

# THE FLOTATION OF A GIBBSITIC BAUXITE ORE

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## Abstract

Efforts are now being made to develop improved flotation technology for the efficient processing of low grade bauxite ores. Such resources are classified according to the primary bauxite mineral (gibbsite, boehmite, or diasporite) and according to gangue minerals (quartz, clays, iron oxides, etc.). The flotation response of gibbsitic bauxite ores with and without desliming is discussed with respect to flotation strategy, mineralogy, and liberation characteristics.

## 1. INTRODUCTION

Bauxite ore is the primary mineral resource for the production of aluminum metal through several physicochemical processes, the first producing alumina and the last producing, aluminum metal. The aluminum ore minerals in bauxite include gibbsite  $[\text{Al}(\text{OH})_3]$ , diasporite  $[\alpha\text{-AlO}(\text{OH})]$  and boehmite  $[\gamma\text{-AlO}(\text{OH})]$ . Gangue minerals generally include iron oxides (Hematite –  $[\text{Fe}_2\text{O}_3]$ , Goethite –  $[\text{FeO}(\text{OH})]$ ), silicates (quartz  $[\text{SiO}_2]$ , kaolinite  $[\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4]$  and others such as rutile/anatase  $[\text{TiO}_2]$ ). Bauxites are found mostly in lateritic regions (tropical areas) with gibbsite being the dominant mineral together with some boehmite. Bauxites can also be found in silicate rocks which are formed from the weathering of clays and clayey limestone and are known as karst bauxites (Andersen et al. 2009).

The production of aluminum metal generally is accomplished by the Bayer process, which is a wet chemical caustic leach process followed by crystallization and calcination, forming alumina. The alumina is then treated by the Hall-Heroult process, a fused salt electrolytic reduction to aluminum metal. The efficiency of production is dependent upon certain variables such as available alumina, reactive silica, impurities, and mineralogy. Thus, the efficiency of aluminum production varies with the bauxite characteristics of the feed material. Generally, high grade bauxite ore is fed directly to the Bayer process, but these high grade resources are being depleted. Low grade bauxite resources may require processing by flotation in order to prepare a material suitable for feed the Bayer process.

Current bauxite processing practice consists of crushing, for particle size reduction, scrubbing for removal of fines, and sometimes wet screening may be employed to remove silica minerals. Heavy media separation is also applied to remove high-iron bearing minerals, but the overall recovery is far from optimum. Recently, efforts have been made to establish a more selective process that can be applied to low grade bauxites with high silica-to-alumina ratio. Of all the bauxite-processing strategies, flotation is the most attractive and many researchers have been engaged in the study of bauxite flotation.

Flotation of bauxite can be done in a specific medium to separate the aluminum minerals from the silicates. After the initiative of Russian researchers (Andreev et al. 1973 and Balashova et al. 1979), Chinese researchers have made significant contributions to this field, and since 2000, several studies have been published by Hu et al., 2005; Zhao et al., 2010, among others, reporting advances in the flotation of diasporic bauxite ores. Bittencourt et al., have reported the flotation of kaolinite and quartz from gibbsitic bauxite ores. A lack of studies for this type of ore has been noted in the literature due to the generally higher grade resources available for gibbsitic ores compared to diasporic ores.

The world run-of-mine bauxite production in 2010 reached more than 200 million tons according to the United States Geology Survey, USGS. Australia leads the ranking with 70 million tons, followed by China and Brazil with 40 and 32 million tons respectively. The production growth rate over the last years has been, on average, 5% per year as indicated at USGS report.

## Flotation of Bauxite Ores in Industry

The first flotation plant for bauxite processing was installed in Zhongzhou, Henan Province, China. The ore contains 65% diasporite as the primary bauxite mineral with kaolinite, illite and pyrophyllite as the gangue silicate minerals. A grinding circuit with cyclones reduces the ore size and eliminates fines smaller than 45 microns which corresponds to 3.5% of the feed mass. The cyclone underflow is sent to flotation which includes one rougher, two scavengers and two cleaner stages. The plant has a yield of 78.8% and an aluminum recovery in the concentrate of 84.9% with a ratio of alumina to silica greater than 11 (Liu et al. 2005). Considerable flotation research has been done on Chinese bauxite ore and several review papers have been published (Hu et al. 2003). Flotation results also show that for a wide pH range, diasporite exhibits a better floatability than kaolinite with cationic collectors such as dodecylamine (Hu et al. 2003).

