the testing plan was to evaluate the best operating condition for each of the three classification steps individually. Different operating pressures, apex and vortex diameters were tested for each classification step. Pilot test results were evaluated in terms of underflow and overflow particle sizes, connected to the present work objective, to separate from tailings to product flow, the fraction coarser than 0.010 mm. For each set of tests, a scatter plot with the percent of particles finer than 0.010 mm on the underflow, versus the percent of particles coarser than 0.037 mm on the overflow was evaluated. Optimum outcome from the tests would be to minimize both indicators, as lower presence of fine particles on the underflow, means lower presence of high reactive silica grade clay minerals, and lower presence of coarse particles on the overflow, means lower loss of high available alumina grade particles to tailings.

For the first step of classification, 8 different conditions were tested, as listed in Table 1, with feed solids concentration by weight of 8 %, reproducing tailings slurry characteristics from Mineração Paragominas' industrial operation.

Table 1. Operational conditions tested for 1st step of classification.

1st step			
ID	**Pressure (kPa)**	**Apex (mm)**	**Vortex (mm)**
1	200	5.5	12
2	400	5.5	12
3	200	7.0	12
4	400	7.0	12
5	200	4.5	12
6	400	4.5	12
7	400	7.0	10
8	400	5.5	10

Test ID 2 was selected to generate a sample for evaluating the performance of the secondary step. Testing condition to evaluate the secondary step of classification is presented in Table 2. For fine particles classification in hydrocyclones, low solids content and high-pressure drops are recommended [7], so primary step underflow received water dilution seeking solids concentration by weight of 15 % on secondary step feed. Same was applied to secondary step underflow prior to feeding the tertiary step of classification.

Table 2. Operational conditions tested for 2nd step of classification.

2nd step			
ID	**Pressure (kPa)**	**Apex (mm)**	**Vortex (mm)**
9	400	5.5	12
10	200	5.5	12
11	400	7.0	12
12	200	7.0	12
13	200	7.0	10
14	200	5.5	10

To evaluate the tertiary step of classification, two long run tests were carried out for feed sample generation as described in Table 3. One combining the operating conditions set as the best balance between product quality and coarse particles recovery: Test ID 2 for the primary step and Test ID 9 for the secondary step. The other one had in primary and secondary steps, setups that maximized coarse particles recovery, regardless of the concentration of fine particles in underflow: Test ID 7 for the first step and Test ID 14 for the second. The rationale was to potentially optimize the results by increasing overall circuit recovery in the first two steps and using the tertiary step to obtain a product with low concentration of fine particles. For the tertiary step itself (tests ID 17 to 24) hydrocyclone pressure was 400 kPa.

Table 3. Operational conditions tested for 3rd step of classification.

3rd step - 1st Campaign				**3rd step - 2nd Campaign**			
ID	**Step**	**Apex (mm)**	**Vortex (mm)**	**ID**	**Step**	**Apex (mm)**	**Vortex (mm)**
15	1	7	10	19	1	5.5	12
16	2	5.5	10	20	2	5.5	12
17	3	7	10	21	3	5.5	12
18	3	5.5	12	22	3	7.0	12
				23	3	4.5	10
				24	3	5.5	10

For each tested condition one sample was taken from underflow and overflow, keeping the same acquisition time, making it possible to dry and weigh the samples to calculate mass recovery to underflow by dividing underflow mass by feed mass (sum of under and overflow masses).

Circuit product, tertiary step underflow, was reserved to allow complementary studies seeking chemical quality improvement such as flotation and centrifuge classification. The tailings, hydrocyclones overflows, were transported back to Mineração Paragominas to be disposed in the tailings management system.

3. Results

3.1 Characterization

Table 4 shows the pilot tests head (feed) sample chemical and specific weight characterization. The results are consistent with typical Paragominas' tailings chemical composition and specific weight.

Table 4. Head sample chemical characterization.