## Brazilian Bauxite Ores

In Brazil, there are two main bauxite areas with different mineralogy. One is located in the north region of the country (State of Para) and the other in the central-south region (State of Minas Gerais). While more than 85% of the total Brazilian bauxite production comes from the north region, the central-south region is also looking to expand plant capacity. Although the north region has high-grade aluminum deposits, the central-south region has better infrastructure for a plant installation and product distribution. Besides the high alumina content, the bauxite from the north region contains mostly kaolinite as the silica mineral, while the deposits from the central-south region contain both kaolinite and quartz.

Production in the north region reached over 30 million tons with a run-of-mine ore containing 55% alumina in average. The current practice at these plants consists of 'ore-washing', which consists of scrubbing to remove the natural fines and desliming by hydrocyclones after crushing and grinding, with an overall metallurgical recovery around 40% and mass recovery of 60%. A similar recovery is observed in the central-south region where 5 million tons are produced from an ore containing approximately 45% alumina processed through the 'ore-washing' process. Table 1 presents more details concerning these deposits and its production. Besides the alumina content, the bauxite ore from the Pará region differs from the Minas Gerais bauxite ores with respect to the silica mineralogy. The ore from the Pará region contains mostly kaolinite while the ores from the Minas Gerais contain mostly quartz.

**Table 1. Brazilian bauxite deposits and productions**

	Pará		Minas Gerais	
	Trombetas	Paragominas	Poços de Caldas	Cataguases
ROMS, Millions of tons	20.6	10.0	2.3	2.4
Alumina, %	55.0	55.0	45.0	45.0

Source: Brazilian Mining Institute, 2009  
§ Run of mine

Some efforts have been made to process the tailings from the washing process by flotation of the slimes. The strategy is based on the insoluble silica flotation followed by magnetic separation and results in a concentrate containing 54% available alumina and at a recovery of 81.2%. In this case, the ore was from a Minas Gerais deposit and the reagent schedule included ether amine as collector and starch as depressant at pH 10 (Massola et al. 2008).

#### Flotation of Kaolinite and Gibbsite

Some of the surface properties associated with the kaolinite crystal structure affects the wettability, aggregation, and dispersion. It is reported that adsorption may take place on both the faces and edges of kaolinite particles (Gupta et al., 2009; Hu 2004). The apparent point of zero charge of kaolinite varies from pH 3 to pH 4 while the PZC for gibbsite is around pH 9.0 (Hu et al. 2005; Miller et al. 2007). The most promising strategy for separating kaolinite from diasporic or gibbsitic bauxites is the reverse flotation strategy where the kaolinite is floated and the bauxite mineral is depressed.

Anionic flotation of gibbsite using fatty acids as collectors has been investigated by Andreev et al. (1973) and better flotation response was reported at pH higher than pH 9.0. The depression of kaolinite can be achieved with hexametaphosphate as reported by Balashova and Kuznetsov (1970). It was suggested that this effective depression of kaolinite by hexametaphosphate is due to the surface replacement of silicon tetrahedron by phosphorous tetrahedron (Black and Low 1950) but such consideration must require further investigation.

Direct flotation of a diasporic or a gibbsite concentrate is possible but it is uncertain if residual reagents will influence subsequent processing during digestion for alumina production. Finally it has been reported (Ma et al. 2009), that the flotation behavior of pure kaolinite with amines at various pH values and ionic strengths was opposite to that of oxide minerals such as quartz. The flotation of kaolinite depends on the type of the amine used as collector. In contrast to quartz, the flotation recovery of kaolinite increases with an increase in ionic strength (Ma et al. 2009). Generally, from the literature, it is evident that most bauxite ores are fine grained and only liberated at smaller particle sizes. In order to develop a

more efficient process capable of treating lower grade bauxite ores, experiments were designed for a gibbsitic bauxite ores, using a rod-mill grinding circuit followed by flotation with and without desliming. It is expected that issues such as liberation and fine particle flotation will be critical and are being given particular attention in this research program. Initial results are presented and discussed in this paper. As the necessity of treating lower grade bauxite ores arises, flotation technology must be considered. It is expected that higher grade and recovery can be achieved even when treating marginal bauxite ores with lower grades.

## 2. MATERIALS AND METHODS

### Gibbsitic Bauxite Ores

Samples were collected from the State of Para, in the eastern part of the Amazon region, at the Paragominas mine. The Miltonia gibbsitic bauxite deposits have formed by deep tropical weathering of the Ipixuna Formation. The bauxite layer forms a nearly continuous tabular body, less than 5m thick, but extending 20km north-south, and as much as 8km east-west, beneath the plateau surface. The geological profile of the Miltonia deposit has eight horizons, with lateral variation in thickness to characterize the two most significant lenticular horizons: Nodular Bauxite (BN) and the Crystallized Nodular Bauxite (BNC) (Silva et al. 2008)

A 45 kg sample of BN bauxite was obtained and prepared for mineralogical, chemical and liberation analysis and for the preliminary flotation experiments. A 10 kg bauxite sample from BNC bauxite scrubbed at 400 mesh by an attrition scrubber and deslimed at 15 microns after grinding was also received for preliminary flotation experiments.

### Analytical Measurements

#### X-Ray Diffraction

The mineralogical identification of both bauxite ores was performed by X-ray diffraction (XRD) in order to identify the alumina and silica minerals present in the sample. Three sets of samples were prepared for the direct Rietveld analysis technique in a Rigaku diffractometer and the patterns were analyzed by the program JADE.

#### X-Ray Fluorescence

The chemical composition of the BN and BNC bauxite ore was determined by X-ray fluorescence (XRF). The sample was fluxed with lithium borate and subsequently taken for XRF analysis in a Panalytical instrument, Axios Max - Minerals®.

#### Liberation Analysis by QEMSCAN®

Automated systems for liberation analysis using energy-dispersive scanning electron microscopy and energy dispersive spectroscopy (SEM-EDS) are being used by mineral processing engineers because of their ability to generate data for characterization of mineral distributions, associations and texture (Andersen et al. 2009). The QEMSCAN® is a widely used automated SEM-EDS technique.

Samples of BN bauxite ore and flotation products were prepared in polished sections for the feed, concentrate and tailing. The feed was divided into five size classes for analyses as follows: 150-200 mesh, 200-270 mesh, 270-325 mesh, 325-400 mesh and <400 mesh. The samples were prepared and analyzed to determine the overall mineralogy, an estimate of liberation, and the association of alumina and silica minerals before and after flotation. The method applied for analysis of the feed was the particle mineral analysis (PMA). The flotation products were analyzed from field images. The samples consist of polished-thin sections mounted in 25 mm-round epoxy plugs and were carbon-coated prior to analysis. Of course, with such 2D analysis of polished sections, the extent of liberation is overestimated.

## Flotation Batch Tests

### Direct Flotation Strategy

The procedure for preparing the flotation feed for direct flotation experiments was the same as describe previously for reverse flotation where the particle size of the ground feed was 85% less than 200 mesh. The flotation strategy consisted of one rougher stage followed by one cleaner stage as shown in figure 2. The percent solids during rougher flotation was 20% and sodium hydroxide was used for pH adjustment (between pH 10.5 and pH 11.0). Sodium silicate was used for dispersion of the fines while alkyl hydroxamate (monocarboxylic fatty acid and alkyl alcohol) produced by Cytec was used as collector. The conditioning time was fixed at 3 minutes, rougher stage of flotation at 5 minutes and cleaner stage of flotation at 3 minutes.