Av. Alumina (%)	Re. Silica (%)	Specific weight (g/cm³)
16.1	23.6	2.8

Figure 4 shows the head sample particle size distribution, with 98 % passing 0.037 mm. Sample d_{80} is 0.012 mm, d_{50} 0.005 mm and d_{20} 0.002 mm. As for the chemical composition, particle size distribution is also consistent with typical Paragominas' tailings characterization.

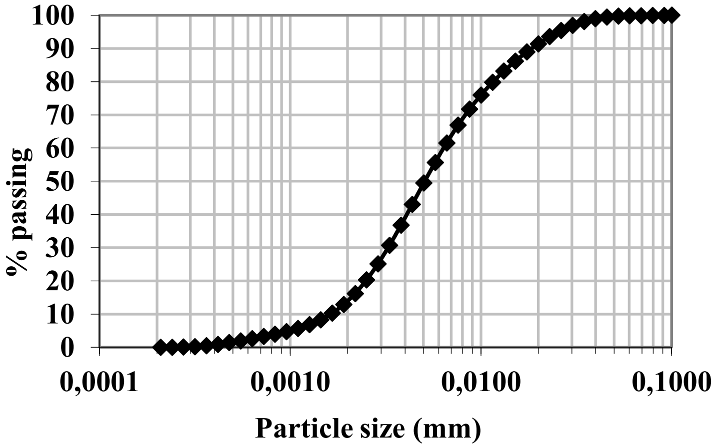

Figure 4. Head sample particle size distribution.

Material characterization from the different operating conditions tested on the pilot plant are shown in Table 5 to 9.

Table 5. Results from primary step of classification pilot tests (1/2).

ID	Flow	C_w (%)	Chemical composition (%)		Particle size (%)	
			Av. Al_2O_3	Re. SiO_2	Passing 0.010 mm	Retained in 0.037 mm
1	Overflow	7.6	12.4	26.0	80.7	3.0
	Underflow	20.7	27.6	14.6	42.4	9.8
	Feed	8.9	16.1	23.2	71.4	4.6
2	Overflow	7.4	11.7	26.5	85.6	1.3
	Underflow	19.3	26.5	16.1	47.1	7.6
	Feed	8.9	15.8	23.7	75.1	3.0
3	Overflow	6.9	12.2	26.4	85.9	1.6
	Underflow	14.1	23.4	18.2	64.7	4.4
	Feed	8.5	16.2	23.4	78.3	2.6
4	Overflow	7.2	11.9	27.1	83.7	1.6
	Underflow	15.0	23.9	17.7	62.4	4.6

	Feed	8.7	16.0	23.9	76.5	2.6
5	Overflow	7.7	10.7	22.2	82.4	2.7
	Underflow	24.1	29.6	13.5	42.2	11.3
	Feed	8.9	14.5	20.4	74.3	4.4
6	Overflow	8.7	12.7	23.0	83.3	1.9
	Underflow	24.7	29.5	11.0	63.4	7.3
	Feed	10.0	16.1	20.6	79.3	3.0

Table 6. Results from primary step of classification pilot tests (2/2).

ID	Flow	C_w (%)	Chemical composition (%)		Particle size (%)	
			Av. Al_2O_3	Re. SiO_2	Passing 0.010 mm	Retained in 0.037 mm
7	Overflow	7.2	11.0	24.0	85.5	1.7
	Underflow	12.4	20.4	17.7	74.0	2.3
	Feed	9.0	15.6	20.9	79.9	2.0
8	Overflow	7.3	11.3	24.6	92.8	0.3
	Underflow	13.8	21.9	15.5	63.4	7.3
	Feed	9.1	15.8	20.8	80.5	3.2

Table 7. Results from secondary step of classification pilot tests.