### Reverse Flotation Strategy

For the reverse flotation experiments, the sample was crushed by a roll crusher with an opening of 1.2 mm and then 250 grams of material was ground for 12 minutes with a rod mill at 50% solids to reach 85% passing 200 mesh and 55% passing 400 mesh. The flotation strategy consists of one rougher stage and one scavenger stage of flotation as shown in figure 1. The conditioning time was set at 3 minutes, the rougher flotation at 5 minutes, and scavenger stage at 3 minutes.

The percent of solids during rougher flotation was 25% and sulfuric acid was used for pH adjustment (between pH 3.5 and pH 4.0). Sodium hexametaphosphate (+80 mesh, 96% from Aldrich Chemicals) was used in solution for the dispersion of fines while for depression of the iron oxide minerals, in this case hematite, a modified starch (HX-927 from Cytec) was used. For these reverse flotation experiments, a condensate amine acetate (also called fatty amidoamine acetate) collector was selected based on previous bauxite flotation research in our department.

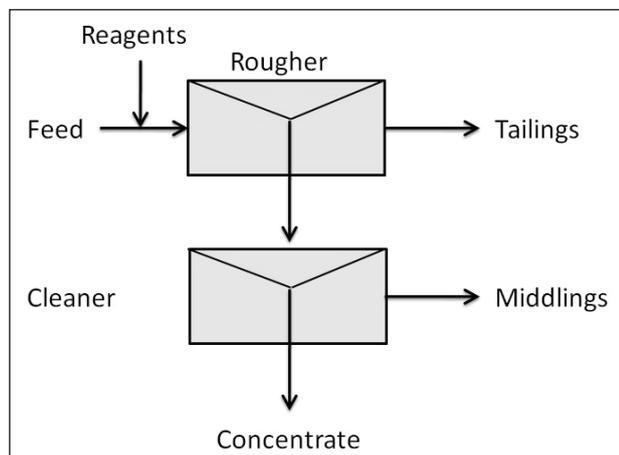


Figure 1. Direct flotation strategy for Paragominas bauxite ore with 'Tailings' and 'Middlings' as the froth product.

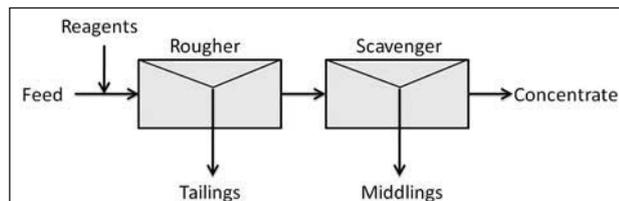


Figure 2. Reverse flotation strategy for the Paragominas bauxite ore with 'Concentrate' as the froth product.

## 3. RESULTS AND ANALYSIS

### X-Ray Diffraction

The mineralogical identification of both samples was performed using X-ray diffraction (XRD) in order to identify the main alumina and silica minerals present in the sample. The results revealed a small amount of quartz, insignificant for flotation considerations, suggesting that the main source of silica is from kaolinite. The results reveal also the presence of gibbsite as the major aluminum mineral, hematite and goethite as the iron minerals and anatase as the titanium mineral source.

### X-Ray Fluorescence

The chemical composition of the gibbsitic bauxite ore was determined by XRF analysis and the results are presented in table 2.

Assay [%]	Al <sub>2</sub> O <sub>3</sub>	SiO <sub>2</sub>	Fe <sub>2</sub> O <sub>3</sub>	TiO <sub>2</sub>	LOI	Al <sub>2</sub> O <sub>3</sub> /SiO <sub>2</sub>
BN	54,03	7,21	9,63	1,71	27,1	7,49
BNC	55,42	6,58	7,35	1,64	27,7	8,42

For both BN and BNC bauxites, estimations of the mineralogical composition based on chemical analysis reveals the mineral distribution as follows: 65 - 70% gibbsite, 10 - 14% kaolinite, 2 - 8% hematite, 1 - 3% anatase and 5 - 8% of other minerals.

Analysis made by the Paragominas plant laboratory in 2009 indicated the losses during scrubbing. The removal of particles < 400 mesh during scrubbing eliminated 28% mass of the BN bauxite and 37% mass of the BNC bauxite. Chemical analysis of BN bauxite revealed a significant presence of kaolinite in this fraction where SiO<sub>2</sub> content was 18.1%. The head analysis, particles > 400 mesh, revealed a significant presence of the gibbsite as the alumina content in this fraction, 46.3% Al<sub>2</sub>O<sub>3</sub> followed by 9.90% SiO<sub>2</sub>, 18.1% Fe<sub>2</sub>O<sub>3</sub> and 2.30% TiO<sub>2</sub> which is relatively lower grade than the BN bauxite sample received for this research but still falling within the range expected due to the variations of the BN and BNC layer in the ore body. The role of scrubbing is to eliminate the natural fines containing mostly kaolinite particles that keep the silica content at a high level for processing. This operation implies an alumina recovery of 82.1%, meaning that 17.9% of alumina is lost during the scrubbing operation.

### Liberation Analysis by QEMSCAN®

The BN sample was taken for liberation analysis using automated energy-dispersive scanning electron microscopy and spectroscopy (SEM-EDS, QEMSCAN). The material was crushed and ground for flotation feed, and divided into five size classes for liberation analysis as follows: 150-200 mesh, 200-270 mesh, 270-325 mesh, 325-400 mesh and <400 mesh. The method applied for analysis of the flotation feed was particle mineral analysis (PMA). The polished sections were analyzed for the major mineral constituents and special attention was given to the aluminum oxides and silicates (clay minerals).

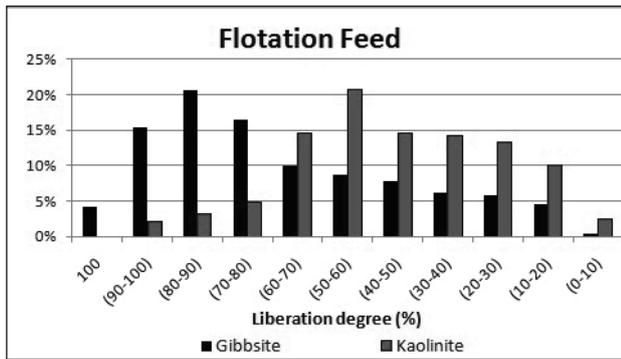


Figure 3. Liberation analysis of gibbsite and kaolinite from composite feed (90% minus 200 mesh), all particle size classes – BN bauxite.

The aluminum oxide minerals (gibbsite) exhibited a greater degree of liberation than the clay minerals (kaolinite and illite). More than 50% of the aluminum oxide minerals were found in particles with a composition exceeding 70%, which means that for particles exceeding 70% aluminum oxide, the extent of liberation was greater than 50%. In contrast, the clay minerals were not so well liberated. Only 8% of the clay minerals were found in particles containing more than 70% of clay. Most of the clay minerals were found in particles that contain less than 50% of clay. The feed distribution also had fines less than 10 microns that may have been associated with iron oxides minerals such as hematite.

### Flotation Results – Without Desliming

#### Reverse flotation

Table 3 presents the yield, grade and recovery for reverse flotation of the BN bauxite ore. The reverse flotation reagent schedule was adjusted to meet the alumina/silica ratio specifications and the corresponding grade and recovery are reported.

**Table 3. Reverse flotation results for BN bauxite without desliming. Collector concentration 400 g/ton.**

	Yield	Grade		Recovery		Al <sub>2</sub> O <sub>3</sub> /SiO <sub>2</sub>
		Total Al <sub>2</sub> O <sub>3</sub>	Total SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	SiO <sub>2</sub>	
Concentrate	69,30	57,10	5,81	70,40	60,24	9,83
Middling	9,53	54,70	8,06	9,28	11,49	9,34
Tailings	21,17	53,90	8,92	20,31	28,26	8,34
Feed	100,0	55,77	6,68	100,0	100,0	8,34

#### Direct flotation

Table 4 presents the yield, grade and recovery for direct flotation of the BN bauxite ore. The reagent schedule for the direct flotation experiment was adjusted to meet the same alumina/silica ratio specifications and the corresponding grade and recovery are reported.