ID	Flow	C_w (%)	Chemical composition (%)		Particle size (%)	
			Av. Al_2O_3	Re. SiO_2	Passing 0.010 mm	Retained in 0.037 mm
9	Overflow	10.0	15.2	22.2	83.3	0.2
	Underflow	46.2	34.5	7.0	25.6	12.6
	Feed	16.7	25.1	14.4	53.8	6.6
10	Overflow	11.4	17.1	21.5	79.6	4.1
	Underflow	42.8	34.7	6.9	27.9	16.6
	Feed	17.4	25.3	14.7	55.4	9.9
11	Overflow	11.4	15.0	23.6	81.4	0.3
	Underflow	38.8	34.0	8.0	30.0	12.9
	Feed	17.9	24.8	15.5	54.9	6.8
12	Overflow	11.7	16.6	20.5	77.9	0.1
	Underflow	35.0	33.8	6.9	31.8	11.9
	Feed	17.1	24.8	14.0	55.9	5.7
13	Overflow	10.4	15.2	20.9	83.4	4.1
	Underflow	30.0	31.3	9.9	38.9	8.7
	Feed	16.9	24.7	14.5	57.2	6.8
14	Overflow	10.9	15.9	21.5	79.7	0.1
	Underflow	32.8	32.8	8.6	35.1	10.5
	Feed	16.9	24.8	14.6	56.0	5.6

Table 8. Results from tertiary step of classification pilot tests (1/2).

ID	Flow	C_w (%)	Chemical composition (%)		Particle size (%)	
			Av. Al_2O_3	Re. SiO_2	Passing 0.010 mm	Retained in 0.037 mm
15	Overflow	9.7	12.4	26.5	89.4	1.1
	Underflow	15.7	30.3	15.6	69.0	3.5

	Feed	12.1	21.5	21.0	79.0	2.3
16	Overflow	8.9	13.9	25.9	89.2	0.0
	Underflow	25.3	30.3	15.5	52.0	6.9
	Feed	13.3	22.3	20.5	70.0	3.5
17	Overflow	12.4	17.3	23.2	77.3	1.4
	Underflow	41.8	35.7	11.2	36.4	11.6
	Feed	14.1	30.0	15.0	49.1	8.5

Table 9. Results from tertiary step of classification pilot tests (2/2).

ID	**Flow**	**C_w (%)**	**Chemical composition (%)**		**Particle size (%)**	
			Av. Al_2O_3	**Re. SiO_2**	**Passing 0.010 mm**	**Retained in 0.037 mm**
18	Overflow	6.9	15.6	24.4	72.5	1.3
	Underflow	35.4	37.1	11.2	35.2	10.2
	Feed	15.6	30.5	15.3	46.7	7.5
19	Overflow	8.2	12.2	26.6	90.6	0.0
	Underflow	18.0	26.5	18.0	61.6	3.8
	Feed	10.4	17.6	23.3	79.6	0.0
20	Overflow	8.8	15.2	25.0	83.8	0.0
	Underflow	41.7	36.6	11.5	31.7	12.7
	Feed	14.6	25.9	18.3	57.8	0.0
21	Overflow	2.3	15.8	23.9	77.3	3.0
	Underflow	49.6	41.0	7.7	19.9	15.6
	Feed	11.2	36.8	10.4	29.5	13.5
22	Overflow	2.3	15.1	23.7	74.6	0.9
	Underflow	39.6	40.6	8.4	22.1	14.8
	Feed	11.0	36.5	10.8	30.4	12.6
23	Overflow	2.5	15.6	23.9	83.1	1.5
	Underflow	54.9	41.8	7.6	19.5	14.3
	Feed	12.1	37.4	10.4	30.3	12.1
24	Overflow	2.9	15.1	23.4	80.4	1.8
	Underflow	37.5	40.6	8.0	24.3	15.0
	Feed	13.9	36.9	10.3	32.5	13.1

3.2 Pilot Tests

Among the tested conditions for the primary step of classification, Test ID 2 was selected as the better balance between minimizing the presence of fine particles in the underflow and coarse particles in the overflow. The scatter plot with results from the primary step of classification is shown in Figure 5.

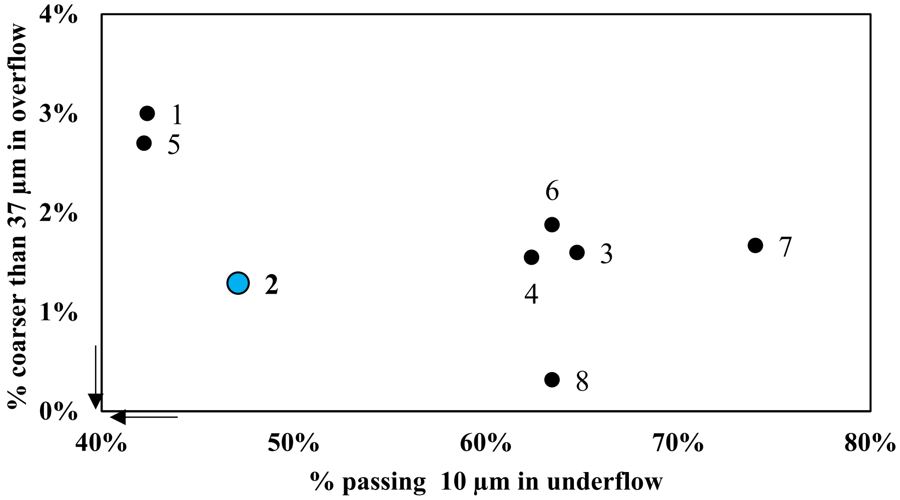

Figure 5. Primary step of classification: Performance on different operating conditions.

To generate a sample to test the secondary step of classification, a long run test was carried out for the primary classification step, with Test ID 2 operating conditions: pressure 400 kPa, apex diameter 5.5 mm and vortex diameter 12.0 mm.

For the secondary step of classification, Test ID 9 was selected as the best operating condition, combining the minimum concentration of fine particles in the underflow among the tested conditions, with near to zero presence of particles coarser than 37 µm in the overflow, as shown in Figure 6.

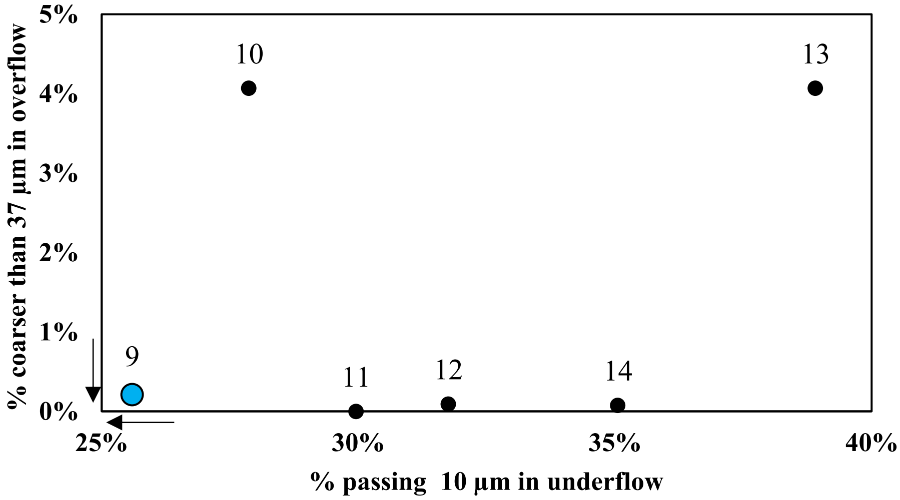

Figure 6. Second step of classification: Performance in different operating conditions.

Present work target of generating a product with less than 20 % of particles finer than 0.010 mm was achieved with operating conditions from Test ID 21 and Test ID 23, as shown in Figure 7. Test ID 23 presented lower loss high alumina grade coarse particles to overflow and was than selected as the best setup for the tertiary step of classification.