	Yield	Grade		Recovery		Al <sub>2</sub> O <sub>3</sub> /SiO <sub>2</sub>
		Total Al <sub>2</sub> O <sub>3</sub>	Total SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	SiO <sub>2</sub>	
Concentrate	70,30	58,20	5,85	72,90	59,75	9,95
Middling	13,84	52,70	8,89	12,99	17,87	9,02
Tailings	15,86	49,90	9,71	14,10	22,38	8,15
Feed	100,0	56,12	6,88	100,0	100,0	8,15

### Flotation Results – With Desliming at 15 microns

#### Reverse flotation

Table 5 presents the yield, grade and recovery for reverse flotation of the deslimed BNC bauxite ore. The reverse flotation reagent schedule was adjusted to meet the alumina/silica ratio specifications and the corresponding grade and recovery are reported.

**Table 5. Reverse flotation results for BNC bauxite with desliming at 15 microns. Collector concentration 200g/ton.**

	Yield	Grade		Recovery		Al <sub>2</sub> O <sub>3</sub> /SiO <sub>2</sub>
		Total Al <sub>2</sub> O <sub>3</sub>	Total SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	SiO <sub>2</sub>	
Concentrate	71,84	56,50	5,57	73,11	58,58	10,14
Middling	19,21	53,40	9,79	18,46	27,53	8,64
Tailings	8,94	52,72	10,61	8,48	13,89	8,13
Feed	100,0	55,56	6,83	100,0	100,0	8,13

#### Direct flotation

Table 6 presents the yield, grade and recovery for direct flotation of the deslimed BNC bauxite ore. The reagent schedule for the direct flotation experiment was adjusted to meet the same alumina/silica ratio specifications and the corresponding grade and recovery are reported.

**Table 6. Direct flotation results for BNC bauxite with desliming at 15 microns. Collector concentration 1000 g/ton.**

	Yield	Grade		Recovery		Al <sub>2</sub> O <sub>3</sub> /SiO <sub>2</sub>
		Total Al <sub>2</sub> O <sub>3</sub>	Total SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	SiO <sub>2</sub>	
Concentrate	62,65	58,30	5,51	65,80	50,44	10,58
Middling	10,79	52,80	9,78	10,30	15,42	9,37
Tailings	26,55	49,90	8,81	23,90	34,14	8,11
Feed	100,0	55,48	6,84	100,0	100,0	8,11

## 4. DISCUSSION

Mineralogical characterization of Paragominas bauxite ore was made by XRD, XRF and QEMSCAN®. Gibbsite was identified as the predominant aluminum mineral while kaolinite was identified as the predominant silica mineral. The complex texture and liberation features make flotation without desliming somewhat challenging. The presence of fines has a significant impact on flotation selectivity but the results show that the flotation strategy is promising. Fine particles, defined in the range of 4-20µm, possess low collision efficiency with bubbles and the subsequent bubble-particle attachment probability is limited. In practice, fine particle flotation can be improved by allowing long residence times and by working at high collector dosages. Several technologies have been developed which aim at increasing bubble-particle collision efficiency, either by decreasing bubble size or by increasing apparent particle size (Miettinen, et al., 2010).

The data reported in the literature indicate a PZC of kaolinite varying from pH 4.2 to less than pH 3.0. The PZC for gibbsite occurs at pH 8.9. The heterogeneity and the unique structure of the kaolinite particles such as the difference in charge at the edge and face surfaces (Gupta and Miller, 2010) may account, in part, for these results. Based on the classical explanation for the cationic flotation of oxides and silicates, good flotation with a cationic collector in the pH region where the mineral surface

is negatively charged should be expected (Smith and Akhtar 1976) but such is not the case with kaolinite (Hu et al 2005). The aggregation of particles at low pH and the dispersion at higher pH also may account for the anomalous flotation response of fine kaolinite particles.

The fine particles (less than 45 microns) generated after rod-mill grinding, represent more than 50% of the particle mass and would have a significant impact on the reagents dosage if part of it, was removed before flotation. Although a desliming process would be more desirable for flotation efficiency, the overall recovery of the aluminum oxide minerals is of greatest concern. In order to accomplish flotation with this large amount of fines, reagent consumption is quite high. In the case of reverse flotation without desliming, the collector dosage used was 400 grams per ton while for direct flotation, 2,000 grams per ton of collector was required to meet with grade and recovery specifications. On the other hand, the removal of particles less than 15 microns, required half or less collector to accomplish with the same product quality. The overall recoveries in the case of deslimed flotation were slightly lower, in the range of 60-63% considering the losses during desliming, while the recoveries with the non-deslimed were around 70-72%.

Further study of the phenomena involved in the dispersion and aggregation of the colloidal clay particles is required for an improved design of the flotation process for the separation of kaolinite from bauxite ore. The QEMSCAN® liberation analysis of the reverse flotation products (bauxite concentrate and silica tailings) also provides more evidence to support the flotation

strategy considered. Figure 4 reveals the degree of liberation for the concentrate and tailings products for both aluminum oxides (gibbsite) and clay minerals (kaolinite). In the concentrate, almost 90% of the aluminum oxide particles are found with a composition exceeding 50% while all clay minerals particles have a composition of 30% approximately. In contrast, the composition of clay minerals particles in the tailings was found in the range of 50-60% while the aluminum oxide particles have no more than 20% mostly.

## 5. SUMMARY AND CONCLUSIONS

The flotation of low grade bauxite ores has been studied extensively in recent years and new reagents schedules and flotation strategies have been developed. This includes the development of new collectors for the removal of clay minerals (kaolinite) from bauxites ores. Both direct and reverse flotation without desliming resulted in alumina recoveries around 70% for aluminum oxide with ratios of alumina to silica in the alumina oxide product of about 10. The desliming of fines would be an effective alternative for bauxite processing, especially for lower grade ores. But due to the overall losses and recoveries from desliming operations, it may be necessary to develop flotation technology for the fine material. While flotation without desliming is desired in order to avoid alumina losses, the presence of slimes leads to high levels of reagent (collector) consumption and a corresponding increase in operating cost. The economic balance between these two factors is a major issue which must be considered in the development of flotation technology for the processing and recovery of aluminum oxide minerals from bauxite ores.

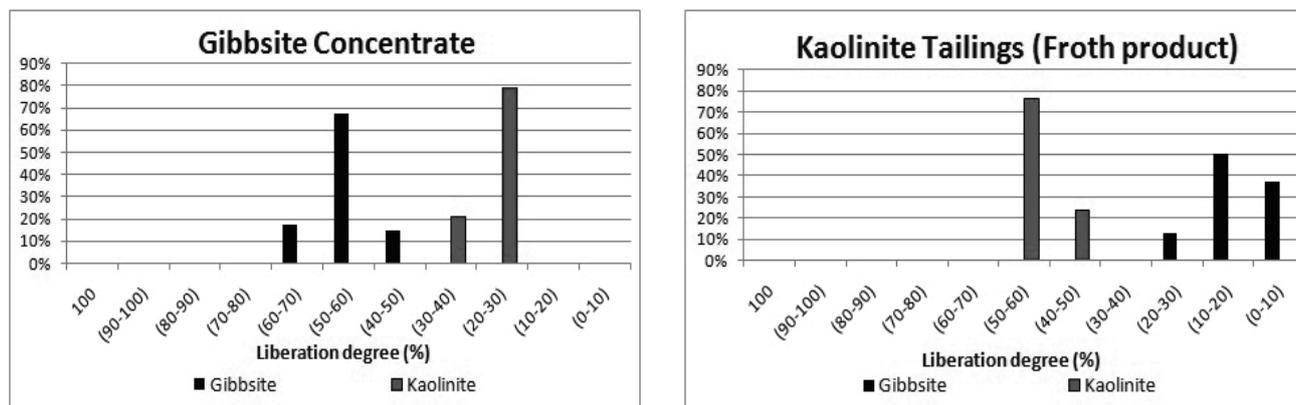


Figure 4. Liberation degree of gibbsite and kaolinite in the (a) concentrate (b) tailings. Reverse flotation of the BN bauxite ore.

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