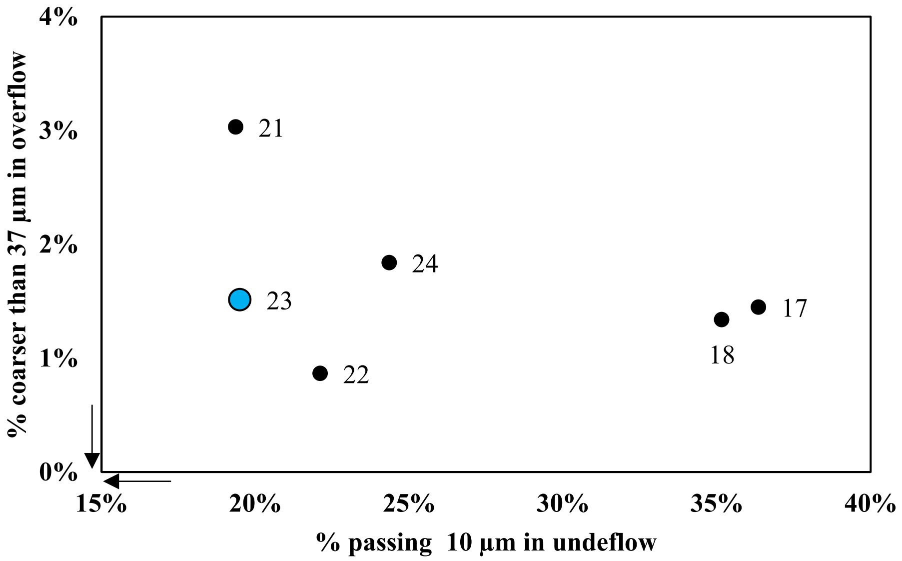

Figure 7. Third step of classification: Performance on different operating conditions.

Tertiary step tests carried out with feed samples generated seeking higher recoveries (Tests ID 17 and 18, tertiary step 1st campaign) presented on average 15 % (percentage points) more fines passing 0.010 mm when compared to Tests ID 21 to 24, fed with a sample generated seeking a balance between product quality and recovery. A summary of the balanced pilot test results in terms of mass, available alumina and reactive silica distribution in each classification step feed, overflow (OF) and underflow (UF) is shown in Table 10, together with chemical composition and the mass fraction finer than 0.010 mm.

Table 10. Summarized pilot test results.

Indicators	**Primary step** *Test ID 2*			**Secondary step** *Test ID 9*			**Tertiary step** *Test ID 23*		
	Feed	UF	OF	Feed	UF	OF	Feed	**UF**	OF
Mass distribution (%)	100.0	27.2	72.8	27.2	13.9	13.2	13.9	**11.5**	2.4
Av. Alumina distribution (%)	100.0	46.0	54.0	46.0	32.5	13.5	32.5	**30.1**	2.4
Re. Silica distribution (%)	100.0	18.5	81.5	18.5	6.2	12.4	6.2	**3.7**	2.4
Av. Alumina grade (%)	15.6	26.5	11.7	26.5	36.5	15.3	36.5	**41.0**	15.6
Re. Silica grade (%)	23.7	16.2	26.5	16.2	10.5	22.1	10.5	**7.7**	23.6
% passing 0.010 mm	78.2	55.8	86.6	55.8	29.8	83.1	29.8	**19.8**	77.2

4. Conclusions

The use of small-diameter hydrocyclones to process traditional Amazonian bauxite tailings seeking a higher recovery of available alumina to product has shown potential application from a technical perspective. With three classification steps in series, 30.1 % of available alumina was recovered to the product stream (tertiary step of classification underflow) with only 3.7 % recovery of reactive silica to product. Available alumina grade increased from 15.6 % in pilot plant feed to 41.0 % in the product, while reactive silica grade reduced from 23.7 % to 7.7 %. Nevertheless, the product obtained from the pilot tests has an alumina / silica ratio of 5.3, which is still low compared to current Mineração Paragominas' product specification and further beneficiation, through flotation for instance, could be beneficial.

5. References

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